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Edited by:
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FRODE DREVLAND
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AUT
School of Future Environments AUT
Lean Construction Australia and New Zealand

Proceedings of the 32nd Annual Conference of the International Group for Lean Construction (IGLC 32)

Dayana Bastos Costa, Frode Drevland and Laura Florez-Perez (editors)

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Proceedings of IGLC32

32^{nd} ANNUAL CONFERENCE
of the
INTERNATIONAL GROUP
for
LEAN CONSTRUCTION

Edited by
Dayana Bastos Costa

Frode Drevland

Laura Florez-Perez

Conference Chair

Mani Poshdar

Auckland

New Zealand

July 1th – 7^{th} 2024

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FOREWORD

When planning the 32nd Annual Conference of the International Group for Lean Construction (IGLC32) in New Zealand, we anticipated challenges due to its remote location. Reflecting on the dip in participation seen at IGLC23 in Perth, Australia, we were prepared for a potentially smaller turnout. However, we are delighted to report that this year's conference attracted significant global participation. While this year's 110 published papers mark a decrease from last year's record of 150 in Lille, France, the number aligns well with recent trends at IGLC conferences.

This year's proceedings reflect contributions from authors affiliated with institutions in over 25 countries, as detailed in Table 1. Notable themes include the integration of lean principles with emerging technologies, such as digital twins, artificial intelligence, and BIM, highlighting how these innovations enhance decision-making and workflows. The synergy between lean and sustainability is another key focus, with studies addressing circular economy practices, waste reduction, and carbon emissions.

Table 1 Papers published per country

Country of the first author's institution	Published papers
Brazil	16
Australia	10
Peru	10
USA	10
Finland	8
Germany	7
New Zealand	6
Norway	6
United Kingdom	6
Canada	5
Chile	5
Denmark	3
India	3
Indonesia	3
Israel	2
Colombia	1
Estonia	1
France	1
Ireland	1
Japan	1
Mexico	1
Qatar	1
South Africa	1
Switzerland	1
Zimbabwe	1
TOTAL	**110**

Production system optimization continues to be a vital area of research, with significant work on takt planning, cycle time variability, and modular construction. The human aspect of lean is also well-represented, with papers exploring collaboration, communication, and psychological safety within construction teams. Education and knowledge transfer, critical for lean adoption, are emphasized in studies on effective training programs, while lean's impact on health, safety, and quality remains a cornerstone of ongoing research.

Table 2 Papers per track

Track	Papers submitted	Papers accepted
Lean Theory	5	3
Product Development, Value and Design Management	5	4
Contract and Cost Management	9	8
Production System Design	9	7
Production Planning and Control	29	24
Health, Safety and Quality	4	3
Supply Chain Management	2	2
BIM and Enabling Lean with Innovative Technology	20	16
Modular and Off-Site Construction	11	10
Lean and Green	13	13
People, Culture and Change	20	17
Learning and Teaching Lean	3	3
TOTAL	**130**	**110**

A rigorous double-blind peer review process ensured the quality of these proceedings. This would not have been possible without the dedicated efforts of our 12 track chairs (Table 2) and 143 reviewers from 35 countries, who contributed their time and expertise. Their contributions reflect the collaborative spirit of the IGLC community.

Table 2 Track chairs

Track	Track chair name and affiliation
Contract and Cost Management	Thais Alves *San Diego State University, USA*
BIM and Enabling Lean with Innovative Technology	João Soliman Junior *University of Huddersfield, UK*
Lean Theory	Olli Seppänen *Aalto University, Finland*
Health, Safety and Quality	Fidelis Emuze *Central University of Technology, Free State, South Africa*
Learning & Teaching Lean	James Smith *Brigham Young University, USA*
People, Culture and Change	Paz Arroyo *DPR Construction, USA*
Production Planning and Control	Farook Hamzeh *University of Alberta, Canada*
Product Development, Value and Design Management	Rodrigo Herrera *Pontificia Universidad Católica de Valparaíso, Chile*
Production System Design	Carlos Formoso *Federal University of Rio Grande do Sul, Brazil*
Lean and Green	Professor Kristen Parrish *Arizona State University, USA*
Supply Chain Management	Emmanuel Daniel *University of Wolverhampton, UK*
Modular and Off-Site Construction	Beda Barkokebas *Pontificia Universidad Catolica de Chile*

We extend our heartfelt gratitude to the local organizers at the Auckland Institute of Technology, whose dedication made this event possible. In particular, we would like to thank the Conference Chair, Mani Poshdar, for his exceptional leadership and commitment. Their hard work ensured that this conference not only succeeded logistically but also fostered an engaging and inspiring environment for participants.

We hope these proceedings inspire continued innovation and collaboration, advancing lean construction toward a more efficient, sustainable, and inclusive future.

Dayana Bastos Costa, Frode Drevland, Laura Florez-Perez

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LEAN CONSTRUCTION FOR INNOVATION: A SYSTEMATIC REVIEW OF IGLC PROCEEDINGS

Darcy Zelenko [1] and Duncan Maxwell [2]

ABSTRACT

The implementation of Lean Construction (LC) is hindered by a lack of comprehensive understanding of innovation in the built environment, making it hard for firms to implement potential improvements. This paper contests that a consideration of LC as innovation can stimulate greater uptake, because it encourages firms to think more broadly about its implementation. The study aims to understand contributions to innovation scholarship from the perspective of LC, and to build an argument for considering LC as innovation to increase uptake. Papers published in IGLC conferences across the last 25 years form the basis for a systematised literature review (SLR), that utilises thematic analysis to synthesise understandings about innovation from the LC community. From the findings, six major themes emerge relating to innovation that are prominent in the reviewed literature: Relationship of LC to Innovation, Innovation Models, Barriers, Drivers, Innovation Strategy Essentials, and Collaborative Efforts. The paper argues that LC be considered an innovation for construction in and of itself, and a theoretical model is presented to aid understanding of LC as innovation. Future research pathways are identified, for example workshops with LC experts and practitioners to verify and expand the findings of this paper.

KEYWORDS

Innovation, Lean construction, Built Environment

INTRODUCTION

LC is a production management philosophy that seeks to minimise waste and increase value (Koskela et al., 2002). It has been demonstrated to be a contributor to addressing issues of stagnant productivity in the construction sector (Li et al., 2012). It is based on the following underpinning principles; value, value stream, flow, pull, and perfection (Bertelsen & Koskela, 2004) These principles are enacted through implementing key lean practices of; Just In Time (JIT), Total Preventative Maintenance (TPM), Total Quality Management (TQM), and Human Resource Management (HRM).

The term Lean Production (LP) was coined by John Krafcik in his Master's thesis and came to prominence as a catch-all for the principles underpinning Ohno's Toyota Production System as a result of the influential study of Womack et al., published as *The Machine That Changed The World* (Leong et al., 2015). LP can be considered a form of managerial innovation (Belfanti, 2018), and first radically transformed the Japanese automotive industry. The adoption of Lean's counterpart in construction has yet to take hold in the sector — in as comprehensive

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a way as the global automotive production sector — and productivity in the sector continues to stagnate. Reasons for the inability for Lean to take hold in construction relate to insufficient knowledge, a lack of sufficient training, and issues relating to maturity of the concept. Across the past decade, studies have demonstrated an industry awareness for LC in a general sense (Gao et al., 2020) but practitioners are less aware of specific associated principles and tools and as a result uptake has remained limited (Ahmed et al., 2020). Although Lean can be likened to a tool to enable innovation, in construction this been limited to minor changes of a technical nature.

INNOVATION

Influential economist Joseph Schumpeter developed an understanding of *"innovation"* as "any *"doing things differently"* in the realm of economic life" (Schumpeter, 1939). He details these differences as five types of innovation:

- Introduction of a new good, or a new quality to an existing good.
- Introduction of a new process to a specific industry
- Inception of a new market
- Creation of new supply lines of input materials
- Organising industry in a new way

Innovation in construction is often linked to the interpretation of the sector as a 'product system' (Blayse & Manley, 2004). The prevailing definition of the term in construction is that proposed by Slaughter (1998) as *"…the actual use of a nontrivial change and improvement in a process, product, or system that is novel to the institution developing the change."* Xue et al. (2014) calls for a more holistic understanding of innovation, absent in recent contributions. Innovation diffusion theory offers holistic ways to consider the diffusion of new methods or technologies (Rogers et al., 2014). This knowledge is used by firms and institutions to inform decisions about innovation investment to ensure the most optimal allocation of resources in pursuit of growth (Sundbo, 1995). Schumpeter established a wide range of interpretations of innovation, however the prevalent interpretation by Slaughter constrains the meaning. The is a gap of understanding between what innovation can be perceived as more generally, and the construction-specific interpretation of the term. As a broad production management philosophy, LC provides a more holistic lens from which to broaden interpretation of innovation.

SCOPE OF INVESTIGATION

This scope of this paper is limited to describe innovation across the construction value chain and focuses on activities that are crucial to the creation of buildings. Despite this narrow focus, there are influences of construction innovation, situated within the wider built environment. The nomenclature used in this paper reflects this thinking.

Koskela (1992) defines construction as a production-focussed sector, involving the design, and assembly of objects that are by nature, fixed in place. The products of construction are unique due to the combination of production-based factors that differentiate buildings (physical structures) from other things that humans create. Bertelsen and Koskela (2004) outlines 'peculiarities' that differentiate construction projects from the outputs of other production-based sectors as; possessing a one-of-a-kind nature, existing in situ, through the cooperation of temporary multi-disciplined teams.

OBJECTIVES AND STRUCTURE

The objectives of this paper are: to understand the contributions to innovation theory made by the IGLC community; to discern if there is precedent within the community for the philosophy of LC to be considered as innovation; and if so, to understand how can this precedent can be used to increase innovation uptake in the construction sector.

A SLR and thematic analysis is used to analyse innovation scholarship from the IGLC proceedings database — representing the state-of-the-art in LC research and practice — from the past 25 years. The results are synthesised into six themes that help to address the objectives. The discussion reflects on the results of the SLR to make the argument for considering LC as innovation. Such a consideration allows for a more holistic approach to be taken to understand and implement LC. The construction innovation model being developed as part of a PhD research project is then refined, utilising the inputs of the SLR to present an LC-specific innovation model to assist LC practitioners increase implementation. The paper contributes new knowledge to innovation theory from the IGLC community, and makes the argument to consider LC as a form of management innovation to enable greater uptake. The paper concludes by outlining implications for research, discussing limitations of the study, and highlighting potential opportunities for future work to verify and refine the findings.

METHODOLOGY

The approach to research taken by the study was to utilise a SLR, and thematic analysis to synthesise the findings. SLRs provide a structured and transparent process to undertake a qualitative analysis, that is reproducible and reliable (Tranfield et al., 2003). Thematic analyses are useful in the context of this paper because they enable the extraction of common themes and divergent perspectives from a wide array of studies, essential for synthesising broad research findings (Braun & Clarke, 2006).

The following research question was formulated to direct the SLR:

What is the relationship between LC and innovation from academic literature, across the past twenty-five years?

To answer this question the IGLC database was searched for papers mentioning ‘innovation’ across the past 25 years through Google Scholar and Publish or Perish (Harzing, 2007). For efficiency, a majority (300) of the 514 entries returned (according to Google Scholar ranking) were selected for review. These 300 papers contained no duplicates and were initially screened for eligibility. The criteria for initial eligibility were that a paper had to propose new knowledge about innovation in the built environment, through the inclusion of model, framework, or formulated understanding, that was not part of a literature review, or background section. The initial screening process reduced the pool of papers down to 24 for subsequent thematic analysis. QSR Nvivo 14 was the platform chosen to analyse the data collected (QSR International, 2024). A ‘lean-coding’ approach was utilised for the researcher to create a focused initial pool of themes and codes to commence data analysis, that was then refined or expanded as necessary (Creswell, 2013).

RESULTS

SAMPLE ANALYSIS

Thematic analysis was used to analyse the 24 eligible papers from the IGLC database and derive codes relating to the furthering the understanding of innovation in the built environment. The distribution of publications from 1999 to 2023 (Figure 1) shows that research activity concerning Lean Construction and innovation has been ongoing. There is a wide geographical distribution of papers (Figure 2) across different continents suggesting the potential for international collaboration. The United States is the country that has produced the most amount of research about innovation in the context of IGLC proceedings.

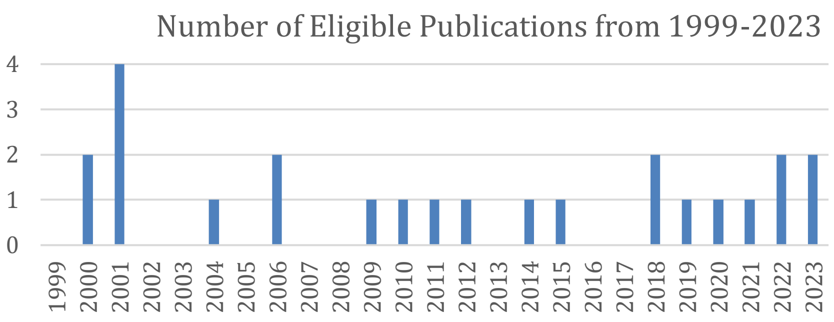

Figure 1 - Number of publications per year, from 2010 to 2021

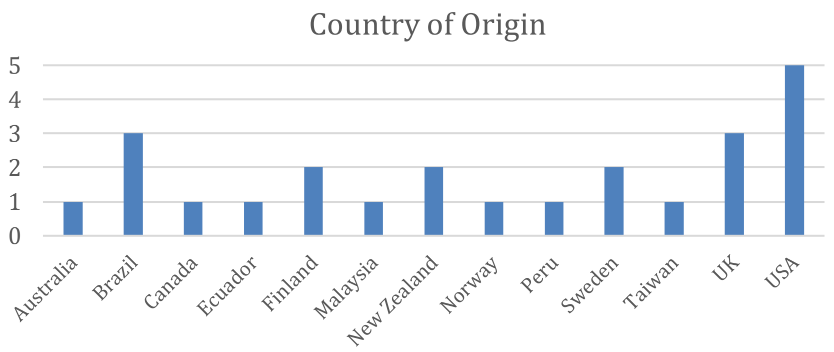

Figure 2 - Number of publications per year, from 2010 to 2021

A synthesis of data was derived through grouping similar codes into categories that based on similar concepts and meanings (Allen, 2017). The categories were then reviewed and refined by revisiting the dataset of eligible papers, that resulted in the emergence of key themes. The key themes were then constructed and underwent a further review process to ensure they adequately captured the meaning of the constituent codes.

DEVELOPED THEMES

The developed themes are as follows:

Relationship of LC to Innovation

- The first theme synthesises the relationship between LC and Innovation, derived from IGLC literature (Table 1), the thematic analysis of the SLR established that Lean *is* a form of managerial innovation in itself, and can provide support to facilitate broader innovation.

Innovation Operations - Existing LC Context

- The second theme identifies operational understandings of innovation in the LC context, in IGLC literature. The SLR identified 7 examples of different understandings used to describe aspects relating to innovation (Table 2).

Barriers to innovation

- The third theme identifies barriers to innovation in IGLC literature (Table 3).

Drivers of Innovation

- Theme 4 concerns drivers of innovation, prevalent in IGLC literature, outlined Table 4.

Innovation Strategy Essentials

- The fifth theme identified, points towards a systemic approach that is required for innovation to drive sector-wide change, one that shifts away from siloed, project-centric endeavours (Table 5).

Collaborative Efforts

- The sixth and final theme that emerged from IGLC literature that stressed the importance of collaborative efforts in driving innovation (Table 6).

Table 1: Innovation and LC

Lean is a form managerial innovation

- LP is viewed as a radical managerial innovation (Gomez, 2009; Koskela & Vrijhoef, 2000)
- Lean Production (LP) is innovative approach to the management of production systems (Hirota & Fomoso, Carlos T., 2001)
- Lean can form part of an innovation strategy (Iordanova et al., 2020)

Lean is a facilitator of innovation

- Lean is a tool for establishing an environment for innovation (Etges & Caten, 2023)
- LC can help drive innovation (Etges & Caten, 2023; Hirota & Fomoso, Carlos T., 2001).
- Incorporation of lean principles would drive industry-wide innovation (Hunt & Gonzalez, 2018)
- Implementing Lean principles both before and during the innovation process is essential for minimising flow waste and enhancing teamwork (Roman & Li, 2014).
- Lean theory can be used as a conceptual foundation to explain innovative practices in construction (Etges & Caten, 2023; Tommelein & Beeche, 2001).
- Last Planner System (an innovation) generated using LC principles (Hunt & Gonzalez, 2018)

Table 2: Innovation in Existing LC Context — Operational focus

Model Name	Description of model
Technological Capability (Freitas & Heineck, 2012)	Classifies innovation by level of technology
Implementation Scheduling (Ballard, 2001)	Implementation strategy combined with Target Cycle Time
Creative Process Support (Berg et al., 2018)	Teamwork and brainstorming methods used to generate new ideas
Problem-space Framework (Etges & Caten, 2023)	A “Double Diamond” approach to identify pain-points and propose innovative solutions
Drivers of Change (Henrich et al., 2006)	Implementation model considering absorptive capacity, and drivers
Manufacturing Templates (Koskela & Vrijhoef, 2000)	Explains transfer of production templates from manufacturing to construction
Simplified Diffusion Model (Poshdar et al., 2019)	Diffusion model from the perspective of the user

Table 3: Innovation barriers as identified

Boom-bust Cycle
• Inhibits investment and companies can't take a long-term view (Hunt & Gonzalez, 2018)
• Margins are low in bust, and actors are too busy in boom (Leiringer, 2001)
Organisational Culture
• Ingrained culture of operation inhibits innovation (Hunt & Gonzalez, 2018)
• Inherent organisation of construction, and theory deficiencies (Koskela & Vrijhoef, 2000)
• Organisations don't want to jeopardise control and often maintain status quo (Leiringer, 2001)
• Unwillingness to share IP amongst project actors (Hunt & Gonzalez, 2018)
• Inability or reluctance to address problems (Koskela & Vrijhoef, 2000)
• Myopic supply chain management, and the diffusion challenges posed by organisational and institutional structures (Koskela & Vrijhoef, 2000).
Operations
• Working practices of construction managers – too task oriented with not enough time allotted for reflection (Hirota & Fomoso, Carlos T., 2001)
• Planning effectiveness Schedule deviation (Castillo et al., 2015)
• Potential for innovation initiatives to collide (Leigard & Pesonen, 2010)
• Hard to measure efficiency in construction, and benchmark data (Henrich et al., 2006)
Cost
• Projects need to be viable, ahead of consideration for innovation (Kennedy et al., 2023)
• Competitive bidding pushes down budget for innovation (Leiringer, 2001)

Table 4: Main drivers of innovation in LC

A Culture to Support Innovation
• Companies can foster a culture of innovation by improving professionalism and efficiency. This can be practically achieved through improved onsite practices, the introduction of quality assurance practices and safety rules (Davey et al., 2000).
• Develop a culture that facilitates innovation, by fostering a willingness to take risks, experiment, but also acknowledging and learning from failures (Hamzeh, 2011).
• Action Learning can be used to drive cultural change to foster innovation (Davey et al., 2000).
• Role of change agents (Leigard & Pesonen, 2010; Poshdar et al., 2019).
• Reform the patent process to create innovation-friendly culture (Stevens, 2022).
• There is a negative hierarchal relationship that separates consultants and clients, from contractors, inhibits innovation from occurring (Hunt & Gonzalez, 2018)
• Achieving buy-in from entire team in required to implement an innovation(Hunt & Gonzalez, 2018; Roman & Li, 2014)
Unique Project Requirements
• The adoption of innovation by contractors was due to site specific issues, with one contractor stating "We look for innovation when we are forced to" (Hunt & Gonzalez, 2018)
• The project nature of construction provides the ability to silo innovation trials, facilitating a "narrow and deep approach" (Arbulu & Zabelle, 2006).
• Innovation should also consider the inherent advantages* of construction of; zero stock, high flexibility, and satisfactory social needs (Chang & Lee, 2004)

Table 4 continued: Main drivers of innovation in LC

Role of Client

- Clients can be an important innovation enabler due to a combination of their experience, and technical knowledge (Hunt & Gonzalez, 2018).
- Improved engagement between academia and industry for networking to incubate research collaboration, both in regards to LC and innovation more generally (Hunt & Gonzalez, 2018).
- Theory of Inventive Problem Solving as an enabler of innovative ideas (Roman & Li, 2014)

Market Forces

- Competitive pressures, market pull, and technology push all drive firms to adopt new technologies (Chang & Lee, 2004)
- Push-driven innovations come from pressure from customers, suppliers, or regulators. Pull-driven innovations arise from recognized performance gaps (Henrich et al., 2006)
- New materials and/or equipment launched into the market usually trigger innovation initiatives in construction (Henrich et al., 2006).

Table 5: Innovation Strategy Essentials

Need for Government Reform

- Government needs to take a larger role in fostering innovation in the built environment at all stages. ie support for inventors, incentives for innovation, and the allowance of innovation on construction projects through the use of performance-based specifications (Stevens, 2022).
- Construction contract structures, such as design-bid-build inhibit innovation due to the separation of design, and construction (Hunt & Gonzalez, 2018).

Strategies for Adapting and Managing Innovation

- Innovation (technical change) in construction should; be driven my market pull, should be limited to construction component standardisation, and consider the available labour market (Chang & Lee, 2004).
- Highly impactful innovation (radical or organisational innovations) from other industries need to be abstracted, then adapted to fit a new context (Koskela & Vrijhoef, 2000).
- Efficient information exchange for efficient innovation management (Castillo et al., 2015).
- Creativity is necessary to foster innovation, and needs to be defined clearly by management, and what creative practice aims to achieve(Berg et al., 2018).

Knowledge Management and Market Alignment

- Trivialisation of innovation due to a loss of credibility coming from a saturation of ‘low-quality’ information (Etges & Caten, 2023).
- Firms should dedicate time to understanding real market need ahead of adopting a technology for sake of technology-push (Chang & Lee, 2004).
- Organising a company's learning processes in a considered manner facilitates the accumulation of technological capability, that is needed to generate and manage innovation (Freitas & Heineck, 2012).
- Translating knowledge into formalised structures and disseminating via dedicated roles leads to better accumulation and continuity, despite staff turnover (Freitas & Heineck, 2012).
- Companies that are seen to be innovative attract staff (Bou Hatoum et al., 2022).

Table 6: Collaborative Efforts

Strategic Partnerships Create Opportunities for Innovation
• Partnering to deliver tailored technological solutions across projects (Freitas & Heineck, 2012)
• Increased levels Industry-led research partnerships, that combines public resources and industry knowledge creates a more innovative environment, (Gomez, 2009; Stevens, 2022)
• Collaborative work involving universities, suppliers, and companies is essential for innovation development (Roman & Li, 2014).
Construction Firm Networks are Important for Diffusion of Innovation
• Large enterprises have the capacity to utilise R&D investment to drive innovation (Etges & Caten, 2023; Poshdar et al., 2019). SME don't have this ability, and instead need to rely on clusters and networking to innovate (Poshdar et al., 2019).
• SMEs adopt the innovation successes of market leaders (Etges & Caten, 2023)
• The interrelated nature of SMEs on construction projects can facilitate or impede innovation diffusion (Poshdar et al., 2019) .
Innovation Collaboration Requires Support and Resources
• Collaboration, through structured settings like workshops with practitioners from across different firms, has been demonstrated to help develop skills to further innovation strategy (Etges & Caten, 2023).
• Collaborative practices help discover, facilitate and implement innovation, but are time consuming (Berg et al., 2018; Hunt & Gonzalez, 2018; Stevens, 2022)

DISCUSSION

Viewed as a whole, the SLR points towards how innovation can be more deliberately pursued in LC. The resulting IGLC Innovation Model compiles the data to present an holistic pathway for this journey where Lean is both a strategic and managerial enabler of innovation, a path that has drivers as well as barriers, and where collaboration is an key factor in a broader suite of more operationally-focused understandings.

The SLR supports the earlier claim by Belfanti that Lean has been considered a managerial innovation (Table 1). LC creates an environment for innovation to occur, the SLR revealed how Lean principles, and LPS act as innovation drivers. Furthermore, Lean theory was suggested as useful in explaining innovative practices in construction.

Current understandings of innovation in IGLC literature are not holistic in scope, and instead tend to concentrate on singular, technical focus areas. The aspect of implementation was most prevalent in identified operational-focused understandings of innovation in LC, ahead of ideation and classification (Table 2).

Major innovation barriers that the SLR identified fell under four classifications. These barriers primarily related to the organisational culture and operations of construction (Table 3). The boom-bust cycle of construction, and cost, were identified as secondary barriers.

A number of innovation drivers emerged as a result of the SLR (Tables 4-6). First, the role of culture in supporting innovation were identified by a significant number of papers as an innovation driver (Table 4). Also, the role of the client, market forces, and unique project requirements of construction, were identified by a lesser number of papers as drivers of innovation.

Additionally, the key role of strategy was identified as a prominent driver of innovation across a number of different levels (Table 5). The management of knowledge to; accumulate technological capacity, and to best understand market needs, was identified prominently in the SLR. The SLR also identified strategies for adapting and managing innovation, and need for government reform to a lesser amount as possessing strategic importance to driving innovation.

Finally, the importance of collaborative efforts was identified in by the SLR as a key driver for innovation in IGLC literature (Table 6). The use of strategic partnerships was seen as important to create opportunities for innovation. Networks of construction firms were also seen as crucial to the diffusion of innovation across the sector. A need to adequately support and resource Collaborative efforts was identified as important for their viability.

The content generated from themes three to six can be synthesised into a model of influencing factors on innovation, as described by IGLC literature (Table 7).

Table 7: IGLC Innovation Model

Themes	Sub-themes
Strategy Essentials	Government Reform, Strategies for Adapting and Managing Innovation, Knowledge Management and Market Alignment
Drivers	Role of Client, Unique Project Requirements, Culture, Market Forces
Barriers	Boom-bust Cycle, Organisational Culture, Operations, Cost
Collaborative Efforts	Strategic partnerships, Construction firm networks, Adequate resources

The work of this paper contributes to an ongoing PhD research project that is examining the value of understanding and pursuing innovation in an holistic way, across the built environment disciplines. Holistic thinking enables firms to identify outside factors that can be valuable to consider When applied to the innovation process, holistic thinking can a targeted pursuit of more impactful innovation, and the increased economic growth it brings (Mazzucato, 2011). What this IGLC Innovation Model reveals is the importance to LC innovation and implementation when considered from a similarly connected and holistic standpoint. Such a perspective can consider the multi-factorial benefits of lean that sit across the value chain and work from the strategic level of business down to the operational benefits felt in projects.

When considered together, the themes and sub themes proposed in the IGLC Innovation Model shifts practitioner thinking away from an operational level, towards taking a broader approach to pursuing innovation. Such an approach is useful because the selection, analysis, and comparison of potential innovations for implementation can be informed by more-informed thinking. The holistic approach proposed in this paper encourages firms to devote time to strategising innovation through first developing capacity in knowledge management to build technological capacity, and recognising the important role of collaboration, through aspects such as construction firm networks, can play in achieving successful innovation implementation. This is alongside considering other aspects of innovation, that feature more prominently in construction innovation literature, like drivers, and barriers.

The emerging model proposes a way to consider innovation from an holistic standpoint in a LC-specific context and can be useful to managers to facilitate the adoption of LC, increase its uptake/utilising, or to explore specific technical process innovations that LC can support. The model can be used to assist firms in understanding wider factors, associated with innovation implementation. This can help managers to better make the case for both LC, and other innovation, within the wider construction sector.

The themes covered in the SLR present a guide, showing the relationship of LC to Innovation, revealing that innovation models already exist and are supporting LC, but also identify barriers and drivers of innovation. To increase uptake of innovation the final themes identify the need for a strategic approach and one that is inherently collaborative. The IGLC Innovation Model links LC and innovation. This is interesting because it represents a combination of two related efforts in the built environment, both broadly aimed at improving construction productivity. As the construction sector continues to evolve, the IGLC Innovation model can be useful to practitioners in guiding the adoption of innovation that meet the demands of future construction projects.

CONCLUSION

This paper examines the relationship between LC and innovation in the construction sector, utilising a SLR of IGLC proceedings from the last 25 years. The findings of the SLR were bundled into six key themes that represent the major contributions towards innovation theory from the perspective of LC scholarship. The findings are used to support positioning LC as a form of managerial innovation. The argument is made that this allows innovation theory to be utilised to help increase uptake through increasing an understanding about the role of LC for managers. The research uses the findings of the SLR to introduces an IGLC-specific Innovation Model, that is aimed at enhancing comprehension and increased uptake. Considering LC as innovation can allow for a greater body of research to be drawn upon to facilitate greater diffusion in industry. Correspondingly, augmenting built environment innovation theory with LC theory also sees a combined approach taken to boost innovation uptake. While a connection has been established, the research is limited by its theoretical nature. Further work is needed to strengthen the case for the IGLC Innovation Model. Empirical studies are needed to build-out the argument, and test the validity of the Model. This should be complimented with expert workshops to feed-in input from industry that can be used for further refinement, and help contribute to Lean Theory to improve productivity in the construction sector.

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TAKT TIME PLANNING IN CONSTRUCTION AND ITS IMPACT ON THE WORK-LIFE BALANCE FOR INDIVIDUALS AND FAMILIES

Samuel F. Merrill[1], James P. Smith[2], Clifton B. Farnsworth[3] and Evan D. Bingham[4]

ABSTRACT

This paper explores the time management challenges in construction management, emphasizing the prevalence of crisis-oriented work, stress, and burnout. Integrating Takt Time Planning (TTP), a method that establishes production cadence, proves to be transformative in effective construction scheduling. TTP yields benefits like the establishment of flow, enhanced problem detection, and waste reduction. Despite a growing body of research on TTP, there is a notable gap regarding its impact on the ability of individuals to achieve and maintain a healthy work-life balance in the construction industry. The focus of this paper is to explore current research and literature to investigate the connection between TTP and its impact on work-life balance and emotional health. Through a literature review and synthesis of information, the authors identified a likely connection between TTP implementation and an improved well-being for construction professionals and their families.

KEYWORDS

lean, takt, construction, scheduling, work-life balance, family life

INTRODUCTION

TIME MANAGEMENT IN CONSTRUCTION MANAGEMENT

Time management is a crucial aspect in the lives of construction managers because it enables the manager to prioritize their tasks, improve their productivity, and by so doing, reduce their stress and maintain a healthy work-life balance (Jex, et al., 1999). In the popular book, *The 7 Habits of Highly Effective People*, Covey presents the notion that all tasks can be categorized by two factors: urgency and importance. To help his readers visualize this concept, Covey used an Eisenhower Matrix (Refer to Figure 1) to show how and where people spend their time.

According to Covey, those who are most effective at time management spend much of their time in quadrant two and spend as little time as possible in the other quadrants (Covey, 1990). Construction managers, however, tend to find themselves spending the majority of their time in quadrant one. This is especially true once their project falls behind schedule. In the book, *Construction Scheduling: Principles and Practices*, Newitt writes that oftentimes project managers "…go from crisis to crisis, with the project managing them rather than them

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managing the project…Most managers tend to live and die in quadrant one" (Newitt, 2009, p. 7).

Newitt elaborated on this concept further when he went on to write, "One of the major concerns with construction managers is the total control that projects seem to take over the manager's life. It is not uncommon for project managers to find themselves consumed by a project. Many work 60 to 80 hours per week, with 65 to 70 hours the standard. These long hours, in addition to the associated pressures of meeting the project objectives, tend to take their toll on managers. This type of lifestyle, if it continues over several years, threatens not only the personal health of the manager but also the manager's relationship with his or her family. "Burnout" is a problem in the management circles of many construction companies. As stated earlier, the key is to learn to control your projects so they do not control you." (Newitt, 2009, p. 8)

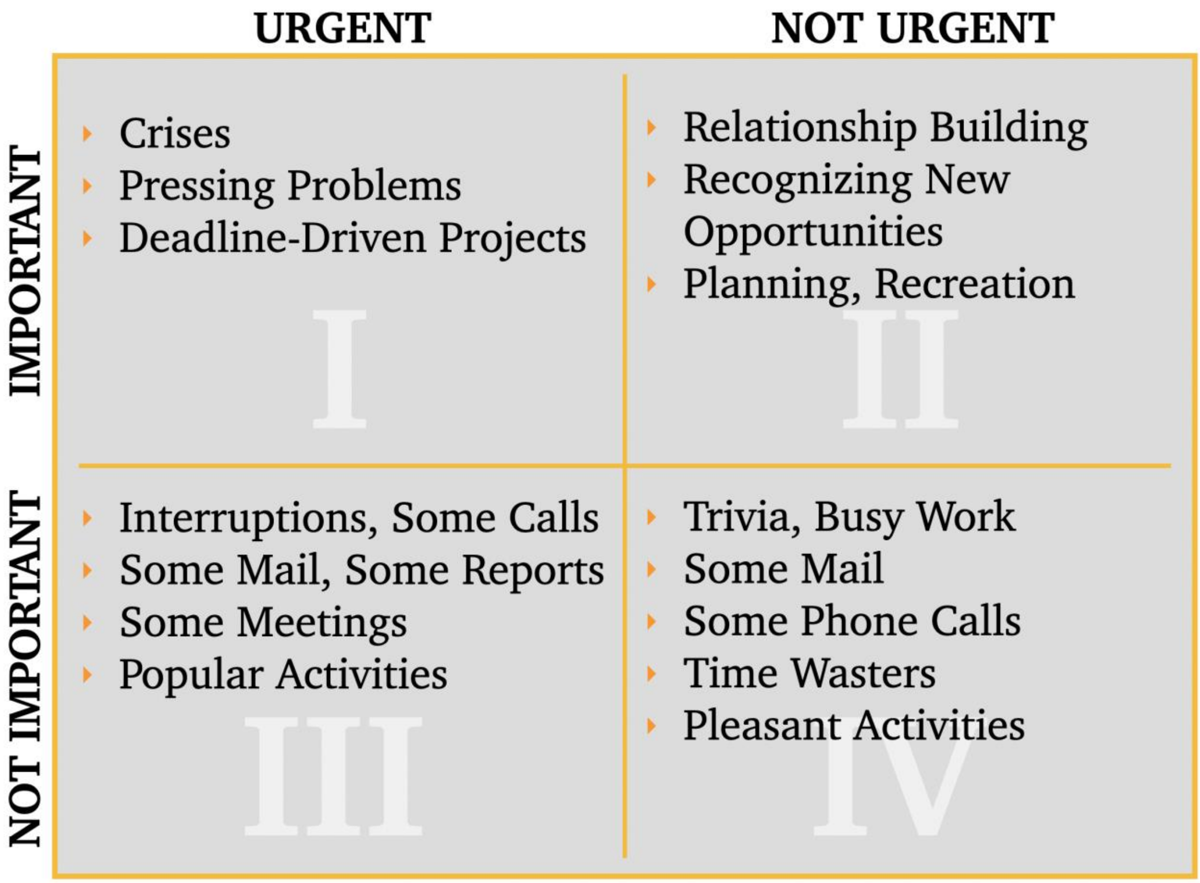

Figure 1: The Time Management Matrix (Covey, 1990)

The main means by which construction managers control the various aspects of their projects is through effective scheduling. Scheduling is the primary tool for organizing, coordinating, and communicating the planned methods and procedures that will ensure project objectives are met and accomplished. While good scheduling establishes a structured and controlled process for which the necessary tasks are to be accomplished, effective scheduling seeks to establish a process that enables the project to be completed in the most productive manner possible. Effective scheduling thus empowers managers to spend the majority of their time in quadrant two and less time addressing the crises and pressing problems that usually arise from ineffective scheduling.

TAKT TIME PLANNING

Takt time planning in construction is a work structuring method that aligns the production rates of trades by pacing work through a set of spatial areas in a set sequence. By so doing, project teams can create a continuous workflow, reliable handoffs, and an opportunity to continuously improve the production system (Frandson, 2019). When incorporated into construction scheduling and used in conjunction with principles from systems such as the Last Planner® System (LPS) and Scrum, Takt is a tool that project managers can use to shift their time and energy towards the more productive tasks of quadrant two. Takt Time Planning is a powerful instrument in the hands of the construction manager because it enables project teams to take control of their projects through the establishment of rhythm, consistency, and continuity (Binninger et al., 2019).

The word Takt comes from the German word 'Taktzeit' which means beat, rhythm, or cadence (Haghsheno et al., 2016). Takt refers to the cadence or regularity in which activities are to be completed. Since the early 1900s, Takt has been an important practice in the manufacturing industry (Tommelein et al., 2022). Takt is not a new method in the field of construction. In fact, the first recorded use of Takt, in the United States, was in 1930 when work commenced on the Empire State Building (Haghsheno et al., 2016). While reflecting on the speed and efficiency of the construction of this famous New York City structure, Flyvbjerg wrote that in "an era when people marvelled at the efficiency of factories churning out cars…the Empire State designers were inspired to imagine their process [for building the Empire State building] as a vertical assembly line – except that the assembly line did the moving …while the finished product stayed in place" (Flyvbjerg et al., 2023, p. xvi). Although the implementation of Takt into project schedules has been increasing in popularity (in the US) since the completion of the Empire State Building, Critical Path Method (CPM) continues to be the dominant method that is utilized in construction scheduling and planning. A survey conducted in 2003 found that 98.5% of the top 400 ranked contractors, in the construction industry, utilized CPM in their scheduling and planning needs (Kelleher, 2004).

Despite the benefits and widespread adoption of CPM, many construction companies still struggle to complete their projects on schedule. One publication reported that large projects typically take 20 percent longer to finish than originally scheduled (Agarwal et al., 2016). While another study, conducted by Dodge Data & Analytics, found that a staggering 61% of typical projects finish behind schedule (Lean Construction Institute, 2024). While CPM is useful in visualizing a project's workflow it does not enable project teams to clearly see and manage the project's trade flow (Kujansuu et al., 2020) and logistical flow (Tommelein et al., 2022). As shown in Figure 2, TTP allows for the visualization of and control over all three types of flow.

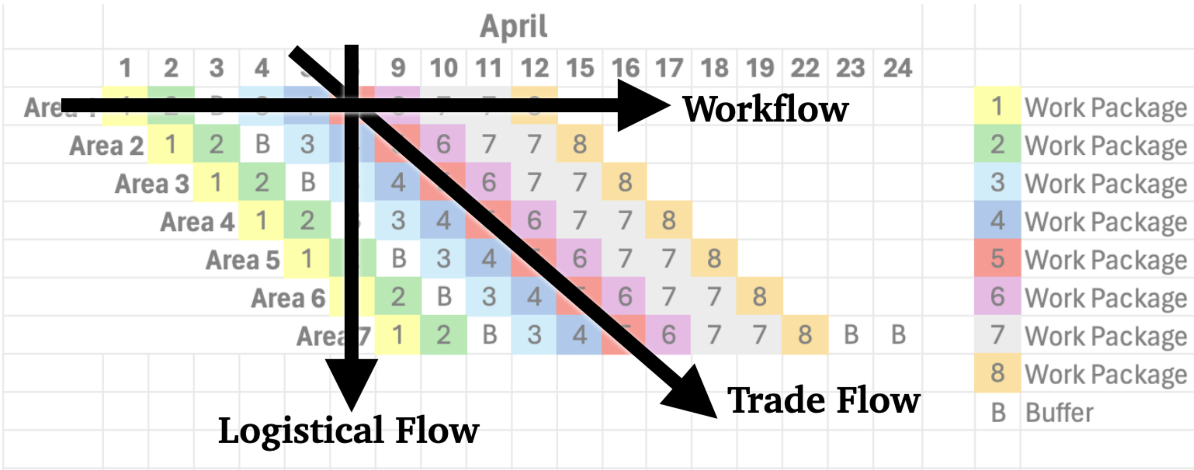

Figure 2: Types of flow that are visible and manageable when using TTP in a schedule

This paper is a literature review that is focused on exploring current research and literature surrounding the benefits of Takt Time Planning. This is done in an effort to investigate and better understand a possible connection between TTP and improved emotional health/work-life balance for construction managers. While TTP likely produces similar results for the tradesmen or labourer in the field, this paper only focuses on the relationship between TTP and project management (project managers, superintendents, foremen, and project/field engineers).

LITERATURE REVIEW

METHODOLOGY AND OVERVIEW

To investigate and better understand a possible connection between TTP and its impact on the work-life balance and emotional health of project managers, the authors explored current research and literature discussing the benefits of TTP. Over one-hundred and ten papers were reviewed that discuss TTP in construction. It's worth noting that of those papers, ninety-seven were published in an IGLC conference. An additional thirty papers, examining the topic of work-life balance, were also reviewed.

When reviewing the papers discussing TTP, abstracts were read and any mentions of a benefit surrounding the use of TTP in construction were recorded by tallying a table. Those papers were then read to ensure that the paper examined one or more benefits of TTP. The authors found that twenty-eight papers specifically addressed benefits of TTP (Refer to Figure 3). A breakdown of those papers, into broad categories, is as follows: 35% improvement to flow and duration, 18% improved communication, 18% enhanced problem detection, 14% improved accountability, 11% increased waste reduction, and 4% improved jobsite cleanliness.

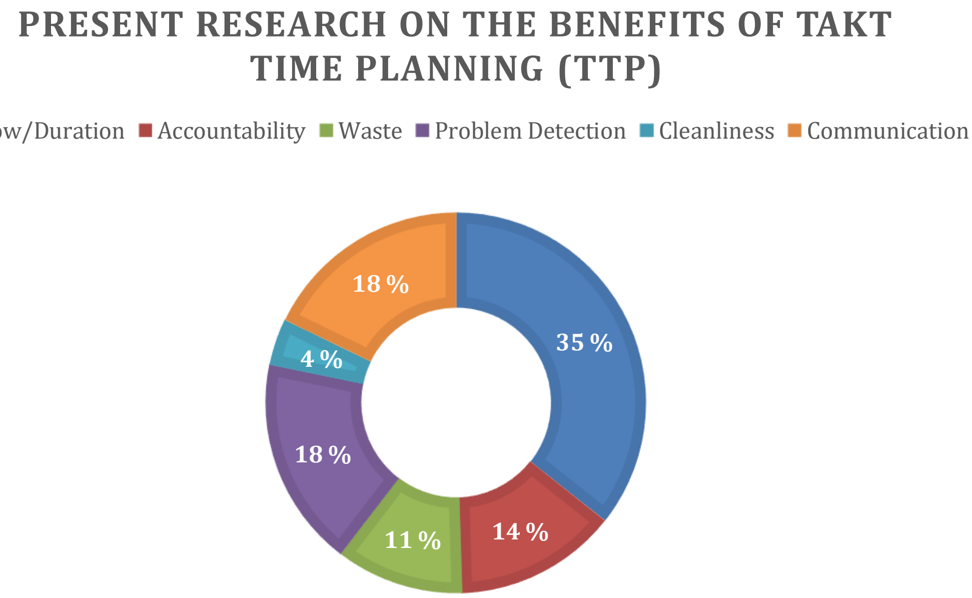

Figure 3: Research papers addressing the various benefits of Takt Time Planning

Researchers seem to have spent substantial efforts and resources exploring the benefits of TTP. For example, as TTP takes advantage of several production laws and principles, including Little's law, the law of Bottlenecks, the law of Variation, and Kingman's formula (Modig et al., 2011), it has been possible for researchers to demonstrate the mathematical underpinning and theory behind the application of TTP (i.e., Wardell, 2003).

BENEFITS OF TTP

During the review of existing literature, on Takt Time Planning, eight key advantages or benefits were identified by the authors. The existing body of research does not, however, make any connections between the use of TTP and an improved work-life balance for project managers. The eight identified benefits of TTP are:

1. Establishes Trade and Logistical Flow

   By activities being worked on at the same rate and work areas released at standardized times and at a sustainable pace, trade flow is established (Kujansuu et al., 2020). Aspects such as pull planning, buffering, levelling, and packaging help to establish realistic and sustainable project durations. When aspects of the Last Planner® System (LPS), such as weekly work planning and pull planning, are used in conjunction with TTP, workflow reliability is established and the handoffs between the trade partners are defined (Ballard et al., 2021). As TTP makes the logistical flow of the project more visible to project management, logistical challenges can be planned for and addressed (Tommelein et al., 2022).
2. Enables One-Process Flow

   If work areas are released to only one trade at a time, a ‘finish as you go’ approach becomes the standard. This minimizes ‘work in progress’ (Faloughi, et al., 2015) and can result in higher expectations for quality/craftsmanship and fewer rework/punch items. Fewer rework/punch items often result in fewer schedule delays, costs, and unnecessary movement of the trades.
3. Enhances Problem Detection

   Problems, anomalies, and issues are easy to identify in the visual organization of TTP. TTP highlights what needs to be done and what stands in the way of completing those tasks (Frandson et al., 2014). As problems are detected earlier, in what is known as a ‘Make Ready Process’ (MRP), a culture to address issues before they become a problem is established (Frandson, 2019). An increased standard of accountability for all members of the project reinforces the practice of early problem identification and remediation.
4. Establishes Accountability

   As TTP clearly outlines the work/trade/logistical flows, trade partners can be held accountable for material procurement, adequate worker counts, and meeting the established production outputs. Because of the increased transparency in the construction process, for all parties, (Dlouhy et al., 2016) the general contractor can track the project’s progress and review key indicators with their trade partners to identify shortcomings and encourage improvement and ownership.
5. Reinforces Healthier Project Durations

   TTP is based upon mathematical production equations and production laws (Tommelein et al., 2022). These laws and principles (combined with the implementation of buffers/pull planning/levelling/packaging) create realistic project durations that can be held and maintained. Through the optimization that comes from the production laws and principles, the overall project duration can be reduced significantly. In a recent case study, TTP was able to reduce the, “planned and actual construction durations up to ~70% of the total work days” (Apgar et al., 2023).
6. Reduces Waste

   The construction industry is a big culprit when it comes to waste. The industry often struggles to fully conceptualize the true extent of the waste that it generates (Viana et al., 2012). Typical forms of construction waste include material, time, and money. Excessive material inventory and storage on jobsites, is one common predecessor to waste generation. Time can be wasted as workers spend extra time sifting through materials in order to find the right material and/or because of improper staging they will spend extra time moving materials around in order to gain access to the needed materials. Waste of material can occur because materials are more likely to become damaged, stolen, or temporarily lost amongst the other materials and/or materials are thrown away more readily because of the natural perception that there is still plenty of available material. Excessive material storage often results in waste of financial resources as it costs money to remedy damaged, stolen, or misplaced materials. Additionally, extra man hours are needed to organize/find/access materials. TTP enables contractors to enforce 'just in time' delivery. This ultimately increases worker productivity, supports jobsite cleanliness, and decreases project waste. (Kujansuu et al., 2020) When materials arrive only when needed, variability is decreased and the stability of the production is increased (Haghsheno et al., 2016).

7. Increases Jobsite Organization/Cleanliness

   TTP is a location-based schedule. At times, project managers will arrange for multiple trades to work in the same area at the same time. However, TTP can be used to sequence trades to flow from one area to the next and in such a manner that the trades are never working in the same area as another trade. Therefore, each trade is solely accountable and responsible for the zone (area) they are in. As such, trades can be kept accountable for maintaining jobsite cleanliness in their work areas. This is often done through a lean process referred to as the 5S's. Clean and organized workplaces have been proven to increase productivity and better the work environment (Sanchez et al., 2023). Clutter wastes time and hinders standardization. Clean jobsites not only help improve safety and satisfaction (for both the builders and those that have commissioned the building) but also improve productivity. Jobsite cleaning methods, such as composite cleans, will become unnecessary to implement.

8. Enhances Communication and Organization

   TTP schedules are easy to understand and interpret. As TTP gives the fieldcraft a transparent view of production, they will always understand where they should be working (Kujansuu et al., 2020). When TTP schedules are communicated, on a daily basis (with every trade partner), cohesion and coordination are greatly improved, unlocking the energy and potential of a unified team (Wandahl et al., 2023). Because the trade partners are equipped with the knowledge of what needs to be done and where, they can think and act for the benefit of the project as a whole.

LIMITATIONS OF TTP

It is important to note that several studies have recorded issues arising in projects utilizing TTP (Kujansuu et al., 2020). One such paper, reported that workers felt an increased amount of stress when TTP was implemented because of stricter timelines and workflows (Frandson et al., 2015). Another paper noted that while TTP results in greater efficiency, a failure to identify realistic construction rates resulted in significant schedule delays (Binninger et al., 2019; Apgar et al., 2023). While these types of papers cast some doubt on the effectiveness of TTP, other research papers have provided seemingly contradictory findings (Kujansuu et al., 2020).

Any methodology that improves time management, when implemented correctly, will likely have a positive impact upon work-life balance (ie the Last Planner® System). TTP is not the exclusive solution to improving work-life balance. However, the preponderance of research has found that implementation of TTP can be successful and is beneficial to the various parties involved in construction projects. In one study, where a Norwegian contractor had tested TTP on several of their projects, the employees were asked at project completion if they would be interested in using TTP on future projects. "They were unanimously positive, and wanted to contribute to making it work better. They realized that in order for TTP to work it is essential that everyone got on board with it…" (Vatne et al., 2016, p. 180). In addition to the importance of getting all parties engaged and bought in on the adaption of TTP, there are several other conditions that must be met before the implementation of TTP will be successful (Apgar et al., 2023). This includes appropriating proper efforts toward planning before the project commences and then dedication to monitoring, controlling, and making continuous improvements/adjustments during the execution of the project (Lehtovaara et al., 2022). Like implementing any new practice, one must expect a period of adjustment as project teams become familiar with the new processes and iron out the initial kinks. With time, the unfamiliar will transform into familiarity, and the adoption of TTP can be successful - leading to enhanced project efficiency and success.

WORK-LIFE BALANCE AND FAMILY LIFE

Maintaining a good work-life balance is a well-researched topic amongst government and educational institutions. Research by the Australian Government found that long hours of work have serious negative effects on the institution of the family, relationships, and society (Pocock, 2001). Research conducted by members of the University of Maryland concluded that "…regardless of how flexible employees' schedules were or how much responsibility they bore for home and family duties, the more hours a week they worked, the more work interference with family they reported" (Major et al., 2002, p. 434). Research suggests that long work hours are related to increased conflicts at the home, the workplace, and indirectly to psychological distress.

When a proper work-life balance is established and maintained, individuals have an increased ability to be healthy and productive in all areas of their lives. Identifying the ideal allocation of hours needed in order to establish a work-life balance is difficult to do. However, the general principle is that a surfeit amount of time spent at work will interfere with one's private life and vice versa, an excess amount of time spent in one's private life will interfere with work.

Maintaining a work-life balance is essential in preserving familial relationships and in the positive development of future generations. In a study submitted to the Queensland Department of Industrial Relations, the authors noted that long working hours restrict the number of hours that parents can spend with their children which may have a negative impact upon the emotional and intellectual development of the child (Pocock, 2001). The family is the basic unit and building block of society. Research has found that good family relationships aid parents when coping with stress, seeking to develop healthier habits, and/or growing their self-esteem (Thomas et al., 2017). As such, preserving a healthy family life is a worthwhile endeavor that ensures that individuals, communities, and nations will flourish and thrive.

Maintaining a work-life balance is also important for the individual. Hobbies, exercise, recreation, and personal/decompression time are all dependent on a work-life balance. Individuals who are able to pursue these aspects and areas of their lives will find that they will have more motivation, energy, focus, and patience at work. In the United Kingdom, sixty-one companies participated in a four-day working week pilot program. Out of the sixty-one companies that participated, fifty-six companies (92%) decided to continue the four-day work week after the pilot program had ended. Companies found that while business performance and productivity were maintained, their employees reported significant declines in burnout, stress, anxiety, fatigue, and improved mental and physical health (Frayne, et al., 2023). TTP benefits may have the potential to allow for the implementation of a four-day work week in the construction industry.

TTP and an Improved Work-Life Balance

The implementation of TTP in construction scheduling not only enhances project efficiency but it also likely plays a pivotal role in establishing a healthier work-life balance for construction professionals. As the relationship between TTP and an improved work-life balance has not yet been studied by researchers, at this time it is not possible to confirm such a correlation. Given the existing body of knowledge, it is possible to identify causality between effective time management and an improved work-life balance.

One of the fundamental reasons for the potential correlation, between TTP and an enhanced work-life balance, lies in TTPs ability to establish realistic and sustainable durations for project schedules. The careful planning and allocation of resources, through TTP methods, minimizes the likelihood of unforeseen delays and disruptions. TTP thereby reduces the likelihood that construction professionals will need to work extended hours to recover lost time. TTP helps project teams to focus on the important/nonurgent tasks before they become important/urgent (Refer to Figure 1). This proactive approach to project management helps foster a more stable work environment, enabling project teams to have the ability to allocate time towards their personal and family commitments.

Furthermore, TTP encourages an effective communication and accountability framework throughout the lifecycle of the project. Effective communication and coordination are crucial for addressing issues promptly. These efforts help avoid any last-minute crises that will often result in construction professionals working extended hours. The open lines of communication and coordination that are facilitated by TTP foster an engaging work environment, where everyone on the project is aware of the needs of the project and is empowered to identify and think through potential issues. This proactive approach to identifying problems allows for problems to be resolved before they are compounded and push project milestones to the right.

Taking into account the various advantages that TTP brings to the table, such as project optimization and efficiency, one can begin to see how TTP fosters an environment and culture that directly contributes to the improved well-being of project teams.

Current TTP Trends

As mentioned in the introduction, presently, TTP is an underutilized project management tool. This is unfortunate as TTP serves as a leukocyte that defends against project pathogens which lay dormant but, because of ineffective construction practices and error, often arise to wreak havoc upon projects and their teams (Love et al., 2009). While TTP has been growing in popularity, especially in European countries like Germany, (Haghsheno et al., 2016) it seems that the majority of contractors in the United States have yet to fully embrace the adoption of TTP as a standard practice in their means and methods. This includes all areas of construction: residential, commercial, industrial, heavy civil, etc. As many construction projects fall short of the project objectives, there is a need for contractors to more fully adopt and implement lean construction methods like TTP (Högnabba, 2021).

Additional Benefits Of TTP

Researchers have recently begun studying mental health in the construction industry. One such researcher noted that, “The construction industry is particularly vulnerable to mental health issues, as the [construction] environment contains many occupational stressors such as: high production pressures, dangerous work, [and] complex decision-making” (Sherratt et al., 2018; Oswald et al., 2019, p. 1050). As mental health and well-being have been linked to a healthy work-life balance, TTP will likely emerge a critical tool in future efforts to improve the mental health and well-being of individuals in the construction industry.

In the same manner of increasing accountability between the general contractor and their trade partners, TTP also has the potential to improve the accountability between the contractors and the project owners. Research has found that, "Negotiating a fair and concise contract minimizes ambiguities and consequently, reduces disputes. As such, the contract serves as both sword and shield - a sword to enforce action and compliance when necessary, and a shield to prevent straying from agreed work scope and obligations" (Ottesen et al., 2015, p. 4). TTP both sharpens the sword and hardens the shield. Schroeder highlighted this when he wrote, "Unaccountable people, teams, and companies want roadblocks hidden so they can more easily transfer blame and costs. Accountable people, teams, and companies will love Takt planning and knowing the truth in bringing roadblocks to the surface so we can manage around them as a team…" (Schroeder et al., 2021, p. 13). TTP brings to light the actions (or inactions) of the party that interrupted the project's flow and caused a delay in schedule and/or an increase to the project's cost. TTP encourages all parties to collaborate in a Make Ready Process so that roadblocks and issues can be identified and addressed before they become a problem. This ultimately shifts project teams from reacting to crises (quadrant one) to being proactive and focused on the tasks of quadrant two.

CONCLUSION

While conducting a comprehensive review of existing research on Takt Time Planning, the authors identified eight core benefits associated with its implementation. Although the benefits of TTP have been well-documented, there is a notable gap in academic research concerning the positive effects that TTP has on individuals, families, and work-life balance. Establishing a direct connection between TTP and the assumed benefits of improved personal/family life and work-life balance is challenging due to the numerous external factors. However, as further research is conducted and data is collected, a compelling argument will likely be constructed that links reduced working hours (from the use of TTP) to an enhanced family life and work-life balance. A carefully designed survey conducted on subjects using TTP, to its capabilities, will likely find a reduction in normal working hours. Further research could then confirm any correlation between TTP and the improved well-being of individuals and families who are involved in projects utilizing TTP. As developers, owners, investors, general contractors, trade partners, and members of the construction industry in positions of influence and power better understand the implications of adopting Takt Time Planning for their employees and those in their stewardship, it is the hope of the authors that they will see TTP as an essential component of effective project management and adopt it into their standard operating procedures and contracts.

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THE DESIGN-CONSTRUCTION COMMUNICATION LOOP: A CONCEPTUAL MODEL FOR COMMUNICATION ERROR ANALYSIS

Frode Drevland[1] and Fredrik Svalestuen[2]

ABSTRACT

The paper introduces a novel conceptual model designed to analyse and mitigate communication errors within the design-construction interface of construction projects. Recognising the complexity of communication in construction projects, the model integrates three foundational theories: Koskela's Transformation-Flow-Value (TFV) theory, Gero's Function-Behaviour-Structure (FBS) model, and Shannon and Weaver's communication theory. This interdisciplinary approach allows for a comprehensive examination of the information flow between the design and construction processes, highlighting potential transformation and flow errors at each stage. The model categorises errors into transformation errors, intrinsic to specific processes, and flow errors, which result from upstream issues, providing a framework for targeted quality control measures and root cause analysis. However, the model acknowledges its limitation in addressing the temporal aspects of communication, a critical factor in construction project management. The paper argues that, despite this limitation, the model offers significant insights for academics and practitioners by providing a structured method to identify, analyse, and address communication errors, thereby enhancing the efficiency and effectiveness of information exchange in construction projects.

KEYWORDS

Lean construction, theory, construction communication, information flow

INTRODUCTION

Studies from around the world point to poor and lacking communication as one of the main culprits for various issues in construction projects – including being a leading cause of delay (Doloi et al., 2012), rework (Yap & Tan, 2021), dispute (Gamil & Abd Rahman, 2022), poor productivity (Al-Rubaye & Mahjoob, 2020), as well as one of the main barriers to the implementation of sustainable construction (Susanti et al., 2019). Other studies point to the unique characteristics of construction projects - such as their complexity (Cakir et al., 2022) and having a multicultural workforce (Loosemore & Lee, 2002) – being the cause of significant communication issues.

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While there is no lack of literature pointing to communication as a substantial issue for the construction industry, there is generally a dearth of research on communication in construction projects (Emmitt et al., 2009). In the literature review leading up to the paper, we found few papers reporting in-depth empirical studies nor trying to develop any further theoretical understanding of communication issues in construction projects.

In the lean construction community, authors often mention communication. However, little of the published research is primarily concerned with communication issues. Of all the papers published through the Lean Construction Journal and the proceedings of the annual IGLC conferences, nearly eight per cent include the word “communication” in the abstract. However, less than half a per cent includes the word in the title.

Furthermore, lean construction-related papers about communication tend to focus on the practical use of concrete methods, tools or technologies for improving communication – such as Design Thinking (Spitler & Talbot, 2017), Last Planner System (Lagos et al., 2022), Stakeholder Management (Sosa & Torre, 2021), Design Metrics (Mulholland et al., 2022), and tablets (Aasrum et al., 2016).

Tools and technologies can undoubtedly alleviate communication issues. However, there are areas where they have fallen short. According to Dainty et al. (2007), the flow of information between the design and construction processes is a particular problem in the building industry. Even with newer collaborative contracts and faster communication with ICT- tools like BIM, the industry fails to rectify the problem. We would argue that this failure can be attributed to a failure to understand the communication taking place properly. Before developing tools and technologies to support communication better, we must clearly understand what is being communicated and the very nature of the communication process.

The advent of lean construction brought production science back into project management, and construction projects are now commonly referred to as production systems (Koskela & Ballard, 2003). We would argue that the design and construction processes of construction projects can be considered distinct but tightly coupled production systems. One produces an immaterial product – the design – and the other produces the physical manifestation – the built facility. Furthermore, we would argue that understanding the communication between the design and construction processes can require understanding the coupling between them from a production-theoretical point of view.

While several frameworks have been developed to support communication processes in the construction industry (Zerjav & Ceric, 2009), none consider such aspects. Common for them all is that they “are based on identifying a series of project phases in terms of communication’s form and content that is taking place during a particular phase”. We would argue that such models work well for prescriptive purposes – to define what information should be delivered, when, and how. However, they do little to help us understand or analyse communication errors in construction projects.

This paper introduces a conceptual model designed to serve as an analytical framework for identifying and addressing communication errors within the design-construction production system interface. This endeavour synthesises insights from three seminal theories across production, design, and communication: Koskela’s Transformation-Flow-Value theory, Gero’s Function-Behaviour-Structure framework, and the Shannon-Weaver communication model. Integrating these foundational models lays the groundwork for a comprehensive understanding of the flow of information and immaterial products at the critical juncture between design and construction processes.

The paper begins by describing the three foundational models. Subsequently, we articulate the development of our integrated model, the Design-Construction Communication Loop (DCCL), emphasising its capacity to elucidate the complexities and potential pitfalls in communication between the design and construction process. We then introduce a typology based on the DCCL, which categorises common communication errors at the design-construction interface. In the concluding sections, we explore the practical implications of the DCCL, highlighting its potential to improve information flow and project efficiency in construction. While we recognise the model's contributions, we also address its limitations, such as not accounting for time, paving the way for future research to refine and expand the DCCL's applicability.

FOUNDATIONAL MODELS

This section introduces the three fundamental communication, production, and design models. These form the basis of the Design-Construction Communication Loop (DCCL) model, detailed in the next section. We have chosen each model for its significant impact in its respective field, and together, they provide a solid framework for understanding communication between the design and production processes in construction projects. This section aims to succinctly outline the key features of these models, setting the groundwork for our integrated approach in the subsequent part of the paper.

PRODUCTION – THE TFV THEORY

Koskela's (2000) Transformation-Flow-Value (TFV) theory has been instrumental in shaping our understanding of production in lean construction, making it a natural choice for our model's foundation.

Koskela identified three distinct conceptualisations or views of production: transformation, flow, and value. He integrated these into the TFV theory, offering a comprehensive framework for examining production systems. The traditional view, which he termed "transformation", sees production as converting inputs into outputs, breaking down larger processes into smaller, optimisable parts. However, this view often overlooks non-value-adding activities like transportation and waiting, which Koskela addresses in the "flow" aspect. This second concept focuses on streamlining the movement of materials and resources, identifying and minimising waste.

The third concept, "value", challenges the potential sub-optimisation of focusing solely on transformation. It emphasises understanding and fulfilling customer needs, both internal and external, ensuring that each step in the production process contributes to the end goal.

Koskela extends the TFV theory to all production systems, including design work. He argues that design activities are transformations—designers turn customer needs into solutions. The flow in a design process is typically the flow of information between each designer, and the value aspect is a means to an end discussion between designer and customer.

COMMUNICATION – THE SHANNON–WEAVER MODEL

Communication theory is a diverse field encompassing various perspectives and models. Craig (1999) notes that while there are numerous theories, they generally align with one of seven traditions, each offering a different lens through which to view communication:

1. Rhetorical – Communication as a practical art of discourse
2. Semiotic – Communication as intersubjective mediation by signs
3. Phenomenological – Communication as the experience of otherness
4. Cybernetic – Communication as information Processing
5. Sociopsychological – Communication as expression, interaction, and influence
6. Sociocultural – Communication as the (re)production of social order
7. Critical – Communication as as discursive reflection

Of these seven conceptualisations, modern models for communication theory tend to belong to the cybernetic tradition (Craig, 1999). In the cybernetic tradition, communication is understood as the exchange of information and knowledge among individuals. – essential in complex building projects. While authors have proposed various refinements and variants, the existing models all track back to Shannon & Weaver's (1949) seminal work, *The Mathematical Theory of Communication*. Figure 1 shows their model.

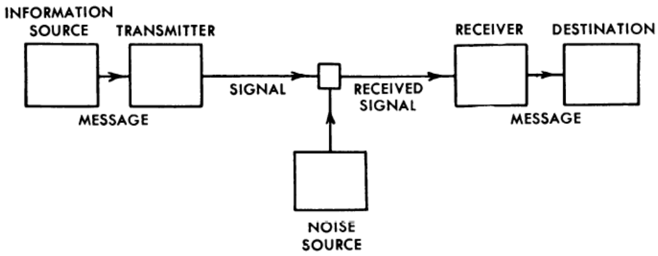

Figure 1: Schematic diagram of a general communication system (Shannon et al., 1964)

Shannon & Weaver's model, initially developed at Bell Labs, was primarily focused on the accurate transmission of signals, not necessarily as a comprehensive communication theory (Ritchie, 1986). However, it inadvertently became foundational in the field of communication, providing insights into both engineering and human interaction aspects. Despite its widespread application, the model has been critiqued for its limited capacity to fully represent human communication complexities (Heath & Bryant, 2013)

Addressing these critiques, various adaptations have been proposed over the years. This paper particularly references a variant by Kaufmann and Kaufmann (2009), which introduces significant modifications to the original model. The primary distinctions in this variant include a feedback loop and the recognition that noise can impact any part of the communication process, not solely the transmission channel.

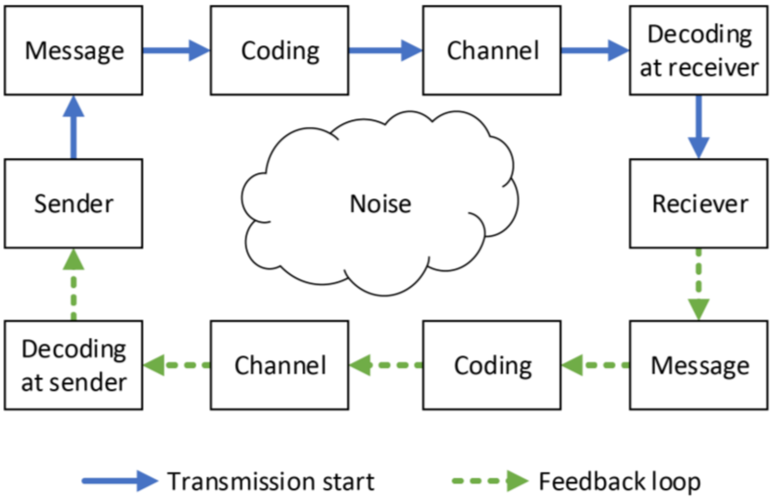

Figure 2 Components of the communication process (based on Kaufmann & Kaufmann, 2009)

Shannon and Weaver's original model centred on noise as information loss during transmission. Subsequent interpretations by other authors, such as Coupland, Giles, and Wiemann (1991); Fiske (1990); and O'Sullivan (1994), have broadened this concept to include losses due to faulty encoding or decoding. While different authors acknowledge the difference between noise in the channel and other noise (Brogan, 1974; Coupland et al., 1991; O'Sullivan, 1994; Pearson et al., 2005), there are no standard naming conventions. Since encoding and decoding are internal processes with the sender and receiver, this paper refers to noise affecting encoding and decoding as *internal noise* and noise affecting the transmission through a channel as *channel noise*.

Channel noise tends to be physical (O'Sullivan 1994). Common examples include background traffic noise during a conversation or sunlight obscuring a projection screen. Such noise is usually overt and can be relatively easily addressed. For instance, if a phone call is marred by poor reception, the receiver might suggest hanging up and calling back or switch to a different communication medium. Therefore, channel noise often leads to delays rather than direct errors, provided the communication process incorporates feedback mechanisms.

In contrast, internal noise encompasses a variety of more subtle interferences. One key type is semantic noise, defined by O'Sullivan (1994) as disruptions caused by differences in meaning. Differences in meaning can arise from language issues, such as inconsistent or ambiguous wording, or socio-cultural disparities between the sender and receiver, with professional jargon as a prime example. Another significant category is psychological noise, which pertains to interference from personal biases and assumptions (Rothwell, 2004). This noise stems from an individual's preconceptions and can significantly distort the intended message. Understanding and addressing both channel and internal noise is crucial for effective communication in complex environments like construction projects.

DESIGN – THE FBS MODEL

Design research, emerging formally in the 1960s and 1970s, initially grappled with significant challenges. According to Gero and Kannengiesser (2014), early efforts in this field were hindered by the lack of established terminologies and universally accepted concepts. Additionally, the prevailing perception among researchers was that design was a unique, irregular process lacking consistent patterns or principles.

This perspective shifted as subsequent studies delved deeper, focusing not just on the superficial aspects of design but on uncovering its inherent regularities. Researchers started recognising patterns and consistencies within the design process, moving towards a more structured and theoretical understanding of design as a discipline. This evolution marked a critical transition in design research, laying the groundwork for developing more refined and comprehensive design theories and models.

One of the foremost examples of this approach is the Function-Behaviour-Structure (FBS) model, conceived by Gero (1990). The model represents a significant leap in conceptualising the design process, offering a framework that deciphers the ontology of design across various applications. The FBS model has evolved considerably since its initial introduction. This paper defers to the version of Gero and Kannengiesser (2014).

The Function-Behaviour-Structure (FBS) model, as depicted in Figure 3 and elaborated by Gero and Kannengiesser (2014), provides a systematic approach to design. It begins with identifying the purpose or requirements (R) of an artefact, for example, a building. Designers then determine the functions (F) the artefact needs to fulfil these requirements. The design process's ultimate goal is to create a comprehensive design description (D) that encapsulates these functions.

However, the FBS model posits that a direct transformation from function to description is not feasible in a design system. Before developing a description, there must be a defined structure (S) – a detailed arrangement of the artefact's components and their interrelationships. For example, in architectural design, this structure includes elements like doors, windows, walls, and their spatial and functional connections.

A direct transformation from function to structure is rare and, according to Gero and Kannengiesser (2014), does not constitute design in the traditional sense; it is akin to selecting a ready-made solution from a catalogue. Instead, the design process involves deriving expected behaviours (Be) from the set of functions. These behaviours provide a framework for how the artefact should operate to fulfil its functions.

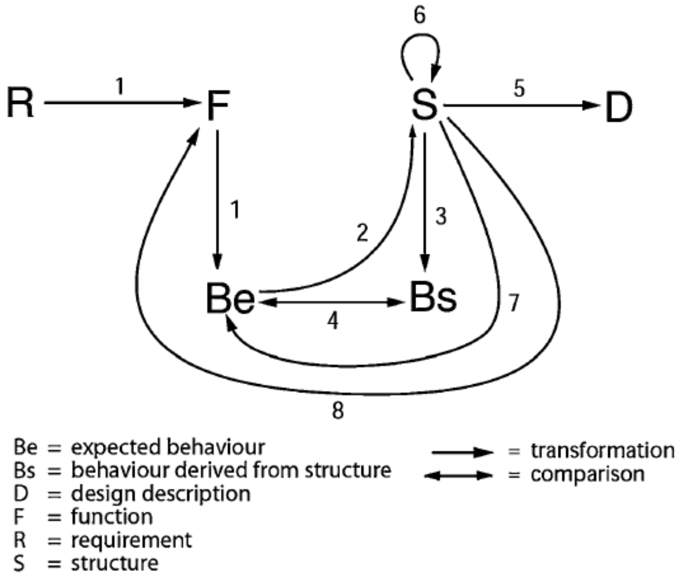

Figure 3: Gero's FBS-model for design (based on Gero and Kannengiesser 2014)

Designers then work on synthesising a structure that aligns with these expected behaviours. Once a structure is proposed, its likely behaviour (Bs) is analysed. If this actual behaviour aligns with the expected one, the design is considered successful, leading to the final design description (D). If not, the process involves reformulation, which may include iterating on the structure or revisiting the expected behaviours and functions.

The FBS model is outlined through eight key transformation processes:

- Formulation (R to F, and F to Be)
- Synthesis (Be to S)
- Analysis (S to Bs)
- Evaluation (Be compared with Bs)
- Documentation (S to D)
- Reformulation Type 1 (S to a revised S)
- Reformulation Type 2 (S to a revised Be)
- Reformulation Type 3 (S to a revised F, via Be).

THE DESIGN-CONSTRUCTION COMMUNICATION LOOP

We will start explaining the developed DCCL model by considering the relationship between design and construction using Koskela's TFV theory. The DCCL model considers both design and construction as transformation processes. The design process transforms customer requirements – including end-users needs and specifications from the construction process – into an intangible product, the building design. The construction process then converts this design into a tangible product, the physical building.

Key to this transition is the concept of flow, particularly in the movement of the design to construction. Unlike physical products, the design, an intangible entity, is transmitted not through physical means but via communication. Communication is the vital link between the design and construction stages, akin to a conveyor belt in a manufacturing setting.

The third aspect of the TFV theory is value. It might seem evident that the value produced by the design process is embodied in and equal to the drawings and descriptions the design process produces. However, we propose that these elements are better understood as communication artefacts. Design is about creating knowledge; thus, the actual product and value created lies with Gero's structure (S) of the FBS model. This idea implies that while designers may conceive an effective solution, translating or encoding this solution into drawings and descriptions is critical. This transition from Structure to Description in Gero's model is akin to encoding in communication theory.

This understanding leads to the DCCL model depicted in Figure 4, where various flow shapes represent transformations, actions, documents, and products. The model encapsulates the journey of a customer requirement being transformed by the design process into a solution, which the designer process encodes into a communicable form. The construction process decodes this information and transforms it into a physical product based on its interpretation of the communicated design. Importantly, this model emphasises two-way communication: the construction process also communicates back to the design team, potentially requesting new solutions or seeking clarifications, thus completing the design-construction communication loop.

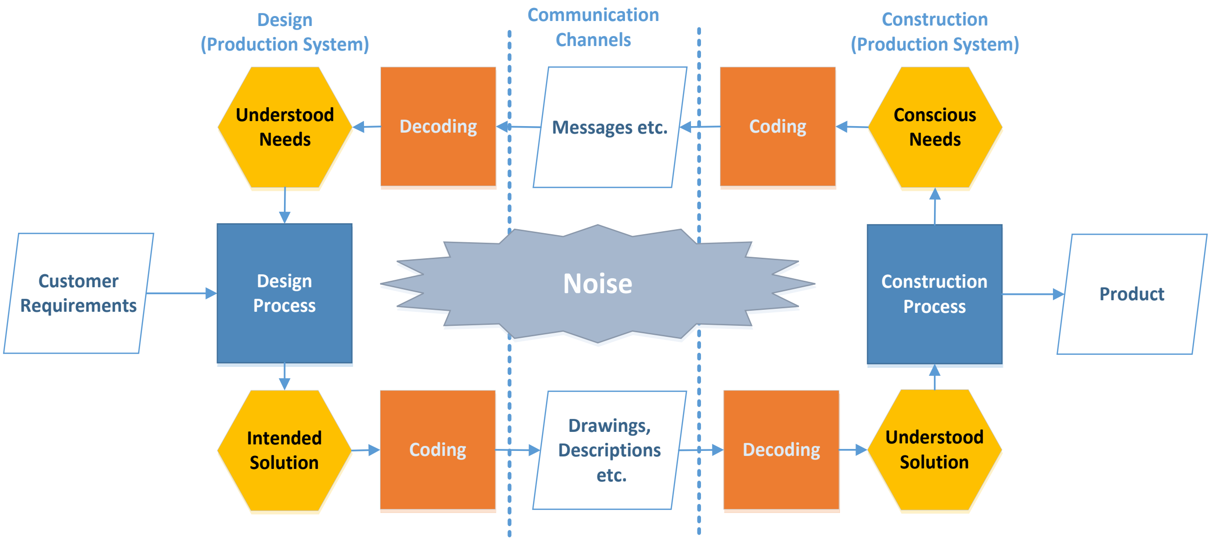

Figure 4: The DCCL model

The DCCL model has three main interconnected parts: the design production system, the construction production system, and the communication channels linking them. The model begins with the **Customer Requirements,** the needs and specifications driving the entire process. These requirements are akin to the Requirements (R) in Gero's FBS model and form the basis for the subsequent **Design Process**. It is important to note that defining these needs typically occurs in a pre-design phase, which is outside the scope of the DCCL model.

The Design Process transforms the Customer Requirements into an **Intended Solution**. This process mirrors the FBS model, where Requirements (R) are converted into a Structure (S). In other words, this step in the DCCL models phase encapsulates several steps of the FBS model, representing a high-level abstraction.

The Intended Solution, the output of the design process, corresponds to the Structure (S) in the FBS model. The next step, **Coding**, involves translating this solution into communicable forms like drawings, descriptions, or models, effectively serving as the transmitter in Shannon & Weaver's terms.

These outputs, **Drawings, Descriptions, etc.,** represent the media travelling through the communication channel. The channel varies, from face-to-face meetings to digital platforms like email or document servers.

The **Decoding** step is where the construction team interprets these transmitted designs. This process involves transforming the explicit design descriptions into an implicit understanding of the solution, laying the groundwork for the construction process.

The **Understood Solution** is the outcome of the decoding step, forming the basis for the **Construction Process** – the physical transformation of materials into the built facility, based on this interpreted design.

Conscious needs arise within the construction process, reflecting the team's need for additional information, clarifications, or modifications from the design team. These needs may range from requests for more detailed descriptions to identifying and addressing design errors.

Finally, **Messages etc.** represent the media used to convey these conscious needs from the construction team back to the design team, completing the communication loop and ensuring a dynamic, responsive process.

To illustrate the model with a practical example, consider this scenario: The project owner has a specific requirement for an elevator that can lift 10 people or 1200kg up three floors from the basement. This requirement is conveyed to the design team, which then transforms it into a detailed intended solution. The designers encapsulate their solution in a description using the most appropriate medium, such as a Building Information Modeling (BIM) model. This BIM model is then transmitted via a suitable communication channel, such as email or a shared digital server.

Upon receiving the BIM model, the construction team accesses and interprets the encoded data to understand the design intent. If the construction team finds the information sufficient and clear, they proceed with building the elevator. However, if there are perceived issues, such as missing details or impracticalities in the design, they will initiate a feedback loop. They articulate their concerns in a message, which is then sent back to the designers through a communication channel like email. Upon receipt, the designers decode the feedback and make necessary adjustments to either the design itself or its description, ensuring it aligns with the construction team's needs and clarifications.

This sequence of interactions highlights multiple potential points of failure that could lead the final product to deviate from the project owner's initial requirements. The following section will introduce a categorization scheme designed to help identify and address these potential discrepancies.

CATEGORISATION OF COMMUNICATION ERRORS

In the context of the DCCL, we created a typology for categorising communication errors between the design and construction processes, as detailed in Table 1. This categorisation framework identifies the different outputs from the model's stages and associates two primary types of errors with each output: transformation errors and input errors. This division draws from Hopp and Spearman (2011), who differentiate between process and flow variability.

Transformation errors, in our context, are those that originate entirely within a specific transformation process. They are intrinsic to the process in which they occur. For example, a flaw in the construction phase, such as incorrect implementation of the design, would be categorised as a transformation error

Input errors, on the other hand, are errors that are not inherent to the process itself but are consequences of preceding issues, i.e. somewhere in the preceedcing flow of transformations. For instance, a flaw in the final product might stem from a number of different upstream issues, such as a fundamental flaw in the initial design concept, or errors in how the design was communicated (encoded) in the design documents. Similarly, issues might arise during the construction phase due to misinterpretation (decoding) of the design documents.

Table 1 Typology of communication errors in the DCCL model

	Transformation	Input
Design process	Errors in transforming customer requirements and construction process needs into a viable design solution, such as design flaws or oversight of critical requirements; failure to recognise the need for additional information or clarification.	A well-executed design process, but based on misinterpretation, ambiguity, or omission of customer requirements and construction needs, leading to an incomplete or inadequate design solution.
Coding of Design Solution	Inaccurate representation of the design in drawings, descriptions, or models, such as incorrect details or omissions.	The intended design solution is correctly encoded, but the solution itself is inherently erroneous or incomplete.
Communication Channel (Transmission of Design):	Technical issues like data corruption or loss during the transmission of design documents.	Flawless transmission, but propagating errors from previous stages, such as transmitting outdated or incorrect design documents.
Decoding of Design Solution (Construction Process' Interpretation):	Misinterpretation or misunderstanding of the design documents by the construction process.	Correct interpretation of received design documents, but the documents themselves are flawed or incomplete.
Construction process	Errors in the physical construction process: E.g. implementation of the design, use of wrong materials, or construction faults; failure to recognise the need for additional information or clarification.	Correct execution of the understood solution, but the solution was misunderstood, degraded in transmission, inaccurately described the intended solution, or contained inherent design flaws.
Coding of Conscious Needs (Construction Feedback)	Inaccurate representation of the construction team's needs or issues.	The conscious needs are correctly encoded, but they do not represent the true needs of the construction process.
Communication Channel (Conscious Needs)	Technical issues in the transmission of needs, like data corruption or loss.	Propagation of errors from earlier stages, such as sending outdated or incorrect requests for information (RFIs).
Decoding of needs (Design Process' Interpretation)	Misinterpretation by the design process of the needs communicated by the construction process.	Correct interpretation of received needs description, but the description itself is flawed or incomplete.

By categorising errors in this way, we can more accurately pinpoint their origins and address them effectively. This categorisation can aid in distinguishing between errors arising from the inherent nature of a process (transformation errors) and those propagated from earlier stages (input errors), thereby facilitating a more targeted approach to mitigating communication errors in construction projects.

DISCUSSION AND CONCLUSION

This paper developed a conceptual model to serve as a framework for understanding and analysing communication errors at the interface between design and construction in production systems. Our approach integrated insights from three critical areas: production, communication, and design theory. This integration aimed to create a unified model that encapsulates the information flow dynamics between design and construction, an aspect not comprehensively addressed by existing models.

The DCCL model posits that the root cause of communication errors in construction projects often resides in complex causal chains. By dissecting these chains, the model helps academics and practitioners better comprehend and address these errors. The model can serve as a foundation for developing strategies and tools to identify and mitigate these errors, enhancing the efficiency and effectiveness of information flow between the design and construction processes. For example, we believe the model could be particularly beneficial for conducting root cause analysis of communication-related issues.

However, the DCCL model was developed using a purely conceptual approach. While we believe in its utility, empirical research is essential to ascertain its full applicability and effectiveness. Such research would involve validating the model in real-world construction projects and assessing its utility in identifying, analysing, and addressing communication errors. A crucial aspect of this validation is ensuring that the model has sufficient coverage to accurately capture and describe all communication errors across a variety of scenarios.

One known limitation in this regard is that the model focuses solely on the 'what' and 'how' of communication and does not consider the 'when.' Timing is a critical factor in the construction industry, where delays in communication can lead to significant inefficiencies and challenges (Gamil & Abd Rahman, 2022). Incorporating a temporal dimension into the model could provide a more complete understanding of communication dynamics in construction projects. However, doing so runs the risk of overcomplicating the model. A conceptual model is meant to “facilitate the comprehension or the teaching of systems or states of affairs in the world” (Greca & Moreira, 2000). Adding more aspects or details to the DCCL model likely makes it less suitable in this regard.

Nevertheless, excluding temporal aspects from the core model does not preclude their consideration in empirical research and practical applications. One possibility is to integrate the DCCL model with Value Stream Mapping, where each step of the DCCL could be mapped as processes or outputs on a value stream map.

In conclusion, the DCCL model presents a promising advancement in conceptualising information flow within construction projects. However, its potential to significantly impact the field hinges on rigorous empirical validation. The model's theoretical insights must be tested and refined through practical application and empirical research to ensure its efficacy and relevance in real-world settings. Such validation is crucial to substantiating the model's utility as a tool for enhancing communication and improving efficiency in the construction industry. This process will confirm its applicability and refine its components to better address the nuanced challenges faced by practitioners.

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OPTIMIZATION OF DESIGN COORDINATION PROCESSES FOR A 7-STORY MULTIFAMILY BUILDING USING VIRTUAL DESIGN AND CONSTRUCTION (VDC)

Alvaro Enrique Merino Chocano[1], Diego Alfredo Fernández Bustamante[2], and Alexandre Almeida Del Savio[3]

ABSTRACT

Traditional construction and property companies often find themselves bound by conventional project management and design techniques, which can lead to delays during the design phase. This situation needs to be avoided. This study presents a process optimization for the design stage of multifamily buildings using Virtual Design Construction (VDC) - a collaborative project management approach. Focused on a case study involving two residential buildings developed by the same property company in Lima, Peru, this research commences with a comprehensive analysis of the existing design processes from the projects. By pinpointing key sources of variability and streamlining the design flow, the proposed VDC implementation aims to enhance compliance with project timelines and the approval of design drawings. The optimized process yielded tangible results, significantly reducing design time, completing tasks ahead of the scheduled deadline, and improving the delivery of technical files by 25%. These outcomes underscore the benefits of this optimized process, including enhanced project efficiency and improved design quality, thereby making a compelling case for applying VDC in similar construction projects by property companies.

KEYWORDS

VDC, BIM, collaboration, concurrent engineering, process optimization.

INTRODUCTION

The construction industry, a dynamic field where professionals always look for innovative tools and methodologies to streamline and automate processes (Hermida, 2022), has witnessed the emergence of a potential game-changer, Virtual Design and Construction (VDC). This approach, which involves a shift from traditional 2D drawings to a comprehensive 3D model that integrates all project information (Del Savio, 2018), holds the promise of revolutionizing the industry. The transformative potential of VDC becomes evident when an integrated team collaborates in creating and managing information and decision-making using this approach.

Despite the constant evolution of new technologies, traditional property companies have not fully adopted these changes (Cantó, 2017). Various challenges in the development of residential

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building projects include, in addition to productivity issues, low design quality, inconsistent drawing production (Alvarez et al., 2021), incompatibilities between specialties (Bravo & Ramirez, 2019), lack of clarity in information (Almonacid et al., 2015), delays and cost overruns (Figueroa et al., 2021).

One key factor contributing to these issues is the deficient stakeholder communication during the design stage. The lack of efficient communication leads to delays as team members focus on individual objectives rather than project ones (Del Savio et al., 2022). Incompatibilities and team fragmentation hinder the maximization of project performance (Ma et al., 2018).

This study explores a collaborative management method to address previously discussed issues, focusing on the VDC methodology. VDC is a project management framework developed at the Centre for Integrated Facility Engineering (CIFE) at Stanford University, aiming to enhance the design, construction, and operation of projects via Building Information Modeling (BIM), Integrated Concurrent Engineering (ICE) and Project Production Management (PPM) (Del Savio et al., 2022). From a design perspective, VDC provides an integrated objective among the team, guiding them to the client's specific needs and generating production metrics to measure the results of the processes (Majumdar et al., 2022a). This involves delivering the project design on the agreed-upon date using BIM, ICE, and PPM (Majumdar et al., 2022b).

Motivated by the challenges presented within the construction sector, this work investigates the effect of implementing VDC to enhance stakeholder communication during the design coordination stage, aiming to reduce the overall time spent in this phase. The general objective of this research is to optimize the processes of the design stage for a residential building using VDC as a collaborative project management methodology. It involves analyzing the existing processes of the property company, identifying key sources of variability, and focusing on a more coordinated design flow to ensure compliance with delivery time and approval of the design drawings of the project.

This investigation starts by describing the methodology and the case study. Then, it analyzes the existing literature on VDC. Next, it explains the proposal for implementing VDC and its application in optimizing the design coordination processes in the case study. The results obtained from the VDC-based process were compared against the traditional process used in the former project of the property company under study. Finally, discussions and conclusions showed how VDC can enhance the design coordination process.

LITERATURE REVIEW

Fosse, Ballard, and Fischer (2017) investigated the benefits of utilizing collaborative work methods with digital tools and explored the factors driving this work and its limitations. The benefits of VDC implementation were measured using quantifiable metrics.

Kunz and Fischer (2020) examined the adoption of VDC in the construction industry and analyzed its economic impact. The study measured the benefits of using the VDC framework in the construction industry and assessed the global growth of VDC adoption.

Del Savio et al. (2022) provided an updated approach to the VDC methodology, offering a comprehensive review of current tools and methodologies. The approach is supported by its benefits related to client and project objectives, specifically regarding project costs and timelines. Implement VDC in a project starts from the client's objective, which is examined according to the relationship between the product (P), the organization (O), and its processes (P) within the POP matrix to create the foundation from which the VDC framework is developed (Del Savio et al., 2022). Once the framework's objectives are established, each component is studied in detail to develop production objectives, controllable factors, and metrics that enable the project to achieve its goals.

Balcazar et al. (2023) studied the construction process optimization of concrete structural elements using VDC, solving 60 possible clashes before construction. Quinteros Perez et al. (2023) studied the optimization of time in the processes of plumbing systems with VDC, reducing design time by 5% and execution time by 23%. Salazar et al. (2023) studied time optimization in diamond drilling operations in mining projects using VDC, resulting in a time optimization in operations of 10%. Barcena et al. (2023) studied optimizing the construction process time of a reinforced concrete reaction slab using VDC, resulting in a time reduction of 44 days. Palpan et al. (2022) studied a project's time reduction with an industrial process managed with BIM, resulting in a time reduction of 16%. Tuesta et al. (2022) studied the reduction of structural rebars' assembly time using VDC, resulting in a time reduction of 31%. Bustamante et al. (2023) proposed a VDC framework for curtain wall construction process optimization.

RESEARCH METHODOLOGY

This research is exploratory (Morales, 2015), analyzing the benefits of implementing a collaborative management methodology in the design stage of a residential building developed by a property company. The goal is to reduce variability and delays by identifying key optimization factors in the traditional workflow. This experimental research is quantitative (Babativa, 2017) and involves the implementation of the VDC methodology in a building project. The impact was measured through data collected using performance metrics. See Figure 1 to follow the research methodology.

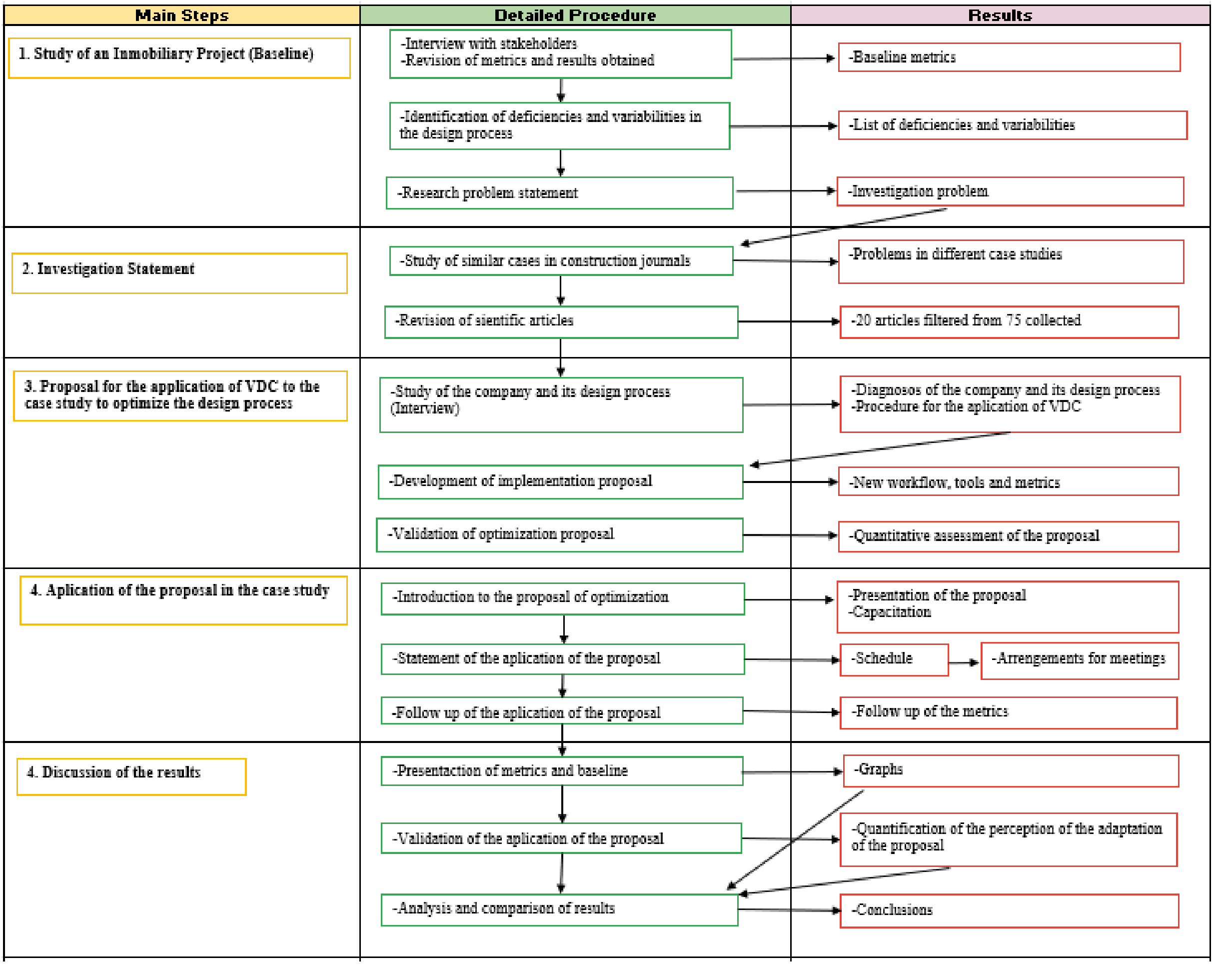

Figure 1: Research Framework.

To formulate the research problem, an in-depth examination of a building project in the design phase was conducted. Interviews with stakeholders, revision of metrics and results of previous projects, and identifying deficiencies and variabilities in the design process were carried out. The case study was initiated to test the hypothesis about a new company project. The development of a new workflow for project design began with interviews with the designers and project management teams to diagnose the current work methodology of the company.

For the optimization proposal, an interview with the construction manager, a Civil Engineer with more than 10 years of experience in building projects, provided insights into the company and its design process. A literature review of the VDC methodology applicable to the design process was conducted. Combining this review with interview data, an optimization proposal for the design process was crafted. The proposal started by elaborating a POP matrix and a VDC framework. The proposal was presented and then validated through a survey directed at participants in the design phase of the new project.

Following the proposal, a training process for staff and a schedule planning for the design process were executed. The planned changes in the workflow were implemented, and their application was monitored throughout the design stage with recorded metrics defined in the VDC framework. Performance metrics results were compared with those of the previous project to verify if improvements in the design process had occurred. The criteria for comparing both projects during their design phase included:

- Difference between approval of the preliminary project design and the delivery of the final technical file of the specialties involved in the design stage.
- Differences in drawing versions of the designers created to deliver the technical file.
- Difference in time between change requests from the company and drawing updates from the designers.

Finally, a survey was conducted to gauge the satisfaction levels of individuals involved in the design phase. Based on 13 questions, it provided valuable insights into the overall design process. In conclusion, a summary of the main findings about the improvements in the drawing delivery and stakeholders' satisfaction with the VDC implementation was presented, in addition to further research recommendations and limitations.

CASE STUDY

This study is based on two projects located in the district of Surco in Lima, Perú. Both buildings are residential projects from a property company that uses traditional methods, including 2D models for designing and coordinating their residential buildings and non-integrated working methods in their processes.

The projects are:

- A new project started in 2023 and finished in 2024. It has 7 stories, 2 units per story, and a land area of 1700 m2.
- A former project (benchmark project) started in 2021 and finished in 2022. It has 5 stories with 2 units per story, having a land area of 1900 m^2.

Both projects were carried out by "Venti Grupo Inmobiliario" (the Company).

RESULTS

The POP Matrix and the VDC framework were developed with the client and project objectives as its focal point and the production metrics table that guided the methodology implementation during the design phase. Subsequently, the obtained results for each component during the implementation were presented. Finally, a comparison was drawn between the results of the design phase implementing the VDC methodology in the new project and those obtained in the former project of the Company.

CLIENT AND PROJECT OBJECTIVES

As a result of the interview with the project manager, it was identified that the Company aimed to initiate the presale of the new project units to obtain bank financing for starting construction in August 2023. With this in mind, the project objective was identified as reducing the time of the design stage to achieve the final architectural design by June 2023.

POP MATRIX

The company's information was graphed and integrated into the POP Matrix, as shown in Table 1, to facilitate the client's objective of understanding its operation.

Table 1: POP Matrix for the new project.

	Function	Form	Behavior
Product	Final project design deadline delivery date: June 2023	Optimizing the effectiveness of project coordination by replacing the use of CAD drawings with a BIM model.	Successfully implement BIM to replace the traditional interference detection procedure (CAD).
Organisation	Start pre-sale campaign date: June 2023	Having increased effectiveness and reduced the time for plan updates.	Having resolved issues presented within an established time frame.
Process	Improve productivity in the design stage and reduce time spent	Having established a continuous flow of drawing production to meet the established schedule.	Meeting the deadlines for deliverables for the designers.

VDC FRAMEWORK

The information obtained and graphed in the POP Matrix supported the development of the VDC framework of component objectives. Figure 2 identifies the client and project objectives based on their needs, and the proposed uses of ICE, PPM, and BIM tools aim to integrate operations among stakeholders to accomplish these objectives.

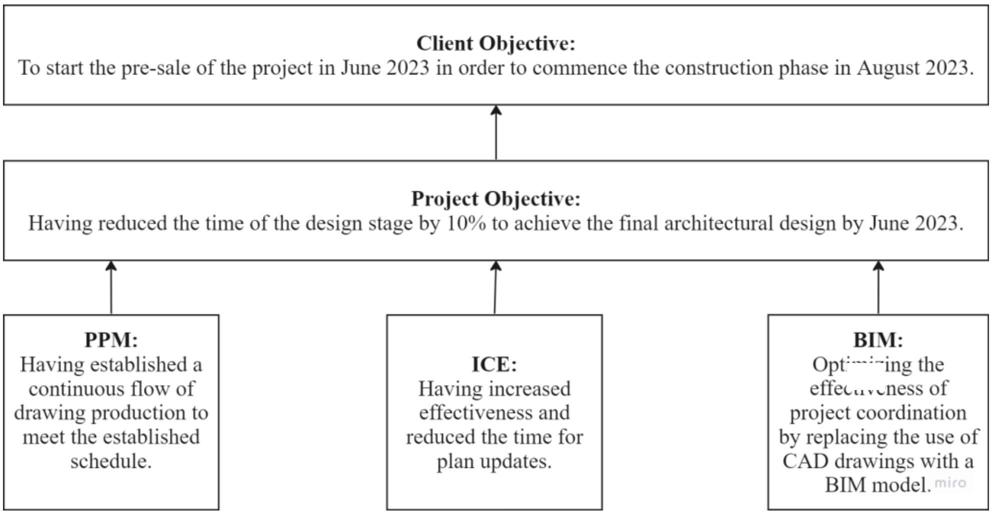

Figure 2: VDC Framework for the new project.

Next, Tables 2, 3, and 4 present the production objectives (PO) and controllable factors (CF) for PPM, ICE and BIM, respectively, along with their respective goals and sources of information.

PROJECT PRODUCTION MANAGEMENT (PPM)

Existing Process

The workflow was graphed based on the information the project manager gave in his interview (Figure 3). The timeline of the workflow is divided into three stages:

1. Planification: This stage's initial architectural design is carried out. This phase defines the provisional architectural design that serves as the basis for commencing the design of other specialties.
2. Stage 1: The process phase is where the specialty drawings are initially designed according to the architectural plan. Subsequently, the compatibility process begins. This process is repeated until the majority of incompatibilities and interferences are resolved.
3. Stage 2: This stage occurs after the technical file is delivered to the Municipality Office (responsible for the licenses to build) and continues until the start of construction. It may include drawing updates if required by the Municipality Office.

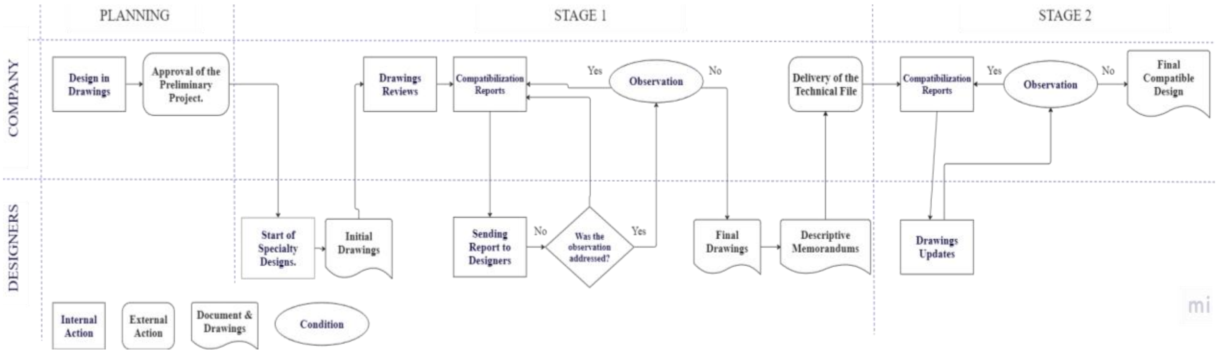

Figure 3: Traditional design workflow.

To initiate pre-sales ahead of schedule, it was necessary to reduce the time related to the design development. In the pre-sale context, obtaining architectural distribution drawings at the earliest opportunity became essential.

Proposed Process

Implementing VDC improved the design workflow using tools to enhance productivity at different process stages, as shown in Figure 4.

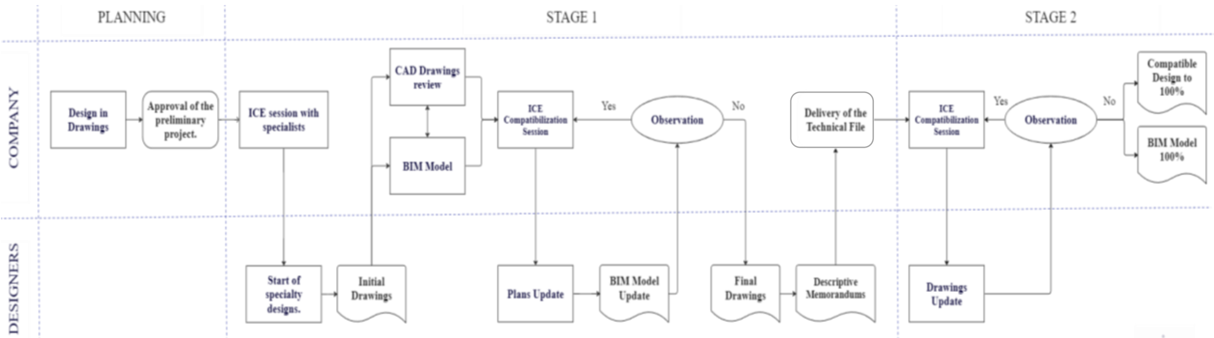

Figure 4: Improved design workflow with VDC.

The integration of the VDC methodology improved the design workflow. The proposal was presented to the Company and explained how it would improve the project's design stage. Then, the stakeholders were surveyed to validate the proposal, resulting in a 96% approval.

Utilizing a BIM model throughout the workflow allows for clarity in information among project members, enhancing coordination and information exchange in the process.

Additionally, using ICE sessions instead of email requests fosters an environment of integrated decision-making.

On the other hand, the PPM helped to complete the scheduled milestones. To achieve this, the production control was carried out using Lookahead and Takt-Time Planning tools (see Figure 5) to monitor activities performed by each designer. These activities were scheduled and worked in each ICE session. Tasks included updating drawings, preparing the descriptive memorandum, and addressing observations from non-executable tasks. The ICE sessions helped to coordinate the due tasks for the upcoming weeks and the delivery date deadlines for the design deliveries.

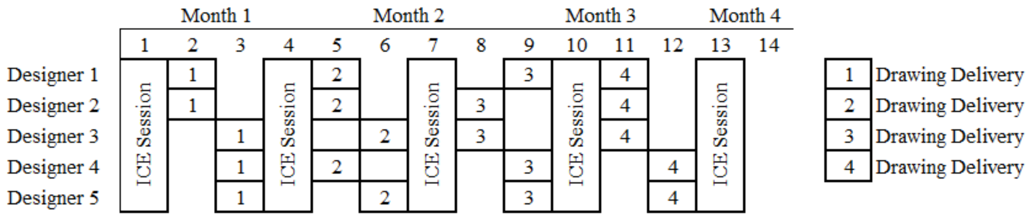

Figure 5: Takt Time Planning for task deliveries.

In the sequence, Table 2 presents the metrics table developed for the PPM component and Figure 6 shows the results obtained. The PPM production metric was tracked based on classifying the activities before the ICE sessions, which helped identify activities that could be addressed during the sessions.

Table 2: Summary of metrics for production objectives and controllable factors of PPM.

		Description	Metric	Target Value	Source of information
PPM	PO	Meeting the deadlines for deliverables from the designers.	Number of working days for the delivery of updated plans.	≥6 working days	Schedule
	CF	Classifying Lookahead activities into constrained and unconstrained activities.	Percentage of classified activities.	100% ± 10%	Lookahead

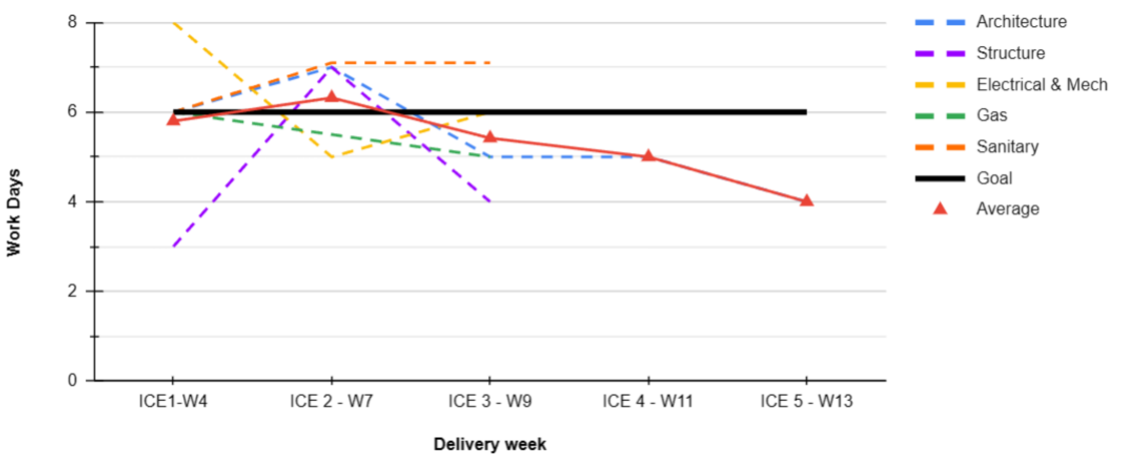

Figure 6: PPM Production Objectives: Drawings updated.

INTEGRATED CONCURRENT ENGINEERING (ICE)

Implementing ICE sessions helped to reduce issue-solve time latency by replacing email communication with sessions for real-time query resolution. These sessions were coordinated within the project management team and scheduled with relevant designers to address the decisions, such as interferences in the design.

The required information to carry out the session was provided to the designers at least three working days before the sessions, ensuring they could prepare potential solutions for discussed interferences and maximize session efficiency. Table 3 outlines ICE production metrics. To register the metrics, a control record document was employed to register all discussed issues and attendance.

ICE sessions were conducted in the project, including an initial ICE 0 session to introduce the project objective and schedule potential dates. The sessions lasted between 1 and 2 hours, during which observations were addressed, current progress was analyzed, and plans with the raised observations were scheduled.

Table 3: Summary of metrics for production objectives and controllable factors of ICE.

		Description	Metric	Target Value	Source of information
ICE	PO	Having resolved the scheduled issues during ICE sessions.	1. Percentage of issues resolved per session.	100% ± 10%	Interference Log
			2. Percentage of guest attendance.	100% ± 10%	Sessions Documentation
	CF	Working days in advance for the delivery of necessary information for the ICE session	Number of working days in advance for the delivery of information.	3±1	Emails with information submissions

Building Information Modeling (BIM)

BIM helped to maximize project coordination efficiency through powerful visualization and understanding of the project within the VDC framework. This was achieved using BIM to involve the comprehensive detection and solution of interferences in the design.

BIM implementation in the project focused on the Company's transition from CAD to BIM. To assess this shift, usage incidence was compared between the two during various ICE sessions throughout the design stage. Table 4 presents the production metrics for the BIM component. The number of 2D sheets modeled measured the progress of the modeled information, and the interference log kept track of the method for detecting the incompatibility.

Table 4: Summary of metrics for production objectives and controllable factors of BIM.

		Description	Metric	Target Value	Source of information
BIM	PO	Replace the traditional interference detection procedure with the VDC proposal.	Percentage of incompatibilities detected with the BIM model.	≥75% ± 10%	Interference Log
	CF	Generate a 3D LOD 300 model to detect interferences.	Percentage of modeled information.	100% ± 10%	Revit Model

Figure 7 shows the number and percentage of interferences identified by BIM and CAD tools. Since the second session, most interferences have shifted to be identified with BIM.

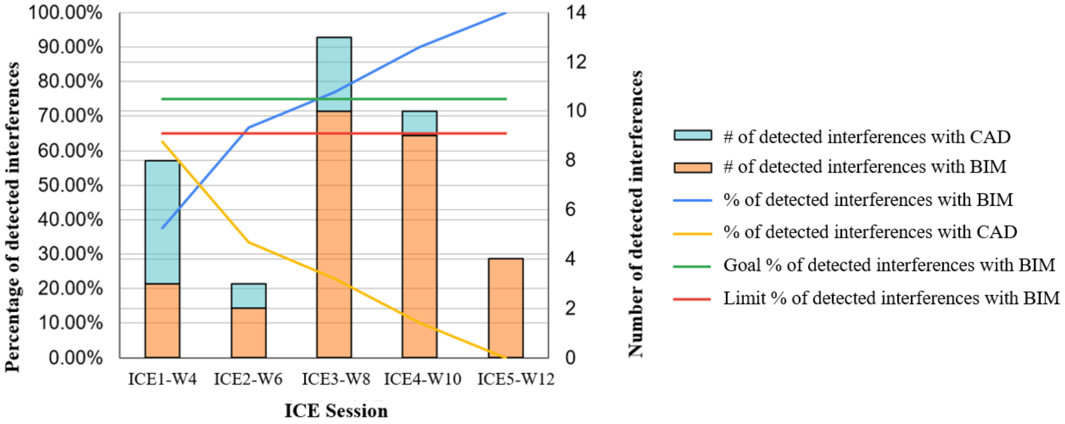

Figure 7: BIM Production Objective: incompatibilities detected.

Satisfaction with the VDC Application

Key project stakeholders were surveyed using 13 questions to evaluate the VDC application. As depicted in Figure 8, the findings show that the stakeholders expressed high satisfaction levels for nearly all questions - 12 out of 13 received the top satisfaction rank of 5 out of 5.

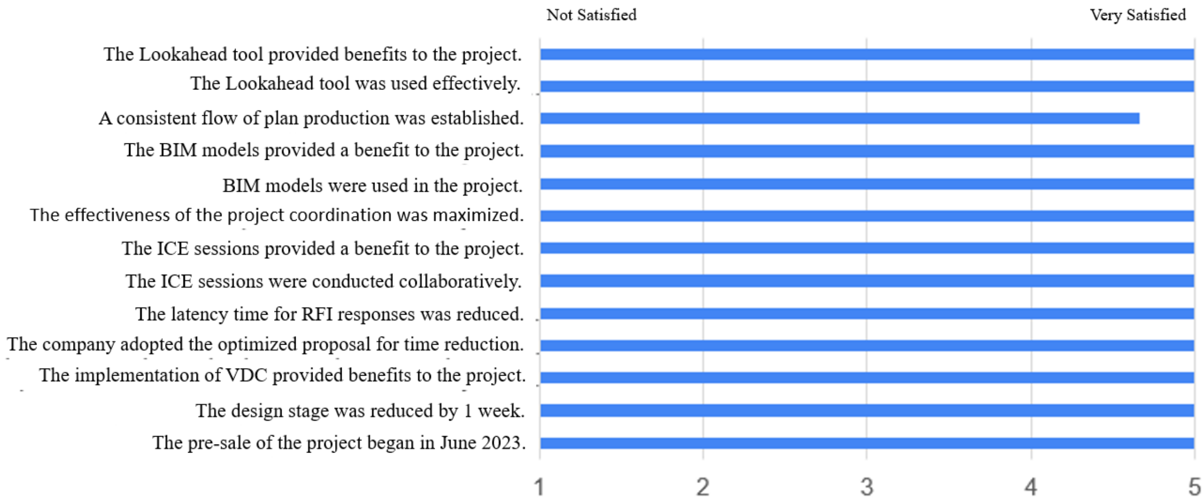

Figure 8: Stakeholder survey on the VDC application.

Comparison of Results

Figure 9 presents the average time required to update the drawings to assess the effectiveness of the optimized workflow for the new project using VDC compared to the traditional approach used in the former project.

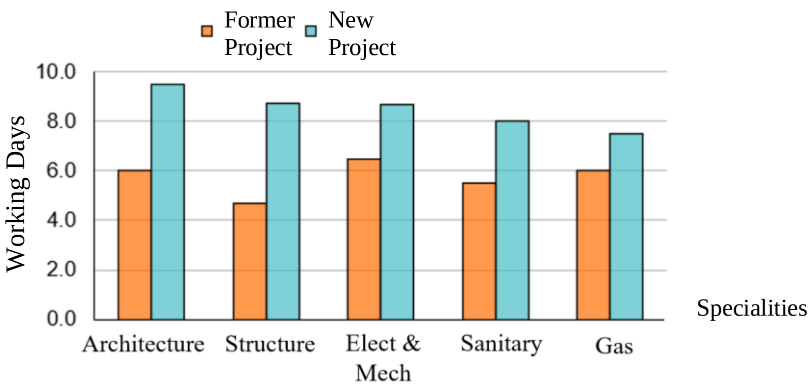

Figure 9: Average time comparisons to update drawings between the new and former projects.

DISCUSSION

The analysis of the Company's design process for the former project revealed the opportunities for improvement in several areas, including:

- Enhancing efficiency by minimizing downtime between email responses to expedite decision-making tasks.
- Streamlining the identification and solution of interferences to eliminate bottlenecks and facilitate a smoother project design process.
- Improving communication to reduce the need for constant redesigns of architecture and other specialties.
- Establishing clear information channels among participants to enhance overall clarity.
- Ensuring timely delivery of the technical files by addressing and mitigating delays in the planned schedule.

As for the results obtained, the production objectives were monitored throughout the design phase, looking to meet the objective and striving for continuous improvement. During the ICE sessions, issues were resolved using CAD or BIM. PPM production metric was tracked based on classifying the activities before the ICE sessions, facilitating identifying activities that could be addressed during the session.

The lookahead application was successful, achieving the 100% target for the controllable factor of classified tasks. This allowed identifying non-executable tasks and the respective coordination to ensure interferences could be resolved in the ICE session. In addition, a consistent production flow was maintained. Thus, achieving the goal of on-time deliveries on most agreed-upon dates resulted in a total compliance rate of 84%, above the minimum limit of 75% (see Figure 7).

The surge in BIM utilization exhibited a direct correlation with the percentage of project information that was modeled. The targeted percentage was achieved during ICE session 3 (week 8, ICE3-W8), as depicted in Figure 7, with the complete design being modeled. This contrasts ICE session 2 (week 6, ICE2-W6), where only 72% of the required information had been modeled by that point.

CONCLUSIONS

Implementing the VDC methodology has proven to be instrumental in enhancing the efficiency of the project's design stage, resulting in a remarkable 25% improvement in the time taken to deliver technical files. This notable achievement can be attributed to the systematic reduction of variability in the drawings update process, the effective identification and resolution of interferences through BIM, collaborative problem-solving in ICE sessions, and the establishment of standardized production timelines for updated drawings using PPM.

The proposed optimized process, designed for ease of use as a collaborative management tool, holds significant potential for property companies during the design stage. This is corroborated by the high satisfaction levels and adaptability expressed by the project stakeholders in surveys conducted on VDC implementation.

Furthermore, the pivotal role of BIM in detecting project interferences is underscored, with the degree of success directly proportional to the availability and modeling of project information. This proactive approach allows for the improved detection of most interferences in the project's early stages.

Emphasizing the critical nature of active stakeholder participation in ICE sessions, the research highlights the necessity of collaborative decision-making to resolve interferences promptly. The ICE sessions facilitate real-time problem-solving and ensure the timely updating of drawings, contributing to the project's overall success.

This research's main contribution is an optimized design process with VDC that can be applied in similar construction projects. It addresses construction industry challenges with the application of VDC and demonstrates its effectiveness in reducing design delivery time, resolving interferences and improving stakeholders' satisfaction.

This investigation is limited to projects and companies sharing similar characteristics. It is important to note that more complex and bigger projects can face different problems, and their application process could differ. The project's design phase schedule limited the resources and times for the proposal and the VDC framework application. Additional resources and time can enable the development of procedures and manuals for the current application.

For future investigations, it is recommended that an economic evaluation of the proposed implementation be conducted, which should include the additional costs and savings generated by the optimized process.

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EXPECTATIONS AND PERCEPTIONS – DAILY MANAGEMENT MEETINGS IN DESIGN

Joonas Särkilahti[1], Olli Seppänen[2] and Eelon Lappalainen[3]

ABSTRACT

Daily Management (DAM) has generated many benefits in construction, but it has been less used and studied in design management. This case study of a Finnish structural design firm provides insights into the expectations of designers regarding DAM and Daily Management Meetings (DMM), as well as their perceptions during a short experiment on implementing DAM and DMM in daily structural design work. The research data for the case study were collected through interviews, observation, and a survey conducted with the company's larger structural design group. The main expectations of survey respondents and interviewees included improving the identification of design constraints, ensuring and enhancing the flow of information and increasing trust and team spirit. Interviewees who participated in the experiment highlighted the importance of being able to estimate their own workload and task duration, as well as gain improved knowledge of the concurrent work of other team members. Interestingly, in a larger group with many design managers, the benefit of improving the evaluation of each designer's workload was not anticipated as a significant benefit. This study contributes to highlighting DAM's implications for designers' self-management of their work.

KEYWORDS

Lean construction, construction design process management, daily management, daily management meetings, design management

INTRODUCTION

Efficient construction design process management (CDPM) is hindered by several different factors, such as poor communication among team members (Sousa et al., 2017; Galaz-Delgado et al., 2021), lack of trust (Uusitalo et al., 2019), inefficient information flow (Pikas et al., 2020), and insufficient knowledge of process' progress and others' work (Tauriainen et al., 2016; Svalestuen et al., 2018). These challenges can be mitigated by utilizing lean design management (LDM) (Tauriainen et al., 2016; Pikas et al., 2020; Fosse & Ballard, 2016).

An important part of lean-based management is daily management (DAM), which consists of many different tools, methods, and practices (Nicholas, 2018; Charron et al., 2014; Kennedy, 2019). One of the essential practices of DAM are daily management meetings (DMM) (Kennedy, 2019; Nicholas, 2018).

Daily meeting practices have been adapted and utilized in many different fields for a long time compared to the construction industry (Mariz et al., 2019). In recent years, the effects of DMM have begun to be more widely studied in the construction industry (Wandahl et al., 2023;

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Zender & de Soto, 2021). Studies carried out in the construction industry have yielded many promising results regarding the benefits of DMM. There have, however, only been a few studies conducted in the context of CDPM (Lappalainen et al., 2022; Streule et al., 2016). While these studies have identified the positive effects of DMM, such as improved communication among design teams and enhanced detection of constraints, they do not specifically focus on the benefits and drawbacks of DMM. Both aforementioned studies, in addition to examining DMM, discuss various other practices and tools. This broad scope limits the extent to which the results can be attributed solely to the DMM. The aim of this study is to address this research gap.

DAILY MANAGEMENT

DAM is an important tool of Lean management (Liker & Convis, 2012). DAM aims for efficient process execution and monitoring and for the continuous improvement of operations (Kennedy, 2019; Charron et al., 2014; Nicholas, 2018). This is pursued via various tools, methods, and practices. Of these, the following are the most relevant and most discussed in the Lean literature: Appropriate Measures, Daily Management Meetings, Visual Management, Leader Standard Work, Problem-solving & Learning, and Tiered Accountability. (Kennedy, 2019; Nicholas, 2018; Charron et al., 2014; Liker & Convis, 2012; Gao & Low, 2014.)

According to Nicholas (2018) and Kennedy (2019), DMM is an especially important part of DAM. Nicholas (2018) also points out that the comprehensive implementation of DAM is a long process that changes the operating culture of the entire company. Therefore, it is not recommended to try to implement all the tools and methods of DAM at once; instead, the process should start by trying out individual tools, such as DMM, and adapting them to suit the company's operations (Nicholas, 2018).

DAILY MANAGEMENT MEETINGS

DMMs usually consist of briefly discussing the previous day's performance and possible challenges, as well as setting goals for the coming day and ensuring that the work can be carried out without problems. The goal of a DMM is to enhance the identification of different problems and constraints related to the work, thus enabling problem-solving, learning, and continuous improvement, which is the ultimate purpose of DAM. (Kennedy, 2019; Nicholas, 2018; Charron et al., 2014; Gao & Low, 2014.)

DMM has been implemented and applied in many different fields for a long time compared to the construction industry (Mariz et al., 2019). The effects and benefits of DMM have been studied over the years, especially in the manufacturing industry (Poksinska et al., 2013; Wester & Hitka, 2022), in the healthcare sector (Donnelly et al., 2017; Schatz & Bergren, 2022), and in the software development industry (Stray et al., 2016). These studies have found that implementing DMM improves communication and information flow, enhances the identification of constraints and problems, increases the team members' awareness of the progress of the process, enhances the team members' commitment, and increases trust and team spirit.

DAILY MANAGEMENT MEETINGS IN CONSTRUCTION

In the construction industry, lean construction is often associated with the Last Planner System® (LPS), which was developed in the industry in the early 1990s for project production control (Daniel et al., 2015; Ballard, 1994). Since then, LPS has started to be used in the industry not only for production control but also as an aid for CDPM (Fosse & Ballard, 2016; Daniel et al., 2015). LPS is based on versatile, structured, complementary, and regularly held meetings on a monthly, weekly, and daily basis (Fosse & Ballard, 2016; Hamzeh et al., 2009). Although daily meetings have been part of LPS for over 20 years (Ballard & Howell, 2003), research into their benefits has remained remarkably low in the construction industry compared to many other industries (Mariz et al., 2019; Wandahl et al., 2023).

Although studies that deal at least in part with DMM can already be found in the construction industry in the early 2000s (Salem et al., 2005), similar studies have become more common only in the last 10 years or so. Only a very small part of these studies (Wandahl et al., 2023; Ghosh, 2014) deal exclusively with DMM and their effects. In most of the studies where DMM is a part of the topic, DAM is reviewed comprehensively (Mariz et al., 2019; Lappalainen et al., 2022) or different Lean construction tools and their effects are compared (Salem et al., 2005; Noorzai, 2023). The use of DMM has increased in construction sites in recent years with the implementation of Takt production (Dlouhy et al., 2016; Haghsheno et al., 2016). Keeping pace and the quick reaction it requires are ensured with the help of daily Takt meetings (Haghsheno et al., 2016).

In studies conducted within the construction industry, DAM and DMM are often reviewed in relation to Lean and LPS (Wandahl et al., 2023; Gao & Low, 2014). However, in recent years, DMM has also been implemented in construction projects via the Scrum system originating from the IT sector based on Agile management (Streule et al., 2016; Zender & de Soto, 2021). Although there are several differences between LPS and Scrum and their use, the systems are relatively similar in terms of DAM and DMM (Lappalainen et al., 2022; Zender & de Soto, 2021; Streule et al., 2016).

Implementing DMM has yielded many of the same benefits in the construction industry as in other industries. The most relevant of these are related to increasing and improving communication between team members (Salem et al., 2005; Ghosh, 2014; Streule et al., 2016) and to the developed ability of teams and individuals to identify and solve problems and constraints (Mariz et al., 2019; Lappalainen et al., 2022; Noorzai, 2023). Streule et al. (2016) and Ghosh (2014) also identified as one of the positive effects of DMM that it helps team members get a better understanding of what work others are doing, which also increases understanding of the entire process and its progress.

Based on the results achieved in the construction industry, as well as in other fields, DMM could potentially reduce many of the challenges of CDPM. However, most studies in the industry that deal with DMM are limited to construction. Despite a few isolated studies (Lappalainen et al., 2022; Streule et al., 2016), DMM or DAM in general have not yet been extensively researched in the context of CDPM. Therefore, the aim of this research was to investigate the benefits and possible drawbacks of DMM in CDPM. The investigation is based on interviews, a survey, and a case-project experiment.

METHODS

The research method chosen was a case study of the structural design unit of a Finnish engineering firm. In the case study, a survey and six semi-structured interviews (SSIa) were first conducted to elicit expectations of the benefits and possible drawbacks related to DMM. The survey and interviews focused on the staff of the regional offices. After investigating the expectations, a week-long experiment was carried out in a case project to investigate the perceived benefits and drawbacks of DMM. Related to the experiment, data were collected via participant observation, as well as four semi-structured interviews (SSIb). The experiment and interviews were conducted with a small design team in one of the offices.

The case study aimed to obtain a real-world perspective on the relationship between expectations and perceptions of DAM and DMM in a design context (Yin, 2018). According to Yin (2018), case studies are essential for explaining real-world interventions and illustrating specific themes of evaluation. The design firm chosen as the case study is part of a joint industry–university research consortium of researchers and the Finnish construction industry (Lavikka et al., 2020), and when researchers asked for volunteers in the consortium workshop, the case company representative volunteered their company for the study. The company employs about 2200 people and has a turnover of about 220 M€.

The questions of the semi-structured interviews (SSIa) and the survey related to expectations were designed based on a literature review. Feedback on the survey questions was requested and obtained from the development manager of the case study company. The survey and interviews aimed to find out what people's expectations are regarding the benefits and drawbacks associated with DMM. It was possible to participate in the interviews face-to-face or via the Microsoft Teams application. The responses were grouped into themes. The survey was conducted on a company development day using the Mentimeter electronic survey tool. At the beginning of the event, the lead author introduced the background information of the survey to the participants. The survey results were reviewed with the participants during the event, and the data were evaluated separately by the researchers after the event. The theming was done in an Excel spreadsheet.

In the case project chosen for the experiment, DMM had not been utilised before, and the participants had no previous experience of DMM. The lead author conducted participant observations during the meetings and wrote down observations in field notes, which, according to Flick (2006), is the most common and effective way to document observational data. The questions of the semi-structured interviews (SSIb) were designed to elicit the experiences of the participants in the experiment regarding how they perceived the use of DMM in their design work. The interview questions were developed based on the observations made during the experiment as well as the information obtained earlier related to the expectations. The interviews were recorded and transcribed. It was possible to participate in the interviews face-to-face or via the Microsoft Teams application. The interview responses were evaluated and grouped into themes in an Excel spreadsheet. The research process is presented in Figure 1.

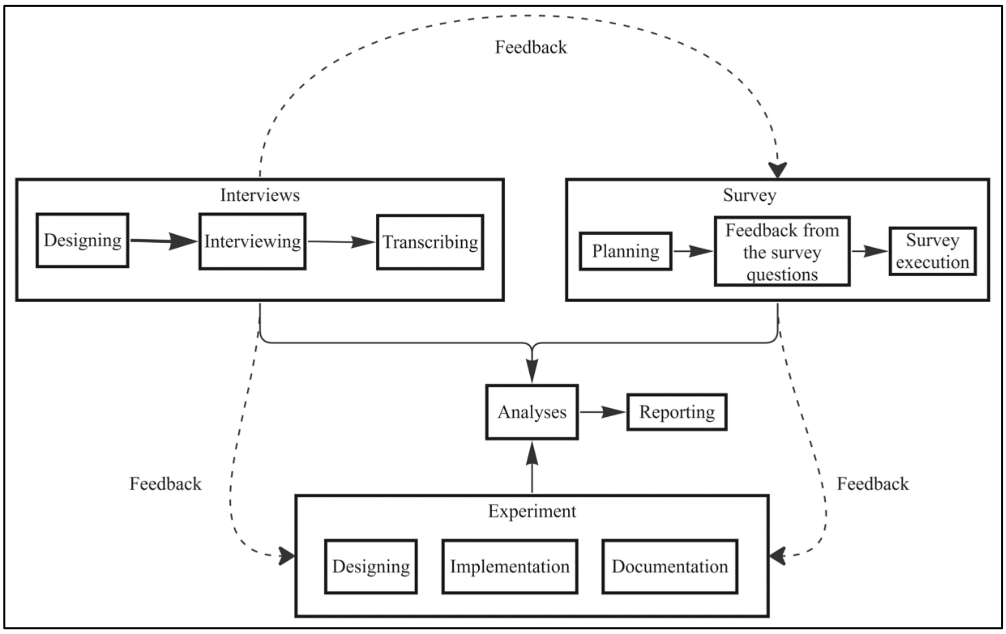

Figure 1. Research design.

This study uses a combination of research methods, which increases the validity of the study by examining several different perspectives, with common points indicating a closer description of reality, as Jack and Raturi (2006) argue. By triangulating results from literature reviews, interviews, and surveys, the inherent weaknesses of each method are compensated for, following the approach recommended by Turner et al. (2017). As argued by Yin (2018), the findings and conclusions of the case study gain reliability from being drawn from this diverse set of data sources rather than from individual methods.

FINDINGS

In this section, expectations regarding the benefits and drawbacks of DMM are presented. These were elicited using a survey and interviews (SSIa). The survey was conducted during a 1-day design manager workshop. The interviews were conducted over a period of 45 days. Two of these were carried out face-to-face, while four were held remotely via Microsoft Teams. All interviews were recorded and subsequently transcribed. The longest interview lasted 72 minutes, and the shortest was 27 minutes in duration. On average, the interviews lasted 44 minutes.

After presenting the main expectations, the results of the experiment are reviewed. The experiment aimed to obtain information about the perceptions of DMM in a real context by implementing them in a case project. The results were elicited by interviewing (SSIb) the members of the case project. The lead author also participated in the DMMs held during the experiment as an observer. This enabled the investigation of possible challenges and drawbacks related to DMM and its implementation. The interviews were conducted over a period of 4 days, and two of them were held face-to-face, while the other two were held remotely via Teams. Again, all interviews were recorded and subsequently transcribed. The longest interview lasted 26 minutes, and the shortest was 15 minutes in duration. On average, the interviews lasted 20 minutes.

EXPECTATIONS

A survey (n=34) and interviews (n=6) were utilized to determine expectations regarding the benefits and drawbacks of DMM. Table 1 presents the themes that came up the most regarding the benefits, as well as the proportions of answers related to them.

Table 1: Expected benefits of daily management meetings

Theme	Survey (n=34)	Interviews, SSIa (n=6)
Improves communication	6 %	83 %
Enhances information flow	18 %	67 %
Enhances identification of dependencies between tasks	12 %	17 %
Ensures workflow	15 %	50 %
Improves assessment of own workload	6 %	-
Enables better monitoring of progress	9 %	33 %
Enhances identification of constraints and problems	24 %	-
Increases trust and team spirit	12 %	33 %

There is a noticeable distribution in the answers to the survey and the interviews regarding which themes were emphasized the most. For example, only a small portion of the survey answers (n=34, 6 %) related to improving communication, while in the interviews this theme came up distinctively the most (n=6, 83 %). In the survey, enhancing the identification of constraints was seen as the greatest potential of DMM (n=34, 24 %), while in the interviews this theme did not come up directly at all. Themes that received a relatively large number of responses in both sets of collected materials were enhancing information flow, ensuring workflow, and increasing trust and team spirit.

The survey and interviews also aimed to obtain information about the expected challenges and drawbacks of DMM. In the survey, there were fewer responses (n=30) regarding these compared to the benefits (Table 1). Table 2 presents the themes that came up most regarding the drawbacks, as well as the proportions of answers related to them. The implementation of DMM is expected to be challenging, especially due to time constraints. In the interviews, the most cited (n=6, 67 %) drawback of DMM was that they would take too much time away from other daily work. The problem of finding a standard time that suits everyone every day was frequently mentioned in both the survey (n=30, 33 %) and the interviews (n=6, 50 %). One of the reasons identified in the survey (n=30, 13%) for this drawback is that designers and project managers often work on several different projects simultaneously.

Table 2: Expected drawbacks of daily management meetings

Theme	Survey (n=30)	Interviews, SSIa (n=6)
The meetings require too much time daily	17 %	67 %
Challenging to find a time slot that suits everyone's schedule	33 %	50 %
Difficult to get everyone to commit to the practice	20 %	50 %
Challenging to get designers to critically evaluate their own work and performance	10 %	33 %
Designers may experience the practice as an excessive supervision of their performance	7 %	17 %
There might not be new things to go through in the meetings every day	7 %	33 %

As can be seen in Table 2, there are also expected to be many other drawbacks regarding DMM. In two interviews, it was discussed that it can be challenging to get people to commit to the practice due to the other challenges presented in Table 2. In the survey (3 responses, 10 %) and in one of the interviews, it was pointed out that DMM might be perceived more openly if everyone was aware of their benefits.

PERCEPTIONS POST-EXPERIMENT

A week-long experiment was conducted to obtain concrete results about the benefits and drawbacks of DMM. In the experiment, DMMs were implemented in a structural design case project, where a similar practice had not been utilized before. The main project team consisted of four members. The case project members were interviewed (SSIb) after the experiment to determine how they perceived the DMM. Table 3 presents the key perceived benefits that stood out in these interviews.

DMM were consequently perceived to have positive effects especially on the planning and execution of work tasks. This was also felt to have a positive effect on the ability to estimate the amount and duration of work. The design project manager also found it to be beneficial that with DMM, they knew more precisely every day what everyone was going to do, as this made it easier for them to follow the progress of the process more closely.

The DMM experiment was conducted efficiently in terms of time-consumption. The average duration of the meetings was only 8 minutes, with the shortest lasting 6 minutes and the longest lasting 11 minutes. This, to some extent, refutes the expectation that DMMs require a lot of time each day.

Table 3: Key perceived benefits of the daily management meeting experiment

Key perceived benefits	Interviews, SSIb (n=4)	Extracts from interviews
Facilitates the planning and execution of work tasks	75 %	*"…easier to plan and complete your own work…each day. Working is also more efficient when you think before you do."*
Develops the ability to evaluate workload and task durations	50 %	*"… clearer picture of what you were going to do that day…easier to estimate how much time the work required."* *"… you can also regularly observe in the meetings whether your own estimations have gone right or wrong, which further develops your assessment ability."*
Helps especially the project manager in monitoring the progress	25 %	*"[The project manager] could hear and see what goals everyone set for the day, and how the tasks were going, which made it easier to keep in track with the process progress."*

Although the DMM experiment was successfully implemented, there were also some drawbacks associated with the new practice. Perhaps the most significant challenge that emerged during the experiment was scheduling a meeting that all members of the case project team could attend. While there were no days when no one attended, there was almost always at least one team member with scheduling conflicts, often due to other meetings or site visits. One of the most expected drawbacks of DMM was that it could be challenging to find a time slot compatible with everyone's schedule. The experiment's findings thus confirm that this is a real obstacle. In contrast with construction workers, designers tend to have several meetings during the day, for instance, with other designers or with the client. They also often work on several projects at the same time. The project manager of the case project recognized in their interview that flexible working hours also pose a challenge for scheduling DMMs. Holding these meetings first thing in the morning ensures that there are no interruptions in the workflow (Ghosh, 2014; Wandahl et al., 2023). However, this is quite difficult in design offices compared to construction sites, where workers typically arrive at the site at the same time, as employees in design offices may start their workdays at different times. Finding a common time is, therefore, particularly difficult in design.

Observations of the meetings revealed that the same topics and issues were frequently discussed, often without significant new additions. This issue also emerged during the investigation of the expected drawbacks of DMM, as noted in Table 3. In their interviews, the majority of the case project team members (3 out of 4) attributed this to the compact size of their project team. They noted that they naturally discuss things with one another even without the necessity of DMM.

DISCUSSION

This exploratory study showed that various benefits can be achieved by implementing DMM in CDPM. The findings propose that the main expected benefits of DMM include improved workflow, better information flow, and enhanced trust and team spirit. The findings from the experiment reveal that DMM facilitates more efficient planning and execution of work tasks, aids in evaluating the amount and duration of tasks, and is particularly beneficial for project managers in monitoring progress. These outcomes generally align with the initial expectations, highlighting DMM's positive impact on design management efficiency. However, while one of the main findings of the experiment was that DMM had positive effects on the participants' ability to evaluate their own workload and task durations, this theme only barely came up in the survey (n=34, 6 %). It is also noteworthy that there were no remarks relating to this theme in the six interviews (SSIa) regarding the expected benefits. There can be several different explanations for this. The prominence of this theme in the experiment may be attributed to factors such as the type of case project and the working methods of its members.

The findings also indicate that there are various design-specific challenges and drawbacks associated with DMM. Based on the responses from the survey and interviews (SSIa), it is expected that DMM will consume too much time from other daily work. The findings from the experiment refute this expectation, with the average duration of the held meetings being under 10 minutes. However, it is important to consider the compact size of the case project team. The meetings could be quite easily kept short, since there was usually not much to discuss with only a few participants involved. Numerous studies, particularly those focusing on Scrum, emphasize the importance of using a pre-prepared agenda to maintain efficiency in DMM (Stray et al., 2016; Streule et al., 2016). Using a ready-made agenda could be recommended, especially with larger project teams, where the scope of discussion can be more extensive.

The findings show that integrating DMM into everyone's schedule is expected to be particularly challenging. The experiment confirmed this common expectation, as finding a suitable time for everyone proved particularly challenging. This was primarily due to issues specific to design, such as flexible working hours and members working simultaneously for multiple projects. Unfortunately, there is no direct solution to this challenge. Stray et al. (2016) suggest that DMM should be organized in a manner that minimizes disruption to team members' daily work. The most suitable time for DMM consequently depends on the situation and should be agreed upon collectively by the project team before implementing the practice. Although it would be useful to hold a meeting first thing in the morning to ensure an efficient workflow, as previously discussed, the meeting can also be scheduled later in the day if it better accommodates everyone's schedule. For instance, Stray et al. (2016) noted that their study's case project team found holding a meeting just before lunch to be the most effective practice. This timing could perhaps also be more suitable for design teams that operate under flexible working hours.

While the findings of this study provide valuable insights into the benefits and challenges of DMM in CDPM, there are some limitations and areas for improvement. First, the study's focus on a single design unit of a Finnish engineering firm may limit the generalizability of the findings. Cultural and organizational factors specific to the firm may influence the outcomes, which might differ in other contexts. Second, the experiment period was relatively short, which may not capture the long-term effects and adaptations of the DMM practice. The experiment focused on only one case project, which also limited the generalizability of the findings. However, the validity and reliability of the related findings was increased by combining several data collection methods (Turner et al., 2017). This was realized in both phases of the empirical research process, as data related to the expectations were collected by combining interviews and a survey, and data related to the perceptions were collected by combining interviews and observation. Finally, the study relies heavily on qualitative data from interviews and a survey, which, while insightful, may benefit from the inclusion of quantitative measures to provide a more comprehensive analysis.

The findings of this research are relevant and valuable for both industry and academia. For the construction industry, this study establishes that various benefits can be achieved by implementing and utilizing DMM in CDPM. Previous research in the industry has yielded many promising results regarding the benefits of DMM and DAM in general (Wandahl et al., 2023; Mariz et al., 2019; Lappalainen et al., 2022; Ghosh, 2014). The findings of this study generally align with the results of previous research. For instance, Lappalainen et al. (2022) found that the reliability of task execution increased when DMM and DAM were implemented. The findings obtained through the practical experiment in this study align with this, thus validating the results of Lappalainen et al. (2022). The experiment also demonstrated the positive effects DMM have regarding the work of the design project manager. This, in turn, confirms the results of Wandahl et al.'s (2023) study, according to which DMM facilitates construction site managers' work and time management.

Although the effects of DMM have been researched in the industry, the topic has not yet been extensively researched in the context of construction design processes. This study affirms that the positive results achieved on the production side of construction are also valid in design, although there are unique challenges, such as finding a common time. Consequently, the study provides a general basis for the topic, and the findings can be used as an aid for further research, thus alleviating the research gap.

The topic can be approached from many different perspectives, offering numerous avenues for further research. For instance, comparing the effects of DMM across different design processes in the construction industry could illuminate the generalizability of the benefits and applicability of DMM within the CDPM context. Another compelling topic for future research would be investigating whether Wandahl et al.'s (2023) findings on DMM's impact on construction site crew productivity are also applicable to construction design teams. To ensure a robust and comprehensive analysis, such research could benefit from utilizing quantitative methods or a combination of qualitative and quantitative approaches.

Hopefully, this short paper will inspire design project managers to explore the use of DMM, perhaps in conjunction with other DAM practices, in their future projects. Broader adoption of such practices would facilitate advancing the much-needed further research on the topic.

CONCLUSION

This study aimed to investigate and compare the expectations and actual experiences of DMM in CDPM, consequently addressing a significant research gap in the field. This objective was pursued by conducting a case study of the structural design unit of a Finnish engineering firm.

The findings obtained through a survey and interviews showed that various benefits are expected to be gained when implementing DMM in design. Based on this study, these expectations are especially related to enhancing information flow, ensuring workflow, and increasing trust and team spirit. The findings also show that there are various expected challenges regarding the implementation of DMM in design. These especially relate to time consumption and scheduling.

The findings obtained through a practical experiment showed that DMM facilitates the planning and execution of work tasks, which in turn develops the ability to assess workload and estimate task durations. DMM can also help, especially the project manager, to monitor the progress of the process. The experiment also confirmed the expected challenges regarding the scheduling of meetings, proving that finding a common time for DMM is particularly difficult in design.

Although the research has some limitations, the findings provide valuable insights regarding the benefits and drawbacks of DMM in the context of construction design processes. Therefore, this study can be used as a basis for more comprehensive further research.

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BUILT ENVIRONMENT DESIGN KNOWLEDGE FRAMEWORK SUPPORTIVE OF RESILIENT HEALTHCARE

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ABSTRACT

Although the evidence-based design (EBD) literature investigating the influence of the built environment (BE) on health services performance and outcomes is extensive, its contribution to resilient healthcare is scarce. This work presents a framework of BE design knowledge supportive of resilient healthcare. Firstly, a systematic literature review based on EBD, complexity, and resilience resulted in generic BE design knowledge that represented the role of BE in supporting resilient healthcare at different levels of abstraction. Next, the knowledge was used for thematic analysis in case studies in two teaching hospitals, tailored to workflows that occurred in the connecting areas to and from an intensive care and other hospital units of a large public hospital in Brazil and the surgical service of a private hospital in Australia. Joint findings allowed the development of a framework hierarchically composed of four meta-principles, seven principles, seven prescriptions, and 181 practical examples emphasizing a systems perspective that considers intra and inter-hospital workflows and areas. The resulting knowledge guides designers of both BE and operations phases during decision-making to support resilient health services. As a limitation, the framework was not applied during those phases, representing one of the main suggestions for future work.

KEYWORDS

Evidence-based Design, Built environment, Complexity, Resilient Healthcare.

INTRODUCTION

Health services are Complex-Socio Technical Systems (CSSs) in which care provision is possible due to dynamic interactions between human, technical, and organisational elements influenced by the external environment (Braithwaite, 2018). An emerging property that arises from these interactions in CSSs is resilient performance (RP), a phenomenon that, in the context of health services, is investigated underneath the realm of resilient healthcare - i.e., *"the ability of the healthcare system (a clinic, a ward, a hospital, a county) to adjust its functioning prior to, during, or following events (changes, disturbances or opportunities), and thereby sustain*

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required operations under both expected and unexpected conditions" (Hollnagel et al., 2013). In the myriad of interactions, the built environment (BE) is a technical system that supports activities and shapes the relationships between processes, technologies and stakeholders (Hicks et al., 2015; Hollnagel, 2014; Real et al., 2017). Therefore, BE should support resilient healthcare, as its relevance for the performance of health services has been acknowledged by several studies on BE influence on both patient outcomes and caregivers´ performance (Real et al., 2017; Machry et al., 2021).

The body of knowledge on the influence of BE on health services has been produced under the umbrella of evidence-based design (EBD) (Ulrich et al., 2008; Zhang et al., 2017). The EBD literature focuses on the BE impacts on efficiency and safety of care provision from factors such as privacy, noise, light, access to outdoor spaces, accessibility, and layout (to the external environment, accessibility, and layout (Rybkowski; Greer et al., 2021). From the viewpoint of lean construction, EBD is useful for generating value to stakeholder - e.g., patients and staff members - and workflows - e.g. health services (Zhang et al., 2016). Nonetheless, EBD studies are commonly criticized for neglecting the complexity of health services, overlooking the interactions that occur in the BE and missing the need to support RP (Halawa et al., 2020; Łukasik and Porębska, 2022). From a resilient healthcare perspective, this EBD drawback is a failure to acknowledge the gap between work-as-imagined (WAI) in design and protocols and work-as-done (WAD) in reality (Ransolin et al., 2020; Machry et al., 2021; Joseph et al., 2022). This gap arises from the everyday variability of complex systems, a condition that requires RP – which is commonly unveiled in the successful outcomes of WAD and highlighted by resilient healthcare (Bueno et al., 2021). However, EBD tends to produce knowledge based on the WAI formalised in guidelines rather than the WAD on site, which leads to a lack of comprehension of the complexity and resilience during the design of health systems. Moreover, while EBD is a source of knowledge for designers, it is bound to a specific context and does not provide a standard for repetition, which contributes to the fragmentation of EBD knowledge (Zhang et al., 2016).

Therefore, *the aim of this paper is to propose a framework of BE design knowledge supportive of resilient healthcare***.** It is based on a systematic literature review (SLR) and two empirical studies carried out in different hospital units, on in Brazil and the other in Australia. The SLR investigated EBD studies on complex socio-technical systems and resilient healthcare resulted in a generic BE design knowledge supportive of resilient healthcare (Ransolin et al., 2022). The corresponding knowledge is structured according to different levels of abstraction, from high-level general design guidance, to low-level practical solutions that are highly context-dependent. Then, the knowledge was applied as a heuristic device for data analysis, being tailored to the specific context of two empirical studies. Thus, the case studies investigated the WAD of hospital workflows in (i) the connecting areas to and from an intensive care unit (ICU) of a large public hospital in Brazil (Ransolin et al., 2024a), and (ii) the surgical service of a private hospital in Australia (Ransolin et al., 2024b). This investigation is relevant for design management, a traditional lean construction topic that can explore the resulting framework to develop theories and practices for designing resilient healthcare.

DESIGN KNOWLEDGE FOR RESILIENT HEALTHCARE

The myriad of complex interactions in health services cannot be completely controlled and anticipated, but they can be partially subject to the influence of design (Plsek & Greenhalgh, 2001; Wachs et al., 2016). Similarly, resilience emerges partly from CSS self-organisation dynamics and partly from intentional design decisions to support it. This latter is associated with the concept of Design for RP, defined as "*the use of design principles to support integrated human, technical, and organisational adaptive capabilities*"(Disconzi and Saurin, 2022).

Albeit not addressing RP, the EBD framework proposed by Zhang et al. (2019) was devised according to design principles (e.g., 'comfortable environment'), followed by design parameters (e.g., 'light'), which gave rise to sub-parameters (e.g., 'daylight'). Saurin et al. (2013) developed guidelines for coping with complexity based on resilience theory (Table 1), so they were used as a point of departure for this research work that applies to health services.

Table 1: Guidelines for coping with complexity and their definitions (Saurin et al., 2013; Bueno et al., 2019).

	Guidelines for coping with complexity	Definitions
1	Supporting visibility of processes and outcomes	Promotion of real-time visibility to either formal or informal work practices for a user-intuitive CSS functioning (Clegg, 2000; Galsworth, 2017).
2	Designing slack	Human or technical for absorbing uncertainty - i.e., spare resources that can be activated when necessary (Nohria & Gulati, 1996; Formoso et al., 2021).
3	Encouraging diversity of perspectives when making decisions	Diversity of perspectives helps to manage uncertainty and requires high levels of trust, low power differentials, and apt decision-makers (Page, 2010).
4	Monitoring and understanding the gap between work-as-imagined (WAI) and work-as-done (WAD)	Awareness of the daily variabilities in performance and outcomes implied in CSSs. The reasons and consequences of this gap should be investigated (Hollnagel, 2017).
5	Monitoring unintended consequences of improvements and changes	Interventions interact between themselves and the environment, creating negative or positive unintended consequences (Perrow, 1984; Ogrinc et al., 2015).

The design knowledge framework presented in this paper comprises meta-principles (i.e., the guidelines of Saurin et al., 2013), principles, prescriptions, and practical examples. Design principles are at a higher abstraction level and refer to a group of prescriptions that share similar goals (Kuechler and Vaishnavi, 2012; Ransolin et al., 2022). According to Vaishnavi and Kuechler (2015), a design prescription is a suggestion for action in a given circumstance to achieve an effect. Instantiations of the prescriptions in a particular context are practical examples at the lowest level of abstraction (Ransolin et al., 2022).

RESEARCH METHOD

RESEARCH DESIGN

This research work used qualitative methods as their utility to uncover complexity has been recognised (Rapport and Braithwaite, 2020). Firstly, a SLR explored how the EBD literature addresses complexity and resilience in BE health services (Ransolin et al., 2022). Furthermore, case studies allow for developing both generalizable and context-specific knowledge (Yin, 2017), which is consonant to develop BE design knowledge across different levels of abstraction. Then, two case studies were successively conducted in teaching hospitals, investigating the particularities of workflows in different hospital settings. The first case study was conducted in a large (around 6,000 employees) public and tertiary hospital in Southern Brazil, where we paid attention to the interactions between an adult ICU and other hospital units - e.g., in-patient wards and non-clinical areas such as warehouse - across a three-building complex (Ransolin et al., 2024a). The second case study was undertaken on the first floor of a medium-sized private hospital in NSW, encompassing elective surgical service flows (Ransolin et al., 2024b). Both empirical studies followed two major stages: (i) characterisation of the health service flows and BE, and (ii) development of the design knowledge. The joint analysis of the findings from the SLR and the case studies allowed the identification of emerging patterns that gave rise to a design knowledge framework to address the main research objective.

DATA COLLECTION AND ANALYSIS

In Ransolin et al. (2022), an SLR followed the steps proposed by the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) (Moher et al., 2009), which are: 1) identification of the papers; 2) screening; 3) eligibility; and 4) inclusion. From 2412 records identified from seven databases and five manual inclusions, 2220 were screened, 397 were fully assessed, and 43 papers were selected for qualitative analysis. The search string was composed of variations of keywords related to the following domains: study object (e.g., built environment, EBD); context (e.g., health services); approaches (e.g., complexity, resilience); outcomes (e.g., safety, well-being); and stakeholder (e.g., patients, staff). The selection of publications was not limited by year; papers were filtered in English and related to similar areas (e.g., engineering, social science, business and management, arts and humanities). The screening considered four exclusion criteria: (i) non-scientific texts; (ii) conference proceedings; (iii) literature reviews; and (iv) content unrelated to healthcare facilities (e.g., ethical aspects), or the research aims (e.g., risk analysis). In the eligibility step, the resulting publications were scanned in order to exclude papers that did not contain any of the following keywords in the full text: Complex*; Resil*; Flex*; Adapt*; Flow; Evidence-based Design (EBD). Finally, the included publications were fully analysed.

Empirical data collection was carried out by the first author after the ethics committees of both hospitals approved the respective research projects, and participants provided written informed consent before being interviewed. Table 2 presents the total hours of data collection in each case study, according to the sources of evidence used. In total, 133 hours of data were gathered using all data collection techniques in both empirical studies (Ransolin et al., 2024a/b).

Table 2 – Total of data collection (hours) of case studies associated with the sources of evidence.

Data collection	Sources of evidence				
	Document analysis	**Non-participant observations**	**Semi-structured interviews**	**Meetings with hospital staff**	**Total (hours)**
1st case study – ICU connecting areas (Ransolin et al., 2024a)	-	50	30	1	81
2nd case study – Surgical service (Ransolin et al., 2024b)		30	16	6	52
					133

Documents considered for analysis were Brazilian and Australian BE design regulations, guidelines, and architectural floor plans of both hospitals of the case studies. Non-participant observations were conducted during visits and walkthrough sessions to observe workflows performed by frontline staff members. Semi-structured interviews involved two main questions: (1) Could you give an overview of your daily work and the relevant workflows for this hospital unit? and (2) how does the BE facilitate or hinder everyday work regarding these workflows? Please illustrate these implications with a situation experienced by you or a colleague.

Interviewees were divided into five categories: management, administrative/supporting, engineering, clinical assistance, and patients/family members. Meetings with hospital staff helped identify interviewees, defining workflows and areas from which data would be collected, and presenting and discussing the design knowledge framework.

Data collected in the SLR and the case studies was subjected to a content analysis (Pope et al., 2000). This process encompassed familiarisation, identifying themes, coding, charting, mapping and interpretation and was performed successively according to the development of each study. Familiarisation involved multiple readings of primary and secondary data - i.e., papers selected in the SLR, regulations, interview transcripts, and observation notes. Themes were defined previously and imposed for analysis as a heuristic device, being performed successively, allowing tailoring it to each study context. In the SLR (Ransolin et al., 2022), themes corresponded to the guidelines for coping with complexity – i.e., design meta-principles (Table 1). Next, the first case study (Ransolin et al., 2024a) considered the seven design principles developed in the SLR as themes (Ransolin et al., 2022). Then, the second case study (Ransolin et al., 2024b) used as themes for analysis the design prescriptions developed in the previous case study (Ransolin et al., 2024a). Figure 1 illustrates the selection of themes for data analysis in each study of this research work, which corresponded to the levels of the design knowledge framework.

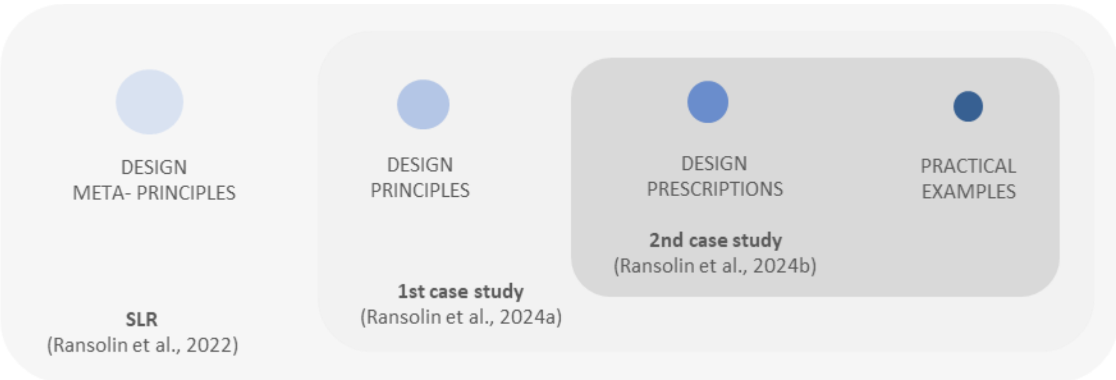

Figure 1: Thematic analysis of the studies in a successive and complementary order according to design knowledge framework levels.

Data coding was performed independently by at least two authors (e.g., NR and TAS) according to the themes defined for each study, based on agreements from meetings to achieve consensus. In the RSL, the coding stage was carried out in four steps with different levels of abstraction corresponding to design meta-principles, design principles, design prescriptions, and practical examples (Ransolin et al., 2022). The charting stage corresponded to the synthesis of findings from the previous stages of content analysis. In the RSL, the knowledge structure was established, representing the different levels of abstraction – i.e., design meta-principle, the corresponding principles, prescriptions and practical examples (results section). In the case studies, findings were schematically represented in Tables that associated the practical examples with each design prescription, tailored to different health services. Lastly, the mapping and interpretation stage related to the discussion of design knowledge resulted in each of the studies in light of the EBD and resilient healthcare literature. Details of methodological procedures can be found in the respective sources (Ransolin et al., 2022; Ransolin et al., 2024a/b).

RESULTS

Figure 2 presents the BE design knowledge framework for resilient healthcare. At the highest abstraction level, the four design meta-principles corresponded to the complexity guidelines

(Table 1). The seven design principles are applications of the guidelines for the BE in health services (Ransolin et al., 2022). In the two lowest abstraction levels, empirical data were linked to the structure, being useful in structuring the presentation of the findings in Ransolin et al. (2024a/b). The design prescriptions correspond to the application of the principles to a context. There is no one-to-one relationship between principles and prescriptions – e.g., the same prescription emerged from multiple principles. The resulting seven design prescriptions are tailored to the context of the case studies (Ransolin et al., 2024a/b). Then, the last framework level is composed of 181 practical examples of real situations where the BE is supportive of resilient healthcare in the health settings, linked with hospital workflows and areas (Ransolin et al., 2024a/b).

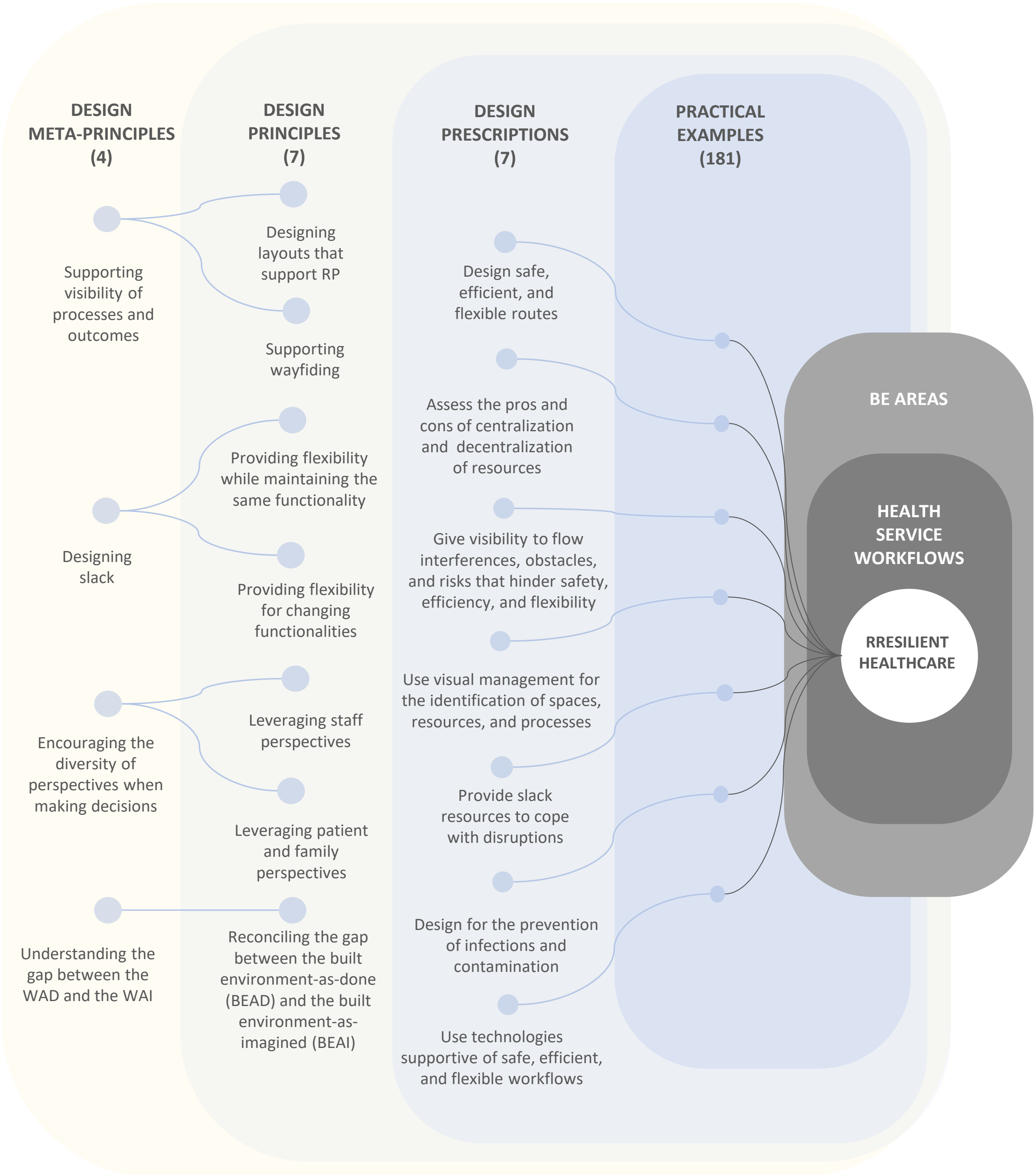

Figure 2: Framework of BE design knowledge for resilient healthcare.

The seven design principles were established in the SLR (Ransolin et al., 2022). The first design meta-principle - supporting visibility of processes and outcomes - derived into two design principles: ‘designing layouts that support RP’ and ‘supporting wayfinding’. The former is illustrated as BE configurations that improve the efficiency of operations and support users´ safety, well-being and interactions. Supporting wayfinding is associated with providing orientation and navigation of users across BE in health services. The second design meta-principle - designing slack - contributed to the design principles: ‘providing flexibility while maintaining the same functionality’, e.g., adaptation, customisation, and expansion, and ‘providing flexibility while changing functionalities’, i.e., changing the main purpose of spaces.

Then, the third design meta-principle - encouraging diversity of perspectives when making decisions - gave rise to two design principles related to ‘leveraging patient and family perspectives’ and ‘leveraging staff perspectives’. The fourth design meta-principle - monitoring and understanding the gap between work-as-imagined (WAI) and work-as-done (WAD) – is translated into ‘reconciling the gap between the built environment-as-done (BEAD) and the built environment-as-imagined (BEAI)’, as the BE design (i.e., BEAI) should be strongly based on the understanding of how people use the BE in reality (BEAD). Lastly, for the fifth design meta-principle - monitoring unintended consequences of improvements and changes - to be effective, this monitoring demands the application of all the design principles above mentioned.

The resulting seven design prescriptions are listed in Figure 2 and were refined to the context of hospital workflows in the ICU connecting areas and surgical services case studies – i.e., two empirical studies (Ransolin et al., 2024a/b). Table 3 presents similarities between some practical examples from the case studies to illustrate the relevance of the design prescriptions for different contexts.

The first design prescription is exemplified by designing direct connections between hospital units in different buildings - e.g., walkways on all floors (1st case study). Similarly, direct connections are necessary to promote ease of transfer and access among surgical phases, using back-of-house corridors – e.g., the ICU should be close to operating rooms to ensure quick patient transportation (2nd case study). Freeing corridor width according to requirements is also present in practical examples from both case studies, as follows: place workstations in the corridors while maintaining the minimum free width of corridors set by regulations (1st case study) and comply with corridor width requirements for clinical areas – e.g., corridors should be wider enough to fit ICU beds that are larger than regular ward beds (2nd case study). The second prescription encompasses practical examples from both case studies related to having a mix of centralised and decentralised storage to share resources among hospital units. For instance, the 1st case study shed light on the importance of designing supporting areas that serve more than one hospital unit, avoiding duplication of resources, and sharing expensive and scarce equipment or infrastructure between ICUs and other hospital units - e.g., tomography, defibrillators, crash carts, pharmacy. In turn, the 2nd case study presented the example of designing centralised storage for general items shared among surgical phases and decentralised storage areas for specific surgical items – e.g., drugs with a higher risk of misuse must be stored in a locked cabinet shared among the operating rooms, allowing control and ready access nurses. The third design prescription is associated with practical examples of preventing interactions between dirty and clean flows. The first case study illustrates the use of dedicated lifts for patients to avoid flow interferences and the design of separate storage for dirty clothes from clean clothes (1st case study). It is also exemplified by prioritising patient flows in corridors and lifts and the signage for the dedicated use of lifts for patient transportation during busy surgery days (2nd case study). This prescription also emphasizes the visual demarcation for equipment storage based on practical examples of signalising an allocated area for parking supply carts and unloading materials near the ICU pharmacy (1st case study) and demarcating visually with lines or colours on the floor and walls to indicate where equipment can be stored (2nd case study).

Table 3 – Illustration of similarities between practical examples from each empirical study (Ransolin et al., 2024a/b).

	Design prescriptions	**Similarities between practical examples from each empirical study** 1st case study - ICU connecting areas (Ransolin et al., 2024a)	2nd case study - Surgical service (Ransolin et al., 2024b)
1	Designing safe, efficient, and flexible routes	Design direct connections Free corridor width according to requirements	
2	Assess the pros and cons of centralisation and decentralisation of resources	Design a mix of centralised and decentralised storage to share resources among hospital units	
3	Give visibility to flow interferences, obstacles, and risks that hinder safety, efficiency, and flexibility	Prevent interactions between dirty and clean flows Provide visual demarcation for equipment storage	
4	Use visual management for the identification of spaces, resources, and processes	Design an intuitive signage	
5	Provide slack resources to cope with disruptions	Provide backup for expansion *Design multiuse spaces*	
6	Design for the prevention of infections and contamination	Distribute dispensers and PPE consistently Give visibility to sterile zones	
7	Use technologies supportive of safe, efficient, and flexible workflows	Provide devices to hold and open doors Avoid patient changes between stretchers Implement alerts to aware staff	
	Practical example "design multiuse spaces" from each case study	 Large warehouse for the storage of equipment and supplies during the COVID-19 pandemic	 Perioperative patient bay being temporarily used as equipment storage

The fourth prescription is related to practical examples from both empirical studies on designing intuitive signage. It can be achieved by self-explanatory direction signage for hospital flows and areas - e.g., using colours and symbols (1st case study) and progressive information disclosure at the right time to minimise the number of decisions required by users (2nd case study). The case study in the surgical service also presented practical examples of strategies to reinforce people's mental maps by demarcating boundaries of different with singular elements. The fifth prescription is connected with practical examples that will strengthen the need to anticipate backup for necessary expansions – e.g., ICU bed capacity during crises (1st case study), and extra inventory spaces (2nd case study) - and design multiuse spaces – e.g., spaces that can also serve as a warehouse of equipment and supplies during demand fluctuations (1st case study), and support areas that allow conversion to operating rooms (2nd case study). The sixth design prescription is grouped with examples from both case studies that share the concern of distributing dispensers and PPE and giving visibility to sterile zones. The 1st case study illustrated the need for placing hand sanitizers in the corridors and at the entrance of the hospital units and designing dedicated routes between restricted areas – e.g., transit of sterilized materials and access to the warehouse elevator. In turn, the 2nd case study underlined the consistent distribution of dispensers and PPE with ease of access across the service and using disposable drapes to cover the operating table, trolleys, light handles, and robot arms to make sterile zones visible.

The last design prescription is associated with practical examples that share three similar topics. Providing devices to hold and open doors is illustrated by the need to temporarily keep the fire door open during the team's passage in an emergency, e.g., a patient resuscitation call (1st case study), or to automatically open doors in high-traffic areas, e.g., between the operating room and induction room (2nd case study). Avoiding patient changes between stretchers is another shared topic of this prescriptions, illustrated by the use of flexible ICU beds that should accommodate the attachment of equipment for critical patient transportation between hospital units and allow procedures in the surgical centre (1st case study). The need for specific patient stretchers could be anticipated in the admission to reduce patient handling and stretchers in corridors – e.g., if a bariatric patient is admitted, a larger bed should be provided in the preoperative phase (2nd case study). Finally, implementing alerts to make staff aware is illustrated by notifications to indicate when storages of waste are full and need to be collected at the units (1st case study) and by call systems with buttons inside operating rooms to signalise the supporting areas that orderlies and clinical staff are needed and warn the surgical team that the patient waiting in the induction room is ready to enter the operating room (2nd case study).

The 1st case study, developed in the ICU connecting areas, linked 63 practical examples that were associated with 11 hospital workflows, as follows: people (resuscitation, exams, admission, discharge, visitors) and supplies (drugs and medical materials, dietary, sterilized materials, cleaning, clothing, waste) (Ransolin et al., 2024a). In turn, the case study on surgical services is associated with 60 practical examples with six main flows – i.e., patient/family, staff, supplies, equipment, sterile instruments and materials, and waste (Ransolin et al., 2024b). The complete list of the practical examples from each case study with details of their sources of evidence and associations with workflows and BE areas can be found in the respective papers.

DISCUSSION

Resilience should be supported across all levels of health services, namely macro (e.g., national healthcare system), meso (e.g., hospital workflows), and micro levels (e.g., hospital units) (Berg et al., 2018). However, understanding the interactions between these levels has been an under-explored topic (Ellis et al., 2019). Therefore, the framework is an original contribution to integrating the BE design knowledge across health service levels. At the micro level, the framework is relevant for the surgical services while considering the implications for the meso level when discussing the interactions with other hospital units – e.g., operating rooms should be close to the ICU to ensure quick patient transportation. At the meso level, the framework was developed for the hospital workflows in the interconnecting areas to and from the ICU and other hospital units such as corridors and warehouse. At the macro level, the framework can be useful for identifying BE requirements supportive of resilient healthcare.

Integrating these levels and the interconnection of elements at different levels of abstraction in the knowledge framework provide insights to orient decision-making – e.g., trade-offs between design prescriptions to assign priorities for interventions. Rather than a template for compliance, the framework should help to identify practical examples of the BE implications to RP that otherwise could have remained concealed in the successful WAD. The investigation of the WAD was possible through qualitative methods, in which case study stages and methodological techniques can be replicated in other health settings and resilient healthcare studies.

CONCLUSIONS

This paper presented a framework of BE design knowledge supportive of resilient healthcare based on a SLR and two empirical studies, on in Brazil and the other in Australia. It is hierarchically composed of four meta-principles, seven principles, seven prescriptions, and 181 practical examples. An international readership of academics and practitioners can benefit from the framework, as different contexts are discussed in light of complexity and resilient healthcare. The framework is expected to guide both BE and operations designers in health services.

Some limitations of this work must be highlighted: (i) the framework was conceived based on a resilient healthcare perspective, focusing on everyday work; thus, disasters were considered out of the scope of this work; (ii) the framework was not applied during the BE design or intervention of health services; and (iii) the influence of BE on resilient healthcare was not quantified in terms of the impacts on health outcomes and efficiency. Suggestions for future studies may include the application of the framework during the BE design or intervention of health services, using the framework to develop methods to evaluate the BE support for resilient healthcare, and creating an EBD repository to facilitate the integration and uptake of design knowledge.

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LAST PLANNER SYSTEM: PULL PLANNING AS A DOCUMENTATION MANAGEMENT TOOL IN PHOTOVOLTAIC PROJECTS

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ABSTRACT

The article discusses the application of the Last Planner System (LPS) in the context of infrastructure projects, focusing specifically on the renewable energy sector. A Brazilian company specialized in the design and construction of photovoltaic plants was chosen as the research scenario. LPS was introduced to the company as a tool for production control and management, providing stability to the production system. This article explores the application of LPS in design management, highlighting the complexity of the construction design process and proposing the integration of LPS principles into design management. Pull planning was incorporated into design management to establish a reliable flow in the iterative work performed by designers. The pull planning process is described in detail, including the creation of process flows, document analysis, board assembly, milestone definition, task segmentation of process flows, and weekly schedule structuring. Challenges were identified during the practical application of the tool, leading to the conclusion that there is room for improvement. In summary, this study demonstrates the potential of LPS and pull planning in improving the management of infrastructure projects, with a specific emphasis on documentation and design management in photovoltaic projects.

KEYWORDS

Last Planner System, Lean construction, Pull planning, Solar PV plant

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INTRODUCTION

Infrastructure projects are typically costly enterprises with great strategic importance for a region, country, or organization and high added value for the population (Dave et al., 2013). These projects have lower complexity than building projects, involve a more limited array of professionals, and encompass a wider variety of typologies, such as roads, bridges, and dams, among others (Yabuki, 2010). Interestingly, given their large scale and long execution cycles, infrastructure projects are highly conducive to improvement (Dave et al., 2013).

Improvement, as understood in the context of the Toyota Production System (TPS), focuses on increasing value to customers through waste elimination (Onho, 1988). For this, production systems need to operate in a stable and predictable manner (Onho, 1988).

Building upon this idea, Viana et al. (2010) presented the Last Planner System (LPS) as a tool for production control and management, providing a basic level of stability to the production system and enabling the implementation of more elaborate lean concepts. LPS converts activities that need to be carried out (long term) into tasks that can be effectively performed (medium term), eliminating anything that may prevent or limit production (restrictions) and identifying a set of activities to be undertaken as part of the weekly plan (short term), thereby lending greater reliability to established plans (Ballard, 2000).

A pull planning step and the term "should" were introduced to the LPS practice as a strategy to enhance the connection between long- and medium-term plans (Ballard, 1999). Pull planning offers a new perspective on collaboration and workflows, placing attention on what "can" be done in the current scenario of the project, rather than on what "should" be done (Silva et al., 2022).

Several studies have been conducted on LPS adoption in the civil construction sector. In the context of infrastructure projects, such studies are still incipient (Antonini et al., 2022). A recent study described the efforts put in place by the UK highways supply chain for the creation of numerous continuous improvement cells, in line with its commitment to improve performance and embrace lean construction principles (Tezel et al., 2018). As for infrastructure projects related to energy production, such as photovoltaic power stations, research is even more embryonic. A search carried out in the International Group of Lean Construction (IGLC) database for the keywords "solar," "photovoltaic," and "solar energy" retrieved only three publications related to the energy sector. However, the identified articles did not address themes related to lean principles. Furthermore, Construction of photovoltaic plants has some particularities that must be considered. This type of construction has a fast execution cycle and, as consequence, a short response time and a longer-term constraint analysis. Therefore, these characteristics need to be considered in the process of implementing LPS routines.

In view of these gaps, this study aimed to investigate the application of LPS in the context of photovoltaic projects. The objective is to identify how LPS and pull planning can aid in long-, medium-, and short-term planning for managing documentation (projects, bills of materials, manuals, regulations) over the entire course of implementation of solar photovoltaic plants.

The research is divided into three main sections. First, a brief literature review is presented on lean thinking and LPS, focusing on pull planning. Subsequently, the research context is described. Finally, the developed documentation management method and results are discussed. The article also suggests new perspectives for exploring lean practices in the solar energy farm sector.

DESIGN MANAGEMENT

In the field of construction, both the design process and the resulting product have high complexity (Bolviken et al. 2010). Designing requires an ongoing process of negotiation and adjustment (oscillation or conversation) between criteria and alternatives, resulting in the gradual determination of ends and means (Bolviken et al., 2010). Bolviken et al. (2010) stated that, in simple terms, the decision-making process can be seen as an integral part of the design process. Design management involves effectively overseeing the design process (Best 2006).

As design and construction phases are normally conceived separately (Alarcón & Mardones, 1998), it can be difficult to integrate design and construction information (Alshawi & Ingirige, 2003, as cited in Dave et al., 2008). Common challenges include disruptions at the design–construction interface, such as divergent production sequences and priorities, ultimately resulting in delays, rework, and waiting for project participants (e.g., designers, suppliers, and builders) (Biotto et al., 2022). Dave et al. (2015) suggested an improved design–construction interface, where design information is released with a pull from the master schedule.

To date, lean construction has had far more influence on production than on design. Nevertheless, we believe that it is possible to apply lean concepts to design management. This hypothesis was proposed by Bolviken et al. (2010), who argued that lean construction and LPS principles are equally relevant to design and production in construction.

In this paper, LPS will be used for design management according to a pull planning approach, following a reverse plan of each phase's task, pulling each task from the end milestone toward the phase start date (Alarcon et al., 2004). Pull planning in design is one of the newer additions to the lean thinking toolkit, aiming to establish a reliable flow in the iterative work performed by designers (Tvedt, 2020).

PULL PLANNING

Pull planning was incorporated into LPS to allow the structuring of a project phase or milestone collaboratively among stakeholders (Ballard, 2008). It connects the master and lookahead plans (Biotto et al., 2022). The term pull planning refers to the lean concept of "pull" as a request from downstream, in contrast to the topdown "push" applied in traditional practice (Tsao et al., 2014).

The pull plan can be scheduled using a diverse range of tools, such as Gantt charts (Knapp et al., 2006) or location-based schedule (LBS) techniques, such as line of balance (LOB) (O'Brien et al., 1985), flowline (Kenley & Seppänen, 2010), and takt time planning (Fiallo C & Howell, 2012). In agreement with Biotto et al. (2022), who suggested the use of LBS to plan the whole project in a reverse manner (from construction to design), the authors of this paper believe that LOB and LPS should encompass the entire project. For pull planning and line-of-balance scheduling, it is necessary to define zones, takt times, trade sequences, and trade durations and balance their workflow (Frandson et al., 2013).

Pull planning defines how work will be delivered from one project actor (owners, designers, contractors, suppliers, construction companies) to the next (Tsao et al., 2014). Furthermore, this tool provides the basic technique and approach for establishing "who should be doing what work and when" (Tsao and Tommelein, 2004) in order to achieve the proposed milestones. Pull planning also brings a new perspective on workflow, considering a collaborative approach that focuses on what can be done rather than on what should be done (Silva et al., 2022).

As recommended by Silva et al. (2022), the workshop for implementing pull planning should ideally be scheduled at least one month, if not two, before the beginning of the actual work. In a pull planning workshop, all parties involved in the implementation process should participate collaboratively. Working backward from an end milestone is challenging, especially for project teams that have not pull planned before. Therefore, at the beginning of the workshop, it is important to explain to attendees that the meeting will proceed in three phases, as described by Tsao et al. (2014). (1) The first step is the backward pass. It will define any work necessary to support the end milestone. (2) Subsequently comes the forward pass, when the attendees will check the workflow logic and include any additional activities required to support the end milestone. (3) The last phase is the tightening pass. In this step, the team will divide the work into smaller batches and balance workflows so as to reduce the overall duration. Even with the development of software options to aid in LPS implementation, Tsao and Howell (2022) still recommend the use of sticky notes on walls in pull planning sessions, as they provide a tangible and accessible means for first-line planners/foremen in design and construction to interact in a hands-on manner.

In this article, pull planning will be implemented in design management based on the milestones defined using the LOB technique. As described by Tvedt (2020), pull planning is used to increase productivity in the design phase. The primary objective is to establish a dependable flow in the iterative work conducted by designers, fostering collaborative engagement to formulate the optimal plan for the design phase. This process, in turn, aims to minimize waste (Tvedt, 2020).

RESEARCH METHOD

METHOD DESCRIPTION

This article adopted a design science research approach. This method assists in the search for solutions in the realm of innovation and continuous improvement (Carneiro et al. 2019) while attempting to fill the gap between theory and practice through the development of a reliable artifact (Rocha et al., 2012). Research development should be guided by its practical utility for both the organization and academia, fostering the cultivation and application of theoretical knowledge (Monteiro, 2015; Järvinen, 2007; Lukka, 2003).

As will be described in the next section, the research was conducted in a that integrates last planner routines with the design management.

DESCRIPTION OF THE STUDY COMPANY AND PROJECTS

The study company, hereafter referred to as Company X, stands out in the development and delivery of operational projects for national and international energy sectors under EPC contracts. From feasibility studies to project execution, Company X prioritizes quality, safety, and efficiency, seeking efficient and adaptable energy solutions. Adhering to high levels of quality and sustainability, it follows international standards, protects health and safety, adopts socioenvironmental practices, and holds certifications of excellence. The company is ISO 9001, 14001, 19600, 37001, and 45001 certified.

The study encompassed two projects (P and M) for the implementation of photovoltaic plants. Both projects had the same organizational structure, as shown in Figure 1. Pull planning was developed within the design sector. Project P (Figure 2) consists of a solar park in Ceará State, northeastern Brazil, covering an area of approximately 8.90 km^2. The park contains 443,190 modules, 4,345 trackers, and 13,035 strings, corresponding to a power generation of 295 MWp. The project started in February 2023 and has an execution period of 12 months. The second project, Project M, consists of a solar park located in Piauí State, covering an area of approximately 9.83 km^2. The park contains 676,566 modules, 6,633 trackers, and 1,716 string-inverters, corresponding to 445 MWp. The project started in February 2023 and has an execution period of 14 months.

The design sector is responsible for design management. The plans for Projects P and M were developed by an outsourced, independent project office. The design sector within Company X was in charge of the review, validation, decision-making, and internal approval of the designs.

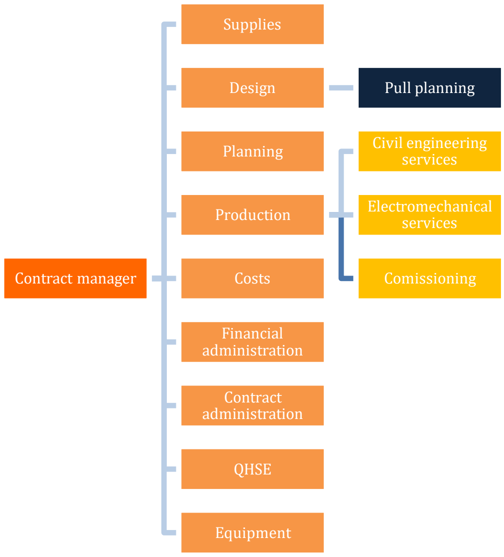

Figure 1: Organizational structure of Projects P and M in Company X

Figure 2: Aerial view of Project P

THE LEAN APPROACH IN COMPANY X

The implementation of the lean approach in Company X (Figure 3) began in February 2023, when the fundamental concepts of lean were applied in a pilot project. This was a crucial milestone for the dissemination of lean principles in construction, expanding their application to various areas of the company. The central goal was the gradual and sustainable integration of lean principles within the company.

The first phase of the project consisted of investigating the company's culture and processes. This phase was called the diagnostic phase, in which pull planning and long-term horizon sessions were applied. After the diagnosis, we focused our efforts on LPS implementation, dividing the actions into long-, medium-, and short-term goals. This period was fundamental to establish a solid foundation for application of LPS principles, referred to here as ramp-up.

In addition to LPS routines and with the objective of supporting its application, logistics studies were carried out to analyze productivity gains and promote integration between logistics and production teams. In this stage, called support, pull planning was carried out as described below.

Throughout the schedule, we dedicated several weeks to field actions through Kaizen events. These events challenged the team to achieve the predefined production rhythms, not only promoting immediate operational efficiency but also cultivating an organizational culture conducive to continuous improvement at all levels.

It is relevant to note that, during implementation of the lean approach, our scope increased, allowing the expansion of practices to different sectors of the company. This achievement highlights the flexibility and adaptability of the lean approach in the face of emerging challenges.

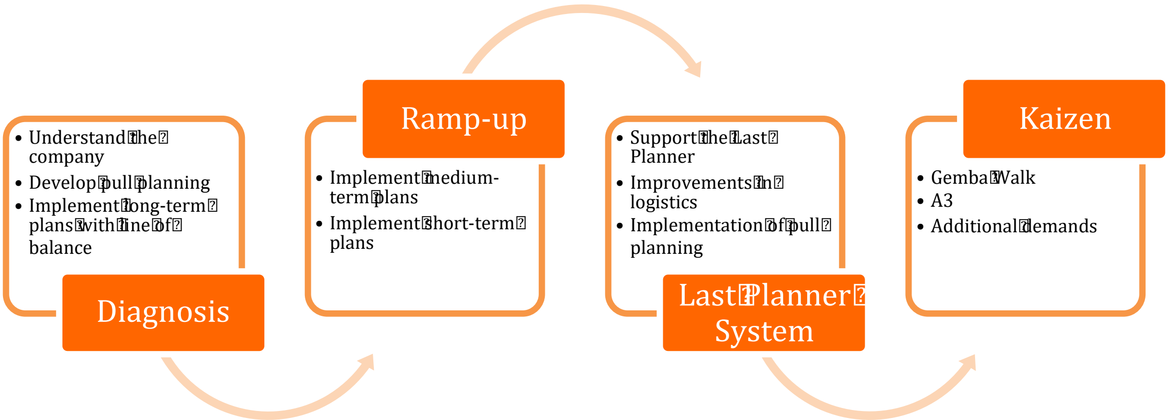

Figure 3: Implementation of lean construction in Company X

RESULTS

The business model of Company X is structured according to the contractual modality of Engineering, Procurement, and Construction (EPC) (Figure 4). Thus, the lean implementation project focused on the areas of supply and construction. LPS routines were used as supporting tools during implementation. The tasks performed by the engineering sector have a great influence on the development of construction and supply activities, generating an impact on job execution. Therefore, it was necessary to identify and structure the flow of tasks and deliveries performed in the field of engineering.

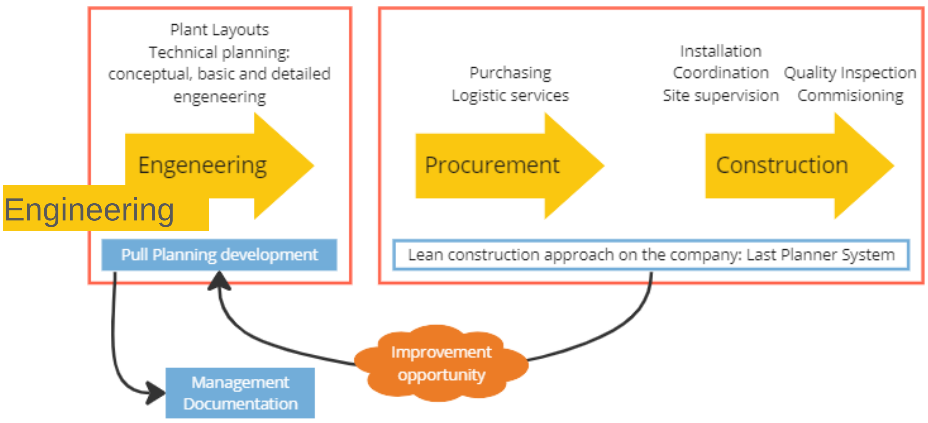

Figure 4: Lean implementation approach and opportunity for improvement

As mentioned, photovoltaic plant projects have specific characteristics. The fast execution cycle demands a short response time and a longer horizon for viewing constraints - in Project M, 8 weeks were analyzed. In supply sector, there was a high lead time for material procurement and production, and in engineering area, tasks focused on project management rather than development, as shown in Figure 5.

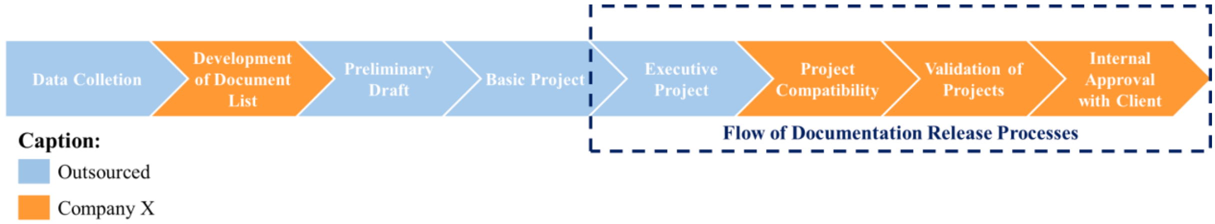

Figure 5: Flow of tasks performed by engineering

Given the need to improve the flow of tasks performed by the engineering sector (Figure 5), pull planning was proposed to improve the structuring of activities in the sector, with a focus on construction planning. Pull planning was implemented in five stages. The first four stages comprised pull planning sessions and the fifth comprised continuous monitoring of the developed plan. This tool allows creating a demand balance for an uninterrupted work system, in which value is obtained in the correct delivery flow (throughput) (Tsao et al., 2014). The workshop helps teams understand the constraints and bottlenecks of tasks and value collaboration. The planning process was carried out backward, taking as reference the milestones of the project, in a collaborative and multidisciplinary way (Tsao et al., 2014).

Pull planning was implemented through the following five stages: (i) definition of the flow of documentation release processes, (ii) documentation analysis (projects, manuals, etc.) and activity alignment, (iii) assembly of the pull planning board, (iv) definition of milestones and process flow for each activity, and (v) structuring of a weekly schedule to be monitored by the engineering sector. These steps are detailed below.

DEFINITION OF THE FLOW OF DOCUMENTATION RELEASE PROCESSES

This is the first step in the development of the engineering pull planning. The stages and flow of the development, analysis, and release of documentations are defined collaboratively with the engineering sector. Here, a flow composed of five activities was developed, encompassing the entire process (Figure 6).

Legend	Activity	Estimated time
	Begin the development of the project/document	Dependent on the document
	Internal analysis and revisions	5 days
	Collaborative posting	10 days
	Time to answer comments	5 days
	Posting for analysis of reviews – 2nd review by the client	3 days
	Released for work	1 day

Figure 6: Description of the activity flow in pull planning

ANALYSIS OF THE DOCUMENTATION LIST (PROJECTS, MANUALS, BILL OF MATERIALS, AND OTHERS) AND ALIGNMENT OF LOB

As mentioned in the chapter "The Lean Approach in Company X", during the diagnosis step, were conducted Long Term dynamics linked to the implementation of the Line of Balance. The objective was to use this tool as the Master Scheduling for the entire project, following the milestones already defined with the client. From the developed LOB, it was possible to map the Document List with all the services defined in this Master Planning. The focus was to identify each document, including projects, manuals, lists, and guidelines, needed for the execution of activities by production teams (Figure 7).

	UFV PANATI - LIST OF GENERAL DOCUMENTS									
GRE Code	Document Description	Code of Discipline	Designer Date (Supplie	New date - Action Plan 2 (Collaborative post	Customer Comment	Designer Comment	Collaborative Status	First Issue	Current Date	Revision Number
PAN-PVG-CV-DWG-010	TERRAPLANAGEM - PLANTA PANATI 5	CIVIL	21/05/2023	26/05/2023			Liberado para Obra	26/05/2023	03/08/2023	01
PAN-PVG-CV-DWG-013	TERRAPLANAGEM - PANATI 6 SEÇÕES TRANSVERSAIS E LONGITUDINAIS	CIVIL	26/05/2023	31/05/2023			Liberado para Obra	31/05/2023	07/08/2023	00
PAN-PVG-CV-DWG-012	TERRAPLANAGEM - PLANTA PANATI 6	CIVIL	26/05/2023	31/05/2023			Liberado para Obra	31/05/2023	03/08/2023	01
PAN-PVG-EL-DWG-006	DETALHES CONSTRUTIVOS - TRAVESSIAS SUBTERRÂNEAS (PAN II)	ELÉTRICA	11/06/2023	16/06/2023	08/06/2023		Liberado para Obra	13/06/2023	02/10/2023	00
PAN-PVG-EL-DWG-009	DETALHES CONSTRUTIVOS - TRAVESSIAS SUBTERRÂNEAS (PAN III)	ELÉTRICA	16/06/2023	21/06/2023			Liberado para Obra	19/06/2023	04/10/2023	00
PAN-PVG-EL-DWG-011	DETALHES CONSTRUTIVOS - TRAVESSIAS SUBTERRÂNEAS (PAN IV)	ELÉTRICA	19/06/2023	24/06/2023			Liberado para Obra	26/06/2023	06/10/2023	00

Distribution of cuttings + Topography	Topographic Location	Stake Map
Staking Tracker + SI	Drilling, Jig, Concreting	-
BT Ditch + Solar	Ditch excavation	BT Traced plan BT Cable Desing Memory Constructions details – BT Ditch
	Terra cable launch	Ground plan
	Pile backfilling	Constructions details – Grounding mesh
	Launch of BT cable + Solar conduit + Backfill	BT Cutting Plan Cable List BT

Figure 7: Description of the flow of activities in pull planning

Assembly of the Pull Planning Board

A pull planning board was assembled, in which the horizontal axis represents the timeline in days or weeks, as required by the project. The vertical axis is composed of the different activities and their respective documents, which are arranged in the order in which they will be executed (Figure 8).

The definition of the axes is the starting point for visualizing the flow of subsequent steps. This definition establishes the level of detail of monitoring activities in short-term planning to be developed at the last stage of the process.

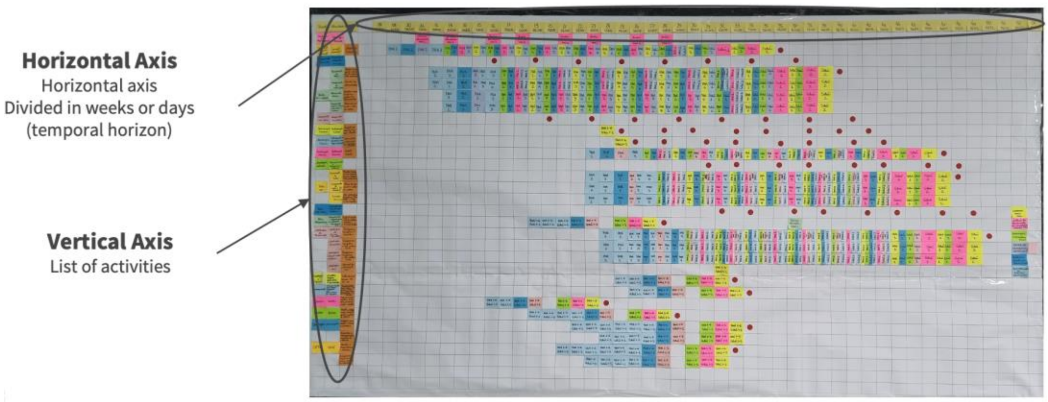

Figure 8: Pull planning board

Definition of Milestones and Process Flows per Activity

For each activity represented on the board, a delivery milestone was defined. In Project P, the milestone was validated according to the date defined in the document list. In Project M, the delivery was adjusted according to the production milestones defined by the balance sheet. It should be noted that, in this case, the unit of delivery of documentation was determined per sub-plot for most documents, as defined in the list of documents. The sub-plot unit is the same adopted in LOB planning, allowing for a better interface between the design and physical planning of the enterprise (Figure 9).

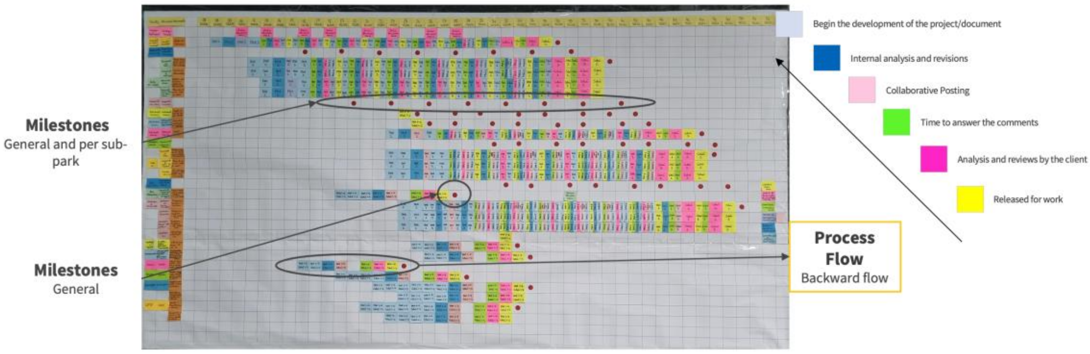

Figure 9: Pull planning board with process flow

Having defined the milestones, we determined the process flow in a backward manner, obeying the estimated delivery times of each stage. The process flow is the lined up colorful post-its that is signaled in Figure 9 as "Process Flow" and each post-it color represents a step of the process, as already explained in chapter "Definition of the flow of documentation release processes". This stage was developed collaboratively with the participation of the engineering sector coordinator, engineers, lean facilitator, planning manager, and lean consultant. With the completion of the process flow, the start date of the activity was determined, so as to meet contractual milestones.

STRUCTURING OF THE WEEKLY SCHEDULE

In the final stage, with the definition of long-term planning for engineering documentation, a weekly schedule was structured, taking into consideration the delivery times defined in each stage of the process (Figure 10).

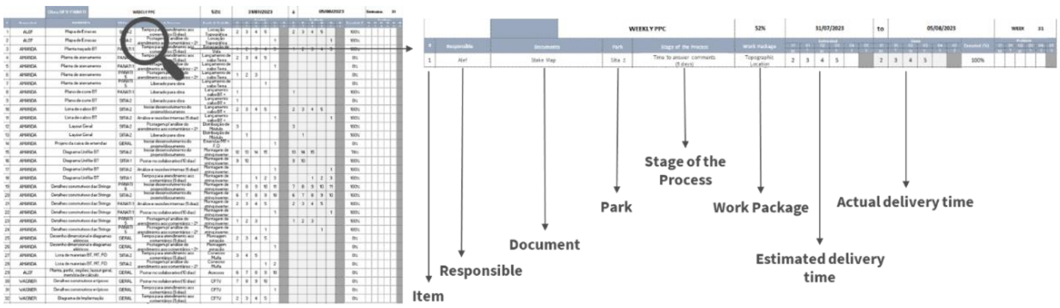

Figure 10: Process flow in the pull planning board

The definition of the weekly schedule allowed the engineering team to perform a short-term analysis for effective decision-making through percent plan complete (PPC) indicators, taking into account the completion of the activities scheduled for the week. In this case, the definitions that directly impact activity execution are communicated in advance to the leaders of the production team and the support team during medium-term planning.

IMPLICATIONS FOR PRACTITIONERS

Pull Planning is just the first step within the implementation of LPS as a routine in the Engineering area. As next steps, it is important that:

- Long Term: The document list and milestones of the Pull Planning continue to be aligned with the Line of Balance and the Master Scheduling;
- Medium Term: The activities developed in the Pull Planning are presented within the Lookahead routine to enable the analysis of constraints of these services by all sectors;

- Short Term: Execution of the Weekly Schedule, with the possibility of Check-in/Check-out, identifying problems for non-completion of the task, PPC and root cause analysis.

In Figure 11, you can see the PPC indicators of the Weekly Schedule of Project P. It is possible to identify that, as a pilot project, there is room for improvement, both in terms of adherence and in the concepts implemented.

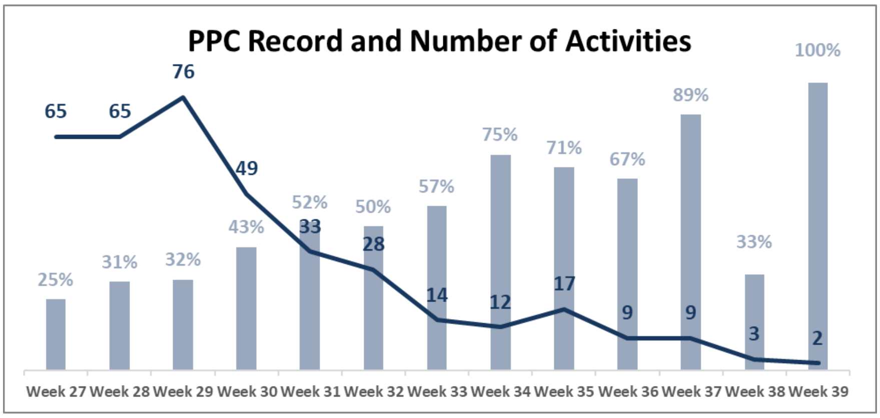

Figure 11: PPC record and number of activities from Project P from Weekly Schedule

CONCLUSIONS

Lean implementation in case study Company X effectively promoted LPS adoption and application of long, medium, and short-term tools. As already mentioned by Tsao et al. (2014) and Tsao and Tommelein (2004), the Pull planning sessions were successful in fostering collaboration and understanding among the entire team and we could understand that the prooseed tool and routine enable the better understanding and visualization of the whole project and the responsibilities considering the defined milestones. But, we could also identify that team members encountered challenges in utilizing pull planning as a management tool.

The proposed pull planning for design management provided the engineering team with greater clarity about the flow and time required for documentation, which directly influences production. Regarding the medium-term horizon, in both projects, teams had problems with anticipating constrains. The teams stopped reporting their delivery milestones in medium-term meetings, minimizing the visualization of constraints and bottlenecks for complying with the planned schedule. In the short-term management of Project M, there was insufficient compliance with the weekly schedule to produce noticeable results. In the case of Project P, the adherence was slightly higher. The planning team carried out the weekly monitoring tasks: the average PPC was 56%, and complementary data revealed an evolution of PPC as the volume of deliveries of the week reduced.

These findings revealed opportunities for improvement. A better connection of the Pull Planning for design management with the line of balance is an opportuninty. In this manner, it is possible to obtain project delivery milestones and use batches consistent with the work front attack plan. For more precise planning, it is advisable to conduct pull planning with the supply sector prior to the engineering sector, as discussed by Biotto et al. (2022). Therefore, the initial supply milestones may be used as the delivery date for the engineering pull planning. In this scenario, it is suggested that the list of documents be developed only after pull planning, to maintain the dates defined during planning.

In general, the Pull Planning for design management has great potential to align the expectations and needs of the various sectors of a project. Pull planning can generate collaborate|on and a better understanding of the demand and pace required by the client.

Additionally, it can function as a managerial tool for overseeing activities and to build a better connection between Engineering and Construction phases in EPC Projects.

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A NEW AUTOMATED SYSTEM FOR RFI PROCESSING: LEAD TIME REDUCTIONS AND STAFF PERCEPTION

Oliver Pitman[1], Kasun Wijayaratna[2] and Cecilia G. da Rocha[3]

ABSTRACT

This paper presents the results of a New Automated System for managing the Request for Information (RFI) process for a Tier 1 Contractor in Australia. A before and after case study entailing two projects was carried out: one using a traditional system based on manual email exchanges (Project S) and one using the new proposed system (Project P). The results show considerable reduction in the standard deviation and average time for completing the requests for information, suggesting a streamlined and more reliable RFI process. Survey results also presented favorable outcomes, with staff noting that Project P encounters fewer delays or instances of unanswered requests. Staff also expressed greater confidence in the accuracy and reliability of responses, along with increased satisfaction regarding collaboration, communication, and the overall performance of the new system. This paper illustrates how lean principles such as "simplify" and "reduce lead time" in combination with a relatively simple innovation can create objective and subjective benefits. Furthermore, it provides practical example showcasing that such innovations do not need to be top-to-bottom driven but can be created and implemented by junior/entering level staff.

KEYWORDS

Request for Information (RFI), Lead Time, Automated system, Collaboration.

INTRODUCTION

Request for Information (RFI) processes are instrumental in guaranteeing the precision and comprehensiveness of construction documents, playing a pivotal role in project success. They are indispensable for averting delays and cost overruns, ultimately elevating the overall project performance. Al-keim (2017) underscores the vital role of RFI processes in project management, emphasizing their substantial influence on the efficiency and success of construction projects. The significance of this research extends beyond individual projects, resonating with the broader construction industry and its stakeholders.

The inspiration for this research stems from the tangible, real-world experiences acquired by the primary author during an internship program. To be precise, these experiences unfolded while actively contributing to a tender team overseeing Project S. Within this setting, the RFI process revealed several inefficiencies, such as delayed responses to technical queries and

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internal disorganization leading to unanswered questions. These observations highlight the pivotal need for acquiring precise and timely information from vendors, a fundamental prerequisite for well-informed decision-making in the construction industry (Mostafa et al., 2020).

The following research paper, based on the final year undergraduate thesis developed by the first author of this manuscript, examines the impact of a newly developed automated system for RFIs processing within a major Tier 1 Construction Contractor in Australia. The system, crafted by the primary author was grounded in lean construction principles, particularly in reducing the number of steps and non-value adding activities (waste). The proposed system aims to consolidate all pertinent RFI data into a unified, easily accessible repository, simplifying workflows and significantly reducing the time dedicated to RFI coordination. The outcome was a notable improvement in efficiency and a substantial reduction in the time invested in RFIs management, leading to heightened productivity and the smooth execution of construction projects. This research thus contributes to the ongoing conversation about integrating automation technologies to enhance construction processes, aligning closely with lean construction principles, and echoing the sentiments expressed by Dowsett (2019).

LITERATURE REVIEW

In an ideal world, building designs would precise and complete with no ambiguities. Yet, this is rarely the case with documents most often being incomplete, having erroneous or conflicting information (Tilley 1997). Revisions and clarifications are thus required in the form of RFI, defined by Hanna et al. (2012) as a formal written request prompted by the contractor to acquire further information or clarification regarding matters concerning design, construction, or other contractual documents. RFIs are commonly utilized within the architecture, engineering, construction industry to address uncertainties and discrepancies, as well as to seek supplementary information (Morales et al. 2022).

From a lean viewpoint, RFI and its associated process can be viewed as a form of waste, more specifically as re-work, especially when related to incomplete, incorrect, or ambiguous information on the original design documentation (meaning this was not done right the first time). However, RFI is still a standard communication process used by companies (Gordon et al. 2023). Existing studies on this topic have mainly focused on this flow of information between architects/consultants and contractors/sub-contractors during construction (e.g. Tilley 1997, Hanna 2012, Chin 2009a, Aibinu et al. 2020). However, RFI also applies to the tender phase as examined on this paper.

RFIs are often pointed out in the literature as key performance metrics (e.g. Hanna et al. 2012, Aboseif et al. 2022). Hanna et al. (2012) develop benchmarks metrics for the assessment of transportation infrastructure projects and propose the following two quantitative metrics: (i) RFIs per million dollars of award contract and (ii) percentage of RFIs answered within the requested time period. Similarly, Aboseif et al. (2022) set out to define successful construction projects and suggest six metrics in four areas (cost, time, quality, and communication). For the last area, two of three metrics are: (i) RFI per million of dollars, and (ii) RFI processing time, with successful projects being defined by having less than 8.6 RFIs per million of dollars and of 7 days or less.

Existing investigations tend to examine RFI and its related process from a “value” lens (i.e. what are the types of RFIs, the impact they have, how to minimize/avoid them), etc but not a “flow” lens, with Chin (2009b) being one of few studies. The emphasis on the former lens is clearly justified and reasonable as we should first and foremost seek to eliminate this re-work waste, and secondly aim to reduce it to. Whitin the first lens, Tilley (1997) proposes RFIs to be classified in terms of types (alternative design solutions, approval, info clarifications, information, confirmation, others) and causes (conflicting info, incorrect info, insufficient info, and questionable info). Filho et al. (2016) organize RFIs types with regards to building systems (architecture, plumbing, fire protection and gas, electricity, etc) and/or interface between these systems. They also propose four general categories for RFIs (correction, omission, verification, and divergence) and five categories for RFIs in structural projects (poor alignment, conflicts, level difference, impracticable celling height, and structure absence), as well as ways to reduce these nine types of RFIs. Lastly, Morales et al. (2002) organizes RFIs in three categories: (i) impact (cost, time, scope, and quality), type (alternative solutions, approvals, clarification of information, others) and cause (conflict, incorrect, insufficient, questionable).

The recognition of these two lenses (value and flow) is also observed by Tilley (1997) in arguing that designs need be "effective" (i.e. serve the purpose for which they were intended) but also "efficiently" conveyed. This entails (Tilley 1997): (i) timeliness (information being supplied when required without delays), (ii) accuracy (free of errors and inconsistencies); and (iii) completeness (provision all the data required). Looking at ways to reduce such waste and increase the efficiency of RFIs processing falls under the "flow" lens. Chin (2009b) is a study example adopting this perspective. The refereed author uses Little's Law to examine Work-in-Progress levels (i.e. number of open RFIs request on a system on any given days) and its impact on delays (i.e. RFIs answered after the time frame required by the contractor, leading to delays in construction). It was found that (i) on-time response rates are low (around 50%) and processing times are unnecessarily long and (ii) delays are correlated to WIP levels, suggesting that a high WIP levels is a major cause of delays in RFI processing times (Chin 2009b).

The research carried out here also adopts a "flow" perspective and proposes a new automated system for RFIs processing. It recognizes that RFIs should be avoided in the first place by ensuring that design documentation is correct, complete, and unambiguous. However, given documentation is fail prone, this additional communication process is most often required. Thus, it becomes necessary to have it as efficient and streamlined as possible. The automated system presented was designed considering the lean principles (Koskela 2000) of (i) reducing the number of steps and (ii) reducing waste (particularly transportation, manifested here as numerous e-mail exchanges until the RFI reaches the recipient who can answer it). The main metric for assessing the success of the new system is the reduction in the cycle time (Koskela 2000), or in other words, the time required for RFI processing to be completed.

RESEARCH METHOD

This study analyzed data from Projects S and L, which utilized the traditional RFI via email and a proposed automated system, respectively. Project S focused on a major transportation initiative, aiming to establish an extensive, high-capacity rail network. The examined package included tasks such as excavating twin bored tunnels, constructing station boxes, creating cross passages, implementing viaduct underpinning for active rail lines, and installing a sewer protection structure. Project L was similar in nature to allow for comparison between the RFI methodologies. During a two-month period in 2023, staff encountered frustration due to delayed responses to vendors, leading to the collection of data tracking question timings and responses. An after-action review was conducted post-tender to evaluate perceptions of the current RFI process and assess potential enhancements for future systems.

The introduction of the new system occurred during the tender phase of a project focused on front-end engineering and design studies for the upstream production facilities of Project L (Battersby, 2023). These studies involved the development of two fields, including well pads and a central processing facility, along with the implementation of a carbon capture and sequestration scheme. Notably, the team was entirely composed of new members unfamiliar with the previous system, limiting the potential for bias. The new system collected RFI data stored in the bid directory folder within the company. The study spanned four weeks in 2023, strategically chosen to align with the busy mid-phase of the tender process, characterized by the highest number of supplier questions. This timing ensured a comprehensive dataset for thorough analysis.

Two main sources of evidence were used to assess the impact of the automated system for RFIs. First, a time delta comparison (differences between the moment an RFI is asked and when it is answered) was undertaken. In Project S this was carried out using the collected emails received and sent by procurement, then manually entering the information into an excel document. For Project P, this data was collected in the automated system. A total of 22 data points (or RFIs) for Project S (5 months, from September 2022 to February 2023) and 74 data points or (RFIs) or Project P (3 months, from August to October 2023) were collected. The RFI peak was during the middle of the tender for both projects. By examining these time intervals, insights were gained into the efficiency of the RFI process.

Furthermore, a survey with staff was carried out to gather subjective data and insights on the traditional and the automated system. Fourteen people from the infrastructure bidding team were interviewed. The survey for Project S focused on the delays and quality of responses to vendor. Eight people from Project P were interviewed were interviewed with the same questions to provide a direct comparison. The questionnaire entails a total of ten closed ended questions focused on: the average answer time of RFI, occurrence of RFI left unanswered or experiencing delays, confidence in the reliability of the RFIs process, etc. The findings for the eight core questions are summarized in Figure 6.

THE REQUEST FOR INFORMATION PROCESSES

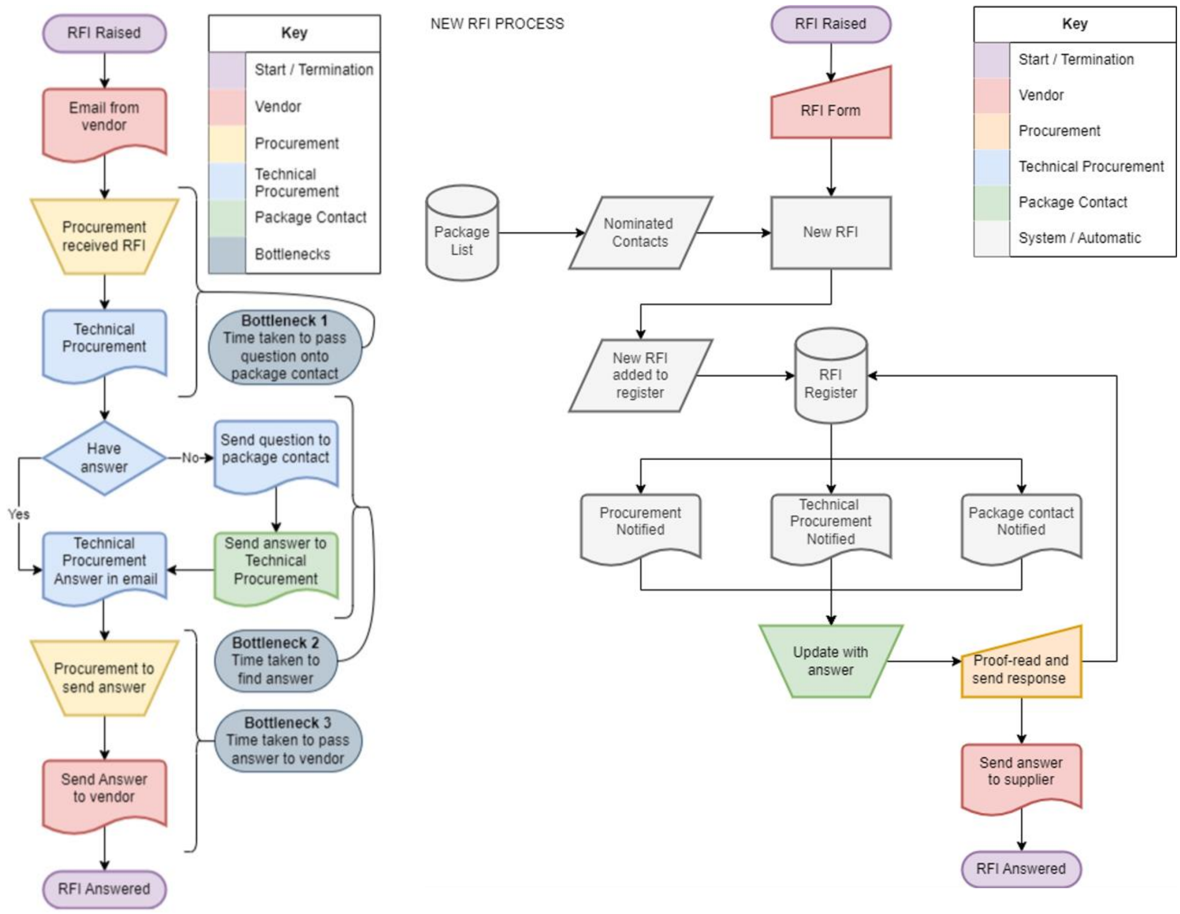
Figure 1 depicts the linear process in the Project S Tender, revealing potential bottlenecks. An RFI may go through up to four handovers before a response, necessitating relay through the same chain. Figure 2 proposes a streamlined solution with automated notifications, centralizing RFI information in a single repository. The top-to-bottom flowchart design aligns with standard principles in software development (Zen Flowchart, 2023).

BEFORE: MANUAL E-MAILS

The sequence commences with the vendor initiating contact through an email to the procurement department. Recognizing the need for a technical response, the procurement contact receives the RFI, either forwarding the request or completing an RFI document, which is then sent to the Technical Procurement team (depicted as bottleneck 1 in Figure 1a). Subsequently, the Technical Procurement team provides an answer or, if unavailable, collaborates with relevant sources like the package scope writer or other members of the construction team to acquire necessary information (indicated as bottleneck 2 in Figure 1a). Once the response is prepared, it is relayed to the procurement contact. Upon receiving the response, the procurement department promptly communicates with the vendor, indicating that the RFI has been addressed and answered (represented as bottleneck 3 in Figure 1a). All communication in this process occurs via e-mails.

AFTER: AUTOMATED SYSTEM

The system was designed using Microsoft Forms, SharePoint Lists, Microsoft Teams, Power Automate, Power BI, and PowerApps. The supplier initiates the RFI by completing a Microsoft Form (Figure 1b), which requires them to enter their details, specify the package of interest, and pose their query. Once this form is submitted, it triggers the generation of an RFI entry within the SharePoint and the request is cross-referenced with the corresponding package number to identify the designated contacts for that package. With every new entry in this list, an automated notification process is initiated, guiding the package contacts on how to maintain and update the RFI information within the list. Once the new RFI is added to the register, three simultaneous notification activities occur (Figure 1) and the RFI is directed to the procurement team for thorough review. Such team then collaborates with technical counterparts for a resolution. Once a suitable response is obtained, the procurement approves the RFI, they select the 'send' option, thereby dispatching the response to the suppliers, while simultaneously updating the RFI status to 'closed', signifying the completion of this process and marking the response time. Several challenges arise during the implementation of the system, notably the adherence of suppliers to the intended usage of the system, alongside the internal maintenance of up-to-date information within the system.



(a) (b)

Figure 1: Traditional RFI Manual Email (a) and Automated RFI (b) processes

RESULTS

PROBLEM DIAGNOSIS WITHIN PROJECT S (E-MAILS SYSTEM)

Figure 1b highlights the three bottlenecks in the former RFI process, specifically: transferring the RFI to technical procurement (1), the time to find the RFI answer (2), and the time taken to relay the answer to vendors (3). Figure 2 presents the distributions of time delays for each bottleneck type in Project S. The "X" denotes the median of the data, and the blue dot (Bottleneck 1) is classified as an outlier in the dataset. Notably, Bottleneck 2 constitutes 66% of the time required to answer an RFI. This extended duration is attributed to technical procurement, when lacking the answer, having to identify the responsible package owner and gather necessary information within the team. This often led to delays and unnecessary distractions for team members without the required information. Consequently, the automated system was developed to eliminate Bottlenecks 1 and 2. This involved streamlining notifications, removing the need to involve unnecessary team members, and concurrently tracking the package creator, who was likely to possess the answer.

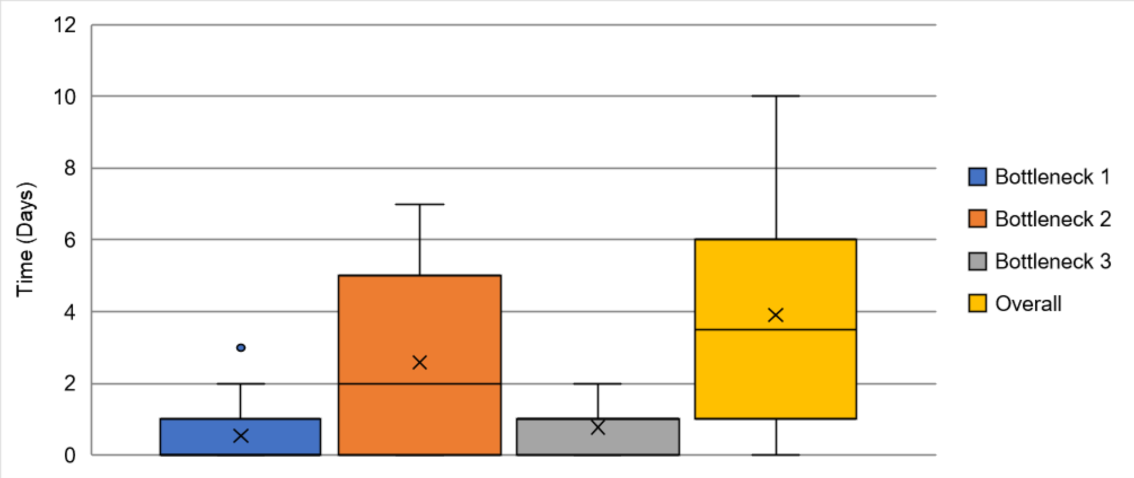


Figure 2: Bottlenecks for Project S (E-mails) based on Figure 1a

COMPARISON OF PROJECTS S AND P

The descriptive statistical analysis of the data gathered from both projects revealed a 49% improvement in mean response times: 3.91 days for Project S as compared with 2 days for Project P (Figure 2). Reliability in response times also improved across Project P, with a 9% reduction of the standard deviation of the response time data. It is important to note that there were many requests for Project P that were answered the day it was submitted resulting in a mode of 0.00, whereas the mode for Project S was 5.00 days.

Figure 3 displays the response time (t) for both the old RFI system (Project S) and the new automated RFI system (Project P) throughout the tendering period. The scatter plot for Project S appears erratic, lacking a discernible pattern. The trend line follows a mostly flat trajectory, with a notably low R2 value of 0.0009, indicating a minimal observable relationship. This suggests that RFIs are neither addressed better nor worse throughout the tender process, aligning with the idea that the previous RFI management approach hindered individuals from adapting to a systematic method, resulting in inconsistent performance. In contrast, Project P tender exhibits an observable learning curve associated with the adoption of the new system, resulting in more efficient responses over time.

Figures 4 and 5 provide a segmented analysis across fourteen-days rolling time intervals, focusing on the standard deviation and mean, respectively. This approach unveils the change in response time over specific time intervals, offering a valuable tool for identifying patterns, fluctuations, or shifts in performance that might be overlooked in longer-term averages. It aids in evaluating the impact of immediate changes or interventions on response times and detecting emerging trends that warrant further investigation.

A notable improvement associated with the New Automated System is evident with regards to mean response as shown in Figure 4. Such system creates significant enhancements as the tender progresses, with a substantial reduction in the mean average of response times as participants become accustomed to the system. For example, Project P's mean response time decreased from approximately 2.7 days to around 0.5 days. This improvement sharply contrasts with the old system, displaying fluctuations in mean response time ranging from 3 days to 7.5 days and no improvement as the tender progressed (response times even became more onerous for some time intervals). Consequently, the Automated System strongly leads to improved responsiveness with diminishing means over time. This pattern suggests that, for this case study, it took approximately 1 to 2 weeks to adapt to the new system, after which response times notably and significantly improved, as evidenced by the sharp reduction observed in Figure 4.

Figure 5 provides an insightful perspective, showing that initially, both projects had closely matched variability in response times during the first week of the tender. As participants adapted to the new system, there was a substantial reduction in response time variance. For example, Project P saw a decrease from approximately 3.3 days to about 0.5 days, a notable improvement compared to the old system, which maintained a standard deviation of around 3.5 days throughout the project duration. The results affirm that the automated system delivered efficiency and reliability benefits in response time for the case study.

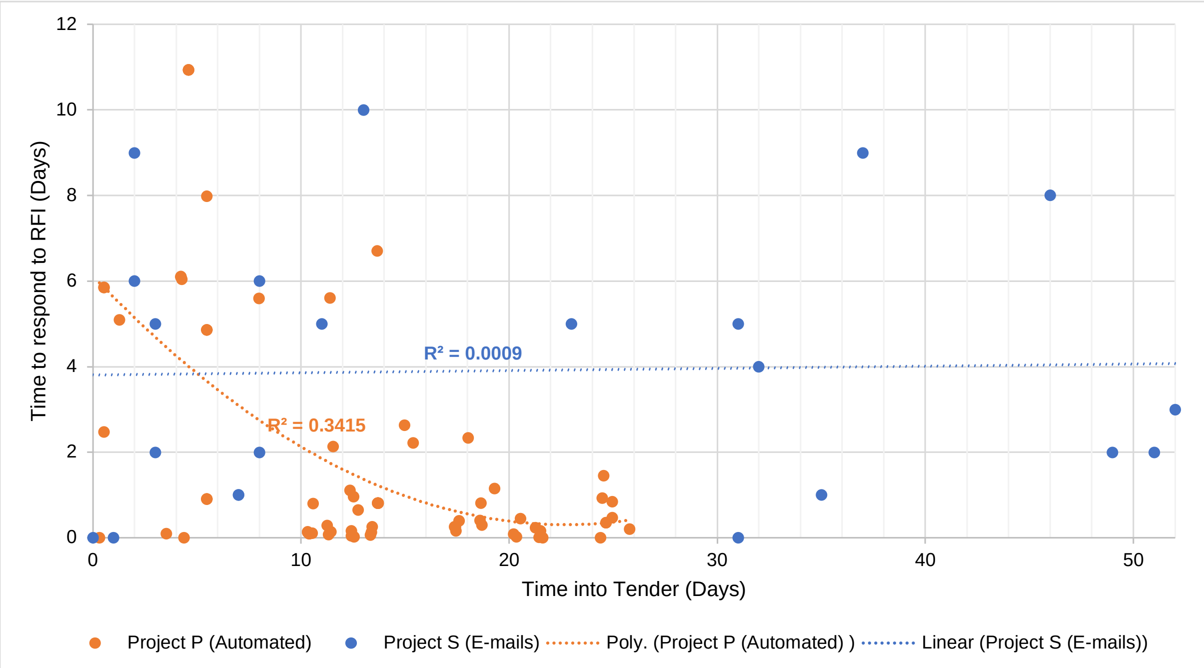


Figure 3: RFI Response Time Scatter Plot Comparison

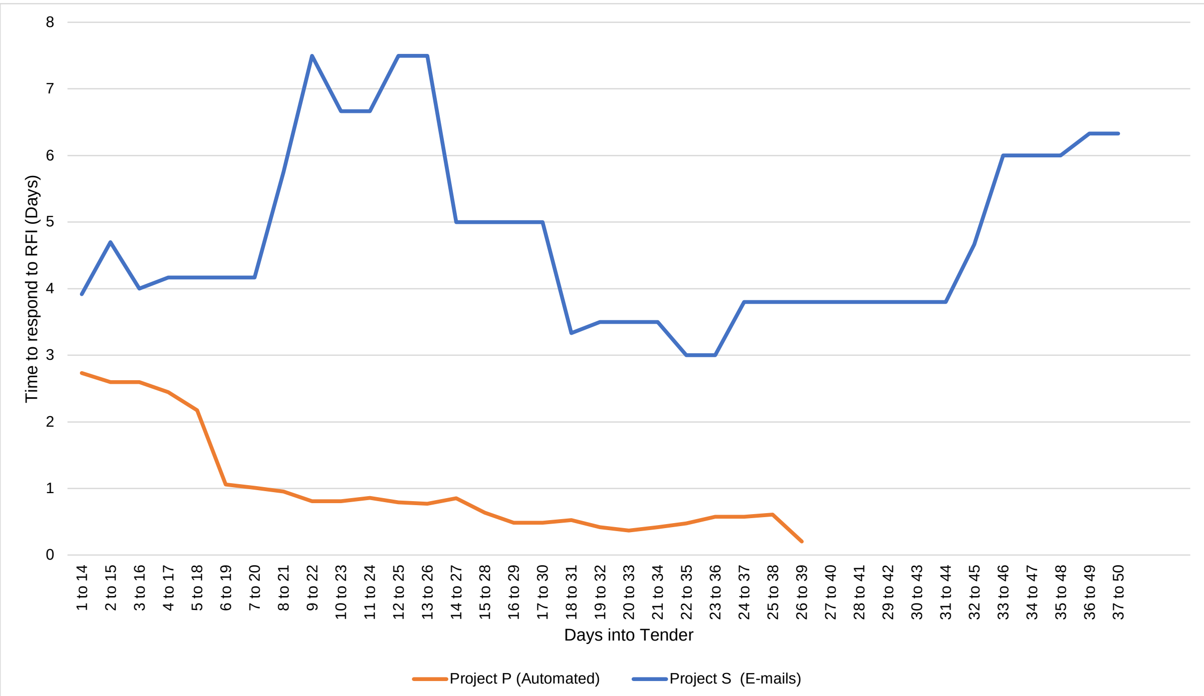


Figure 4: Fourteen days rolling tine horizon of the mean response times

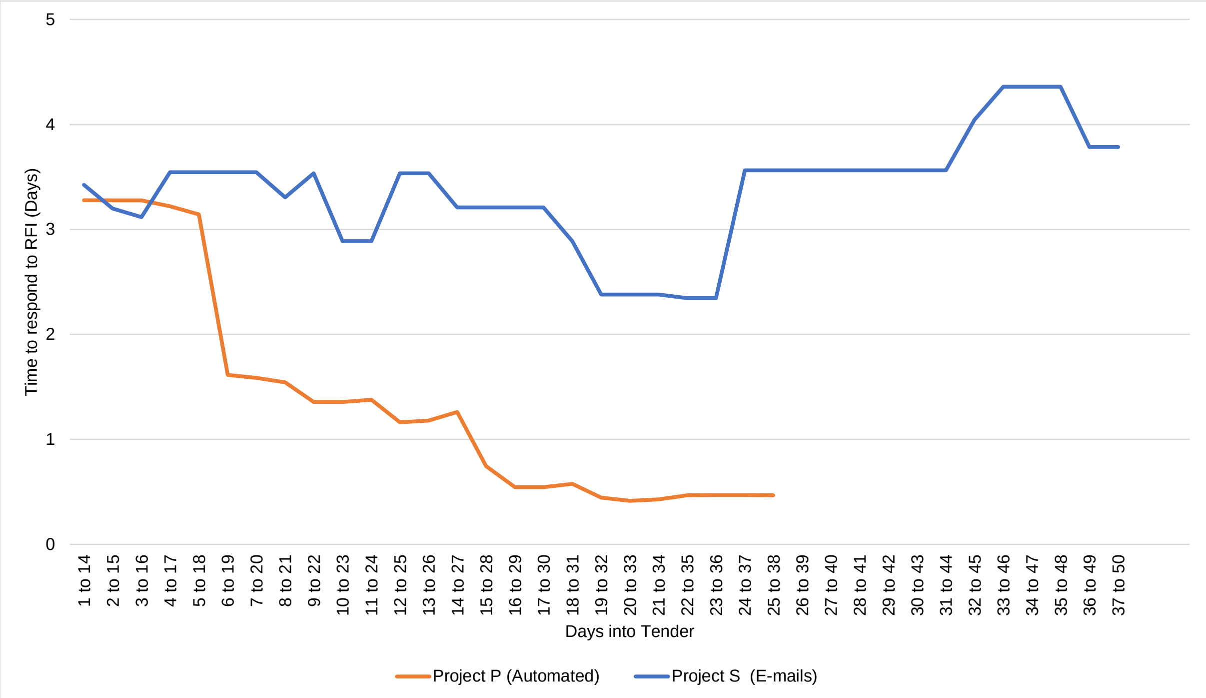


Figure 5: Fourteen days rolling tine horizon of the standard deviation

Survey Results

Figure 6 summarizes the survey results to assess the RFIs systems in Project S and P. Graphs (a) to (c) corroborate the improvements from Projects S to P noted in the objective data, detailed in the previous sections. Staff perceived a shorter lead time to respond to a technical question (a): 29% for 2-5 days for Project S and 38% for 3h or less for Project P. A noticeable decrease was also observed for RFIs that require additional clarification (b) and RFI left unattended or experiencing significant delays (c).

Project P also had a higher levels of confidence on the accuracy and reliability of the information (d) and satisfaction levels regarding the collaboration and communication (e), in comparison to Project S. Staff also perceived the confusion or misunderstandings regarding the status of RFIs or their resolutions to be less recurrent (Figure 6f): every few days in Project S (50%) versus a monthly occurrence for Project P (25%). Lastly, the Automated System (Project P) was consistently more highly rated than the traditional manual email exchange format (Figure 6h): very good or excellent (over 75%) versus poor to satisfactory (50%).

The new system was generally well-received by suppliers and staff, as individuals appreciated the establishment of a consistent and repeatable mode of interaction, in contrast to the previous chaotic and inconsistent nature of the manual system, which relied on email exchanges. Some resistance may have been encountered from smaller suppliers less accustomed to such systems. However, procurement representatives effectively guided them through the process, ultimately leading to improved response times, thereby largely satisfying suppliers with the outcomes.

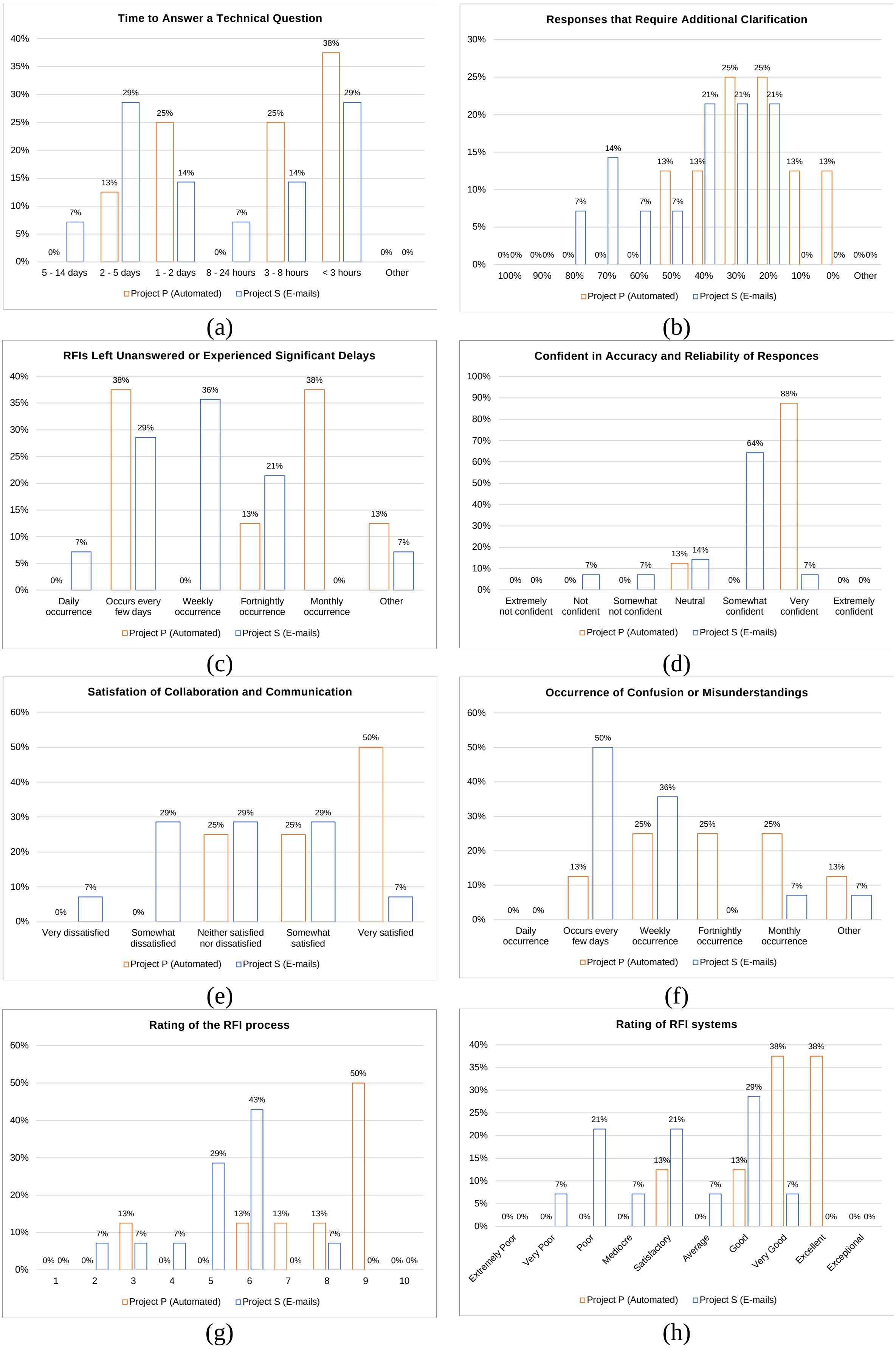


Figure 6: Survey results

CONCLUSIONS

This paper presents the results of a new automated system for RFI processing. A before and after case study, entailing both objective and subjective data, was carried out to assess the reduction in responses lead time and staff perception. Project S used a traditional system based on manual e-mail exchanges, while the new system designed according to lean principles was implemented in Project P. The objective data analysis focused on RFIs during the 3- and 5-months tendering periods for Project S and P, respectively. A reduction on the average lead time for RFI completion from 3.91 to 2 days was observed when comparing the two projects. The enhancements in the mean and standard deviations values can be clearly visualized in the fourteen day rolling averages (Figures 4 and 5). Regarding the subjective data, positive trends across all eight questions (Figure 6) were noted. The automated system was perceived to perform better than the manual e-mail process across all aspects examined, thus also corroborating the results observed for the RFIs data analysis.

In terms of limitations, certain factors, such as project size, complexity, type, prior supplier relationships, and the learning curve of the new system, were outside the scope of control for this study. Project size, complexity, and type could not be regulated due to the unique nature of each project within a feasible timeframe. Furthermore, altering these variables within such a timeframe would be impractical, given the rapidly evolving industry landscape. Different corporations also have varied supplier relationships, influenced by diverse joint venture arrangements, resulting in a range of supplier dynamics. Nonetheless, both projects underwent a fair and competitive procurement process following the company policy. The learning curve associated with implementing a new system is inevitable, as it takes time for all features to be fully utilised. In this sense, the improvements observed here are likely to be heightened if measured for upcoming project although further research is necessary to corroborate that.

Future research in automated RFI management systems for construction projects offers promising avenues for exploration. Building on the comparative analysis between traditional manual exchanges (Project S) and the automated system (Project P), further studies could delve into long-term effects on project timelines and budgets. Exploring user experiences and scalability, as well as integrating AI and machine learning, could enhance predictive capabilities. This research underscores the importance of ongoing innovation to optimise construction project management and outcomes. Lastly, this paper also showcases the potential to combine industry practice and research at an undergraduate level, ultimately, contributing to showcase and demonstrate the benefits of lean via a bottom-up route (i.e. conceptualisation and implementation of new system driven by an entry level staff).

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PERCEPTIONS OF COLLABORATIVE CONTRACTS FROM THE PERSPECTIVE OF LEAN CONSTRUCTION IN CHILE

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ABSTRACT

Pursuing more efficient and collaborative methods in the construction industry has increased interest in collaborative contracts and Lean Construction. Despite their potential benefits, there is a lack of clarity in understanding and applying collaborative contracts in Chile. This study aims to assess the level of knowledge and perceptions about collaborative contracts among construction professionals in Chile and to explore how lean tools and principles support the implementation of these contracts. It employs a two-fold research methodology: a survey to gather empirical data, followed by a comprehensive literature. The survey focused on collecting data on the experience and perceptions of collaborative contracts, while the literature review sought to identify the intersection of these contracts with Lean Construction. The findings revealed a limited and varied understanding of collaborative contracts. Perceived benefits, such as improved efficiency and collaboration, aligned with the principles of Lean Construction. However, challenges were also identified, including the need for greater initial investment, cultural barriers, and complexity in managing multiple projects. The study emphasizes the need for a well-defined concept of collaborative contracts in Chile and posits Lean Construction as a vital tool to address challenges and bolster their implementation.

KEYWORDS

Lean Construction, Collaboration, Contracts, Management, Construction.

INTRODUCTION

Evidence from collaborative contracts demonstrates the superior performance of collaborative projects over traditional approaches (Bilbo et al., 2015; Ibrahim et al., 2020; Mesa et al., 2016). In this context, collaborative contracts emerge as a promising solution, aiming to improve the management and execution of projects through mutual trust, open communication, and better alignment of objectives among stakeholders. Parallel to this evolution, Lean Construction's principles may intersect with these collaborative contracts, suggesting a possibility for more efficient and less wasteful project management approaches. This study aims to assess the level of knowledge and perceptions about collaborative contracts among construction professionals

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in Chile and to explore how lean tools and principles support the implementation of these contracts.

To explore and better understand these trends, a research study was conducted in collaboration with the Construction Technology Transfer Center (Centro de Desarrollo Tecnológico, CDT) of the Chilean Chamber of Construction (Cámara Chilena de la Construcción, CChC) and the Productivity Commission of the CChC.

CONCEPTUALIZATION OF COLLABORATIVE CONTRACTS

Collaborative contracts take various forms in the construction industry, such as strategic alliances, partnerships, relational contracting, and integrated teamwork (Suprapto et al., 2015). These forms, though varied, consistently promote mutual trust, joint problem-solving, and open communication. Specifically, relational contracting is based on recognizing mutual benefits and "win-win" scenarios through more cooperative relationships between the contracting parties (Ling et al., 2014; Palaneeswaran et al., 2003). Such contracts represent a unified yet flexible approach to project management, adapting to the unique demands of different projects and institutional logic and facilitating coordination among multiple parties and shared risk and reward structures (Matinheikki et al., 2019). These structures are tied to the value generated by the final product, creating a system of collaboration and shared responsibility (Cleves & Michel, 2009).

Specific types of collaborative contracts, including Early Contractor Involvement (ECI), Progressive Design Build (PDB), alliances, and Integrated Project Delivery (IPD), emphasize early and ongoing collaboration among all project participants, ensuring collaboration principles permeate every project stage (Woodhead et al., 2023).

Chan et al. (2011) highlight that, despite terminological differences, these contracts share essential elements that enhance project efficiency and performance, such as "Objective Alignment" to optimize project outcomes. Such collaborative approaches surpass traditional fixed lump-sum contracts in promoting "Trust and Transparency" (Larsson & Lasson, 2020; Yang et al., 2019). Additionally, they significantly contribute to risk management through "Risk Reduction" and "Conflict Minimization" (Macneil, 1985; Manu et al., 2015; Yang et al., 2019).

Bresnen (2007) observes that terms like 'partnership' and 'alliance' often overlap, but each captures the essence of long-term cooperative relationships. Recognizing these nuances is essential in grasping the multifaceted nature of collaborative contracts and their evolving role in the construction industry's landscape.

LEAN CONSTRUCTION AND COLLABORATIVE CONTRACTS

Lean Construction promotes efficiency and waste reduction through collaboration, aligning with the Collaborative Contracts ethos that encourages teamwork from the project’s inception (Koskela, 1992; Sarhan & Fox, 2013). While these contracts, including models like PPC2000 and NEC3, aim for mutual trust and shared goals, challenges such as the need for attitude shifts, complexity in intellectual property management, and the risk of non-binding agreements can pose significant obstacles (Woodhead et al., 2023).

Lean Construction and collaborative contracts, which seek to improve client value through integrated practices, require careful navigation when implementing collaborative agreements due to potential drawbacks such as legal uncertainties and substantial upfront investment without guaranteed returns (McAuley & Lefèbvre, 2019). While fostering joint problem-solving and risk-sharing, these investments necessitate meticulous planning to mitigate financial and operational risks (Mossman, 2009; Woodhead et al., 2023).

Furthermore, collaborative contracts that encourage concurrent engineering facilitate the Lean Construction principle of integrating design and construction phases. Yet, this approach demands managing complex acquisition rules and potential collaboration exhaustion, highlighting the critical need to effectively address multiple-party coordination challenges (Johansen & Walter, 2007; Woodhead et al., 2023).

In essence, while lean-oriented contracts promote cost savings and improved project outcomes by preventing inefficiencies (Sarhan & Fox, 2013), transitioning to collaborative contracts requires addressing inherent challenges, including attitude changes and the significant initial investments involved.

RESEARCH METHOD

This study utilizes a mixed-methodology approach, combining insights from a practical survey with an exploratory literature review. The authors applied the practical survey to evaluate the level of knowledge and perceptions regarding collaborative contracts within the Chilean construction industry. The survey was designed through a collaborative effort involving representatives from the Autonomous University of Chile, the Productivity Commission of the Chilean Chamber of Construction, and the Technological Development Corporation (CDT). The dissemination strategy involved a mass distribution to the CDT's comprehensive professional database, courtesy of the Chilean Chamber of Construction. This professional database included 1,400 individuals, yielding a response rate of approximately 6.14%, with 86 professionals providing their insights. This method achieved a substantial and varied industry representation, providing a robust analysis database.

The demographic and professional profiles of the survey respondents represented a comprehensive spectrum within the construction industry, encompassing a range of roles from architects and engineers to contractors and project managers. Among these, a notable 87% of participants hailed from the Metropolitan Region, with 45.5% serving in companies with a national reach and 40.9% working within firms with multi-regional coverage. The respondents also brought a significant breadth of experience; 56.5% had over 20 years in the construction sector, thereby enriching the study with seasoned insights.

Survey questions focused on participants' experiences, comprehension of collaborative contracts, and their perspectives on the associated benefits and challenges. The survey themes encompassed the utilization of collaborative contracts, the types of contracts employed, reasons for their selection, and the perceived pros and cons. Figure 1 shows the areas evaluated in the survey. The aspects investigated included the level of collaboration, collaboration barriers, quality improvements in projects, efficiency enhancements, and risk management tactics. Insights into the challenges encountered and lessons learned were also collected, alongside assessing the respondents' familiarity with collaborative contracts. The characterization of participants included detailed demographic and professional data, such as roles, experience, and company sectors.

An extensive literature review was subsequently undertaken to deepen the understanding of collaborative contracts and Lean Construction. The review utilized Google Scholar as a primary database, with searches centered on keywords such as 'Lean Construction,' 'Project Delivery Method,' 'Collaboration and Partnering,' and 'Collaborative Contract.' This examination aids in discerning the synergy between collaborative contracts and Lean Construction principles, significantly contributing to the study's main objectives, particularly regarding the benefits and challenges delineated in the survey.

Respondent Group	Evaluated Areas	Questions
Yes - Have used collaborative contracts	Collaborative Contracts	• What type of collaborative contract have you utilized in your projects? • Why did you choose this type of contract?
	Advantages and Disadvantages	• Have you been able to detect any advantages or disadvantages in your experience with Collaborative Contracts? • What are the significant differences and benefits you have experienced by using a collaborative contract compared to a traditional contract?
	Collaboration	• Have you managed to evaluate collaboration in relation to the use of collaborative contracts in your projects? • The level of communication and cooperation among the different project team members. • The effective collaboration among the different project team members. • The degree of trust and teamwork among the different project team members. • Have obstacles been encountered in the collaboration? Please evaluate from the project stage versus barriers • Has there been an improvement in collaboration thanks to the collaborative contract?
	Quality	• How do you perceive the quality of the projects in which collaborative contracts have been used has been measured? • Besides your perception, have key performance indicators (KPIs) been used to measure and evaluate the quality of projects with collaborative contracts?
	Efficiency	• Has there been an improvement in project efficiency thanks to the collaborative contract? • How has the efficiency of the projects with collaborative contracts been measured?
	Risks	• Have the project risks with collaborative contracts been managed? • How have the project risks with collaborative contracts been managed compared to a traditional contract? • Have there been any challenges or lessons learned in the implementation of a collaborative contract? What could be improved in future projects?
No - Have not used collaborative contracts	Level of Knowledge	• Are you familiar with collaborative contracts? • What do you believe would be the main challenges and lessons in implementing a collaborative contract?

Figure 1: Questions and evaluated areas in survey.

RESULTS

This section presents a comprehensive overview of the survey findings, delineating the discerned knowledge levels among participants concerning collaborative contracts. The section first explores the insights from industry professionals utilizing collaborative contracts, highlighting the advantages and disadvantages. Perspectives from those not engaged with collaborative contracts reveal their expectations and potential reservations. Finally, the section presents a comparative analysis, synthesizing these perspectives with the challenges and benefits identified, setting the stage for the subsequent section. Here, the authors examine how Lean principles and tools may address collaborative contracts' inherent attributes and synergies, considering aspects such as Trust and Transparency, Risk Management, Efficiency, Quality Improvement, Collaboration, Cultural Shifts, Work Structure, and the investment of initial resources. This intersection of survey results with an exploratory literature review encapsulates the current understanding and potential of collaborative contracts within the industry.

PARTICIPANT KNOWLEDGE LEVEL

The survey’s initial question inquired whether participants had implemented collaborative contracts in their projects. The findings indicate a low usage rate, with only 14% of respondents confirming their participation in such contracts. On the other hand, 86% of respondents reported that they had not used collaborative contracts. However, when these professionals were further questioned about their familiarity with collaborative contracts, 28% acknowledged having knowledge of them despite not utilizing them. This discrepancy highlights a substantial opportunity for growth and educational development in the sector.

In efforts to deepen the understanding of collaborative contracts within Chile’s Architecture, Engineering, and Construction (AEC) industry, it became apparent that there is a divergence in professional interpretations. For instance, one respondent mistakenly identified the Building Information Modeling (BIM) methodology as a collaborative contract. This example highlights the need for a clearer and more precise definition of collaborative contracts to ensure consistency across the industry.

Various contract types have been documented within the subset of construction professionals who have used collaborative contracts. However, no contracts that fully respond to the collaborative contract criteria have been identified. Despite implementing various contractual practices in the industry, there remains a gap in identifying contracts that fully meet the criteria for collaborative agreements. These criteria include effective team integration, shared risk management, and open communication. This underscores the need for a precise definition of collaborative contracts and an in-depth examination of their characteristics to foster true collaboration, going beyond the simple combination of services or methodologies.

PERSPECTIVES OF PROFESSIONALS WITH EXPERIENCE IN COLLABORATIVE CONTRACTS

Professionals who declared having used collaborative contracts select these contracts principally based on economic efficiency, risk and responsibility management, expertise and quality assurance, and operational excellence and client requirements.

Participants also emphasized 'Quality, Timeliness, and Conflict Reduction,' aiming to improve execution times and quality while mitigating conflicts and ancillary costs. 'Fair and Joint Costing' was noted as a benefit, allowing the parties to achieve a target price in a jointly developed project. The need for 'Process and Cost Optimization' was also a driving force, with the recognition that these contracts could optimize processes and costs, sometimes being the preferred contracting method for certain entities.

Finally, 'Client Requirements' also played a role in the contract type selection, highlighting the client's influence in the contractual decision-making process. This range of reasons reflects a nuanced understanding and appreciation of the strategic benefits of collaborative contracts among those who have implemented them in the Chilean construction industry.

Figure 2 shows a clear consensus in identifying both advantages and disadvantages when contrasted with traditional contracts. According to the survey results, a majority have identified benefits, with improved collaboration and communication among the involved parties being the most frequently noted advantage. This is closely followed by better risk management and prompt problem resolution, increased efficiency in project execution, greater transparency in decision-making, and enhanced satisfaction and trust among stakeholders.

Advantages		Disadvantages	
Enhanced collaboration and communication among the involved parties	23,26%	Requires a greater initial investment of time and resources to establish collaboration foundations.	33,33%
Improved risk management and early problem resolution	20,93%	Can be more difficult to implement in projects with multiple involved parties.	23,81%
Increased efficiency in project delivery	13,95%	May require a cultural and mindset change in the involved parties.	23,81%
Greater transparency in decision making	16,28%	Increased bureaucracy in decision making.	4,76%
Increased satisfaction and trust among the involved parties	16,28%	Essential fiduciary compliance of the parties, which is very difficult to achieve.	4,76%
Enhanced control of the project	2,33%	Assigns all risks to the developer.	4,76%
Increased technical capacity	2,33%	Possible increase in contract management complexity.	4,76%
Reduced environmental impact	2,33%		
Meeting cost objectives	2,33%		

Figure 2: Reasons cited by practitioners: Advantages and Disadvantages

Conversely, the disadvantages reflect concerns about the need for a greater initial investment of time and resources to establish the collaboration framework, a challenge echoed by the majority of respondents. Cultural and mindset changes of the involved parties were also cited as significant impediments, along with potential increases in bureaucracy and contract management complexity. One response highlighted the specific risk of developers assuming the burden of unforeseen conditions, such as archaeological findings, without recognizing the associated repercussions.

Therefore, the "Advantages and Disadvantages" section highlights a pragmatic recognition among industry professionals. While collaborative contracts foster a more synergistic and integrated approach to project execution, they also demand a considerable initial commitment and can introduce new complexities into the contractual landscape.

FAMILIARITY WITHOUT ADOPTION: INDUSTRY PERSPECTIVES ON COLLABORATIVE CONTRACTS

Respondents familiar with collaborative contracts but without actual use articulate several advantages such as increased trust and transparency, risk reduction, conflict minimization, improvements in efficiency and economy, early integration, alignment of objectives, and quality enhancements. These perceived benefits align with the fundamental principles of collaborative contracting, indicating an appreciation for the theoretical value these contracts can offer.

Conversely, the disadvantages cited by these respondents highlight cultural barriers, the need to foster teamwork through transparency and trust, concerns about the efficient structuring of work phases, knowledge and education gaps regarding the benefits of the contracts, and apprehensions about profitability. These perceptions reveal the perceived obstacles that could impede the adoption of collaborative contracts.

Figure 3 highlights a paradox wherein the recognized potential value of collaborative contracts contrasts with a reluctance stemming from cultural and practical concerns.

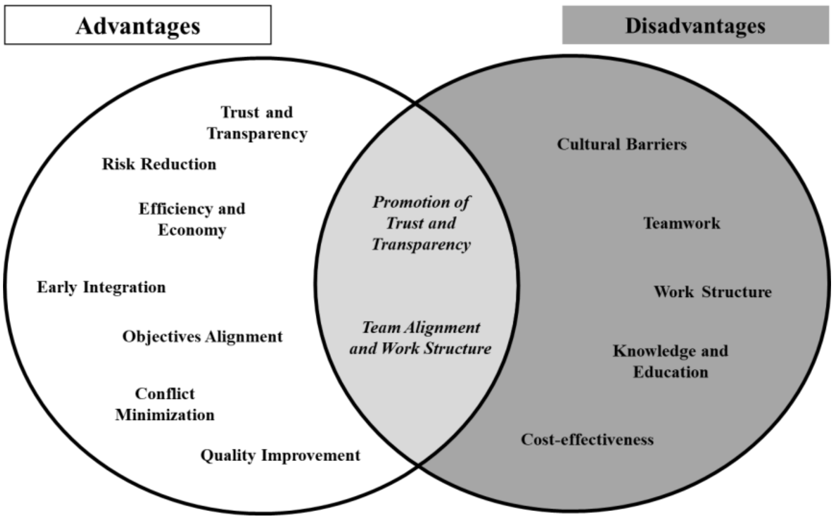

Figure 3: Intersection of Perceived Advantages and Disadvantages of those familiar but have not utilized these Collaborative Contracts.

ANALYSIS OF LEAN TOOLS AND PRINCIPLES IN ADDRESSING THE BENEFITS AND CHALLENGES OF COLLABORATIVE CONTRACTS

This section provides a focused analysis of select potential benefits and challenges of implementing collaborative contracts in the construction industry, as illuminated by Lean tools and principles. The scope is deliberately narrowed to those areas that have shown pronounced synergies with Lean methodologies and collaborative contract frameworks, thus highlighting the instrumental role of Lean Construction in enhancing the efficacy of collaborative agreements.

Experienced users, as well as those who are familiar with but have not utilized these contracts, recognize common benefits, including "Trust and Transparency," "Risk Reduction," "Efficiency and Economy," and "Improvement in Quality." Challenges such as "Cultural Barriers," "Change in Mindset," and "Work Structure" are also acknowledged by both groups, highlighting shared industry concerns.

However, differences arise between users' perspectives and those who are familiar with but have not utilized these. Users emphasize "Increased Collaboration and Communication" as a significant advantage. At the same time, they face the challenge of a "Higher Initial Investment of Time and Resources" and the complexity of "Projects with Multiple Parties." Those who are familiar with but have not utilized these may lack the direct experience to appreciate these nuances fully. Figure 4 presents an overview of the potential benefits and challenges.

Type	Detail	Lean Tool/Principle/Technique	Brief Description
Advantages	Trust and Transparency	Last Planner System® (LPS®)	Promotes transparency and trust through active planning and execution.
Advantages	Risk Reduction and Management	Kaizen	Continuous improvement to identify and eliminate risks and waste.
Advantages	Efficiency and Economy	Lean Production Practices	Reduces overburden and non-value-adding work to enhance efficiency.
Advantages	Quality Improvement	5S	Focuses on quality from design to execution, creating an efficient work environment.
Advantages	Greater Collaboration and Communication	Value Stream Mapping, LPS®, Building Information Modeling (BIM)	Enhances understanding of work flows and improves coordination.
Disavantages	Cultural Barriers and Mindset Change	Lean Training and Workshops, Respect for People	Shifts towards a more collaborative and team-centered approach.
Disavantages	Work Structure	Integrated Project Delivery (IPD), Value Stream Mapping (VSM)	Promotes integrated and efficient work from the project's inception.
Disavantages	Initial Time and Resource Investment	Training, Process Restructuring	Views initial investment as short-term cost for long-term benefits.
Disavantages	Difficulties in Multi-party Projects	IPD, LPS®, BIM	Manages complexity in projects involving multiple teams and disciplines.

Figure 4: Intersection with Lean Construction

Trust and Transparency. Trust and transparency are pivotal in collaborative contracts, a sentiment echoed by industry professionals in our survey and supported by Lean Tools. Integrating Lean tools like the Last Planner System (LPS) into project management practices enhances these elements by facilitating clearer communication and task visibility, as Ribeiro & Costa (2018) demonstrated. Their work underscores the significance of visual aids in presenting information straightforwardly, fostering improved stakeholder communication and collaborative planning. Chiu & Cousins (2020) further confirm that LPS's implementation can lead to better alignment within design teams and schedule adherence. Lühr et al. (2023) contribute a nuanced view, proposing that while transparency promotes a more accurate evaluation of partners' reliability, it does not automatically translate into trust—a reminder that transparency acts as a foundation for, but is not synonymous with, trust.

Risk Reduction and Risk Management. Survey respondents highlighted risk reduction and management as key benefits of collaborative contracts, which Lingard & Lin (2004) and Muchinsky (2006) substantiated through the lens of Lean Construction. With its focus on continuous improvement, the Kaizen principle has been pivotal in mitigating risks by fostering a constant process evaluation and enhancement cycle. Muchinsky (2006) notes the positive ripple effects of Kaizen on job satisfaction, leading to a more organized work setting and preemptive risk handling. Lingard & Lin (2004) concur, emphasizing how process standardization and a quality-centric approach from inception to completion enhance job satisfaction and bolster workers' dedication to their tasks. This collective emphasis on systematic improvement via Kaizen underpins a safer, more predictable project landscape.

Efficiency and Economy. The integration of Lean Construction principles, as identified by Cheng (2015), directly aligns with the efficiency and economic benefits highlighted in the survey regarding collaborative contracts. Lean practices, notably the elimination of non-value-adding activities, play a crucial role in enhancing project outcomes. Cheng emphasizes the importance of a continuous value flow, distinguishing between controllable aspects, like material and equipment management, and uncontrollable ones, such as supply chain and design information dynamics. This foundation of Lean Construction ensures a smoother, more efficient workflow, significantly reducing project costs and timelines, thereby boosting overall profitability and demonstrating the practical benefits of Lean methodologies in realizing the potential of collaborative contracts.

Improvement in Quality. The emphasis on quality improvement, as a recognized benefit of collaborative contracts from survey feedback, is mirrored in Lean Construction principles, notably through adopting the 5S methodology and visual management tools outlined by Bajjou et al. (2017). The 5S framework—Sort, Simplify, Sweep, Standardize, and Self-discipline—establishes an orderly and efficient environment, laying the groundwork for high-quality outcomes in every project phase. Additionally, visual management enhances transparency and safety, facilitating improved communication among project participants. This integrated approach ensures continuous quality improvement from design to execution, demonstrating the synergy between Lean Construction practices and the quality enhancement goals of collaborative contracts.

Greater Collaboration and Communication. Survey findings identify both the enhancement of collaboration and communication as pivotal benefits and challenges within the context of collaborative contracts. Lean Construction, with its focus on fostering a collaborative culture, leverages tools like Value Stream Mapping (VSM) and the Last Planner System (LPS), as detailed by Setiawan et al. (2021) and Mossman (2005), respectively. VSM helps team members visualize the project's workflow, encouraging a unified approach by elucidating each participant's role in enhancing efficiency and customer satisfaction. Similarly, LPS fosters alignment on project goals through regular, collaborative planning sessions, minimizing misunderstandings and ensuring coherent team efforts. Additionally, the integration of Building Information Modeling (BIM), as noted by Liu et al. (2017), offers a shared digital platform that further streamlines team coordination. Together, these methodologies underscore the crucial role of advanced planning and technology in bridging communication gaps and cultivating a cooperative project environment, reflecting the dual nature of collaboration and communication as both a benefit and a challenge in implementing collaborative contracts.

Cultural Barriers and Mindset Change. As reflected in survey responses, addressing cultural barriers and the necessity for a mindset shift has emerged as a notable challenge in the adoption of collaborative contracts. As Moradi and Sormunen (2023) articulate, Lean Construction requires more than adopting tools; it calls for a profound organizational culture shift toward collaboration and team orientation. Key to navigating these barriers is engaging all organizational tiers in Lean-oriented educational activities, which underscore the philosophy's collaborative and continuous improvement ethos. Such initiatives, coupled with senior management's commitment and the promotion of respect and teamwork, are essential in cultivating an environment conducive to embracing Lean methodologies. This strategy underscores the importance of a supportive and inclusive culture in facilitating the transition towards more efficient, collaborative construction practices.

Work Structure. The reconfiguration of work structures emerges as a key challenge respondents highlight regarding implementing collaborative contracts. Adopting Integrated Project Delivery (IPD) and tools like Value Stream Mapping (VSM), Lean Construction addresses this challenge by promoting a seamless, integrated approach to project delivery. IPD, as noted by Mesa et al. (2016) and Viana et al. (2020), fosters a collaborative environment from a project's inception, ensuring alignment of interests and facilitating efficient communication and teamwork. This approach enhances performance and distributes gains and risks more equitably among all stakeholders. Additionally, VSM's role in elucidating the construction process, as demonstrated by Paciarotti et al. (2011) and Serrano et al. (2008), helps pinpoint inefficiencies, thereby streamlining operations and elevating strategic capacity. This dual emphasis on IPD and VSM underlines the importance of structured, collaborative work environments in overcoming the inherent challenges posed by new contract models.

Initial Investment of Time and Resources. The necessity for an initial investment of time and resources has been identified as a challenge in adopting collaborative contracts. This upfront commitment includes extensive staff training, process reorganization, and integration of novel tools and technologies. Despite the initial costs, it is vital to recognize these expenditures as investments towards long-term gains. Nahmens and Ikuma (2012) support this view by showing that Lean Construction can significantly decrease material waste and production hours while enhancing safety, thereby promoting sustainability. This perspective underscores the importance of effectively communicating the value of this initial investment in Lean practices, highlighting its potential to boost project efficiency, quality, and overall financial performance.

Challenges in Projects with Multiple Parties. The challenge of managing construction projects with multiple parties was underscored in survey responses, highlighting the complexity of coordinating diverse teams and disciplines. Lean Construction principles, including adopting Integrated Project Delivery (IPD), are instrumental in addressing these challenges. IPD fosters a unified approach by aligning the interests of all stakeholders and promoting collaborative decision-making, essential in complex, multi-stakeholder projects. Ebrahimi & Dowlatabadi (2018) and Hamerski et al. (2019) emphasize the hurdles encountered in maintaining collaboration and operational efficiency, selecting competent teams, and implementing IPD effectively. Furthermore, tools like the Last Planner System (LPS) and Building Information Modeling (BIM) play pivotal roles in improving project management by enhancing planning and ensuring coherent communication across teams. This approach underlines the necessity of a cohesive strategy to efficiently manage the intricacies of projects involving numerous parties.

This literature review elucidates the congruence between Lean Construction principles, tools, or techniques and collaborative contracts, illustrating how Lean Construction tools can underscore the benefits highlighted in the survey on collaborative contracts. The parallelism between trust and transparency in collaborative contracts and the Last Planner System® (LPS®), or how the Value Stream Mapping (VSM) technique aligns with promoting integrated and efficient work, resonates with the challenges identified in collaborative contracts. Nonetheless, ascertaining the level of Lean Construction knowledge among professionals is paramount to ensure that the identified synergies can be harnessed in practice, thus amplifying advantages and overcoming any disadvantages or challenges.

CONCLUSIONS

The survey underscores a significant shortfall in the uptake of collaborative contracts within Chile's construction industry, with a mere 14% of professionals reporting their deployment. Additionally, only 27% familiarity with these contracts is noted among those not currently employing them. These results suggest fertile ground for incentivizing the use of collaborative contracts, initially through educational endeavors followed by demonstrating their merits in construction projects.

In summarizing the findings from the survey, it is imperative to elucidate the definition of collaborative contracts within the Chilean construction industry to foster their application. The survey indicates a substantial potential for enhancing the adoption rates of collaborative contracts among projects and professionals. However, it also signals the need to explore the underlying reasons for their underutilization.

Building upon the survey's insights, the perceived advantages of collaborative contracts come to the forefront, emphasizing their transformative potential in the construction sector. The professionals´perceptions indicate that these advantages include the establishment of trust and transparency between stakeholders, a cornerstone for any successful collaborative venture. Moreover, they facilitate a reduction and better management of risks, ensuring a more predictable and stable project environment. The survey also identifies efficiency and economy as key benefits, with collaborative contracts perceived to streamlining processes and cutting unnecessary costs, leading to an overall improvement in quality. Notably, these contracts are seen to enhance greater collaboration and communication, which are pivotal in achieving project objectives with aligned stakeholder interests.

Conversely, the survey sheds light on several disadvantages that impede the widespread adoption of collaborative contracts. Cultural barriers and the need for a mindset change present substantial challenges, as they require a shift from traditional practices to a more cooperative approach. Work structure emerges as another obstacle, with existing frameworks often ill-suited to collaborative contracts' flexible and integrative nature. The initial investment of time and resources is a deterrent, with a clear need to demonstrate the long-term value to overcome short-term reservations. Finally, the complexity of managing multi-party projects under collaborative contracts is highlighted as a significant hurdle, necessitating adept coordination and robust conflict-resolution mechanisms. These challenges demand a strategic focus to harness the full potential of collaborative contracts within the industry.

Reviewing the literature reveals a symbiotic relationship between Lean Construction methodologies and collaborative contracts, which proposes a dynamic framework to propel the construction industry forward. Lean Construction, with its core principles and techniques such as the Last Planner System® (LPS®), Kaizen, and Value Stream Mapping (VSM), provides a structured approach that bolsters transparency and trust, key tenets in collaborative contracts. The continuous improvement and risk management inherent in Kaizen and the efficiency ethos of Lean Production Practices directly buttress the fundamental attributes of collaborative contracts focused on efficiency and economic prudence.

Furthermore, Lean Construction's commitment to quality enhancement through the 5S methodology is in harmony with the collaborative contracts' pursuit of elevated standards and greater cooperation. The employment of Value Stream Mapping, LPS®, and Building Information Modeling (BIM) within Lean Construction facilitates an advanced understanding of workflow and communication, capabilities essential to overcoming the cultural barriers and mindset changes frequently perceived as drawbacks in the realm of collaborative contracts.

Lean Construction is committed to enhancing work structures through targeted training and workshops. By promoting respect for each individual and fostering a collaborative, team-centric approach, this methodology effectively addresses the challenges faced in work environments. The initial time and resource investments, often seen as constraints in collaborative contracts, are recontextualized within the Lean paradigm as strategic investments yielding long-term returns, thereby offering a counterbalance to the initial expenditures. Ultimately, the arsenal of Lean Construction tools adeptly manages the complexities inherent in multi-party projects, thus confronting a pivotal challenge of collaborative contracts. The Lean Construction toolbox complements and intensifies the advantages of collaborative contracts, simultaneously offering strategies to surmount their intrinsic disadvantages.

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TRADITIONAL TENDER VERSUS EARLY CONTRACTOR INVOLVEMENT (ECI): A COMPARATIVE ANALYSIS OF WORK HOURS

Lachlan Saunders[1], Kasun Wijayaratna[2] and Cecilia G. da Rocha[3]

ABSTRACT

The strategy of Early Contractor Involvement (ECI), wherein contractors participate in a project's design and planning stages, is seen as an effective approach to address inefficiencies and complex interpersonal dynamics of construction projects. These challenges arise from contracting and procurement systems that do not promote collaboration, leading to delays and increased costs. Tendering, marked by competition and unpredictability, mirrors the industry's fragmentation and waste. Contractors face issues such as scope ambiguity, flawed documentation, market volatility, strict deadlines, and probity. This paper conducts a comparative analysis of two infrastructure projects in Australia, involving a tier 1 Contractor. Each project underwent both a traditional tender and ECI, facilitating comparisons. The results indicate that ECI tends to extend the time and resources utilized by contractors, with Project 1 and Project 2 experiencing increases of 12 weeks and 10 weeks, respectively, along with additional work hours and personnel. Despite ECI increasing time and resources, it improves the tendering process by enhancing certainty, focus, and communication.

KEYWORDS

Collaboration, Tender, Workhours, Collaborative Project Delivery.

INTRODUCTION

Current practices in contracting and procurement contribute to financial waste and hinder collaborative initiatives (Farrell & Sunindijo, 2022). Projects, especially those that are intricate and dynamic, exhibit low productivity, delays, and frequently surpass budgetary limits (Kim et al., 2016). Within project, tendering is a specific stage in the construction industry burdened with inefficiencies, uncertainties, and challenges related to resource allocation. Primary contractors wrestle with the task of securing projects through competitive pricing while avoiding potential cost overruns (Urquhart & Whyte, 2020). Addressing these inefficiencies not only promises clients and contractors increased certainty in tender outcomes but also facilitates smoother handovers to site teams and empowers contractors to trim business expenses or bid for additional work.

The incorporation of the lean philosophy into construction management seeks to maximize value while minimizing waste. A key aspect of this philosophy is the collaborative nature with anticipated engagement of relevant stakeholders. This includes Early Contractor Involvement

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(ECI), which entails the early introduction of the contractor into a project's lifecycle. Typically, ECI involves the contractor providing design, pricing, and scheduling inputs before the primary contract is awarded (Rahman & Alhassan, 2012). This practice generally fosters improved relationships between clients and contractors, enhances constructability, and promotes shared risk. Indeed, innovative project delivery approach (e.g. Integrated Project Delivery, Strategic Partnerships, etc) have been shown to improve overall projects performance (e.g. Paulsen et al. 2023, Hanna et al 2023, Mavik et 2021).

ECI is perceived as valuable for contractors, enhancing productivity during construction (Pheng et al. 2015, Rahman and Alhassan 2012). However, the impact of ECI on the internal operations of contractors remains unexplored, specifically at the tendering stage. Furthermore, there is a lack of consensus in the limited literature concerning its influence on resourcing. While Gransberg (2013) and Pheng et al. (2015) argue that contractor design inputs and concurrent planning can expedite the preparation phase, reducing it by 30-40% according to Mosey (2009), Malvik et al. (2021) present case study evidence suggesting that ECI may extend procurement timelines. Differently, Sødal et al. (2014) observed an increase in time and resources during the design and preparation phases. Additionally, Greenhalgh (2013) emphasised a heightened presence of senior staff during the early stages due to ECI.

This research aims to investigate the effects of ECI on the tendering process and assess the value it may offer. Specifically, it seeks address the following question: (i) What effects does ECI have on the length and resource use (staff numbers, hours, and disciplines) for contractors compared to Traditional tender? This paper is based on the final year undergraduate thesis developed by the first author of this manuscript.

COLLABORATIVE PROJECT DELIVERY MODELS

Non-traditional or collaborative project delivery models (e.g. Integrated Project Delivery - IPD, Strategic Partnerships, etc) are believed to increase the quality of constructing products, while lowering overall costs, and expediting completion times. Indeed, a number of studies set out to assess the performance such models and/or compare these against their traditional counterparts, notably Design-Build (DB) or Design-Bid-Build (DBB) (e.g. Suttie 2013, Assainar and El Asmar 2014, Ibrahim and Hanna 2019, Kulkarni et al. 2012). Kulkarni et al. (2012) examined two proxies for IPD and DBB, respectively, CM-at-Risk (CMR) and Competitive Sealed Proposal (CSP). It was found that the overall cost is more reliable for CMR projects and that reducible changes for error, omissions and design modifications is also lower. Ibrahim and Hanna (2019) examined a data set of 109 projects delivered using DB, DBB, CMR, or IPD and found statistically significant differences among these models in five performance areas (cost, schedule, quality, communication, and change management). The pairwise of comparison of the models also showed that DBB performs noticeably worse than the others, in particular IPD. Assainar and El Asmar (2014) examined the two non-traditional collaborative approaches: (i) Contractor and Subcontractor's involvement in the design phase, and (2) Architect or Engineer (A/E)'s involvement in the construction phase. Statistical tests using performance scores for 30 construction projects complete in the US show that non-traditional approaches are significantly linked to improvement in project quality.

Such studies attest the benefits attained with the integration and collaboration of all stakeholders in early stages of a project. This includes ECI, however, thus new model does alter Contractor's traditional ways of working, particularly during the early non-construction stage. Indeed, the impact of Early Contractor Involvement (ECI) on tendering and its effect in the contractor resourcing is less explored. According to Pheng et al. (2015), ECI typically involves a "two-stage tendering" approach, where, in the initial contract, contractors provide design advice, address key risks, and work towards a target price before the main construction contract is awarded (Pheng et al. 2015). By adopting this initial appointment approach, contractors can differentiate themselves based on experience and capability, moving away from a sole reliance on price (Love et al., 2014). Love et al. (2014) further contend that, even if not all contractors are proficient in ECI, it could still be applied in situations where competitive tendering is limited. Malvik et al. (2021) explored projects with extended procurement phases involving collaboration and negotiation with multiple contractors to establish competitive pricing. For ECIs where contractors contribute to design, this involvement leads to an increase in time and resources during the project's early stages (Sødal et al. 2014). On the other hand, the simultaneous development of project aspects can reduce preparation time (Pheng et al. 2015), a notion supported by Mosey (2009), who quantifies time savings of up to 30-40%.

Gransberg (2013) suggests that procurement times can be reduced through contracting procedures and aggressive deadlines rather than relying on ECI alone. However, contractors' inputs can expedite the design process (Gransberg 2013). Both contractors and clients commonly allocate senior staff to play more substantial and prolonged roles in the early stages of a project, characterized by potential reimbursement of costs but relatively low profit margins (Greenhalgh 2013). Furthermore, project teams, including seasoned project engineers, may be extensively engaged for tasks such as estimating, scheduling, and procurement, as emphasized by Migliaccio and Holm (2018). Long-term benefits in tender resourcing are also recognized by various researchers, such as the reduction of arbitrary tendering highlighted by Love et al. (2014) and the generation of more consistent work streams suggested by Song et al. (2009). Mosey (2009) contends that, even in cases where upfront costs do not necessarily decrease, the initial investment is anticipated to yield enduring advantages.

RESEARCH METHOD

This study focuses on the Tender Process, encompassing the development and submission of pricing, programs, and necessary documentation to compete for project awards, along with associated negotiations and planning, prior to contract execution. Traditional Tendering is operationally defined as the contractor's unpaid development of a tender submission in response to a Request for Tender (RFT) to vie for a project. Early Contractor Involvement (ECI) is conceptualized as a process wherein a contractor is engaged by a client, typically for a fee, at an earlier project stage, offering various services involving design inputs, scope definition, and budget pricing. The tender process, involving pricing development and persuading clients to award contracts, is inherently integrated into this ECI phase. Notably, both examined projects were tendered under both traditional and ECI models.

PROJECTS 1 AND 2

'Project 1' entailed remediation of control systems and valves for a state-owned corporation, denoted as 'Principal 1' (Figure 1a). Having unsuccessfully bid for a Design and Construct (D&C) contract in late 2019 (referred to as 'Traditional'), the Contractor was later appointed as one of two delivery partners in 2021 by Principal 1. The project underwent partial completion, and in 2023, following an Expression of Interest (EOI) directed at the two delivery partners, the Contractor was chosen to enter an Early Contractor Involvement (ECI) stage to evaluate and formulate a scope, subcontracts, pricing, and a program (referred to as 'ECI'). Subsequently, the Contractor secured the Construct-Only contract for the remaining works. 'Project 2' entailed a D&C contract for enhancements and additional filtration facilities at a major water treatment plant for a council, designated as 'Principal 2' (Figure 1b). After being shortlisted following an Expression of Interest, the Contractor submitted a tender proposal in 2021 ('Traditional'). The project experienced a 12-month hiatus before the Contractor was exclusively engaged to undergo an ECI process in 2023 ('ECI'), ultimately securing and executing the contract.

DATA COLLECTION AND ANALYSIS

The data collection involved quantitative data, namely, timesheets for the two projects examined for the traditional and the ECI tender periods, with a further analysis of workhours per discipline for Project 2 (data which is not available for Project 1). Qualitative data was also gathered in the form of six semi-structured interviews involving key pre-contracts and delivery personnel, including a general manager, construction manager, planning manager, and several estimators. A thematic analysis of interviews (Braun and Clarke 2006) method was carried out, in which the transcripts were coded through manual annotation and note-taking, then grouped by theme. This enable uncover distinctive perspectives on the contextual nuances of each project, discern staff perceptions regarding the impact of Early Contractor Involvement (ECI) on tendering, and factors beyond ECI that might have impacted tendering efficiency to be uncovered.

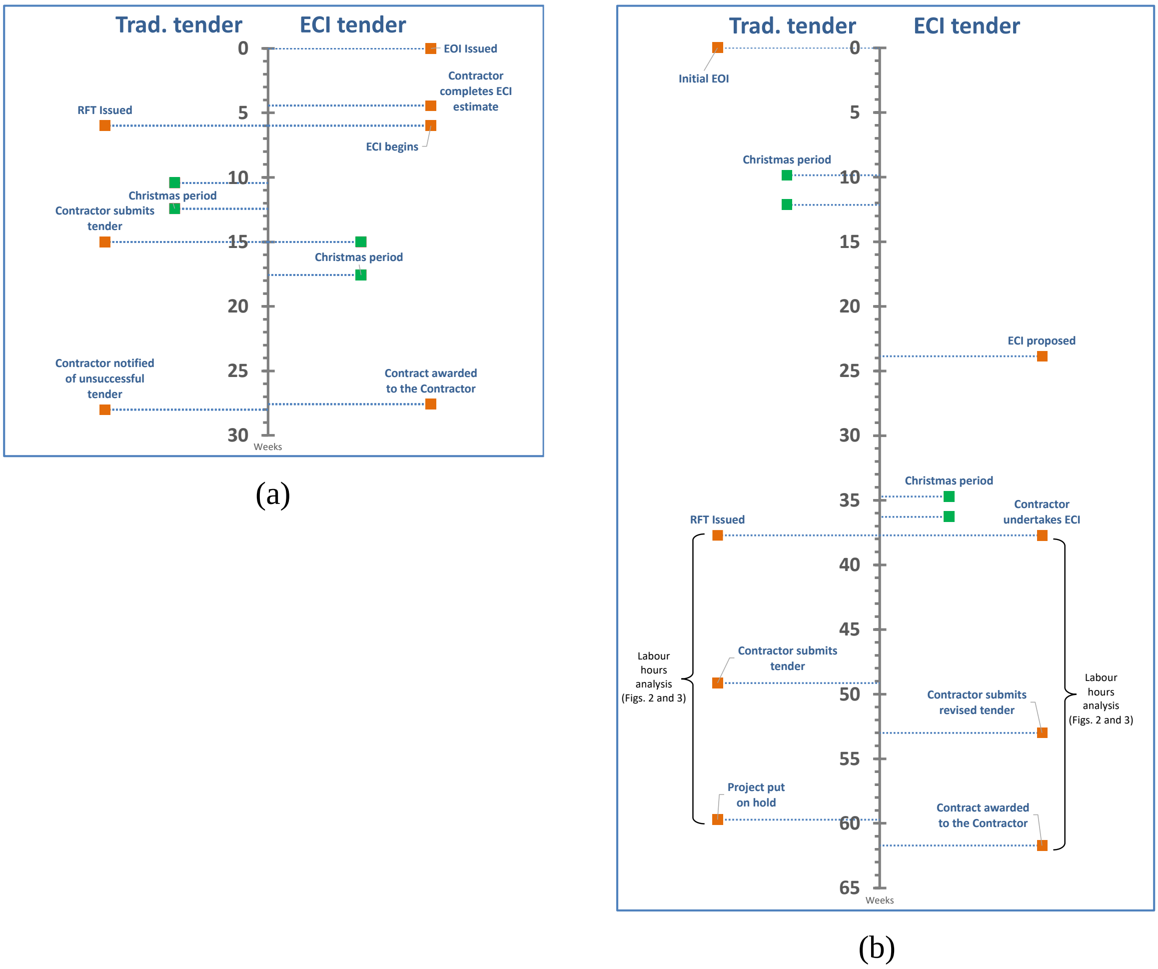


Figure 1: Timelines for Project 1 (a) and Project (2)

RESULTS

PROJECT 1

Length of the Tender Process

The Request for Tender (RFT) for the Traditional stage was released in Week 6 and concluded on Week 15, spanning a total of 9 weeks, as illustrated in Figure 2. Although the plan aimed for contract award in Week 20, the Contractor received notification of their unsuccessful submission only in Week 28, a delay of 22 weeks post-RFT release. Accounting for a two-week

Christmas shutdown period between weeks 11 and 13, the entire process of developing and submitting the tender extended over 7 weeks, with an additional 13 weeks dedicated to awaiting a response, as depicted in Figure 2. This timeline aligns with insights from an interviewee who highlighted the historical duration of tenders, ranging from 4 to 8 weeks, with some recent instances extending up to 16 weeks.

Preceding the ECI stage, an Expression of Interest (EOI) was initiated in Week 0, with the Contractor submitting their proposal in Week 1, as depicted in Figure 2. One interviewee argued that the EOI could be perceived as a business development activity, similar to the efforts of business development staff in ensuring the Contractor's shortlisting for other tenders. Consequently, the time span between the release of the Request for Tender (RFT) and contract award (Weeks 6 to 28) remained consistent for the ECI, mirroring the timeline observed in the Traditional tender, although the duration of active involvement was notably lengthier. Initial discussions and the preparation of an ECI estimate occurred during Week 5, followed by the commencement of the ECI in the subsequent week. While the contract award was initially slated for Week 13, an interviewee pointed out that the allocated timeframe "*was never going to be enough.*" After several months of additional meetings, presentations, and negotiations, the contract was eventually awarded in Week 28.

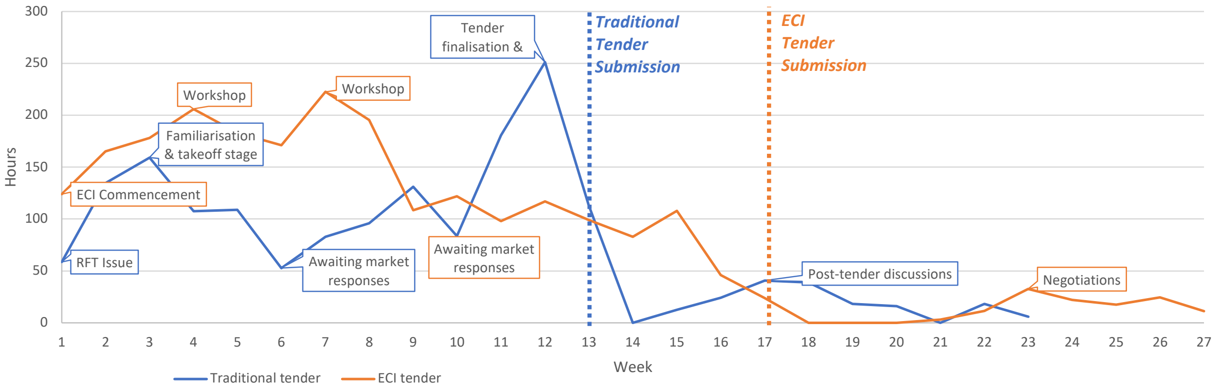


Figure 2: Work Hours Per Week (Project 2)

Views on ECI Impact on Tender Length

Respondents exhibited divergent perspectives on the impact of Early Contractor Involvement (ECI) on tendering duration, reflecting inconsistencies in the existing literature, as observed in the contrast between studies by Sødal et al. (2014) and Pheng et al. (2015). One interviewee asserted an unequivocal extension of the process, with acknowledgment that ECI could have been even lengthier if not for leveraging groundwork from the Traditional tender during the ECI. In contrast, another interviewee emphasized ECI's potential to streamline efforts, allowing the Contractor to approach the market sooner, obtain real-time responses, and expedite the tender process. Project 1 exemplified ECI's capacity to foster collaboration and establish common objectives.

The ECI model was identified as a crucial factor in enhancing efficiency, aligning with insights from Gransberg (2013) on the influence of contracting procedures. Another interviewee concurred, noting that the ECI was approximately four weeks shorter than a typical tender, facilitated by a deeper understanding of subcontractor capabilities and contacts through access to client personnel. Initial concerns about tight timeframes imposed by Principal 1 were addressed, with discussions highlighting scheduled shutdowns and contractual negotiations imposing a hard deadline for the ECI process. Despite varied perspectives on the ECI period's definition, one interviewee revealed a prolonged ECI process marked by extensive project reviews over three months before final pricing, underscoring the lack of consensus in defining the ECI duration.

Overall Resource Usage

One interviewee highlighted the predominant involvement of a single estimator during the Traditional tender, with additional support from undergraduates and site supervisors. In contrast, the ECI witnessed increased participation, encompassing a site team concurrently engaged in another project. Several participants disclosed heightened engagement of construction personnel during the ECI enabling more thorough scrutiny of provided information, provision of advice to estimators, and participation in workshops with Principal 1. The dynamic nature of resourcing during Early Contractor Involvement (ECI) was emphasized, characterized by an initial intensity that could be subsequently increased or reduced based on encountered challenges. The significance of client-funded staffing for the Contractor was underscored, enabling access to vital resources that would otherwise be financially prohibitive. However, the complexity of maintaining the right personnel available for tenders (when projects constitute the primary income source for the Contractor) was highlighted as challenge. Conversely, another interviewee perceived the ECI as a streamlined process primarily orchestrated by management staff—a perspective in alignment with Greenhalgh's (2013) view that such staff plays a more substantial role in ECI tenders compared to traditional ones. Despite the potential similarity in total work hours with the Traditional tender, this interviewee emphasized a more concentrated effort during the ECI, contributing to its perceived brevity.

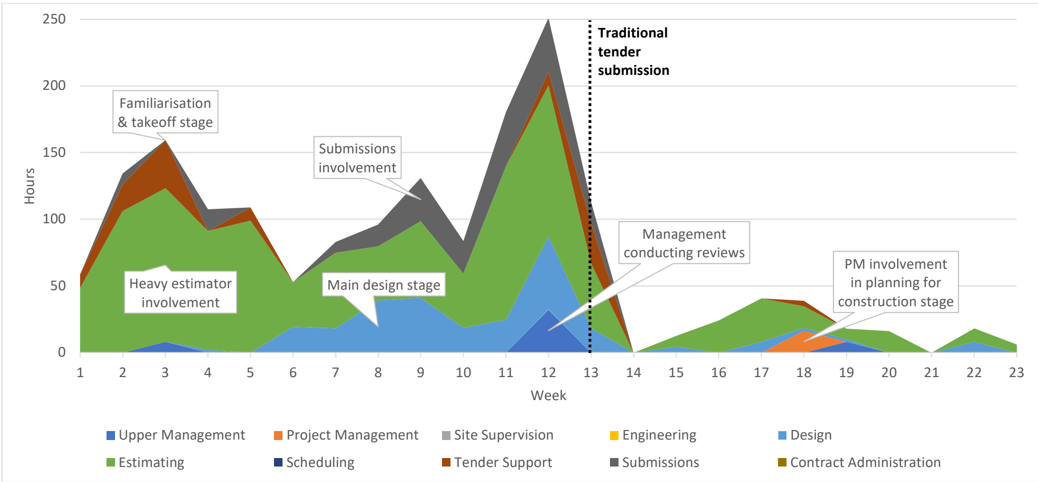
PROJECT 2

Length of the Tender Process

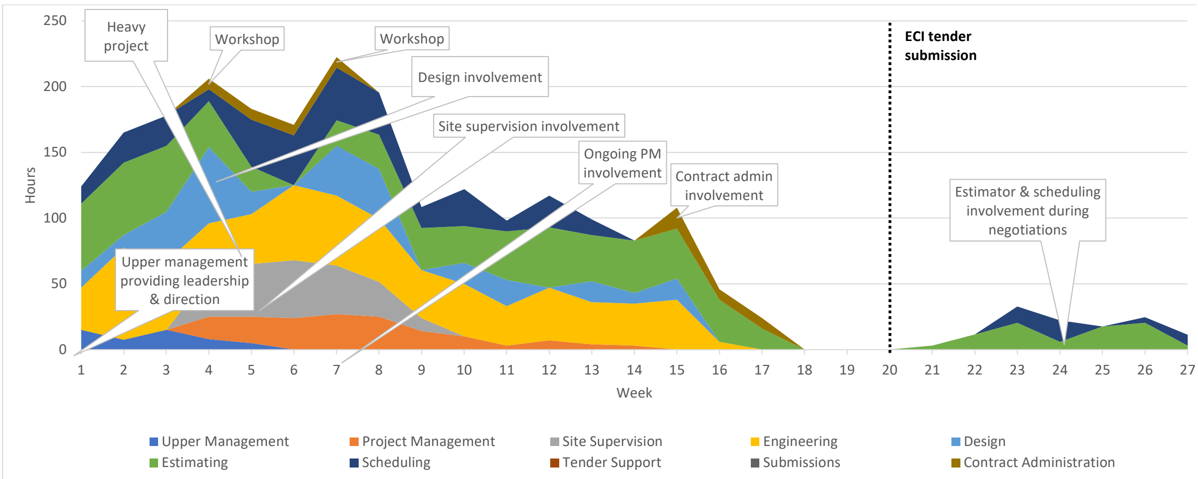
The Traditional tender, characterized as "normal" and akin to typical tenders, extended over 23 weeks, as depicted in Figure 1. The Request for Tender (RFT) process spanned 13 weeks, initiated in Week 38 and concluding in Week 50, aligning with a conventional 16-week Design and Construct (D&C) tender timeframe noted by an interviewee. Figure 1 illustrates an ensuing 10-week period of discussions and negotiations concluding on Week 60. In contrast, consistent with Sødal et al.'s (2014) emphasis on contractor involvement in design, the ECI tender unfolded over 38 weeks, commencing preliminary Early Contractor Involvement (ECI) discussions in October 2022 (Week 24) and culminating in the final contract review on Week 62 (Figure 2). Participants cited increased design inputs and the identification of unforeseen issues as contributors to the extended tender period, enhancing pricing certainty but lengthening the process. Accounting for a two-week Christmas break and a three-week lull post-ECI, a total of 33 working weeks transpired. The ECI stage itself spanned 16 weeks, with the Contractor submitting the revised tender in Week 53. One interviewee highlighted the advanced starting point for the ECI after a two- or three-month traditional tender but suggested minimal impact on the overall process duration. Challenges in obtaining pricing from the supply chain extended the timeline, with one interviewee noting a month spent acquiring competitive market pricing: *"That five months was extended due to some... issues. Responses from the supply chain (were) probably the main issue... (we spent) up to a month getting decent pricing back from the market"*. Additionally, extended pricing negotiations ensued due to hyper-escalation, as observed by a second and third interviewee.

Overall Resource Usage

Figure 2 illustrates the weekly work hours for the Traditional and ECI tenders over time. In the Traditional stage, the total work hours amounted to 1735, distributed among 16 staff members, averaging 108.4 hours per person and 4.7 hours per week. During the RFT stage (weeks 1 to 13), 1560 hours were expended, averaging 5.4 hours per person weekly. Notably, a peak exceeding 150 hours in week 3 (familiarization & take-off stage) was clarified by interviewees as a period involving meetings, document familiarization, and preparation of tender packages for subcontractors and suppliers (Figure 3a). Subsequently, a trough (weeks 5 to 10) occurred while awaiting market responses, succeeded by a peak of 251 hours in week 12 (tender finalization & review) just before tender submission. This peak was succeeded by a substantial decline in work hours, coinciding with post-tender discussions between the Contractor and Principal 2, as noted by one interviewee (Figure 3a).



(a)



(b)

Figure 3: Work Hours Per Discipline in Project 2: Traditional (a) and ECI (b) tenders

In the ECI, a total of 2880 work hours were expended by 19 individuals, including 4 or 5 full-time staff according to one interviewee. The average total hours per person were 151.6, with a weekly average of 4.6 hours. Work hours prior to ECI tender submission reached 2251, with staff averaging 12.8 hours per week each. The initial 8 weeks were particularly labour-intensive, peaking over 200 hours per week twice. Notably, the ECI involved extensive discussions in the first four weeks regarding the possibility and details of ECI, requiring approximately 100 hours per week from staff before tapering off before the Christmas period. This contrasted starkly with the traditional tender, where discussions on the tender process were unnecessary, and the RFT was issued to shortlisted tenderers. The ECI phase included an average of three client meetings per week, unlike the two key meetings in the Traditional tender – a briefing and a site visit. Peaks during this period, such as those in Weeks 4 and 7 in Figure 3b, can be attributed to key workshops. After the ECI submission, several weeks were dedicated to commercial and contractual negotiations, requiring significantly less time from the Contractor's tendering team.

Interdisciplinary & Interdepartmental Resource Distribution

The timesheet data reveals a significant increase in delivery personnel involvement in the ECI compared to the Traditional stage, including five site supervision staff and two project engineers, while none from either discipline were engaged in the Traditional tender. This observation aligns with insights from multiple interviewees emphasizing the intensive participation of delivery personnel in ECI, often in full-time roles, deviating from the traditional approach of assisting with tenders while concurrently working on-site on other projects. This supports Migliaccio and Holm's (2018) perspective that project teams are more likely to be extensively involved in ECI. Additionally, one interviewee highlighted a related phenomenon: in traditional tenders, on-site staff often work on tenders in their spare time, potentially on weekends, leading to their working hours being predominantly allocated to the concurrent on-site project, which might not be considered a cost of the tender by the business. While it is evident that the implementation of ECI resulted in a substantial increase in the number of hours project staff dedicated to Project 2, the data also underscores a second effect of ECI: more accurate logging of staff hours, partly driven by the requirement to submit payment claims to the client based on staff timesheets.

In the traditional tender process, interviewees highlighted the necessity of a submissions coordinator responsible for organizing site meetings, managing client correspondence, compiling non-price criteria, and creating a polished final submission. In contrast, the ECI process did not require a submissions team, likely attributed to the iterative nature of ECI rather than a single submission event. Additionally, the ECI process involved a contract administrator to handle cost-reimbursable aspects, a role not necessary in the Traditional stage. The discipline with the highest involvement in the Traditional tender was estimating, accumulating a total of 1085 work hours with an average of 270 hours per person, followed by the design and submissions teams with totals of 262 and 203 hours, respectively. Estimators and undergraduates exhibited heavy initial involvement, combining for 534 hours in the first 5 weeks, peaking in week 3 (familiarization & takeoff stage). This aligns with activities such as document review, quantity take-offs, and distribution of tender packages. Design team involvement grew subsequently as the Contractor's design consultants-initiated work on a tender design. The peak involvement per person for design staff (averaging 40.25 hours per person per week) occurred between Weeks 8 and 9, presumed to be the primary design stage before the final pricing review and submission. Steady involvement from the submissions team paralleled the work of design personnel.

The paid nature of the ECI, a feature not guaranteed in all cases, significantly influenced increased participation from construction personnel and consultants. An interviewee emphasized that the involvement of design consultants in the ECI process would not have been possible without payment from the Principal, aligning with the concerns expressed by Malvik et al. (2021) and Mosey (2009) regarding contractors' reluctance to engage in unpaid ECI work. Estimating remained the most engaged discipline in the ECI, mirroring the total hours in the Traditional tender (1081 hours), while project engineers assumed a more substantial role during the ECI process. This supports Migliaccio and Holm's (2018) assertions regarding the utilization of experienced project engineers for ECI tenders. The peak during initial discussions (between weeks 2 and 4 in Figure 6) involved extensive estimating efforts (439 hours), 4 hours of senior management input, 8 hours of scheduling contributions to formulate an ECI program, and 56 hours of engineering support.

DISCUSSION

Several interviewees stated that ECI is most suited to complex projects where there is significant uncertainty, such as operational treatment plants like the one in Project 2. Scope definition was one challenge identified, with ECI providing better awareness and understanding of the scope. ECI also reportedly allows the contractor to work with the client to resolve issues due to poor documentation. According to one interviewee, "*the main challenge is (that) we're trying to get the right price*", which is predicated on having the correct information from the client and site. As identified by Tower & Bacarini (2012), this is a fundamentally inexact process. Risks and unknown elements are typically reflected in added risk pricing or tender qualifications. Multiple participants noted that the increased transparency between client and contractor and the additional time spent exploring issues during ECI allow risks to be identified, allocated appropriately, and priced accordingly. One asserted that "*the less uncertainty we have, the more certain we can be on the pricing and the more comfort we can give our senior management that we understand the project*", highlighting the means by which ECI can facilitate more astute business decision-making. For example, in Project 1, past operational issues were identified by the client.

In Project 2, the Contractor owned the design, and interacted with Principal 2 to address them. One interviewee also stated that commercial risks can be better understood, permitting less aggressive contracting. They also argued that the success of an ECI lies in the right resourcing, which provides comfort to all parties that they are receiving the correct information. One participant also remarked that the increase in price typically associated with greater knowledge of risks can be detrimental to a contractor's competitiveness if the tender goes to open market post-ECI. Multiple responses also acknowledged the major challenge of securing engagement from the market – subcontractors and suppliers – to provide pricing, particularly since COVID. However, it was noted that through ECI, the Contractor was able to go to the market with a better understanding of market capabilities, greater confidence they would be awarded the project, and with the ability – and willingness – to be transparent with subcontractors, improving the likelihood of market interest. Subcontractors were reportedly brought to site and into discussions with the client, providing an additional layer of confidence and further mitigating subcontractor-related risks.

Interviewees also clearly identified understanding client expectations and market price escalation as challenges of tendering. One participant stated that the ECI process is reflective of increasingly collaborative construction contracting, with the ability to tap into an engaged client through open forums. Rahman and Alhassan's (2012) study, which revealed the prominence of relationship-related benefits of ECI, confirms this view. Another interview revealed that during the ECI tender Project 2, operators of the treatment plant could be brought in to verify information and identify potential solutions. Yet another interview exposed similar advantages with the ECI tender for Project 1, where the Contractor was able to utilise Principal 1's knowledge of existing issues and risks. That same interviewee noted that same transparency allowed risks associated with escalation pricing during Project 2 to be addressed by the client. An issue that became apparent as interviewees discussed the effects of ECI on the efficiency of tendering was probity, which acts as a barrier to information flow and problem-solving. In a traditional RFT process, the client must provide their answer to one tenderer's question to all tenderers. Interviewees noted that this is typically a lengthy process, with answers often lacking detail. By contrast, they revealed that greater access to the client and the involvement of only one tenderer "does streamline the whole question and answers elements", allowing the contractor to raise ideas, receive feedback, and address potential difficulties without a prolonged request for information (RFI) process.

CONCLUSIONS

This paper examined the impact of ECI during tender on a Contractor's resourcing, and more specifically on staff workhours. Projects 1 and 2, which had both traditional and ECI tender processes (for stages A and B, respectively) were examined in terms of quantitative and qualitative data (respectively, time sheets and semi-structured interviews). The comparative analysis of traditional and ECI tenders suggest that the latter streamlines certain aspects but tends to result in a more prolonged and resource-intensive procedure. ECI in Project 2 did not merely extend the work involved in the tender process across a longer period, resulting in a substantially greater total number of hours spent on the pre-construction phase. Also, the weekly average hours per person more than doubled during the actual tendering period. Tenders involving ECI also showed increased engagement from delivery personnel, including site supervisors, project and site engineers, and project managers, attributed in part to the Contractor being reimbursed for their time in ECI tenders. Despite the extended and more involved tendering process associated with ECI, the qualitative data demonstrated that it offers significant value by addressing challenges like unclear scope, poor documentation, probity, lack of market responses, tight timeframes, and price escalation through enhanced certainty, focus, and communication.

This investigation provides a different angle to existing studies (e.g Suttie 2013, Assainar and El Asmar 2014, Ibrahim and Hanna 2019, Kulkarni et al. 2012) by uncovering the changes in the staff workload in pre-construction phases. Prior research suggests that such additional effort and workhours upfront are paid off by enhancements in the overall project performance. It is nonetheless key to map and outline these changes as done here so stakeholders (e.g. Contractor) can be prepared and plan accordingly. Lastly, it is also important to acknowledge the limitations of this study. It is clear from the qualitative results that factors such as project complexity, client relationships, internal resource capabilities, and the contractual model likely limited the generalization of results. Due to availability of staff, the qualitative data provided by the Contractor only consisted of six interviews with management and estimating personnel. Furthermore, conclusions from the Project 1 were hindered by incomplete timesheet data (i.e. no discipline breakdowns). Also, this paper has only examined the impact of ECI on specific projects and has not given consideration to whether bidding decision-making or tender success is affected by ECI, so the impact of ECI on the total resources used by the organisation for tendering has not been addressed. Furthermore, further to the literary consensus that ECI's primary advantages are attained during delivery, one interviewee suggested that the success of a project would be an indicator of tender success, however this factor could not be examined here due to time limitations.

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COMPETITIVE NEGOTIATED PROCEDURE: EXPERIENCES FROM RV. 555 THE SOTRA CONNECTION

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ABSTRACT

To reduce the number of conflicts in their projects, the Norwegian Public Roads Administration has implemented procurement procedures which allow dialogue and negotiation before the signing of contracts. One of these procedures is the Competitive Negotiated Procedure (CNP). The literature that addresses the implementation and experiences of CNP is limited, despite it has existed for several years. The purpose of this paper is to explore how the CNP can be improved for future use. The study has been carried out as a literature review and a case study. The case study investigated the infrastructure project Rv. 555 Sotra Connection and consisted of a document study and fourteen semi-structured interviews with representatives from the client and the qualified suppliers. The implementation of the procedure was divided into five phases. There were challenges with the procedure. Both the client and the suppliers encountered challenges with the zoning plan, which limited the supplier's ability to implement cost-saving alternatives. The suppliers experienced challenges regarding the client's evaluation of the most economically advantageous tender (MEAT). Both the client and the suppliers highlight that the CNP is demanding, but it allows clarification of ambiguities and risks before contract signing. This reduces the risk of future conflicts.

KEYWORDS

Lean Construction, Competitive Negotiated Procedure (CNP), Procurement, Collaboration, Most Economically Advantageous Tender (MEAT)

INTRODUCTION

Norway implemented a new Public Procurement Regulation on the 1st of January 2017 to efficiently use the resources of society and provide competition in public procurement. The new legislation superseded the previous regulation from 2006. Norway's procurement law is largely based on EU directives, which Norway must implement under the EEA – agreement (Wondimu 2019). The regulation applies to all state authorities, county and municipal authorities, and public law bodies and associations affiliated with them. The Norwegian Public Roads Administration (NPRA) is an administrative body subordinated to the Ministry of Transport and is obliged to comply with the law of public procurement. This involves following the basic principles of non-discrimination, equal treatment, transparency, proportionality and mutual recognition (Lennerfors 2007). For public procurement, the EU directive identifies procurement

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procedures such as open and restricted procedure, competitive negotiated procedure (CNP), competitive dialogue and innovation partnership (Wondimu 2019). The selection of the procurement procedure should depend upon the scope and complexity of the project (Hansen 2019). The law of public procurement creates several barriers for public clients, but involving contractors earlier in projects than today is still recommended (Wondimu et al. 2018a). There is however a lack of research in the IGLC community in the area of public procurement (Wondimu et al. 2018b). There is also a lack of research on the application of LC concepts in the preconstruction phase (Reginato and Alves 2012).

There has been a high level of conflict between NPRA and their suppliers in NPRAs bigger projects, resulting in additional expenses for both parties. Causes of conflict have been errors and deficiencies in the tender specification, interpretation of the contract, and due to use of the lowest price as the sole criterion for awarding the contract (Sabri et al. 2019). To reduce conflicts and thereby reduce waste, NPRA has shifted focus from mere price competition to procurement methods more in line with the principles of LC. The purpose of this shift is to establish an equal understanding of the contract's contents. One of the procedures that allows for dialogue before contract signing is the CNP. This procedure has been allowed by public authorities for several years. The literature review did not reveal much literature that addresses practical implementation or experiences from using this procedure. By looking at an infrastructure project in Norway, this paper aims to fill the knowledge gap. The paper answers the following research questions:

RQ1: How was the competitive negotiated procedure implemented?

RQ2: What are the experiences from the competitive negotiated procedure?

RQ3: How can the competitive negotiated procedure be improved for future use?

This study is limited to a Norwegian infrastructure project and explores the experiences of the client and the three qualified consortiums that made a bid on the project. After a presentation of the theoretical framework and the applied research methods, the findings from 14 interviews are discussed.

THEORETICAL FRAMEWORK

COMPETITIVE NEGOTIATED PROCEDURE

CNP is a procurement procedure that allows the contracting authority to negotiate with the suppliers. The procedure can be used in the following circumstances: a) The needs of the contracting authority cannot be met without adaptation of readily available solutions; b) They include design or innovative solutions; c) The contract cannot be awarded without prior negotiations because of specific circumstances related to the nature, the complexity or the legal and financial makeup or because of the risks attaching to them; d) The technical specifications cannot be established with sufficient precision by the contracting authority concerning a standard, European Technical Assessment, common technical specification or technical reference; e) In response to an open or a restricted procedure, only irregular or unacceptable tenders were submitted (Burnett 2015).

CNP is a two-stage tendering procedure where interested suppliers can request to participate in the qualification stage. The goal of the qualification stage is to select an appropriate number of qualified suppliers that can participate in the negotiation stage. The contracting authority may limit the number of suppliers invited to submit tenders, but the minimum number of suppliers is three in CNP (Telles and Butler 2014). If the number of suppliers interested exceeds the number of suppliers the contracting authority intends to negotiate with, the contracting authority may select suppliers based on predetermined selection criteria. Several selection criteria are used to evaluate and select the suppliers. These criteria must be objective and non-discriminatory (Doloi 2009). The selected suppliers are invited to participate in the negotiations.

Except from the generic principles of public procurement, there are no specific requirements for how to conduct the negotiations. The contracting authority may negotiate all aspects of the tender and the supplier's proposal, but is restricted from negotiating the award criteria and absolute requirements set in the tender documents (Burnett 2015).

While not required to explicitly highlight any weaknesses in the offers, the contracting authority must inform the suppliers of factors that will be given significant or decisive importance in evaluating the bids. The principle of equal treatment requires that the contracting authority should treat all suppliers impartially during the negotiations. Equal treatment of suppliers ensures that all suppliers are given equal opportunities to improve their proposals (Šostar and Marukić 2017). When the contracting authority highlights the strengths and weaknesses of an offer to one supplier, it must also disclose the strong and weak aspects of other offers. This ensures that all suppliers have equal information to improve their offers.

Negotiations can be conducted in multiple stages, with a gradual reduction of suppliers at each stage (Burnett 2015). The reduction will occur through the evaluation and ranking of the revised bids based on the specified award criteria and minimum requirements. The contracting authority is responsible for ensuring that an adequate number of offers remain in the final phase of negotiations to maintain competitiveness. Negotiations are concluded by establishing a deadline for the remaining suppliers to submit their final bids.

AWARD CRITERIA

The EU procurement directives specify two distinct criteria for awarding public contracts; either based on the lowest price or the most economically advantageous tender (MEAT) (Bochenek 2014). If the sole award criteria is the lowest price, the contract will be awarded to the supplier with the lowest price (Lædre 2009; Parikka-Alhola et al. 2006). According to Tavares (2019) contracting authorities often opt for the lowest price as the award criterion due to its simplicity and to avoid any suspicion regarding the evaluation of the various bids. When a contract is awarded by using MEAT as an award criterion, it involves emphasizing the weight of different aspects of a product or service that adds value to a project. It ensures that factors beyond price, such as quality, environment, and social aspects, will be taken into account as part of the selection process (Marcarelli and Nappi 2019; Wondimu et al. 2020).

The award criteria and their corresponding weight shall be established beforehand and made known to the suppliers. The objective of establishing and formally disclosing the award criteria is to achieve the following objectives: a) Enable tenderers to prepare their tenders in a manner that aligns with the contracting authority's stated priorities. b) Ensure that the evaluation of tenders is conducted by the contracting authority in a transparent, reliable, and objective manner. c) Allow relevant stakeholders, such as review bodies, other government entities, or economic operators, to oversee the process and prevent the use of discriminatory or unauthorised award criteria (OECD 2011). Identifying the most economically advantageous tender poses a challenge due to the lack of explicit guidelines in the regulations on how it should be executed (Sebastian et al. 2013; Wondimu et al. 2018c).

According to Ottemo et al. (2018), a point, ratio or price correction system can be used to evaluate MEAT. The point system converts all aspects of the tender into points based on an objective calculation reference. The supplier with the highest number of points is awarded the contract. In the ratio system, each criterion in the tenders gets a basic monetary value if satisfying the minimum tender requirements. When a supplier exceeds the minimum requirements, the added value is added to the basic monetary value. The supplier who achieves the highest value is awarded the contract (Sebastian et al. 2013). By using a price correction system each criterion – except the price – is assigned a fictional monetary value. This monetary value is subtracted from the bid price. The supplier with the lowest corrected bid price is awarded the contract (Chiappinelli and Zipperer 2017). Bergman and Lundberg (2013) suggest that to identify the MEAT, the client must assign a monetary value to the quality. All in all, it is not a good idea to mix cost with value (Schöttle et al. 2015).

LEAN AND COMPETITIVE NEGOTIATED PROCEDURE

Multiple research studies conducted on productivity within the construction industry have shown the potential for an increase of 10-20 % in productivity. This increase can be achieved by improved interaction among stakeholders (Hansen 2019; Wondimu et al. 2017). Lean Construction (LC) aims to maximize value and minimize waste (Bertelsen 2002; Emmitt et al. 2005). It draws its principles from the success of the lean philosophy in the manufacturing industry (Young et al. 2017). The goal is to reduce costs, shorten production times, and increase quality throughout the entire construction lifecycle, from planning and design to completion and operation (Alves and Tsao 2007). In addition, the LC community agrees upon that the goal of projects is to deliver value (Drevland and Lohne 2015). LC is about optimising production systems aimed at delivering value (Drevland and Tillmann 2018). Clients can use CNP to act according to LC principles, i.e. improve processes and project outcomes.

As stated before, CNP allows for negotiations between the contracting authority and the suppliers before contract signing. This allows collaboration with the suppliers to identify uncertainties and potential challenges at an early stage (Kantola 2015). CNP allows for greater flexibility in project planning, design, and execution by facilitating open communication and collaboration among project participants. This flexibility enables the contracting authority to discuss terms of contracts before contract signing, for example making adjustments to the project scope as needed to optimize project outcomes and deliver value to the client (Burnett 2015). Negotiations allow value engineering exercises to be conducted collaboratively among project stakeholders. Value engineering is an approach used to obtain the required component at the lowest total cost without reducing the necessary quality (Ilayaraja and Eqyaabal 2015). By incorporating value engineering into the negotiation process, the project team can identify and implement cost-effective solutions that align with project goals and client requirements.

METHODS

The research was conducted using a literature review and a single case study. To establish a theoretical foundation, a literature review of the relevant literature was conducted. A literature review serves multiple objectives. It can highlight results from previous studies in a research area, and it can provide a framework for comparing your findings with previous findings (Creswell and Creswell 2018; Hart 2001). The literature review used Arksey and O'Malley's framework for literature review. The framework has five steps: 1) uncover research questions, 2) find relevant literature, 3) select literature, 4) map data and 5) collect, summarize and report the results (Arksey and O'Malley 2005). To find relevant literature, an initial search on "Competitive Negotiated Procedure" was conducted in various databases such as Google Scholar, Web of Science, ASCE, Scopus and Science Direct. The search returned a few results across those databases, with some returning no results whatsoever. It became necessary to expand the search area by adding more keywords such as "Public Procurement" and "Award procedure". To identify more relevant literature, various approaches like "Backward Snowballing" and "Forward Snowballing" were used. "Backward snowballing" involves reviewing the list of sources cited in a relevant article, while "forward snowballing" involves reviewing articles that references the relevant article (Webster and Watson 2002). The literature review was used to describe the existing body of knowledge and to formulate the interview questions.

The case study was carried out based on the recommendations of Yin (2014). The project studied is the procurement of a large road infrastructure contract. The contract is the largest single contract entered into by the NPRA and the largest public-private partnership contract awarded in EU in 2021. The contract have a value of 1,98 billion euro (Statens vegvesen 2021). The case was studied through fourteen semi-structured interviews and a document study.

The interview objects consisted of participants from the client and all the joint groups that made a bid on the project. The interviewees were design consultants, legal advisors and a variety of participants in management positions. All the interviews except one were carried out via Teams. The interviews followed an interview guide. The interview guide began with introductory questions, allowing the informant to provide self-introduction. Following the introductory questions, the interview guide was organised based on the identified phases in Figure 1. For each phase, the three research questions were asked, beginning with RQ1, then RQ2 and finally RQ3. The interviews lasted from one to three hours, with some of the participants displaying great interest towards the research. With the respondents' consent, the interviews were recorded, transcribed, and sent as a summary for their approval.

The document study was carried out in a two-stage process. The initial stage of the document study involved acquiring fundamental information regarding the project. The tender document and documents that were created during the tender process such as the evaluation report, were among the case-specific documents studied. The second stage of the document study was conducted after the interviews to identify any inconsistencies between the documents and the interview data.

FINDINGS AND DISCUSSION

The first section in this chapter starts with introducing the practical implementation of CNP, answering the RQ1. The section follows the phase model in Figure 1.

IMPLEMENTATION OF COMPETITIVE NEGOTIATED PROCEDURE

During the study, five phases of the CNP were discovered. The five phases consisted of Preparation, Qualification, Clarification, Negotiation, and Evaluation. Figure 1 depicts the phases, important activities and decision gates throughout the tender process.

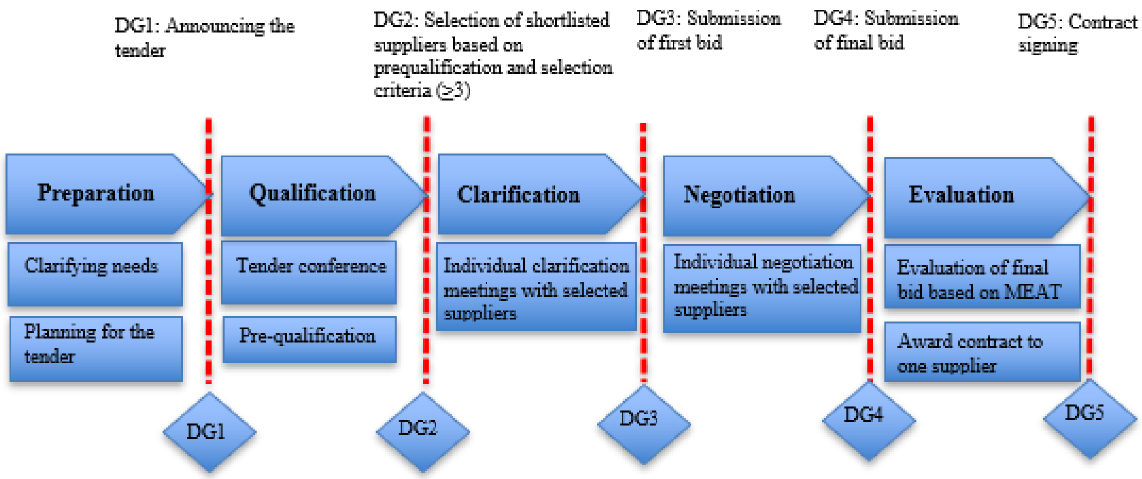

Figure 1: Implementation of Competitive Negotiated Procedure: Phases, main activities and decision gates (DG). Based on findings from the study.

The preparation phase began with the client clarifying the project's needs and how they could be met. Subsequently, the preparation continued by planning for the tender. This included developing tender documents, establishing a negotiation strategy and engaging in marked dialogue with the supplier market. Multiple market and information meetings were held during the process of creation of the tender documents. It was crucial to maintain contact with the supplier market during this phase. This was to prevent the client from creating a tender that the potential bidders did not want. During the meetings, the suppliers had the opportunity to provide feedback to the client on qualification and award criteria. **The qualification phase** began with a tender conference, during which the client invited the industry to an informative meeting, followed by a site visit. During the information meeting, the client presented the project with the main deliverables, contract structure, qualification requirements and the description of the tender process. During the qualification phase, the goal was to select three qualified suppliers who would be invited to submit bids. Following the expiration of the deadline for requests to participate in the competition, the client had four interested suppliers. Out of the four suppliers who submitted a request, only one failed to meet the requirements. During the **Clarification phase**, a total of four clarification meetings were held with each qualified supplier. In the first clarification meeting the client presented the tender documents. The theme for the second clarification meeting was the contract and a review of the works to be performed. The third clarification meeting focused on the financial aspects of the contract. The final clarification meeting focused on questions and clarifications that had emerged from discussions at the previous meetings. Following the clarification phase, the suppliers were to submit their first bid. The first offer represented the beginning of the **Negotiation phase**. The client had planned a total of three negotiation meetings. The first negotiation meeting did concern the supplier’s response concerning award criteria 1: Bid price. The second negotiation meeting did concern the supplier’s response regarding award criteria T2-T5. The final negotiation meeting was a two-day meeting. The submission of the supplier's final bid represented the beginning of the **Evaluation phase**. During this phase, the client had to determine the most economically advantageous tender by evaluating the bids using the award criteria as a basis. The following were the competition’s award criteria:

- T1 Award criterion 1 – Bid Price
- T2 Award criterion 2 – Plan for organisation and execution / 60 million euro
- T3 Award criterion 3 – Traffic management / 50 million euro
- T4 Award criterion 4 – Quality of the infrastructure project / 30 million euro
- T5 Award criterion 5 – Climate and HSE / 50 million euro

The value of T2-T5 represented a potential reduction in the bid price that suppliers could receive. During the bid evaluation, the client would evaluate and determine the competitive price of each supplier. The competitive price was determined using the following method: Competition price = T1 (Bid price) – (T2+T3+T4+T5). When a supplier's solution exceeds the award criteria requirements, it receives a fictional deduction, resulting in a reduced competitive price. To evaluate the different bids, five evaluation teams were formed, each assigned to a reward criterion. The teams were a combination of people who had taken part in the negotiations and others who had not been involved. The contract is then awarded to the supplier with the lowest competitive price as it’s the most economically advantageous tender.

EXPERIENCES WITH COMPETITIVE NEGOTIATED PROCEDURE AND FUTURE IMPROVEMENTS

This section addresses the experiences with the procedure and suggests possible improvements for future CNP projects, answering RQ2 and RQ3. The discussion and suggested improvements are based on the authors’ interpretation of the data from the case study.

Preparation phase

Zoning plan

During **The preparation phase** the client and the suppliers agreed that the zoning plan restricted the possibilities for an optimised production. The zoning plan restricted the possibility of making changes as one of the responsible municipalities stated that making any changes to the zoning plan would lead to a significant delay of several years. This frustrated the suppliers as they meant the client was unwilling to discuss cost-saving proposals that challenged the zoning plan.

The zoning plan offers guidelines to the suppliers regarding choices they can make in design. A zoning plan with a low degree of freedom may constrain the project's ability to incorporate new elements that appear after the zoning plan has been approved. At the same time, such a zoning plan will make the evaluation of the suppliers' solutions easier as the solutions will be more comparable. A zoning plan with a high degree of freedom might complicate the evaluation of solutions, as it can allow solutions that are difficult to compare. A suggested approach is to consider the relationship between the contract strategy and the degree of freedom in the zoning plan. If the planned contract strategy provides suppliers with significant opportunities for influence, then the zoning plan should have sufficient levels of freedom to accommodate this. If a contract strategy is designed to minimise the contractors' influence, it may be beneficial to have a more restrictive zoning plan with limited flexibility.

Lack of continuity in the project organization

One experience mentioned by the client was the lack of continuity in the project organization. Optimising the construction process according to the LC principles is difficult when there is a lack of continuity. Different people were involved in the phases from choice of concept to operation. Decisions restricting future opportunities were made in the early stages. The client created experience reports throughout the project, but an informant from the client noted that the reports did not contain all the information about the experiences that were made. NPRA view each phase of a road project as a separate subproject, each having its project organisations. When transitioning to a new phase of the project, the entire project organisation might be completely replaced. This may be explained by the fact that different phases require different skills and competencies within the project organisation. Lack of continuity might limit the project organization's ability to have a full grasp of the entire project, as individuals may only possess detailed knowledge of the specific phase they were involved in.

The project ought to have mechanisms that guarantee continuity during the transition to a new phase. It might be beneficial to have the project manager, along with key personnel, oversee the project across multiple phases. Ensuring project continuity through personnel can be a formidable task, as it might take several years from the initial planning to the start of construction. Another way to ensure project continuity might be through detailed experience reports containing the five Ws (Who, What, When, Where, and Why) for each experience. These reports can serve as a valuable resource for new team members joining the project at different phases. By documenting key information and lessons learned, the project can maintain consistency and efficiency throughout its lifecycle.

Qualification phase

Qualification criteria

Both the client and the suppliers agreed that the client had chosen the correct qualification criteria during the **Qualification phase**. In the creation of the qualification requirements, the client used both the insights from the Quality assurance 2 report and from previous projects where too many suppliers were qualified. The informants from the client' believed that the qualification requirements were appropriate for the project, as they received a total of four interested bidders and three qualified suppliers.

Based on the findings from the case study (n=1), the respondents agreed that the tender qualification criteria were appropriate. This was achieved by having early marked dialogue and involving suppliers to determine the qualification requirements. As a result, the client got the desired number of qualified suppliers without using selection criteria.

Clarification Phase

Risk distribution

Upon evaluating the tender documents, it became evident to the suppliers that they had to take on too much risk. The supplier noted that the tender document and contract framework originated from past PPP projects and perceived this as a mistake. The previous PPP projects were of a scale that allowed the involvement of Norwegian contractors. The informants from the suppliers held the belief that this project relied on international financing as the project was too big for the Norwegian industry. Initially, the client required the project to be financed in Norwegian kroner. To secure favourable financing conditions, it became necessary to use the international market instead of restricting the financing currency to Norwegian kroner. This measure reduced the supplier’s risk and resulted in a cost reduction for the contracting authority.

The case study (n=1) findings indicate that when the client transfers too much risk to suppliers, the suppliers will add a risk premium that increases the project's overall cost. This is done to ensure that they have sufficient resources to handle this risk effectively. Through the clarification and negotiation meetings, the client and the suppliers can determine the specific risks that each party can assume. The risk should always be allocated to the party with the highest capability to manage it. By effectively allocating risks based on each party's capabilities, the project can proceed smoothly with minimized costs and delays. It is crucial for both parties to have open communication and a clear understanding of their responsibilities in managing risks throughout the project lifecycle.

Road construction guidelines and handbooks

An interesting experience is that participants have different perceptions of the national road construction guidelines and handbooks. Consultants who were interviewed perceive the guidelines and handbooks as positive, they show what regulations to follow. Contractors perceived the regulations to be good for guidance, but that guidelines and handbooks are made for Design-Bid-Build (DBB) projects where the client is responsible for design, i.e. drawings, descriptions, and calculations. At times, contractors perceive regulations as restrictive, as these impose excessive control over how they should execute their tasks. NPRA has primarily used DBB in their projects. This contract type requires a high level of detail from the client since he holds the risk for errors and flaws in the design. This has led to NPRA's internal processes, guidelines, and handbooks being tailored to the needs of DBB. NPRA wants to increase the use of Design-Build (DB) contracts in their projects, but a challenge arises from the fact that the same standards, guidelines, and process codes are utilised in DB contracts.

Based on the findings it can be argued that current guidelines and handbooks need to be revised as they are designed for DBB contracts and restrict the room for manoeuvre that is needed in other contract types.

Negotiation Phase

Quality of the feedback on suppliers’ solutions

During the meetings, the client faced a dilemma between the need to provide counsel, the concept of treating all parties equally, and the obligation to maintain confidentiality. The client is obliged to provide identical information to all suppliers simultaneously. Some informants found it challenging to track the information and comments provided to suppliers to prevent any supplier from gaining a competitive edge. The suppliers had difficulty comprehending the client's feedback and felt that it did not provide valuable insights for evaluating the strengths and weaknesses of their offer. The suppliers regarded the feedback as a hindrance, which reduced the quality of the final product obtained by the client. With more feedback, suppliers meant they could have prioritised value-adding solutions and improved the customer's project.

Feedback from public clients can help suppliers to improve their proposals. To improve their proposals, the feedback must be clear and specific, highlighting the proposals' strengths and weaknesses. In the feedback, the client can emphasize how the supplier's proposal is aligned with or deviated from the minimum requirements and award criteria outlined in the tender document. As the feedback must be based in the award criteria and the minimum requirement in the tender document, the quality of the feedback will significantly influence the proposals received by the client. If the suppliers receive vague feedback, it might be seen as not helpful for suppliers seeking to improve their proposals to add more value for the customer. Workshops and training for feedback givers can also improve feedback quality. This includes advice on common mistakes, best practices, and how to align feedback to client's needs. If the client lacks knowledge of the process of providing feedback, it may cause public clients to adopt a passive approach to ensure compliance with the Public Procurement Act. This can result in their failure to make use of the full range of available actions in providing feedback.

Evaluation Phase

MEAT-Evaluation

The informants representing the client had varied experiences throughout the evaluation of the final bid, but they unanimously agreed that the final bid was evaluated accurately. The evaluation teams performed both an individual assessment and a collaborative assessment to compare the results. The evaluation team found this process to be challenging. Despite the suppliers' evaluation being focused on their solution; the evaluation was required to be conducted simultaneously for all suppliers. The reasoning for this was that if any negative attributes were uncovered in one solution, the remaining solutions had to be examined for the same attributes to prevent favouring one supplier. This made it difficult for the representatives of the evaluation team to evaluate the solutions without comparing them. Another aspect, which was also challenging in the evaluation, was to define added value. The suppliers had varying experiences with the evaluation of the final bid. Upon reviewing the evaluation report, a supplier informant found no difficulties in accepting the evaluation provided by the client. Simultaneously, some members of the winning consortia felt that they ultimately did not know how they were evaluated. Other informants thought the evaluation to solely focus on the aspect of price. If the price was acceptable, the evaluation became also better on the technical side.

The evaluation teams for the final bid the evaluation teams consisted of members who participated in the negotiations and members who did not participate in the negotiations. Having members who have participated in the negotiations during the evaluation process has the benefit of displaying the impact of clarifications and negotiation meetings in the evaluations. The challenge is that unconsciously formed relationships during negotiations can affect evaluation. The evaluation can lose its objectivity and may favour one supplier. Another challenge that was addressed is the possibility that the evaluation could be influenced by the bid price. An approach to solve this is for the suppliers to submit their proposals using a two-envelope system. One envelope would contain the bid price, while the other would contain the response to the award criteria unrelated to the price. A limited number of evaluation members should have access to both envelopes to ensure that the price does not affect the other award criteria.

***Compensation for approved final bid*:**

A notable experience was the level of compensation that the suppliers were granted for an approved final bid. The suppliers, along with the client, perceived the compensation to be insufficient project and suggested that it should have been increased. The compensation was insufficient to cover suppliers' costs towards their subcontractors. It was a big challenge for the client to determine the size of compensation for the suppliers. If too low, it might discourage competition participation. If too high, it might attract suppliers more interested in the compensation rather than the project.

There should be a fair proportion between the expenses incurred by the suppliers and the compensation that is provided for an approved final bid. One possible method for determining the compensation amount is to consider the external expenses that suppliers pay to their consultants and subcontractors during the process of tender preparation and submission.

Demanding process

All representatives from the client and the suppliers acknowledged that CNP was demanding, but they agreed that the appropriate procedure was chosen for the project. According to one of the informants from the client, there has been a high number of conflicts in major projects due to the sole use of DBB and price competition as procurement procedures. When the cost exceeds 200 million euro, the contract is difficult to manage and monitor. This led to disagreements, which in turn resulted in increased expenses for both parties involved. The client states that the suppliers need to comprehend the scope of the project and the specifics of the contract, including the allocation of responsibilities and risks between the involved parties before contract signing. The suppliers had also a demanding process, requiring significant use of both internal and external resources. It is not just the tender process that consumes resources. Winning would require a significant apparatus to support the project.

The initiative to have clarification and negotiation meetings proactively addressed uncertainty and risk conditions that would often come later in a traditional project. Clear communication and a shared knowledge of the project scope and terms before signing the contract give the suppliers valuable insight into the project. The client was also convinced that they achieved a more precise price for the project through negotiating. Although negotiations and clarifications can reduce risks, overall cost, and the likelihood of future conflicts, competitive negotiation is a demanding procurement procedure that may not be suitable for smaller and less complex projects due to the significant amount of resources it demands from both the client and suppliers.

CONCLUSION

This paper shows how clients can use CNP to act according to LC principles during the tendering process by answering three research questions, namely RQ1: “How was the Competitive Negotiated Procedure implemented?”, RQ2: “What are the experiences with Competitive Negotiated Procedure?”, and RQ3: “How can Competitive Negotiated Procedure be improved for future use?”.

The paper has both theoretical and practical contributions. In terms of theoretical contributions, the paper documents the practical implementation of CNP and the experiences from the tender process in a Norwegian infrastructure project. Figure 1 illustrates in what phases the main activities and decision gates of CNP were implemented. The supplier and client experienced better collaboration than they were used to. The clarification and negotiation meetings before contract signing resolved concerns that could have caused problems later. However, the collaboration could have resulted in even more cost-saving solutions if the zoning plan was more flexible. In total, CNP mitigates waste by reducing the likelihood of conflicts.

In terms of practical contributions, this paper contributes to the IGLC Community by explaining a procurement process that allows public clients to implement lean principles in public procurement. The paper suggests improvements for future projects and can act as a managerial checklist for public clients seeking to incorporate lean elements in procurement.

There has been a shift from mere price competition to procurement methods more in line with the principles of Lean, and the consequences should be documented. Therefore, experiences from other recent infrastructure projects that have used CNP should be documented.

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STRATEGIC PARTNERSHIPS BETWEEN PROJECT CLIENT AND CLIENT'S AGENT

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ABSTRACT

Strategic partnership is an emerging project delivery method characterized by long-term collaboration in multiple projects. In this paper, we seek to increase the knowledge about strategic partnerships. From a lean perspective, strategic partnerships could be a potential measure towards mitigating inefficiency caused by lacking continuity and previous relationships. Our purpose is to reveal aspects that can help clients and client's agents organize better strategic partnerships. The client's agent is the contracted adviser who takes care of all the functions which the client's project management cannot handle. A literature review and a case study were conducted, where the case study included eight semi-structured interviews. The findings identify several benefits regarding soft factors in a strategic partnership. However, some challenges are also identified, especially by the client. Based on the findings, four measures are suggested to improve strategic partnerships between client and client's agent: Mutually helping the other part get new projects, ensuring competence development, ensuring availability of demanded qualifications, and more focus on the long-term and future perspective of the strategic partnership.

KEYWORDS

Lean construction, contract and cost management, strategic partnerships, client's agent.

INTRODUCTION

Integration, collaboration, and continuity are highlighted in the Lean Construction literature. This is expressed already in the fundamental literature of the field: Koskela (2000) claimed that projects where the actors have no previous relation will be less efficient by definition. Further, Ballard (2008) claimed that contracts based on relation will increase the likelihood of project success, in theory also decreasing the need for contingency reserves.

While the importance of integration, collaboration, and continuity is clearly stated in the literature, there is still a discrepancy between theory and practice. Even though the conflicting interests of stakeholders in conventional construction projects have been on the agenda for years, the subject is still relevant (Lahdenperä, 2012) and traditional contracts are often a source of opportunism and distrust between the actors (Kadefors, 2004). The profit of one actor, either measured in value or monetary terms, often comes at the expense of another actor's profit.

To face this challenge, new project delivery methods intending to increase the collaboration and integration between the actors have emerged. Commonly known examples of such project delivery methods are alliancing, integrated project delivery, early contractor involvement, and

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different approaches to partnering (Engebø et al., 2020b; Paulsen et al., 2022). A key characteristic of relation-based project delivery methods is that they are based on trust (Lahdenperä, 2012) and mutual commitment between the actors (Walker & Lloyd-Walker, 2012).

A particular collaborative project delivery method that could be used to achieve integration, collaboration, continuity, and, importantly, long-term relations between actors, is strategic partnerships. Strategic partnerships can be defined as "a long-term collaboration between a client and a delivery team on a collective project portfolio." (Jensen, 2021). This implies that strategic partnerships seek to utilize the benefits from both the collaboration in partnering and the long-term perspective of framework agreements. Koolwijk et al. (2022) used a similar definition, emphasizing that the term "strategic" brings a long-term perspective. Strategic partnerships are practiced either through a contract for multiple projects, a contract for a given period, or an agreement where success in one project will lead to new partnering projects (Koolwijk et al., 2022; Paulsen et al., 2023).

Koolwijk et al. (2022) noted that despite the potential of strategic partnerships in the construction industry, this project delivery method has not been adopted in the same magnitude as in other industries. They call for more case studies of the dynamics within strategic partnerships to obtain more generalizable results. Our searches indicate that most literature concerns strategic partnerships between clients and contractors, and that there is a need for more generalizable knowledge. Ferstad et al. (2023) concluded that more research is needed on strategic partnerships in other relations than between client and contractors. Bygballe et al. (2010) similarly concluded that there is a need for studies "from the view of different actors over time". Paulsen et al. (2023) also pointed to a demand for more research regarding strategic partnerships, especially case studies investigating the effects: "There is still a lack of proof of how well strategic partnership is working in practice. […] Therefore, more case studies and interdisciplinary research are needed to further clarify improvements."

This paper builds on the above-mentioned literature by scrutinizing a particular strategic partnership between a client and a contracted client's agent. These actors were chosen as client's agent should have different interests and business model than a contractor (Berg et al., 2021). Further, no previous research on this specific relation was identified. The term client's agent describes a contracted adviser who takes care of functions which the client's project management does not have the capacity to carry out. In Norway, this role is often denoted as *byggherreombud* (Rådgivende Ingeniørers Forening, 2018). The client's agent is henceforth referred to as agent.

The study was conducted to increase the knowledge about strategic partnerships, and hopefully contribute to a broader understanding, which in turn may contribute to establishment of more generalizable knowledge about the subject. The purpose of the paper is to reveal aspects that can help clients and client's agents organize better strategic partnerships, contributing to the delivery of more efficient and effective projects. The purpose was investigated through the following two research questions:

- RQ1: How does strategic partnership affect the relationship between client and client's agent?
- RQ2: What are the resulting effects of this relationship?

STRATEGIC PARTNERSHIPS IN LITERATURE

Collaborative project delivery models are emerging in the construction industry due to their many advantages (Lahdenperä, 2012). There are however plenty of collaborative project delivery methods used in the industry: Tadayon et al. (2018) mentioned 15 different definitions, while Engebø et al. (2020a) mentioned ten different approaches before basing the article on five umbrella terms. Engebø et al. (2020a) also underlined that collaborative project delivery methods cannot be discretely categorized: The magnitude of, and approach to, collaboration in different project delivery methods rather represents a continuous spectre. Ørke et al. (2023) found that the perception of value, and the motivation of value generation, depends on perspective. Engebø et al. (2020b) highlighted that alignment of these factors is crucial for both trust and good collaboration in a construction project.

Even though partnering is a frequently used term, there is no unified definition of partnering, or what such project delivery methods involve (Nyström, 2005). There seems to be a pool of approaches that may be used, meaning that two partnering projects may be quite different, though both are defined as partnering projects. This challenge was addressed by Nyström (2005), who used Wittgenstein's family-resemblance concept to state that even though there are not necessarily any defining common features between the different partnering approaches, they have overlapping similarities. The lacking unified definitions is a weakness of the literature: Varying terms and variations within the same term complicates comparison and linking knowledge from different sources.

In the lean construction literature, collaborative project delivery models are often referred to as either integrated project delivery (IPD) or Lean Project Delivery System (LPDS). Mesa et al. (2019) made a comprehensive review of IPD and LPDS and found that they utilize many of the same perspectives with regard to project organization. To achieve integration among key project participants, both project delivery methods seek to involve key participants in the early stages and form an integrated project team that works together in an environment of collaboration, open communication, and mutual respect and trust.

A common denominator for many collaborative project delivery models is that they are project-specific and not concerned with a long-term perspective. As stated by Beach et al. (2005); most collaboration efforts never reach the strategic level but are sustained for the specific project and focused on short-term benefits. The strategic perspective implies a long-term commitment between organizations across several projects. In their review, Bygballe et al. (2010) highlighted both the importance of a long-term orientation and the difficulties that this poses in practice. Furthermore, Sundquist et al. (2018) stated that succeeding in relationship development and adopting a strategic perspective, rather than a project perspective, requires a shift from competitive bidding in single projects to collaboration across a series of projects. Further, decentralization of authority to the project level needs to be supplemented with increased centralized decision-making to achieve strategic perspective. It is however a weakness within the literature that interpretations of the term strategic seem to differ slightly.

In scrutiny of the limited occurrence of strategic partnerships, Sundquist et al. (2018) found that existing literature pointed to two causes: One being implementation challenges, and the other being lacking knowledge of how strategic partnerships come into being. Berg et al. (2021), on the other hand, concluded that the archetypical roles in the industry cause friction when they are to collaborate in strategic partnerships, due to conflicting business models.

PHASES

In the construction industry, projects are often divided into phases, where the phases depend on the project and the project model of the client (Volden & Andersen, 2018). Samset and Volden (2014), among others, separate between two phases: front-end phase and implementation phase. The cost of changes is lowest in the front-end, continuously increasing as the project develops. Oppositely, the flexibility for changes is at its highest in the front-end, continuously decreasing throughout the project (Olsson & Magnussen, 2007; Samset, 2010).

For this paper, it will only be relevant to separate projects into the front-end phase and the implementation phase, as these are the two phases the interviewees relate to, from their industry perspective. Separating into more phases would not reflect the interviewees' perception of the construction process.

TRUST

According to Lahdenperä (2012), trust is the basis for every relation-based contract. This is supported by Zaheer and Harris (2005), who claimed that across fields of study, there is a common belief that project delivery methods based on relation are dependent on trust. They also claim that trust, especially on organizational level, improves both performance and behaviour. Importantly, Zaheer and Harris (2005) also noted that trust has a time perspective: The benefit from building or showing trust will be gained at some unknown point of time in the future.

KNOWLEDGE GAP

We have found a relatively limited amount of literature on strategic partnerships in construction industry compared to other industries and compared to other collaborative project delivery methods. When searching for "strategic partnership", the vast majority of literature originated from other industries. The identified literature from the construction industry is asking for further research (Bygballe et al., 2010). Strategic partnerships may be practiced between different actors, and much of current literature focuses on partnering between client and contractor (Bygballe et al., 2010). Through the literature review, there has not been identified literature about strategic partnerships focusing on such partnerships between client and client's agent. By examining such a case, we intend to fill this knowledge gap and contribute to a broader understanding of strategic partnerships.

METHOD

The study has been conducted with a bilateral approach. A literature review was executed to get an overview of the existing literature and to reveal knowledge gaps. Fellows and Liu (2022) highlight literature review as appropriate for getting an overview, while Wee and Bannister (2016) support that a literature review is a suitable method for revealing knowledge gaps. To obtain empirical insights into strategic partnerships between client and client's agent, one in-depth case study was conducted. Fellows and Liu (2022) confirm the suitability of case studies, and Flyvbjerg (2006) claims that even if such studies are highly specific, they are of great value for scientific development. Further, he emphasizes that the importance of cases as exemplars should not be underestimated.

LITERATURE REVIEW

The literature review was conducted with two approaches: database search and backward snowballing. The database search was conducted in Scopus and with no defined time range. Searches included a range of terms considered somehow similar. For example, (TITLE-ABS-KEY)-string with "strategic partnership" has, using "AND", been combined with terms such as "sponsor", "owners' delegate", "client's agent", and similar. These searches returned no literature. However, "strategic partnership" AND "trust" returned nine articles within subject of Construction. The relevance of these nine were evaluated based on the abstract. Two articles were considered relevant and included in the study. The database search was supplemented with snowballing based on the results from the database search and literature the authors knew from before. Jalali and Wohlin (2012) support snowballing as a legitimate method, concluding that snowballing gives the same conclusions and answers as structured literature searches.

CASE STUDY

The case chosen is the company Stafr Consulting AS, henceforth referred to as Stafr. Stafr is an affiliated company in the company group Base Gruppen AS. The examined strategic partnership is between Stafr and two other affiliated companies under Base Gruppen AS: Base

Bolig AS and Base Property AS, henceforth referred to as Base. As Base Bolig and Property are real estate developers, Stafr works as the client's agent in projects where Base is the client.

To study the case, a document study and semi-structured interviews was conducted. Table 1 displays the key characteristics of the two methods.

Table 1: Overview of methods for case study.

	Document study	Semi-structured interviews
Available data	Project archives and invoicing system	8 interviewees
Source	Contracts, minutes, and project descriptions	Project managers, 4 from Base and 4 from Stafr
Purpose	Overall insight	In-depth insight

Semi-structured interviews

Semi-structured interviews were conducted to answer the research questions. An interview guide was developed where questions were categorized into three categories. As the paper builds on the work by Ferstad et al. (2023) and Paulsen et al. (2022), the interview guide used the same categories as them: Contract, organization, and relationship. The categories chosen were perceived to represent three major themes of project delivery methods. The duration of the interviews was between 45 and 90 minutes. Five interviews were conducted in person, while three interviews were conducted using Microsoft Teams due to the localization or availability of the interviewee. The interviewees were chosen based on a judgement of which individuals in the case that could share knowledge. Client's project managers and client's agents were, in number, equally represented. Combined with the different roles of the interviewees, this was done to pursue a balanced perspective. These considerations were supplemented and confirmed by the question in the interviews that asked for relevant interviewees: All of the interviewees either proposed interviewees within this sample or confirmed the suitability of the sample. All interviews were recorded and automatically transcribed. Interviews were then analyzed to extract relevant findings that answered the research questions.

FINDINGS

Here we present the findings concerning the case study. The findings focus on how the relationship between client and client's agent is affected by strategic partnerships and the potential effects of this. The results are sorted using the categories from the interviews: Contract, organization, and relationship.

HOW THE STRATEGIC PARTNERSHIP IS PRACTICED

Contract

The interviewees describe an informal contracting process, where the agent is involved in the project in the front-end phase. Due to the close relationship, Base often mentions possible projects to Stafr before they are even decided, and Stafr assists Base in their due diligence and decision process. When Base decides on the project, the collaboration is formalized through a standard contract. However, a characteristic of this strategic partnership was that the contract was given little importance: Some of the interviewees stated no knowledge about the contracts. It is reported that both companies use the same contracts within the strategic partnership as they use with other actors. The interviewees from the client side also emphasize the importance of Stafr being competitive regarding price and competence.

Another characteristic concerned decision-making and authority. Beyond the definitions in the contract, referring to Norwegian Standard (Standard Norge, 2008, 2011), the roles and responsibilities are mostly defined based on relation on project level, or through continuing the practice, i.e. common understanding, from previous common projects. There is no formal decision mandate or threshold value for what decisions the agent can decide: In some cases, the agent knows his authority by experience from the relation, but in most cases, the client and agent collaborate so closely that the client is involved in every decision, eliminating the need for specifying the agent's mandate.

Organization

Compared to a conventional agent, the interviewees report that Stafr is involved in front-end phase, even before the acquisition or in the consideration of a new project, and that their tasks often are extended. All the interviewees categorically answered that it is beneficial that Stafr is involved as early as possible. In addition, the interviewees express that in the strategic partnership, the agents often exceed their defined role, both in time and assignments, in a manner that benefits the project and relieves the client.

Stafr's performance is not measured using any parameters or indicators: Base is rather evaluating their own satisfaction via gut feeling. The organization and cooperation are annually formally evaluated, however, this evaluation reportedly only involves the companies' managing individuals, while other employees, i.e. project managers, are reportedly not present in these evaluation meetings. Beyond the annual evaluation, there seems to be a consensus that issues are being addressed when they pop up, and this is reported as a satisfying practice. However, some report that the feedback given within the strategic partnership is of the same character as would be given to any supplier or contractor.

Relation

The interviewees seem unable to decide whether the relations are mostly on a personal or organizational level, but some express that they believe it would be beneficial if the relations were more organizational, so that the strategic partnership was less reliant on personal relations.

The responses are also lacking direction when it comes to individual preferences: All interviewees emphasize the importance of competence and experience, but many also emphasize that personal relation is crucial too. It however seems like relation is a benefit, while competence is a must.

Spontaneous and informal meetings or settings are also an aspect of the strategic partnership, forming for instance if the employees meet in the hallway, or have an informal chat before or after a meeting. In such settings, where there is no agenda, other subjects are brought up, both personal and work-related.

POSITIVE EFFECTS

In the interviews, several positive effects of strategic partnerships between client and agent are reported.

Firstly, when the client and client's agent have a relation from previous projects, the interviewees experience that the agent has a better basis for acting according to the client's wishes and interests. As a result, the agent is also sometimes given increased freedom to do so.

The importance of continuity is emphasized. It is described that the early involvement of the agent that is practiced in the strategic partnership is highly beneficial: Not only does the agent's competence and experience benefit the project from the start, but the agent also does a better job when it knows the history of the project. For Stafr, early involvement is also an efficient way to secure new projects, on which their business depends.

The performance of the agents is not systematically measured. This allows the agents to allocate their efforts to where they find it most beneficial for the project, rather than chasing good performance according to a score on specific indicators.

Regarding spontaneous and informal meetings, the interviewees have varied experiences Some signify this as an essential part of the collaboration, while others feel that there is little time for such settings. However, all of those who recognize the existence of spontaneous and informal meetings, seem to agree that these benefit the project. Bringing up subjects when there is no agenda increases the mutual overall insight in the projects, and offers a setting for discussing matters that are precepted not sufficiently important or mature for formal, planned meetings. In addition, the informal chats are reported to be more personal, improving the relationship and extending the mutual knowledge of non-work-related subjects.

Except for annual evaluation meetings among the managements of the companies, little formal evaluation of the collaboration in the strategic partnership is reported. However, informal feedback is continuously being exchanged throughout the projects. In order to pursue optimal collaboration, the interviewees emphasize the importance of being able to both give and receive constructive feedback. Further, some of the interviewees explain that since the collaboration can be improved from project to project, learning from previous collaboration, collaboration is better within the strategic partnership than in single project relations.

Another positive effect for both client and agent, is the strategic partnership's effect on work efficiency. Due to the interorganizational relation, there are direct decision and communication lines. This is not only beneficial for the individual's time use, but also for the time the organization uses to process the decision, so that the decision may be carried out faster. Further, when the same employees work together on several parallel projects due to the strategic partnership, some describe that they have status meetings for multiple projects, saving time compared to having separate status meetings for every project. Working together on parallel projects also increases the overall interaction, benefitting communication about the project: If the client makes a phone call asking a question about one project, the agent may use the opportunity to inform about a matter on another project. As a result, time is saved, and information is transferred faster. Lastly, communication is simplified, and efficiency is increased due to the shared history: Challenges and problems can more easily be explained and handled when referring to similar cases in preceding common projects.

NEGATIVE EFFECTS

The role of the interviewee seems to highly correlate with which negative effects of the strategic partnerships that are highlighted.

For Stafr, there is one significant drawback: Due to their commonly known close relation with Base, other real estate developers that consider Base as a competitor, have expressed scepticism regarding using Stafr. Some have explicitly expressed that they will not use Stafr because of the relation, whilst others have demanded proof of a Chinese wall between Stafr and Base. This scepticism is reportedly due to: 1) fear that a contribution to Stafr's revenues will benefit Base, or 2) that information will flow towards Base, to Base's benefit.

The interviewees from the client side however describe several challenges regarding strategic partnerships. Firstly, the client's project managers feel that they lose the flexibility to freely choose agent. They express dissatisfaction with not being able to freely choose the most qualified agent in the market, as the management in Base Gruppen to some extent demands the use of Stafr. As a result, several of the interviewees describe the strategic partnership as a "forced marriage".

Secondly, a lot of strategic partnerships and framework agreements complicate collaboration projects with other companies, i.e. multiple owner projects, for the client. This challenge is emphasized by one interviewee, who had thorough considerations regarding strategic partnerships. He states: "We can't drag a lot of framework agreements and strategic partnerships along if we are to develop projects together with others. Then, they won't choose us".

Thirdly, when Base ties closely to one company, i.e. the strategic partnership with Stafr, their network and range is restrained. When dealing with more companies, more and more diverse experience and competence is shared with Base than Stafr can supply. This effect is increased by Stafr's relatively small size. In addition, before the strategic partnership, companies delivering services to Base hinted Base about project opportunities, hoping that they would be hired if the project was initiated. The client interviewee reporting this problem did not experience that Stafr fulfilled this: He states that the strategic partnership gives Base "fewer tentacles". On the contrary, an interviewee from Stafr highlights this as an advantage of the strategic partnership: He claims that Base and Stafr mutually hint each other about projects, mutually increasing the market position of both companies. However, these two interviewees, reporting contrary perceptions, have not worked together. This last point indicates individual practices; there is no defined practice for this in the strategic partnership.

DISCUSSION

All interviewees, both from Base and Stafr, reported that though relation and trust between client and agent are important, the decisive factor is the individual's competence. The benefits regarding relation in strategic partnerships are well described. However, considering that competence is the decisive factor, the companies in the strategic partnership should probably not solely aim to benefit from the relation. If adequate competence is not present, well-developed trust and relations will not have significant value. As a result, the development of competence, and availability of demanded competence, should not be overlooked in the strategic partnership. It is also natural to assume that the right competence contributes to successful projects, and that individuals who have delivered successful projects together have a better basis for mutual trust and relation. Trusting an individual as an agent may consequently be a result of the individual's previously demonstrated competence.

There is without doubt different perspectives on both the positive and negative effects of strategic partnerships. However, in our study the clients seem to have more hesitations than the agents. A possible explanation is that the agent's increased safety for assignments directly comes at the expense of the client's flexibility to freely choose agent in the open market. The latter is the most emphasized drawback reported by the interviewees representing the client side.

The combination of a good relationship, and spontaneous and informal meetings, seems to lower the threshold for, and ease, communication, be it "stupid questions" or "bad gut feelings". Considering the increasing cost of changes and decreasing flexibility throughout a project (Olsson & Magnussen, 2007; Samset, 2010), one could assume that this lowered threshold for communication increases value and reduces cost, as opportunities and challenges are brought up at an earlier stage.

The early involvement increases the agent's understanding of the client's project value, both helping to develop this in the front-end phase, and looking after this in the implementation phase. This should enhance customer value and effectiveness. This is in accordance with fundamental principles of LPDS, as Ballard (2008), stated: "The job of the project delivery team is not only to provide what the customer wants, but to first help the customer decide what they want. Consequently, it is necessary to understand customer purpose and constraints." Further, this shifts the role of the client's agent in the project team away from the archetypical engineer role, as defined by Berg et al. (2021).

The divergent perceptions regarding whether the strategic partnership contributes to new projects, is an interesting finding. The interviewees reporting divergent perceptions, represent different groupings within the strategic partnership: One comes from Stafr/Base Bolig and one comes from Stafr/Base Property. The divergent reports may indicate that there are no overall guidelines aiming for the companies in the strategic partnership to mutually take advantage of each other in order to get new projects. Rather, it seems like it depends on the individuals collaborating whether this benefit is exploited. A concluding remark regarding this, is that one would assume that if Stafr positively contributed to new, profitable projects for Base, and vice versa, such a favour would also positively influence the relationship.

It seems that most of the interviewees recognize the positive effects resulting from having worked together in the past, in accordance with Koskela (2000), but have thought less of the possibilities of strategic partnerships regarding the future. This does not only appear from which benefits they emphasize: The client's project managers express that they at any point of time want the most competent agent. Only one mentions that this may come at the expense of the extending of competence for the employees in Stafr, and this interviewee also expresses that the agent's competence in each project is more important than developing competence in Stafr. An interviewed agent in Stafr also remarks that it seems like Base struggles to see the importance and benefits of developing Stafr's competence: Base is most concerned with what competence is available in the present. These reflections could be considered in relation to the utterance of one of the project managers in Base: Base' evaluation of Stafr does not differ from the evaluation of other companies. This is counter-intuitive, as one would expect that the long-term aspect of strategic partnerships would influence evaluation.

The relatively low use of strategic partnerships in the construction industry, may have several causes. Firstly, it might be perceived risky to try new project delivery methods, shifting away from the well-known and archetypical roles described by Berg et al. (2021). Secondly, companies lacking a common ownership, like the one in the studied case, might not get the push to enter such a relationship. This supports the statement of Sundquist et al. (2018), that the initiation of partnerships are not sufficiently illuminated. Lastly, the disadvantages, listed in Table 3, may discourage especially clients from initiating strategic partnerships. However, the four recommendations in bullet points in Conclusions, might mitigate this reluctance.

Implementing these recommendations should require little use of resources and no substantial changes, and hence be very feasible. These recommendations may also, importantly, be implemented without increasing the perception that Base and Stafr is the same organization.

The findings regarding the benefit of the soft factors are congruent with the lean literature. For instance, continuity enhances efficiency and facilitates for continuous improvement., in accordance with Koskela (2000). Thus does this paper not only support the current knowledge, but it confirms its application also for strategic partnerships. However, by also pointing out disadvantages following the increased relationship and continuity, the paper contributes to the nuance of the existing knowledge.

CONCLUSIONS

This paper set out to increase the knowledge about strategic partnerships. The two research questions, and the most important findings are displayed in Table 2 and Table 3, respectively.

Table 2: Main findings for RQ1

RQ1: How does strategic partnership affect the relationship between client and client's agent?	
Simple and insignificant contracts	No formal mandate
Early involvement	No measuring using indicators
Evaluation: Running informal and annual formal	Both personal and organizational level relation
Competence is crucial	Spontaneous and informal meetings

Table 3: Main findings for RQ2. C indicates client, whilst CA indicates client's agent.

RQ2: What are the resulting effects of this relationship?	
Positive effects	**Negative effects**
Better mutual understanding, especially regarding interests and purposes	CA: Lost assignments due to too close a relation
Increased continuity	C: Lost flexibility when choosing client's agent
Increased efficiency regarding time and communication	C: Complicating multiple owner projects
Lowered threshold for communication	C: Restrained network/range
Taking advantage of CA's competence in the front-end phase	
CA's extended mandate and role relieves C	

The overall purpose of answering the research questions was trying to reveal aspects that could be improved, and thereby contribute to better strategic partnerships between client and client's agent in the future. Based on our findings and the following discussion, we suggest the following actionable and practical recommendations:

- **Mutually helping the other part get new projects:** Being on the lookout for new projects for the other part, both within the strategic partnership, and also outside. This would involve that Base suggests using Stafr to for instance tenants and other estate developers, while Stafr hints Base when project opportunities occur, for instance, possible plots or partners for multiple owner projects.
- **Ensuring competence development:** Ensuring mutual sharing of competence and experience, compensating for the decreased network for input.
- **Ensuring availability of demanded qualifications:** Clear dialogue between the companies regarding what competence the client demands, in order to counter the lost possibility to freely choose the most qualified actor in the market.
- **More focus on the long-term and future perspective of the strategic partnership:** More effort to enhance the strategic partnership, focusing on the future. The companies should aim not only to take advantage of the past-part of the long-term relationship. One of the main factors of strategic partnerships is the knowledge that the parts are to work together in the future, hence they should accommodate for taking advantages in the future. This also implies that evaluation within the strategic partnership should differ from evaluation with other actors.

The study is limited to only one case, with eight interviewees, all in the same strategic partnership. As a result, little can be said about the generalizability of the results. Strategic partnerships between actors with different roles, or where there is no common owner, may experience different positive and negative effects. However, the benefits concerning relation, trust, continuity, etc. mirror the findings in the literature, especially within the field of lean construction. In a lean perspective, strategic partnerships might be one approach to enhance or ensure such soft factors.

Strategic partnerships with different actors or ownership structures should be researched further. Quantitative information about the effect would also be highly valuable.

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STRUCTURING APPROACH AND CURRENT STATUS OF INTEGRATED PROJECT DELIVERY (IPD) IN GERMANY

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ABSTRACT

The construction industry has been striving for some time to find efficient ways to ensure the successful delivery of project goals for all project participants and stakeholders, while at the same time improving the quality of collaboration and overall productivity. In addition to the use of collaborative methods and tools, Integrated Project Delivery (IPD), developed in the early 2000s, represents an innovative approach to deliver construction projects. Due to the positive results of initial pilot projects, IPD is increasingly attracting international interest. Since 2018, IPD approaches have also been used in pilot projects in Germany. This article presents the current state of research on the development of IPD in Germany and highlights the status of its practical application. Twenty IPD projects in Germany are identified, documented, and analyzed based on various criteria. For the first time, this paper creates transparency on an international level about the five-year development of IPD in Germany. It also provides a basis for more in-depth analysis, particularly regarding the qualitative aspects of the IPD pilot projects carried out in Germany.

KEYWORDS

Integrated Project Delivery (IPD), Germany, structuring approach, framework, implementation, collaboration.

INTRODUCTION

Integrated Project Delivery (IPD) is a project delivery approach that emphasizes increased integration and collaboration among construction project participants. The goal is to minimize waste and maximize efficiency in all project phases. (The American Institute of Architects, 2007) The term IPD was first introduced in the United States in the early 2000s (Lahdenperä, 2012). Due to the limitations of traditional contractual structures, construction and design firms have developed a new approach to align the interests, objectives, and practices of project participants. This approach facilitated better coordination, cooperation, innovation, and optimization in construction projects. (Matthews & Howell, 2005) Initial studies demonstrate that project objectives were achieved significantly better compared to traditional project delivery approaches (American Institute of Architects [AIA], 2012; Cohen, 2010).

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Since the early 2000s, IPD has developed in various directions, influenced for example by collaborative approaches from Australia and the UK (Lahdenperä, 2012). The evolution of IPD can be described using the characteristic feature of a multi-party agreement in international practice. This includes project delivery approaches such as 'Project Alliancing' and 'Integrated Project Delivery' (IPD) as well as approaches from the UK such as the 'Project Partnering Contract' (PPC2000). (Haghsheno et al., 2022)

In recent years, there has been significant research on the implementation of IPD in various countries. The studies address the challenges and opportunities associated with the global spread of IPD. Several studies have examined the implementation of IPD in different regions. For example, Rached et al. (2014) explored the implementation and challenges of IPD in the Middle East, while Forero et al. (2015) investigated the perception and disposition towards IPD in Colombia. The studies by Li and Ma (2017), Aslesen et al. (2018), Erazo et al. (2020), and Dargham et al. (2019) examine the barriers and challenges to implementing IPD in China, Norway, Peru, and Lebanon, respectively. Additionally, Attouri et al. (2023) investigated the legal feasibility of IPD implementation in France.

Examples of German academic research on Integrated Project Delivery (IPD) in an international context include studies on trust in IPD, as presented by Haghsheno et al. (2021), the development of an simulation demonstrating the functioning of IPD elements, published by Russmann et al. (2022), and analyses of the implementation of co-locations in IPD projects, as presented by Szyperski et al. (2023).

RESEARCH DESIGN

A systematic literature review on IPD in Germany was conducted in the first part of this paper. The review examines the development of IPD in Germany in theory and the current state of research. Relevant theoretical studies in English and German were identified.

The analysis of current IPD projects in Germany was conducted using a multi-layered research methodology. To achieve a comprehensive market analysis, various sources of information and types of interaction were combined. A thorough review and evaluation of available information and data from secondary sources was undertaken through comprehensive open-source research. The evaluation process involved analyzing scientific publications, industry analyses, company announcements, and documents and presentations from conferences, seminars, and market information events. Public tenders were also considered. Additionally, targeted bilateral discussions were conducted with market participants to gather additional data, especially data that is not publicly available. Excerpts from the analysis results have already been published in the annual IPD report at the German IPD conference.

DEVELOPMENT OF IPD IN GERMANY AND CURRENT STATUS OF RESEARCH

The construction industry in Germany is facing numerous challenges. Conventional project management is characterized by a lack of integration between project participants, inadequate risk management, a lack of partnership-based cooperation and insufficient conflict resolution mechanisms. In addition, many projects experience cost increases due to errors in cost calculation or tendering, changes by the client or price increases. (Kochendörfer et al., 2021)

Between 2000 and 2015, over 40% of federal building construction projects exceeded their budget and more than 35% did not meet their deadline targets (Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit [BMUB], 2016). This is also reflected in the sector's productivity. While productivity in the German manufacturing industry rose by 27.1% between 2006 and 2016, the construction industry only recorded growth of 4.1%. (Schober et al., 2016)

To address these issues, optimization and innovation potential should be utilized throughout all stages of building creation. This requires collaboration and integration among various service providers and clients. (Girmscheid, 2016)

In 2016, a federal construction reform identified nine areas for action. One of these areas is the implementation of partnership-based contract models to address the lack of sustainable, long-term, and trusting cooperation between project participants. The reform aims to achieve this through early integration of contractors, increased use of risk and rewards regulations, transparent calculation documents, and partnership-based pilot projects. (BMUB, 2016)

Integrated project delivery has been implemented in initial pilot projects in the German construction industry since 2018. The term was initiated by the 'Initiative Teambuilding', which was founded in 2016 and consisted of about 40 organizations from practice and science, which examined approaches for better collaboration already established abroad for the German market. In 2018, a private client organization launched the first IPD pilot project, followed by a public sector pilot project in 2020. (Haghsheno et al., 2022)

The Initiative Teambuilding led to the founding of the 'IPA Zentrum' (The Competence Center for Integrated Project Delivery or IPD Center). The IPD Center is a central platform to enable stakeholders in the construction industry to successfully implement complex construction projects through the use of IPD models in Germany. It significantly contributes to the demand-oriented and resource-efficient construction and maintenance of built infrastructure. The main goal is to create an inclusive networking platform that facilitates the sharing of knowledge and experience, thus promoting the implementation of IPD models in the construction sector. The IPD Center is comprised of more than 80 carrier organizations from across the construction industry. An advisory board, consisting of representatives from eight universities and over 20 professional and trade associations in Germany and Austria, provides strategic guidance to the leadership and incorporates perspectives from politics, professional associations, and academia. Volunteer experts from the IPD community collaborate in various working groups to develop concepts and publications. (IPA Zentrum, 2023)

IPD – A Structuring Approach from Research

The 'House of Integrated Project Delivery' is a structuring approach that was published in 2022 by Haghsheno et al. As illustrated in Figure 1, the structure consists of four pillars based on a foundation. The approach is based on previous work to structure the model of IPD such as Darrington et al. (2009) or Lichtig (2005). The structuring approach includes framework conditions, requirements, and experiences from German IPD projects. In this structured approach, IPD is based on values and a multi-party agreement. The values define fundamental principles of cooperation, while the multi-party agreement provides the legal framework and sets out common rules for cooperation.

Structuring Elements

IPD is based on a multi-party agreement as a legal framework with common rules and values as the basic principles of cooperation. Building on this foundation, the structuring approach consists of four pillars: culture, organization, economy, and methods. The culture pillar describes approaches for establishing shared values. In order to fully exploit the advantages of the model, a change in the project culture and the behavior of the team members is required. Developing a shared understanding of values and creating a sense of belonging are lengthy and complex processes. Various tools can be used as part of project management, such as the development of a project charter, team building, onboarding activities, and structured team reflections.

The organizational pillar refers to integrated structures for communication and decision-making. Efficient decision-making and flat hierarchies require an integrated and interdisciplinary organizational structure to react quickly to changing conditions. In terms of economics, value-based financial incentives are set, and risks are allocated. IPD is most effective when the economic incentives of the partners align with the project goals. Positive economic incentives replace penalties such as liability or contractual penalties. The methods pillar outlines processes for promoting transparency, collaboration, and efficiency. Therefore, Lean Management is a crucial component of IPD, especially the ideals and principles of Lean Management which help in implementing IPD and establishing the right project culture. Methods such as the Last Planner System, Target Value Design, Building Information Modeling, or Choosing by Advantages are utilized. All four pillars are important for the stability of the project and therefore are critical to its success.

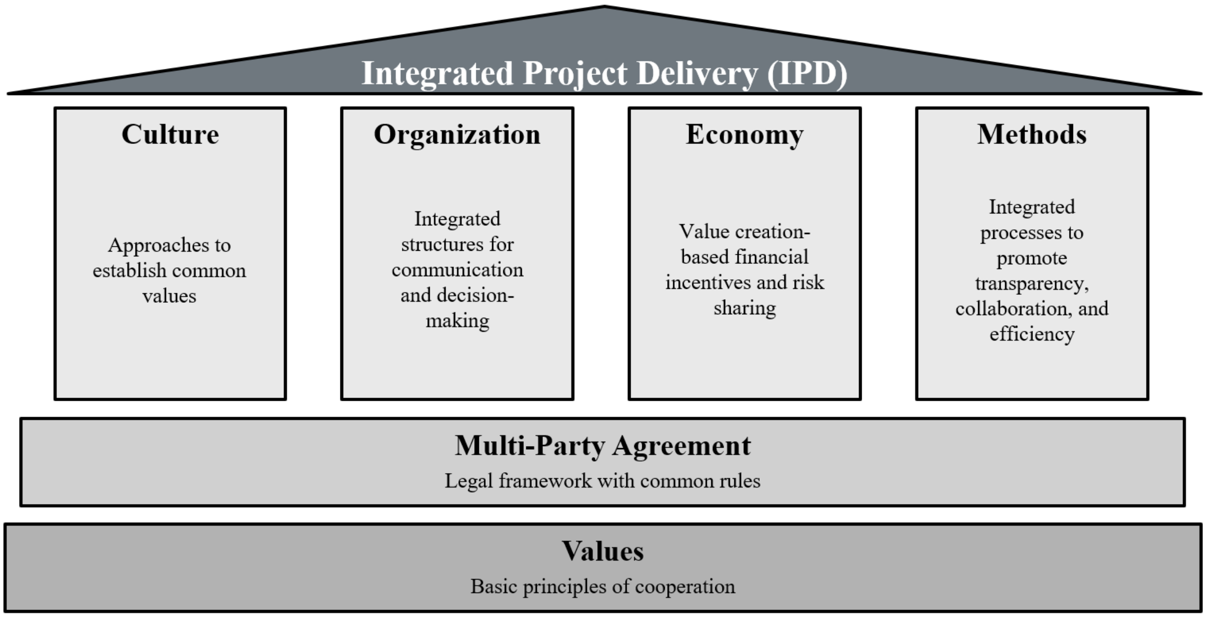

Figure 1: House of Integrated Project Delivery (Haghsheno et al., 2022)

Elements are assigned to the categories of the House of Integrated Project Delivery as sub-items. These elements enable the precise characterization of specific models of integrated project delivery and the classification of projects, considering the implemented elements.

IPD – A Structuring Approach from Practice

Also in 2022, the IPD Center initiated a conceptual framework for the German Integrated Project Delivery model. The characteristics and model components were developed based on initial experience gained from the implementation of IPD in Germany by experts from science and practice. The framework was developed due to the observation that many projects were adopting the new project delivery approach and referring to themselves as 'IPD projects', despite significant differences between the projects. The framework was considered a necessary step to ensure a common understanding in the industry, to enable the identification of IPD projects, and to provide transparency on the underlying concepts.

IPD Characteristics and Model Components

Figure 2 displays the model, which comprises eight characteristics and 21 assigned components. To be classified as an IPD project, a project must cumulatively meet these relevant success factors. Therefore, all 21 model components must be utilized in the project.

One of the key characteristics of a successful collaboration is the establishment of a multi-party agreement in which at least three parties are involved in the rules of cooperation. The early involvement of key stakeholders through a competition of competencies is of significant importance. Besides competencies, skills related to effective teamwork, such as behaviors and attitudes, are also relevant. In addition to joint risk management, which involves identifying, evaluating, and managing project risks and opportunities at an early stage, there is also joint decision making based on shared responsibility for project goals.

The compensation model's incentive system aims to align participants' behavior with project goals. Collaborative working methods aim to enhance effective cooperation, transparency, and collaboration within the project team. This is achieved through the use of BIM and Lean Construction methods.

The framework treats conflicts as a potential for value creation and aims to resolve them as quickly and constructively as possible through solution-oriented conflict resolution. In a final step, understanding and aligning behavior with shared values, the cooperative attitude of the participants, is a mandatory prerequisite for the success of an IPD project. (IPA Zentrum, 2022)

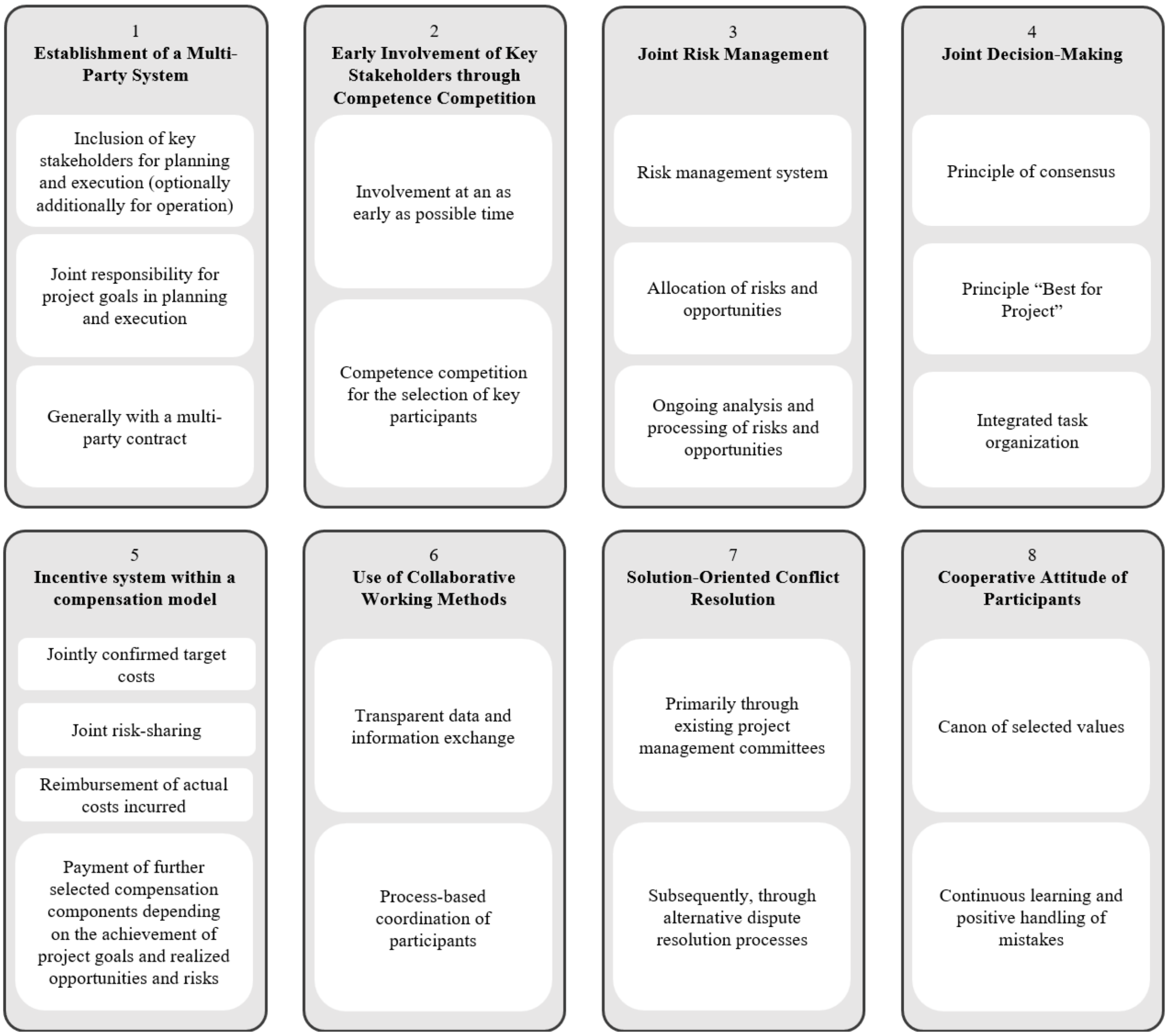

Figure 2: IPD characteristics and model components (IPA Zentrum, 2022)

The structuring approach of Haghsheno et al. (2022) and the framework of the IPD Center are not contradictory, but rather complimentary. Therefore, the essential contents of both approaches are comparable.

CURRENT STATUS OF IPD IN GERMANY: PROJECTS IN PRACTICE

The following section constitutes a comprehensive report, synthesizing pertinent details concerning projects executed through Integrated Project Delivery in Germany. The criteria for an IPD project to be listed are that the IPD characteristics as defined by the IPD Center are present or (foreseeable) and that at least the partner selection phase has begun. The data collected dates back to 2018, when the first IPD project started in Germany. Figure 3 provides an overview of the IPD projects in Germany. In addition to the project name, they are categorized according to project costs. The timeline displays the individual phases of the IPD projects at the respective points in time. As of 2023, there are a total of 20 IPD projects that have either been completed or are currently ongoing, at least in the partner selection phase. Out of the 20 projects, one has been completed, seven are currently under construction, and six are in the 'Integrated Planning' phase. One project is currently on hold, while five others are still in the 'Partner Selection' phase.

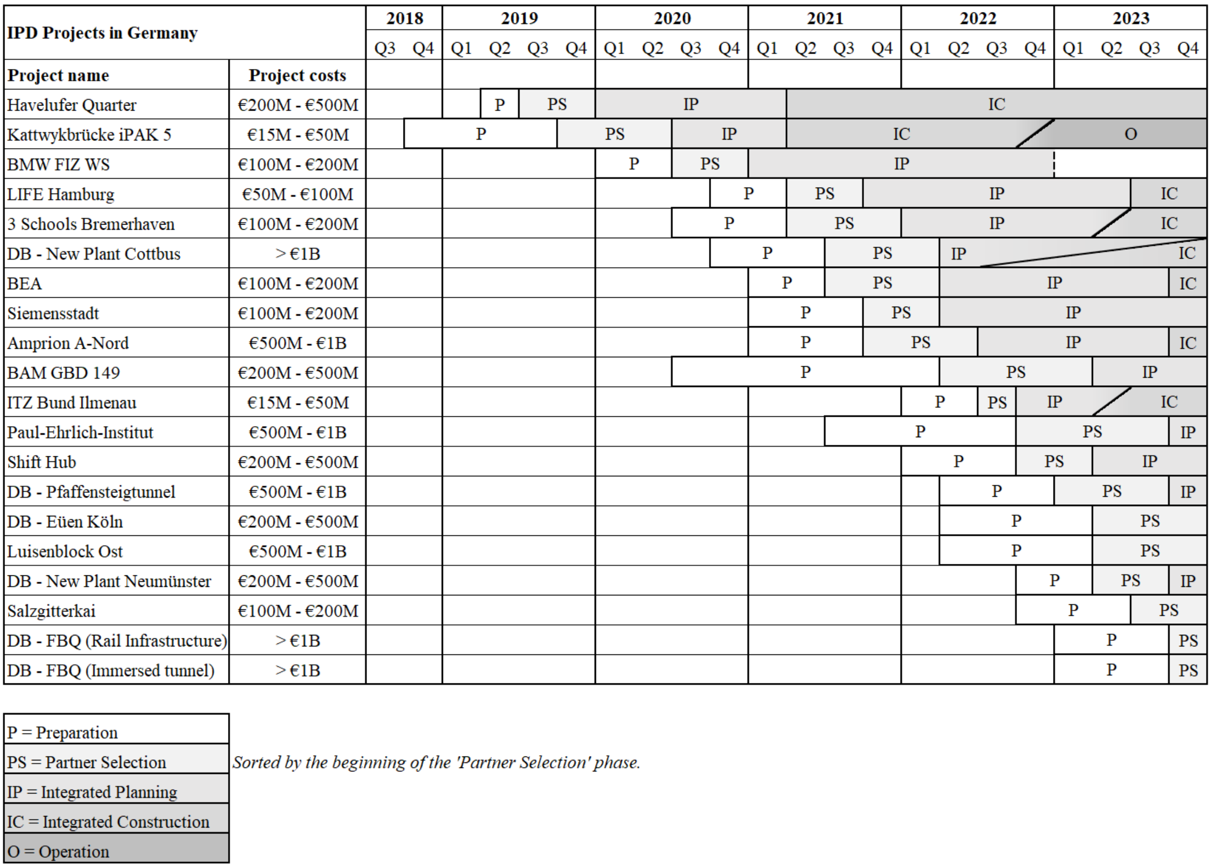

Figure 3: IPD Projects in Germany

In comparison to 2022, there have been two discontinued IPD projects due to a re-evaluation of investment activity in response to changed circumstances, which led to the projects being discontinued for economic reasons. During the period from mid-2022 to mid-2023, eight new IPD projects have been identified and are currently ongoing.

In addition to the IPD projects listed, for which at least the partner selection phase has started, seven other IPD projects are currently in preparation. These are projects for which it is known that a decision has been made in favor of IPD as the project delivery model. IPD is also being intensively discussed as a project delivery model for other projects. However, a final decision has not yet been made on these projects.

Project Costs and Client Structure

In Germany, the smallest IPD projects fall within the project size category of €15 - €50 million, as shown in Figure 4. Analysis of IPD project distribution reveals a preference for implementing the project delivery approach in larger projects. The reasons for this preference are varied. IPD is particularly well-suited for complex projects. Complexity can arise from various factors such as many participants, technical challenges, or large project sizes.

According to the definition provided by the IPD Center, an IPD project must fulfill eight characteristics and 21 associated model components to be classified as such. This may result in increased costs, especially during the initial phase of construction projects. For example, there may be extra expenses for the assessment center to choose partners or for team building activities. Ideally, the initial costs are offset by improved collaboration during the planning and construction phases of the project. For larger projects, the higher initial costs account for a comparatively smaller proportion.

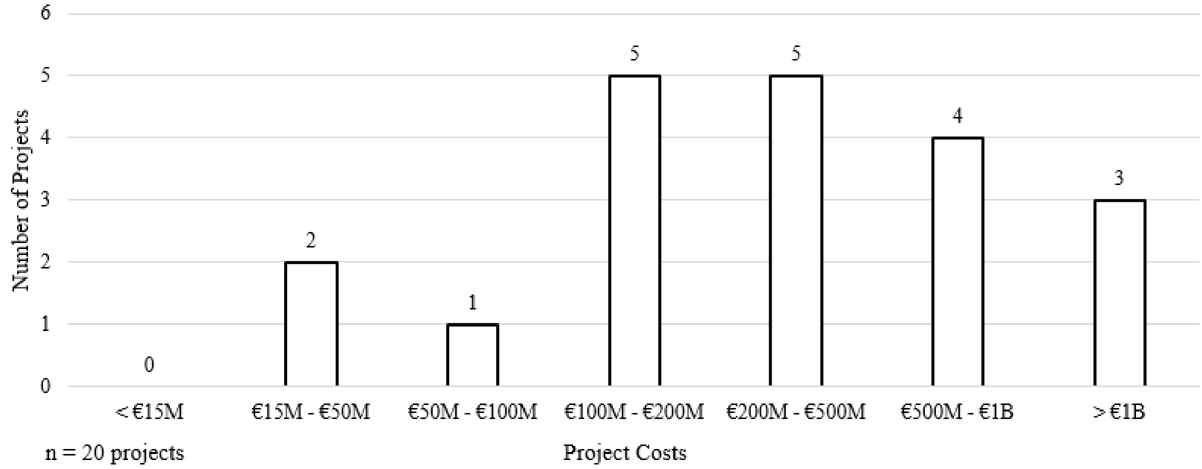

Figure 4: Project costs of IPD Projects in Germany

The distribution of IPD projects clearly shows that IPD is used primarily in larger projects. Out of 20 projects, 17 have a project volume exceeding €100 million. Due to the increase in IPD projects in the area of transport infrastructure, there is a trend towards larger projects. All three projects with a volume of over €1B are assigned to transport infrastructure.

In total, 14 of the IPD projects are being carried out by public clients, while six are being carried out by private clients. A comparison between 2023 and 2022 shows an increase in the proportion of IPD projects in the public sector. The Deutsche Bahn (German Railway) is making a significant contribution to this by driving forward an increasing number of pilot projects.

Type of Use

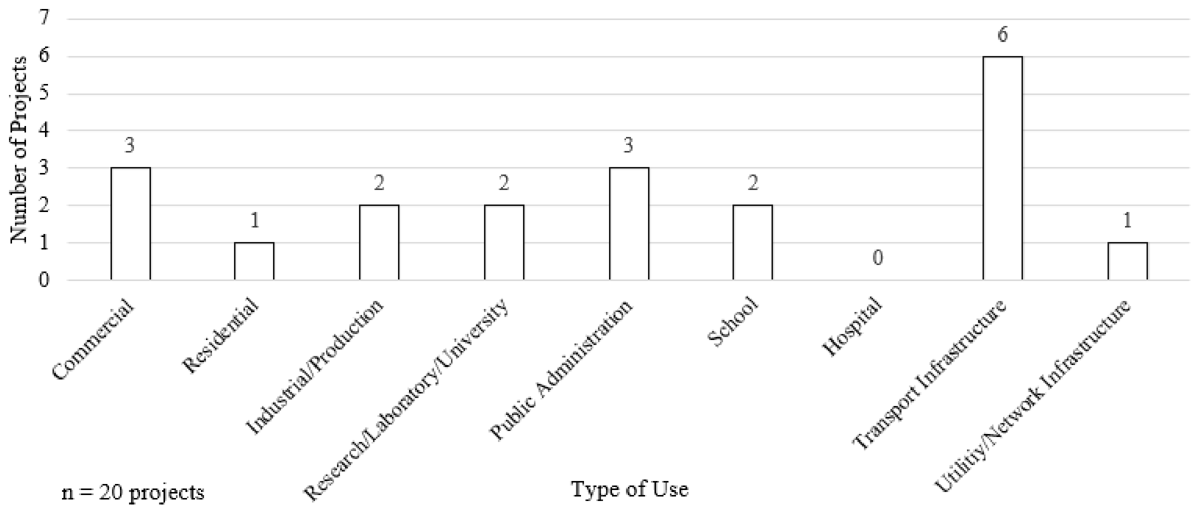

Figure 5: Types of use of IPD-Projects in Germany

Figure 5 displays the distribution of IPD projects by type of use, indicating that the projects can be assigned to a wide range of uses. Three of the analyzed projects can be assigned to the commercial construction sector, one to the residential construction sector, two to the industrial/production sector, and two to the research/laboratory/university sector. Additionally, three projects are intended for public administration use, two for educational purposes, and one for the utilities/network infrastructure sector. As stated in the previous section, six IPD projects were dedicated to transport infrastructure, which accounts for the largest share. The evaluation indicates that IPD is utilized in completing projects in both building construction and civil engineering.

A comparison of new and existing construction projects reveals that the majority of IPD projects concentrate on new construction activities. In cases where projects involve both new and existing construction components, the classification is based on the primary focus of the construction task. While 17 projects are classified as new construction projects, only three projects primarily relate to measures in existing buildings. Existing building measures are typically associated with increased uncertainty and specific requirements. It is to be seen whether the use of IPD for existing building measures will be increasingly preferred by building owners in the future. The benefits of IPD could arise in particular from the flexible management of risks.

Number of Contractual Partners

A further differentiation between the IPD projects is whether the team is put together through separate tender or selection procedures with individual applications or through team applications. 18 IPD projects use the concept of individual applications, while team applications have only been used in two IPD projects.

Figure 6 displays the distribution of IPD projects based on the number of contracting parties in multi-party agreements. The diagram depicts a single project with small dots, and two projects on the same axis with large dots. The IPD Center defines a multi-party agreement as having a minimum of three contractual partners: the client, the key planner, and the key contractor. Criteria for determining the necessary number of key partners generally include the scope of services, their influence on the project's success, their contribution to value creation, and the significance of their expertise for product development and process flows. (IPA Zentrum, 2022)

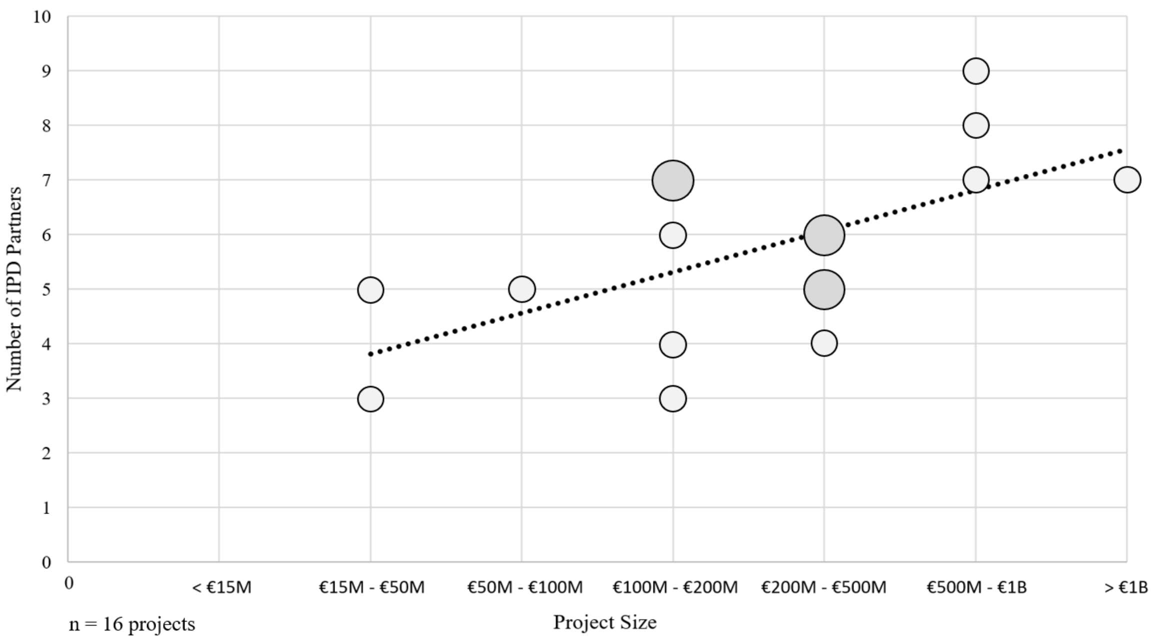

Figure 6: Number of IPD partners in comparison to the project size

The number of contractual partners is also determined by the construction task and the market structure of potential providers. The appropriate team size is being considered in relation to integrated organizational structures and decision-making in committees, without overburdening those involved. This is especially important as the parties involved are undergoing an intensive change process that is accompanied by the implementation of IPD.

The sample relates to 16 projects due to incomplete information on all projects. The distribution indicates that four projects have five contractual partners, while another four projects have seven contractual partners. Two projects have the minimum number of three contractual partners. With nine contract partners, one project has the maximum number of all projects in the sample. Beyond this survey, a trend towards the implementation of projects with even more contractual partners in the German IPD market can be observed in projects currently in the preparation phase. The linear trend line confirms the theoretical explanations that there is a tendency towards more contractual partners with higher project volumes. However, there is no clear correlation between the number of contractual partners and the type of use or other characteristics.

Experience in Completed and Advanced IPD Projects

Experience with IPD projects in Germany has been positive to date. The following section presents experiences from individual projects. For example, the 'Kattwykbrücke iPAK5' project, a lift bridge located in the port of Hamburg, was built to the desired quality and within the planned costs, but the construction time was significantly reduced compared to conventional project delivery. This was accomplished by prioritizing problem-solving over assigning blame when issues arose. The project claimed that Integrated Project Delivery represented a new paradigm of collaboration for them. (Hacker & Schulz, 2022)

The '3 Schools Bremerhaven' project, the parallel construction of 3 schools in Bremerhaven, is drawing positive effects as an interim conclusion, particularly from the earliest possible start of the alliance based on the results of the preparation phase and the client's conditions of satisfaction. In addition, IPD, particularly in combination with BIM and Lean, offers optimal framework conditions for achieving genuine collaboration and a focus on objectives in the project. (Hamel & Rodde, 2022)

The 'Siemensstadt' project in Berlin involves the construction of a high-rise and an atrium building. According to one of the construction companies involved, the risk/reward profile is balanced, and the worst-case scenario can be effectively managed through risk management. The fact that influence can be exerted early in the planning phase and that all partners work together as equals is also highlighted as a positive aspect. Challenges mentioned include complete transparency, i.e. the profit rates and overhead rates known to all, which may be new to the corporate cultures, and the lack of co-determination rights in the selection of other construction partners in the project. During the preparation and validation phase, success factors and advantages were identified, including a realistic client budget, early definition of key systems, and high levels of management support within the client organization. Additionally, the establishment of a project culture based on partnership was successful, and there was a high willingness to try out new processes and roles. The increased time and cost required for validation due to IPD was offset by significant savings in the planning phase and binding cost statements from the construction companies. (Clesius & Warlich, 2023)

Experience from various validation phases of IPD projects shows that a high level of personnel deployment and regular presence in the colocation is necessary. The new project delivery model requires experienced and well-trained personnel. Each contractual partner must have an authorized decision-maker. Project management should be a joint effort of the team and not underestimated. (Schedensack & Büchner, 2023)

CONCLUSION AND FUTURE WORK

Integrated Project Delivery has been utilized in Germany since 2018. An analysis of the theoretical work on this topic in Germany shows that there are two structuring approaches. One approach is the concept of the 'House of Integrated Project Delivery', while the other examines the characteristics and associated model components.

In practice, the authors' research shows that a total of 20 projects based on the definition of the IPD Center had been carried out in Germany by 2023. Most of these projects have a volume of over 100 million euros. The percentage of IPD projects executed by public client organizations is presently on the rise. The evaluation indicates that IPD projects are present in nearly all forms of use and construction. This highlights the potential of the IPD project delivery model for various segments of the construction industry. It is worth noting that the IPD partner selection process also allows for team applications in addition to the established individual application approach. The number of contractual partners in the multi-party contracts range from three to nine.

The analysis demonstrates that the momentum started in 2021 is continuing in terms of the number of IPD projects launched. Therefore, an increasing number of market participants can experience IPD through practical implementation, and initial findings can be evaluated for desired results. In addition to the analyzed projects, several other IPD projects are currently in the decision-making phase. The extent to which the positive development of IPD will continue remains to be seen and will require further monitoring.

In this article, a descriptive analysis was conducted on the gathered data. Research on the documentation of IPD projects in Germany has predominantly taken a descriptive approach, focusing on quantitative core information and framework conditions. However, to not only document but also comprehensively evaluate IPD projects in the future, a qualitative study is necessary. Design features that could be analyzed include compensation mechanisms, risk-sharing contributions, risk and rewards systems, tender criteria and their weighting, the timing of IPD team formation, target cost agreements (planning status), collaborative methods, decision-making rules, and alternative dispute resolution arrangements. This aims to provide additional insights and a more comprehensive understanding through supplementary parameters and qualitative data collection.

As part of a research project funded by the German Federal Ministry for Housing, Urban Development and Building, the authors aim to complement the existing descriptive approach with a qualitative and structured evaluation of information. The objective is to identify correlations between design elements and the processes and outcomes of an IPD project. The study aims to determine the extent to which different design elements influence the processes and outcomes, and what impact they have on the overall process and the achievement of the overall project goals, in order to derive specific recommendations for practice.

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LEAN CONTRACT, COLLABORATIVE POWER: ACCELERATING DELIVERY IN UNDERGROUND METRO PROJECT

Prabhu P[1], Nalin M[2], Ashwetha U[3], Aravind V[4] and Jayarama H[5]

ABSTRACT

This paper examines the practical implementation of lean principles in the contract management and operations of the TU 02 underground metro project in Chennai City, India. The project, a crucial component of Chennai Metro Rail Limited's Phase 2 development spanning 116 km, stands out for its intricate collaboration with multiple contractors. Despite its scale and complexity, CMRL TU 02 project team has embraced lean management principles since its inception. The project encountered about 24-months of delay due to the unavailability of shafts for lowering and retrieving TBMs. This paper provides a detailed analysis of the lean principles applied in Contracts Management to reduce this delay from 24 months to 18 months. The collaborative approach to lean management with clients and General consultants not only mitigated the schedule delay but also minimized TBM idle time, a critical aspect with high risks. Additionally, process optimization techniques, such as Value Stream Mapping (VSM) in the precast yard and TBM lowering cycle time reduction at the project site, are explored, showcasing the effectiveness of lean concepts in complex construction projects.

KEYWORDS

Lean construction, Lean Contract Management, Enhancing project efficiency, Value Stream Mapping (VSM), Big Room Planning and Collaborative Planning.

INTRODUCTION

Chennai, the bustling capital city of Tamil Nadu state in India, is undergoing a transformative phase in Infrastructure upgradation with the ongoing expansion of its metro rail network through CMRL's Phase 2 corridors. The TU 02 project, a significant segment of this expansion, involves the construction of 12 kilometers of twin bored tunnels and key underground station structures critical for enhancing urban connectivity and reducing traffic congestion. It encompasses the construction of diaphragm walls and entry/exit structures for 4 key stations

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namely Chetpet, Royapettah Government Hospital, Thiruvanmiyur, and Greenways Road. The scope of project is summarised in table 1.

Table 1: Scope of the project

Sl. No.	Description	UOM	Total Scope
1	Diaphragm wall	RM	2,757
2	Shaft Excavation	cum	70,352
3	Ring Casting & Erection	Nos	18,366
4	TBM Tunnelling	RM	25,000

The deployment of 8 state-of-the-art Tunnel Boring Machines (TBMs) underscores the project's technological advancement and its role in shaping the city's infrastructure landscape. However, like many mega construction projects, TU 02 faced challenges, including a notable 24-months delay in interface contracts, which necessitated innovative approaches rooted in lean principles for effective contract management and project operation.

COMPLEXITY IN PROJECT

A notable aspect of the CMRL TU 02 project is the execution of 4 launches for each of the 8 TBMs, totalling to 32 drives. The total of 32 launches and 32 retrievals needs to be taken up from total of 16 stations along the alignment. Out of the 32 shafts, 8 shafts are in the scope of Tunnelling Contractor. The balance 24 shafts are in the scope of Interface Station Contractor. The scope of Tunnelling and Station works are depicted in Figure 1.

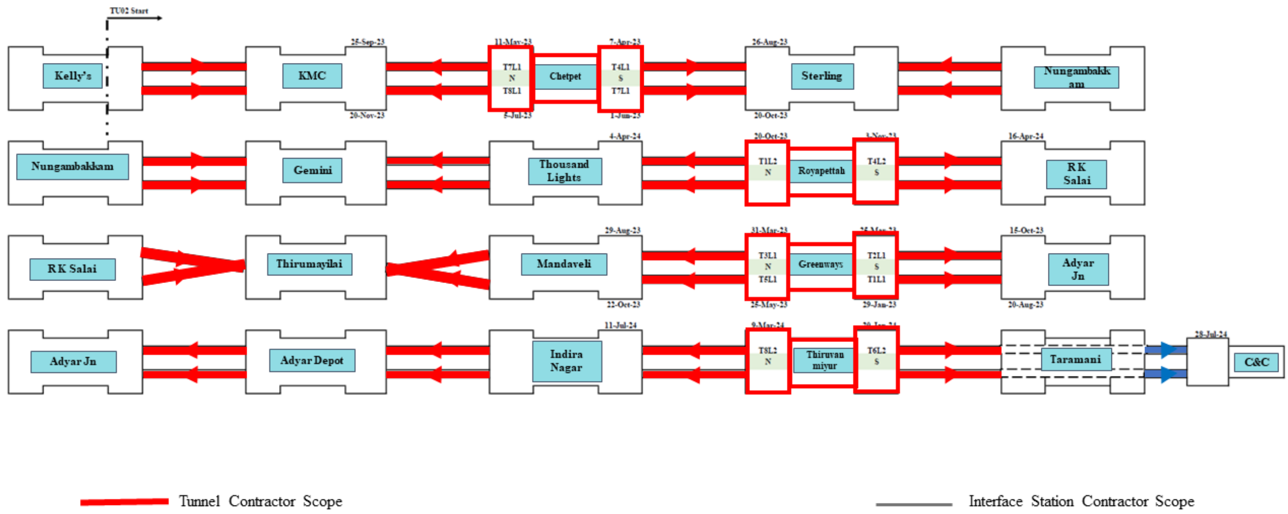

Figure 1: CMRL Phase 2 Corridor 3 – Kellys to Taramani Alignment

However, the complexity of the project was exacerbated by a 24-months impact on project schedule in the interface contract, stemming from various delays with the client. This delay posed a formidable challenge, leading to the postponement of TBM launches and a subsequent ripple effect on both cost and timelines.

To overcome these challenges and optimize project progress, lean initiatives were adopted, necessitating the resequencing of TBM launches and innovative approaches to contract management. This paper delves into the dynamic application of lean contract management principles in the context of CMRL TU 02, exploring strategies employed to minimize TBM idleness, renegotiate contracts, and propel the project forward. Our journey involves reshaping traditional approaches, resequencing TBMs, and converting setbacks into opportunities for efficiency enhancement and collaboration. The overarching goal is to not only highlight the practical solutions implemented but also to contribute valuable insights to the broader field of metro construction project management. Also, this paper explores the implementation of Value Stream Mapping in Precast Yard of the same project to reduce the cycle time of precasting of tunnel rings. As we embark on this exploration, the title encapsulates the essence of our endeavours. The paper describes the intricacies, challenges, and triumphs of CMRL TU 02, as we showcase how a lean approach can truly optimize progress in the dynamic landscape of underground metro construction.

NEED FOR LEAN IN CONTRACT MANAGEMENT

The complexities of modern construction projects, including tight schedules, fluctuating budgets, and multiple stakeholders, underscore the need for lean principles in contract management. Traditional approaches often fall short in meeting the dynamic demands of such projects, leading to inefficiencies, delays, and disputes. Contract documents for construction projects are traditionally prepared to manage conflicts rather than collaboration (Skinnarland and Yndesdal 2010). Lean principles offer a holistic approach to addressing these challenges by emphasizing continuous improvement, collaboration, and adaptability. By integrating lean principles into contract management processes, construction projects can achieve greater efficiency, transparency, and stakeholder satisfaction. Contracts can be structured to exploit the tremendous opportunities for performance improvement (Miles and Ballard 1997).

LEAN AWARENESS LEVEL IN PROJECT

CMRL TU02 is already a lean-managed project where a lean culture was inculcated into the root level of the team. Initiating a culture of lean practices within a construction site required a fundamental shift in mindset and a deep-rooted understanding of lean principles among the project team. At the heart of the project's lean journey was the recognition of the importance of motivating the project team to embrace lean practices. This motivation was cultivated by providing tangible evidence of the benefits of lean through data-driven insights from lean tools such as Work Sampling, Foreman Delay Survey (FDS), and Value Stream Mapping (VSM). Under the guidance of the project director, a dedicated lean implementation team was formed to spearhead the initiative, laying the groundwork for lean practices to permeate throughout the project, including contract management processes. The effectiveness of the lean tools was evident through the improved customer focus and eliminating waste (Refer to Mastroianni and Abdelhamid 2003).

IMPLEMENTATION

A structured approach was adopted to implement lean practices, starting with a focused drive to kickstart the journey. Below (Figure-2) is the Lean Organogram of the project framed to cultivate lean culture in project. Simulations help Lean learners evaluate from a flow- and efficiency- perspective how project team members are managing production system design and control (Tsao and Howell 2022) Lean culture was developed by organizing meetings and training sessions directly at the project site, providing an immersive learning experience for team members. Real-world case studies and interactive lean games (e.g., Airplane game) were utilized to impart hands-on knowledge of lean principles, ensuring that team members were equipped with the skills needed to embrace lean practices in their respective roles, including contract management. Training sessions were conducted extensively across various departments, equipping team members with the skills and knowledge needed to integrate lean principles into all aspects of project management, with a specific focus on contract management.

Approximately 80 team members underwent training, ensuring that lean principles were fully integrated into daily operations, including contract negotiation, execution, and evaluation.

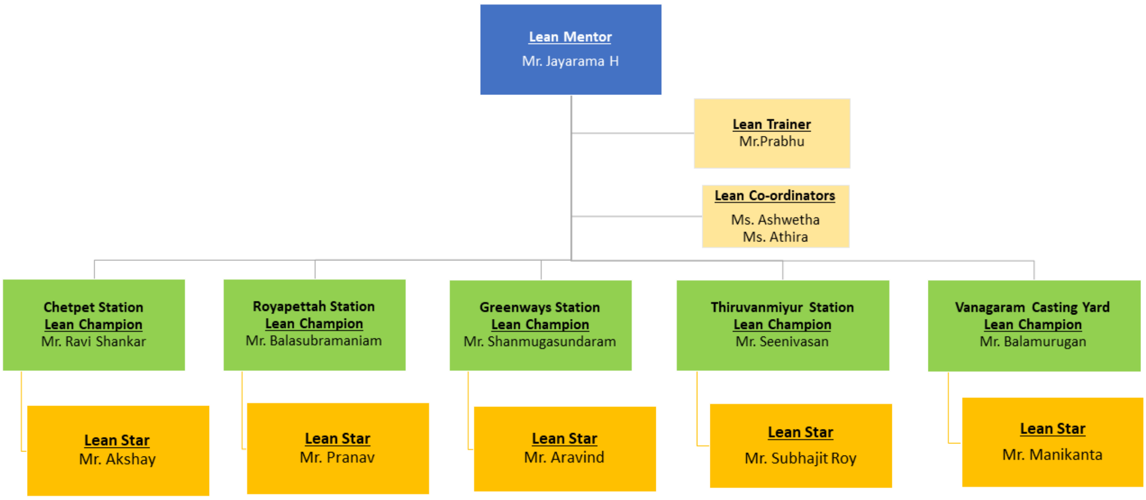

Figure 2: Project Lean Organogram

Consistent weekly review meetings played a crucial role in maintaining momentum and assessing progress. These meetings provided a platform for team members to review Planned Percentage Completion (PPC) achievements, identify constraints, and conduct root cause analysis, fostering a culture of continuous improvement and accountability in contract management processes.

PROBLEM STATEMENT

The project faced significant challenges during its implementation. One of the foremost obstacles was the 24-month delay in the interface contract, which had cascading effects on project timelines and costs. This delay led to the postponement of Tunnel Boring Machine (TBM) launches and subsequent disruptions in construction activities. The level of technical and commercial risk anticipated because of the delay was very high. Additionally, the complexity of the project, compounded by its underground nature and urban setting, posed unique challenges in resource management, stakeholder coordination, fulfilling the contractual requirement, collaborative work with the CMRL contractors, and risk mitigation.

STRATEGIES OF LEAN CONTRACT MANAGEMENT ADOPTED

Lean Contract Management was chosen as a tool to mitigate the challenges faced in the project in terms of delay in time and cost impact from same. Below are the step-by-step lean strategies adopted in the project.

1. Proactive delay notification
2. Establishing the Pull
3. Big Room Planning
   - Phase 1: Initial Level
   - Phase 2: Core Level
   - Phase 3: Senior Management Level
4. Incorporation of Results in Contract

PROACTIVE DELAY NOTIFICATION

Effective communication with the client is paramount in managing mega projects successfully. Letters, emails, and monthly reports uploaded in Project Management Interface System forms part of official communication of project as per contract. As a first step, the Tunnel Contractor prepared the project schedule incorporating the delays as on date and submitted the same to client. The baseline schedule of 54 months got extended by 24 months. The other interface contracts were not awarded to contractors from Client, and it created a huge impact in timeline of tunnelling contract. The technical risk arising out of idling of TBMs under the ground of 15-18m for months is also notified. By systematically documenting and communicating these potential delays, we ensured transparency and facilitated collaborative problem-solving with all stakeholders.

ESTABLISHING THE PULL

The tunnelling contractor established the Lean Concept of Pull in the System (PMI 2017) with Client by exercising on the Key Milestone Dates of Shaft Handover in Contract. The communication was submitted for seeking of Shaft Handover dates (especially retrieval shafts) from client. This established the pull and underscored the gravity of situation to act immediately.

BIG ROOM PLANNING

Lean principles of collaboration and risk assessment were integral in reducing delay. Upon aligning the Contractor, General Consultant and Client on the criticality of the delay, the Contractor implemented the Lean Practice of Big Room Planning. Big Room Planning is a tool that increases the joint work and ownership of all stakeholders and develops mutual trust and respect (Başağa et al. 2019). A Big Room Planning workshop was initiated with all stakeholders to collaboratively discuss and plan to find all measures to reduce the impact of delay. Big Room Planning was taken up at different phases to mitigate delay to the maximum extent. The different phases are explained in detail as below:

Phase 1: Initial level

As a first step, technical representatives from all stakeholders, namely Tunnelling contractor, General Consultant and Client were part of the Initial Big Room Planning. The Handover dates of shafts as per Contract were analyzed and the plan for revised Handover dates were devised. The plan for revised Handover dates were to be derived by resequencing the entire TBM drives, considering different geologies and machine types as the very fundamental factors.

Phase 2: Core level

The stakeholders engaged in rigorous Big Room Planning exercise for second time to finalize the TBM drives and the Hand over dates. Through rigorous permutation and combination calculations, different schedules were arrived and the optimum sequence with less number of idling time is chosen. In addition to resequencing, methodological changes were also proposed to reduce the time of construction. Table 1 describes the comparison of first and second drives of all 8 TBMs.

Phase 3: Senior Management Level

The senior management of all stakeholders sat down for final discussion in concluding the entire resequencing plan, thereby finalizing the schedule. This open collaborative discussion of Big Room Planning reduced the anticipated 24-months delay to 18 months, agreed upon by all stakeholders. This resequencing resulted in a 30% reduction in TBM idle time.

Addressing critical delays

Despite resequencing activities, inevitable delays were foreseen for 4 TBMs starting from 2 stations. To mitigate this, the contractor renegotiated to commence the execution of retrieval shafts in 2 locations, implementing effective risk mitigation measures in contract management. This measure not only reduced TBM idle time but also prevented losses to the contractor. By proactively addressing critical delays, we demonstrated our commitment to efficient project management and stakeholder satisfaction.

Table 2: TBM Mining as per contract vs revised.

TBM No	As per Contract		Revised Sequence	
	1st Drive	2nd Drive	1st Drive	2nd Drive
TBM 1	Chetpet metro to Sterling Road junction	Chetpet metro to KMC	Chetpet metro to Sterling Road junction	Royapettah Govt Hospital – Crossover – to Thousand lights
TBM 2	Chetpet metro to Sterling Road junction	Chetpet metro to KMC	Chetpet metro to Sterling Road junction	Nungambakkam to Gemini
TBM 3	Royapettah Govt Hospital – Crossover – to Thousand lights	Royapettah Govt Hospital – Crossover – to Thousand lights	Greenways road metro to Mandaiveli	Royapettah Govt Hospital to RK salai Jn
TBM 4	Royapettah Govt Hospital to RK salai Jn	Royapettah Govt Hospital to RK salai Jn	Greenways road metro to Mandaiveli	Nungambakkam to Sterling
TBM 5	Greenways road metro to Adyar Jn	Greenways road metro to Mandaiveli	Greenways road metro to Adyar Jn	Mandaiveli to Thirumayilai
TBM 6	Greenways road metro to Adyar Jn	Greenways road metro to Mandaiveli	Greenways road metro to Adyar Jn	Kellys to KMC
TBM 7	Thiruvanmiyur metro to Taramani Cut&Cover tunnel	Thiruvanmiyur metro to Taramani Cut&Cover tunnel	Chetpet metro to KMC	Thiruvanmiyur metro to Taramani Cut&Cover tunnel
TBM 8	Thiruvanmiyur metro to Indira nagar	Thiruvanmiyur metro to Indira nagar	Chetpet metro to KMC	Thiruvanmiyur metro to Indira nagar

INCORPORATION OF RESULTS IN CONTRACT

There were two major changes contractually because of Lean Strategy Implementation.

1. *Changes in the Interface Contract*: The mutually agreed sequence of construction with Tunnelling Contractor has been finally effected in the Interface Contract of other contractors and Client. Collaboration with senior management led to the modification of interface handover dates of underground station contractors to align with the resequenced dates, thereby revising the project's baseline schedule. The final revised TBM sequence is represented in figure 3 and in table 2.

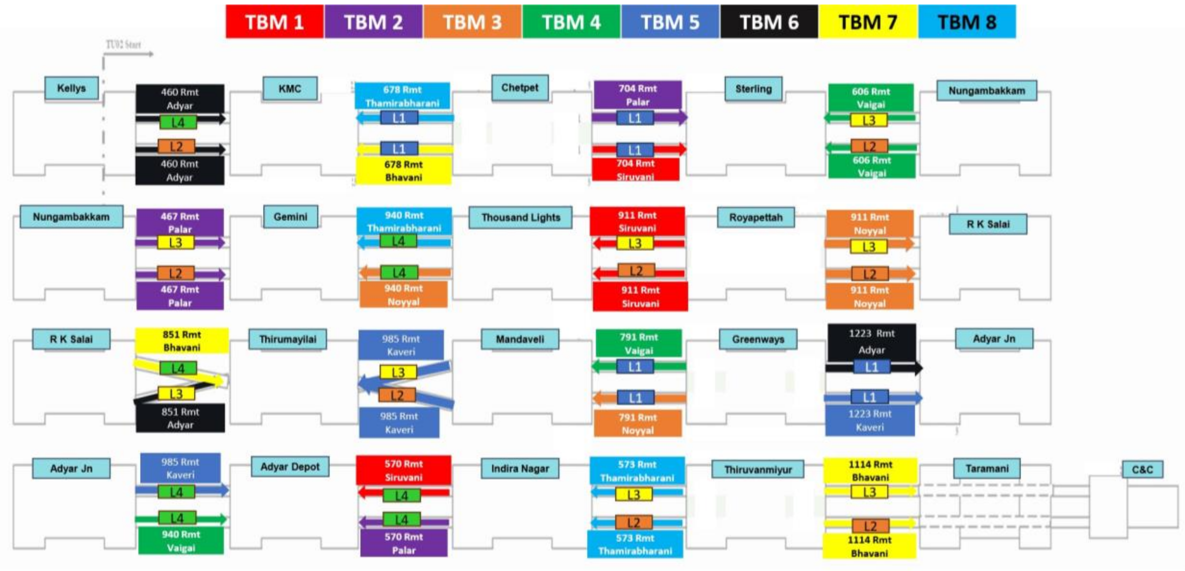

Figure 3: Revised TBM launching sequence.

Table 3: Results of Big Room planning Resequencing - Delay and Idle time reduction

S.no	Description	Project Start	Project End	Duration (In Days)	Duration (In Months)
1	Original Contract duration	09-06-2021	05-11-2025	1610	54
2	Revised duration without Resequencing	09-06-2021	16-10-2027	2320	77
3	Revised duration with Resequencing	09-06-2021	01-05-2027	2152	72

2. *Issuance of Variation Order*: Two number of critical shafts for retrieval were descoped from the Interface Contract and added to the scope of Tunnelling Contractor as a variation order in Contract. Also, it helped the tunnelling contractor to generate more revenue with the existing resources. Hence, the risk was converted into a revenue generating opportunity.

The collaborative nature of Big Room Planning taken up systematically ensured that diverse perspectives were considered, leading to innovative solutions and improved project outcomes.

CONTINUOUS IMPROVEMENT IN TIMELINE

Even after the underground contractors commenced execution at different stations, the contractor ensured further optimization of the schedule by rescheduling within the interface contractor's dates, further minimizing project idle time. This ongoing focus on continuous improvement underscores team’s dedication to maximizing project efficiency and delivering value to all stakeholders. Central to the success of TU 02 was the cultivation of a culture of continuous improvement. The project team encouraged feedback and suggestions from all stakeholders, fostering a collaborative environment where innovative ideas were welcomed and implemented. Regular review meetings and performance evaluations helped identify areas for improvement and drive ongoing enhancements in project execution.

IMPLEMENTATION OF VALUE STREAM MAPPING IN CASTING YARD

The precast yard for tunnel segment manufacturing is located at 20 km from project alignment. The project requires production of 18366 rings from the casting yard. The total cycle time of production of a ring was 16 hours 5 min.

To reduce the cycle time, Value Stream Mapping (VSM) was chosen as the lean tool to evaluate the present cycle time in detail and reduce the Lean Waste (Vilasini and Gamage 2010).

Initial State of VSM

The different activities in production of a tunnel ring are listed and the time taken for each activity is recorded for a continuous 12 days and the VSM is generated as per the figure-4 given below:

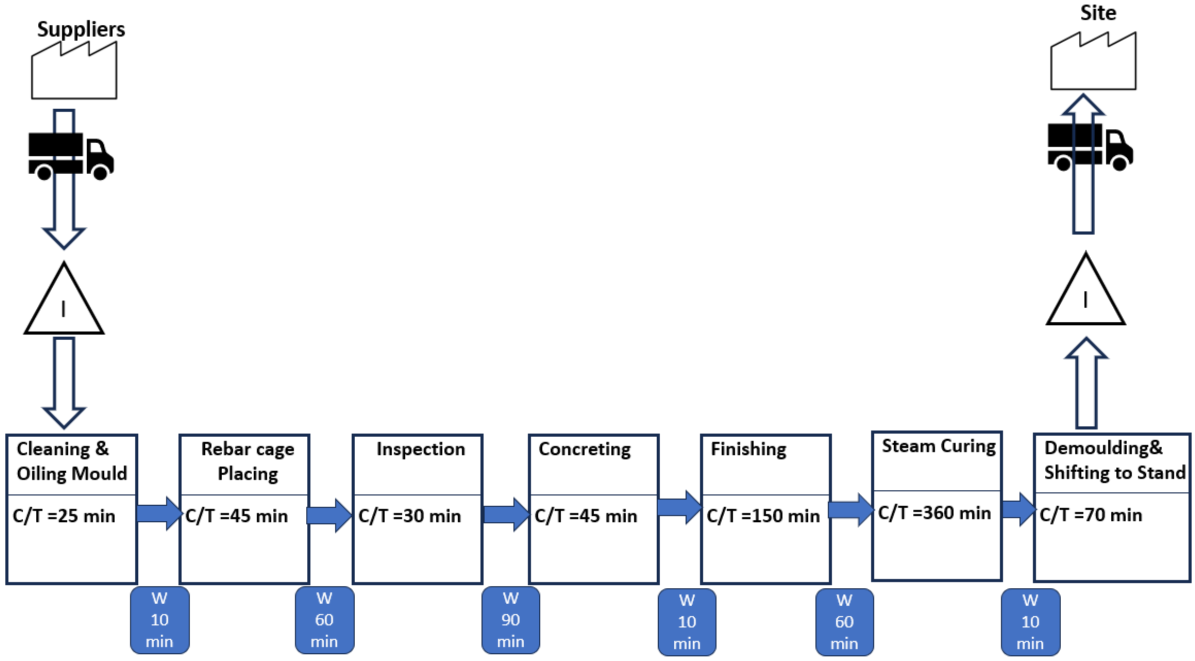

Figure 4: Segment Ring Casting VSM-Initial State.

The total cycle time is 16 hours 5 minutes with the bifurcation of Value Added -12 hours 5 minutes and Non-Value Added- 4 hours.

By collaborative discussion with construction managers, the below measures were taken at each step to reduce the Waiting and Idling time to completely reduce the Non Value-Added time to zero.

1. Increase of rebar crew from 10 to 15 numbers to remove the waiting time of 10 min.
2. Client approval was sought for each ring instead of 3-4 rings together to remove the waiting time of 60 min.
3. Ordering for concrete when the inspection is called for to reduce the 90 min of waiting of concrete.
4. Increase the crew size of finishing from 2 to 6 numbers to reduce the time of finishing from 150 min to 120 min.
5. Increase of one more stand to reduce waiting time for lifting of segment from mould by 10 min.

Below Figure 5 is the future state VSM that was envisaged and later achieved at site. The cycle time has been reduced to 11 hours 15 minutes.

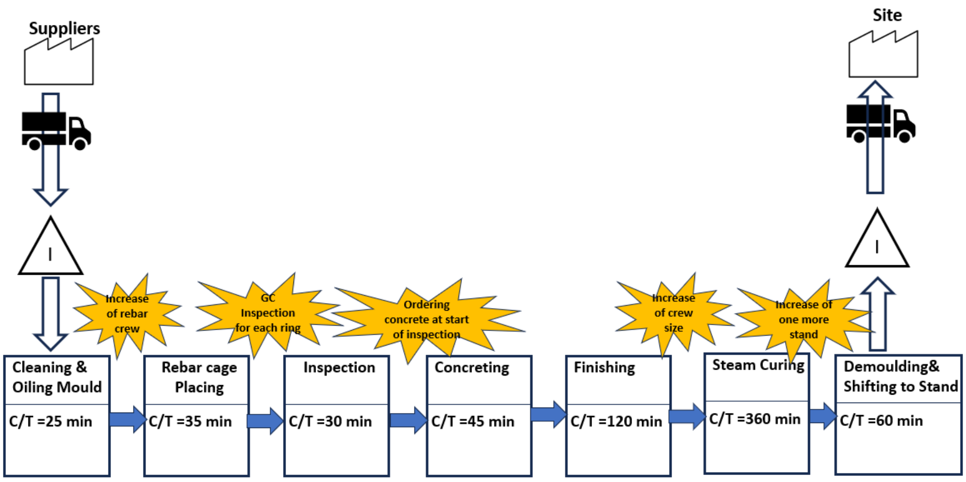

Figure 5: Segment Ring Casting VSM- Future State.

IMPLEMENTATION OF BIG ROOM PLANNING FOR TBM LOWERING ACTIVITY

In the context of tunnelling projects, particularly in densely populated urban areas, the process of TBM lowering and assembly emerges as a pivotal and intricate process. The spatial constraints inherent to urban settings necessitate meticulous planning and synchronization of various resources. It becomes imperative to organize the logistics, deployment of lifting machinery, and assembly teams in a manner that minimizes any downtime for these critical resources. Previously, the assembly of two TBM units consumed a substantial period, stretching over a duration of fourteen days. In response to this, a challenging internal target was set: the goal was to complete the lowering and assembly of two TBM units per shaft within ten days, ultimately achieving the ambitious milestone of four TBM assemblies within a span of twenty days. To accomplish this formidable task, it was imperative to foster collaboration (Rothman 2016) among a multitude of stakeholders.

The different teams involved in this highly critical activity include:

- Specialized Transporters
- Plant & Machinery department.
- Specialized Assembly Team
- Procurement team
- Safety team
- Quality Assurance team
- Administrative team
- General Chennai Corporation (GCC)
- Traffic Police Department
- General Consultant (GC) and
- Customer

The cohesive synergy between all teams was achieved through the implementation of Big Room planning. Within the Big Room planning exercise, a granular examination of the project was conducted. This entailed scrutinizing micro-level plans, proactively identifying potential constraints, and formulating precise action plans. It was during this collaborative process that several previously unrecognized, although crucial, minor activities came to light. The constraints identified and the action measures taken as output of Big Room Planning are summarized in Table 4.

Table 4: Constraints and Action Measures Implemented from Big Room Planning

S No	Constraint Identified	Action Taken
1	The shortage of Umbilical Hoses required for TBM Initial Drive has been identified as the same earlier planned quantity has been engaged in TBM 1 & 2	Immediate procurement order was finalized
2	Traffic Police Approval required from two different jurisdiction is identified	Admin team person in charge is allocated and both approvals were processed in parallel
3	Cutter Protection walls which were required in present shaft and not required in previous shafts was identified	Civil team has been engaged to take up this activity before TBM lowering
4	Crane Positioning: As per crane positioning and lifting sequence, the outrigger of 700T crane needs to be placed on D-wall panel. However, the same panel has been proposed for rectification measures already.	The entire micro schedule has been planned after completion of rectification of D wall
5	Route survey: The activity of joint route survey along with GC was missed in program	The same has been incorporated in program with duration of 2 days

The 700T and 300T cranes being the critical equipment driving the entire task of 7 days, rigorous microlevel planning was done to achieve the Just in Time lowering activity. To ensure the seamless execution of these preparatory tasks, resources such as boom lifts, specialized lifting tools, and scaffolding were meticulously organized and delivered promptly. These concerted efforts, guided by meticulous planning and precise execution, culminated in the remarkable achievement of completing the lowering and assembly of all four TBM units within a commendable twenty-day timeframe. This achievement underscores the effectiveness of a collaborative and detail-oriented approach to construction planning, demonstrating how meticulous coordination and proactive problem-solving can lead to significant gains in project efficiency and ultimately pave the way for the successful realization of complex construction objectives.

Figure-6: Big Room planning at TU02 project site.

RESULTS AND DISCUSSION

1. The adoption of lean principle – Big Room Planning in Contract Management in the CMRL TU 02 project yielded significant results, including:
    a. **Reduction in TBM Idle Time:** By resequencing TBM launches and implementing innovative contract management strategies, we were able to reduce TBM idle time by 30%, minimizing the impact of delays on project progress and cost.
    b. **Optimum Resource Utilization:** Collaborative planning and risk assessment enabled the efficient allocation of resources, ensuring optimal productivity and cost-effectiveness throughout the project lifecycle.
    c. **Timely Project Completion:** Despite the initial delay in the interface contract, the project has been rescheduled within 72 months, meeting client expectations and demonstrating our commitment to delivering quality infrastructure on time and within budget.
2. The adoption of lean principle - Value Stream Mapping in Casting Yard reduced the cycle time of precasting activity from 16 hours 5 minutes to 11 hours 15 minutes. Total time savings of 5.5 months. These improvements in the precast production also directly benefit construction projects by reducing expenses and increasing delivery. (Deffense and Cachadinha 2011)
3. The adoption of lean principle – Big Room Planning for critical activity of TBM Lowering enabled the project team to lift and lower 4 TBMs within a record time of 20 days and saving total of sixty days.

CONCLUSION

The CMRL TU 02 project serves as a compelling case study in the effective application of lean principles in underground metro construction. By embracing collaboration, proactive risk management, and continuous improvement, we were able to overcome significant challenges and deliver a successful project that enhances urban connectivity and fosters economic development. Our experience underscores the importance of lean practices in modern construction projects and highlights the value of collaborative problem-solving and stakeholder engagement in achieving project success. As the construction industry continues to evolve, the lessons learned from CMRL TU 02 will serve as valuable insights for future projects seeking to optimize efficiency, mitigate risks, and deliver sustainable infrastructure that meets the needs of communities around the world.

ACKNOWLEDGEMENTS

We express our sincere gratitude to all the project teams and stakeholders whose invaluable contributions made this research possible. Their dedication, collaboration, and commitment to embracing lean principles in contract management have been instrumental in shaping the insights presented in this paper. Their collective effort and unwavering support exemplify the spirit of continuous improvement and innovation in the construction industry. This acknowledgment serves as a tribute to their hard work and collaboration, which have contributed to advancing project efficiency, collaboration, and overall success. We are grateful for their partnership and the opportunity to showcase their exemplary work in this paper.

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COST CONTROL IN MODULAR CONSTRUCTION: A TAXONOMY FOR EFFECTIVE COST MANAGEMENT

Margaret P. Keorapetse[1], Helena Utzig[2] and Carlos T. Formoso[3]

ABSTRACT

The cost effects of modular construction, which shares the same principles with lean construction, have been a subject of debate among researchers, with contrasting perspectives on how to control costs, compared to traditional construction cost management methods. Proponents of modular construction indicate that it can potentially be cost effective compared to traditional construction. As modular construction is gaining momentum in the construction industry, slowly replacing traditional on-site construction methods, there is a need for new cost control methods. The unique characteristics of modular construction create distinctive cost control difficulties. In this article, an attempt is made to showcase challenges and factors influencing costs in modular construction. The aim of the study is to propose a taxonomy of costs for modular construction processes. The study is ongoing and preliminary results presented in this article seek to understand the production process of modular construction, its associated costs and highlight potential cost control methods that align with the unique features of modular construction.

KEYWORDS

Modular construction, Cost control, Lean construction

INTRODUCTION

The construction industry is currently experiencing a substantial shift towards modular or off-site construction, steadily substituting traditional on-site construction methods in some market segments (Molavi & Barral, 2016). Modular construction utilizes building modules produced inside a controlled setting within manufacturing facilities to be conveyed and assembled on site. The concept of off-site construction has been known for a long time, but was not positively embraced until recently when the industry was subjected to pressure due to swelling labour costs and the need for sustainable buildings and processes (Zhang et al., 2016). In a study done by Assaad et al. (2022) in collaboration with the Construction Industry Institute (CII) in the USA, it was forecasted that off-site construction will grow from its current average percentage of 33.64% to an anticipated average of 54.9% in the future. This predicted increase will mark a substantial 4.33-fold industry growth in the USA over the coming decade. This significant increase indicates the acceptance and adoption of industrialized construction methods in the

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building industry, thus reflecting its potential to transform and restructure the construction methodologies and practices.

Modular construction attracts extensive attention from the construction industry because of its enormous benefits over traditional construction methods. Gibb (1999) states that the least desirable location one would want to construct a building is on a building site. Construction sites are burdened with inefficiency and different types of waste. By contrast, modular construction is usually faster, safer, and more reliable than traditional construction, as well as has reduced on-site labour requirements, improved quality, less wastage, and a lower environmental impact (Nazir et al., 2020). These benefits add to the increasing belief that modular construction successfully deals with the industry's needs for efficiency, sustainability, and value generation (Tsz Wai et al., 2023). However, despite the potential advantages offered by off- site construction, traditional on-site construction methods are still prevalent (Liew et al., 2019).

Modular construction shares the same principles and aims of waste reduction and enhanced efficiency with lean construction. The two approaches can complement each other in setting the pace for improvements in the construction industry. The fast speed construction of modular construction provides time-related cost savings for items such as site supervision, plant and equipment (Zhang et al., 2016). However, the unique features of modular construction, such as off-site manufacturing, transportation logistics, and assembly processes, create distinctive cost control difficulties. These challenges require innovative cost control methods throughout the lifecycle of modular construction projects. The application of lean construction concepts and methods in modular construction can contribute to streamline processes and the fostering of a culture of continuous improvement. This ultimately results in better cost management and project execution. By contrast, there is an ongoing argument that whilst volumetric modules can decrease the labour costs, it may simultaneously increase transportation costs.

This perspective article argues that relying on traditional cost control strategies is inadequate for delivering modular construction successfully. The study proposes a taxonomy of costs for modular construction processes and advocates for cost control approaches that align with the unique characteristics of modular construction, supported by empirical evidence and scholarly insights.

This investigation addresses a gap in knowledge, as little attention has been given in the literature on effective cost control strategies in modular construction. The development of such approaches is essential to ensure the implementation and delivery of modular construction projects in a cost-effective manner.

LITERATURE REVIEW

CHALLENGES OF TRADITIONAL COST MANAGEMENT

Cost management in construction generally involves monitoring the actual performance in comparison to the cost estimates and finding variances (Kern & Formoso, 2004). A major challenge of traditional cost management has been identified as the lack of accurate cost estimating and cost control processes, insufficient information modelling, and the absence of integrating cost management techniques and production management systems (Aziz, 2013).

According to Forgues et al. (2012) the cost estimates are often carried out when the conceptual design is at an advanced level or even finished, making it too late for relevant stakeholders to make informed decisions. Therefore, cost management can play a key role not only in terms of reducing costs but also in the analysis of trade-offs that affect functionality, quality and the long term performance of the building.

Koskela (2000) criticizes most of the cost management methods utilized in the industry for following a standard cost method, strongly based on mass production ideas, which associates most cost items to a finished element derived from design drawings, for example, walls (m2) and windows (units). Koskela further contends that traditional cost management disregards the nature of the product and the production process in question due to its insufficiency of the conceptual base. Kaplan (1984) concurs that it is improbable that any cost accounting system can sufficiently summarize a company's manufacturing operation.

COST IMPLICATIONS OF MODULAR CONSTRUCTION

Previous studies have explored the cost performance of modular construction, discussing the cost effects from contrasting perspectives on the overall cost compared to traditional construction methods. Some of them have explored how some lean principles and methods can improve efficiency and cost effectiveness in modular construction.

Zhang et al. (2016) state that the cost of industrialized construction can exceed the cost of a building delivered through traditional methods. The high costs in modular construction are often attributed to the initial investment in equipment and land for module production, the complexity of the design and materials used (Nahmens & Ikuma, 2012). However, advocates of modular construction argue that while upfront costs may be substantial, they can be offset by reduced labour costs, waste and reduced overhead costs, and potential time savings.

The installation of ready-made module units on-site requires less labour, resulting in decreased labour costs compared to traditional construction, which heavily relies on labour-intensive techniques (Nazir et al., 2020). In this context the application of the concept of standardized work can result in the synchronization of work processes and in higher productivity of the workforce (Bataglin et al., 2020).

Modular construction contributes to improved environmental performance by incorporating lean principles such as reducing construction waste and improving energy efficiency resulting in optimized costs (Nahmens & Ikuma, 2012). Material recycling and inventory control that happen in controlled factory environments align with lean goals of value generation and waste minimisation.

Gibb (1999) suggests that cost reductions can also be achieved through factors such as on-site overhead reduction, stemming from potential time savings due to shorter durations and increased installation efficiency. Pull planning and value stream mapping can assist in identifying and discarding activities that do not add value while incorporating activities that add value like efficient utilisation of resources (Bataglin et al., 2020). This leads to improved project predictability and decreased overhead costs.

While there are no generalised figures on the improved performance of modular construction, some studies have found that modular construction can reduce overall waste weight by 83.2% in large structures and 81.3% in small structures (Loizou et al., 2021); 35% reduction for on-site labour and an overall cost benefit of 8.62% for a hospital development (Court et al., 2009); savings on rework costs that can be as high as 2% in conventional construction (Lawson et al., 2012); and produce 40% less greenhouse gases emission than conventional construction (Quale et al., 2012).

In overall, pull production and Just in Time (JIT) production play a key role in the integration between on-site and off-site processes in modular construction (Innella et al., 2019). Pull production is important for planning and controlling production in the manufacturing plant so it is possible to cope with variability in the project. Construction site production of modularity must pull the delivery of pre-fabricated components from the manufacturing plant to the site for assembly. JIT means production considers only what is necessary, when it is necessary and where it is necessary.

Tam et al. (2005) highlight that savings in modular and prefabrication can be fully realised when the construction process is fully mechanised, changing construction into an assembly industry, and using recycling materials for prefabricated components.

CHALLENGES AND FACTORS INFLUENCING COST CONTROL IN MODULARITY

The cost of transportation has emerged as a primary challenge in modular construction. The high cost emanates from transporting large volumetric modules to the site where they will be assembled (Shahtaheri et al., 2017). The transportation costs increase if the project site and manufacturing facility exist in different countries or far away from each other. Court et al. (2009) advocate for setting up an assembly workshop on the construction site if the space permits or setting up adjacent to the construction site for cost reduction. However, during the transportation and installation, risks related to breakage of modules may be encountered, thus leading to even higher costs (Shahtaheri et al., 2017).

The storage capacity of the manufacturing plants is usually limited and can give rise to costs related to inventories (Nazir et al., 2020). High inventory due to excessive production and non-movement of modules can have a financial bearing in the organisation as storage costs have to be paid. Therefore, a cost effective inventory control of work in progress (WIP) of modules is essential. The use of the JIT approach can potentially promote continuous flow of modules with the aim of precisely matching the demand of the modules with the supply as produced by the factory (Balkhi et al., 2022).

The factory's demand is another important factor for considering opportunity costs. Opportunity cost is related to production time and refers to the potential benefit lost due to one choice (or necessity/obligation) over another (Windheim et al., 2017). In instances of high demand of specific modules, a delay in production can mean increasing the cost associated with the production of certain modules and reducing the company profit. The opportunity to produce more modules is lost at the expense of finalising the required modules (in this case, not by choice, but by the emerging situation).

Another noteworthy challenge is the management of dimensional and geometric variability in modular construction (Shahtaheri et al., 2017). It is expensive to accommodate plant changes during design and construction.

Molavi & Barral (2016) state that there is a high scarcity of skilled workers in the production of modular and prefabricated components. Skilled workers are needed to carry out complex techniques, and intricate designs in the production and installation of components.

The design stage also plays a critical role in cost control. While the actual expenditures associated with the design may be small because each module require a small number of changes each instance, the level of influence on cost control is the greatest during this stage (Gilbert III et al., 2013). Thus, efforts to reduce and control costs should be reinforced at the design stage.

During the production stage, costs arise from materials, labour, and indirect costs of the manufacturing plant. Since production is done in a factory-controlled environment the production of waste is minimal hence reduced cost of production (Nazir et al., 2020). However, the literature does not provide information on the range of costs related to rebuilding components due to damages, transport costs, inventory costs, labour costs and factory costs in modular construction.

The literature review presented in this sub-section pointed out several opportunities to improve the way costs are modelled in modular construction, by considering the nature of the production processes. Therefore, some key cost categories emerge, and should be considered in the proposed taxonomy: logistics costs, opportunity costs, inventory, time-related costs, fixed costs, etc.

POTENTIAL STRATEGIES FOR COST MANAGEMENT IN MODULAR CONSTRUCTION

Clients always expect that the construction work should be done within the budgeted amount, specified quality and on time (Aziz, 2013). Therefore, modular construction requires cost control methods that can achieve the expectations and requirements of the customers.

LEAN CONSTRUCTION

Lean construction is rooted in the removal of wasteful activities from construction processes. Lean construction uses different methodologies and techniques like JIT, pull planning, target costing, value stream mapping among others for the removal of waste in processes. Therefore, it is important to have a cost management system that clearly identifies and highlights the cost of non-value adding activities. A study by Nahmens & Ikuma (2012) done in the USA which applied lean construction for the construction of industrialized housing, construction material waste was reduced by 64% and the production hours were reduced by 31%.

USE OF TECHNOLOGY

According to Sergei & Gennady (2016) the best technology for constructing modular buildings must be able to recognize and understand the factors and features that allow the reduction of the stated costs, labour inputs and work duration.

The support that Building Information Modelling (BIM) provides to off-site construction in managing design risks and improved documentation, has been well documented in the literature (Zhang et al., 2016). The visualisation capabilities of BIM allows early clash detection, speed and accuracy of cost estimation, and enhanced coordination. The use of 5D BIM model allows accurate materials quantities take offs. The benefits of virtual design and construction are evident and cannot be overstated (Zhang et al., 2016). However, the main shortcoming of 5D BIM is its inability to capture time-related costs which are not dependent on quantity take offs.

STANDARDIZATION AND MODULARITY

Standardization is a concept that involves the extensive use of components, methods with regularity and repetition (Viana et al., 2017). Standardization provides better conditions for implementing modular systems efficiently as modularity focuses on standard modules and standard processes. The central idea of modularity is the possibility of decomposing a product into manageable parts (modules) that have standardized forms of interactions (Gibb, 1999). Modularity has been pointed out as a key concept in modular construction, especially when there is a need to customize products according to customer requirements. It enables the development of flexible production systems and has shown to be effective in dealing with complexity in different types of systems (Viana et al., 2017). The literature further indicates that the adoption of modularity brings several benefits that are enhanced when this strategy is related to concepts of industrialized construction such as standardization.

METHODOLOGY

DESCRIPTION OF THE EMPIRICAL STUDY

The study adopted a Design Science Research (DSR) approach, which combines descriptive and prescriptive research to close the gap between practice and theory (Holmström et al., 2009). The objective of DSR is to develop solution concepts, also known as artefacts for classes of complex and relevant problems, considering a certain context, and, in general, have a multidisciplinary character (Voordijk, 2009). DSR was selected because it is oriented towards the creation of new knowledge through design and action rather than just description.

The main artefact to be developed in this investigation is a conceptual model, i.e. a taxonomy of costs for modular construction processes. This taxonomy can support the development of design propositions for the development of cost management systems for modular construction, which can be regarded as a recommendation for action to be taken in a specific circumstance with the aim of achieving a certain result (Voordijk, 2009).

This study has an exploratory nature that sought to get an in-depth understanding of the problem, which is the starting point for developing propositions. The investigation was focused on cost of manufacturing, transportation and the installation of prefabricated modules. The conventional construction activities, often involved in project delivery, were out of the scope of the investigation. The study was developed through three phases; problem definition and comprehension, development of the solution, and analyses and reflection. The three phases were broken into six stages as shown in Figure 1.

(i) Stage 1: sought to identify a gap in knowledge through an in-depth analysis of a practical problem and review of existing literature.

(ii) Stage 2: involved an in-depth theoretical exploration of the identified problem and its specific characteristics. During this stage there was a deep practical involvement with the aim to: understand the production process of the company; understand the flow of information related to costs; and understand how the company estimates and controls costs.

(iii) Stage 3: consisted of collecting and analysing data and understanding the nature of modular construction costs from documents and through observations.

(iv) Stage 4: involved discussions and validation of information with relevant managers. The research artefact was developed, which is the taxonomy of costs for modular construction based on understanding the phenomenon of production.

(v) Stage 5: involved presenting and discussing with company representatives the research products, analysis and diagnosis developed in the previous stages.

(vi) Stage 6: consisted of a qualitative analysis of the contributions of the main research products.

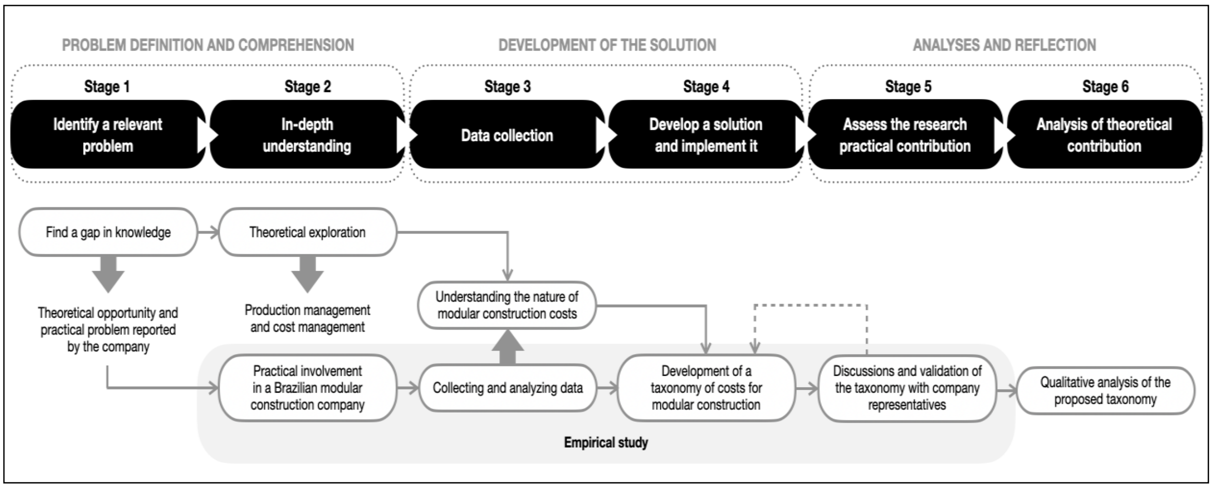

Figure 1: Stages of the Research Design and Development

The empirical study was developed in a Brazilian modular construction company, which develops and delivers complete modular components solutions for projects in different segments (e.g. education, security, residential). The company is responsible for all production, transportation and installation of volumetric modules, project development, execution of on-site installation and management of both factory production and construction work.

The company offers two volumetric modular solutions that differ in terms of the technology used and service to the business segments. This research focuses on the Y modular solution for the education market segment, whose volumetric unit has a standard dimension of 3x6x3m and is formed by a steel structure module (chassis) combined with slabs and external cladding (various types and number of panels). The modules were diverse and involved personal customization combined with pure customization. There was limited repetition of the same module. The structural module is delivered with finishing with hydro-sanitary and electrical installations and internal and external floor and wall finishings.

The family of modular products for schools consists of 46 standard products made up of several volumetric modules. Standard products are used for both new projects and expansions of existing schools.

The company was selected mainly because of its long experience and relevance in the Brazilian modular construction sector. The company was also involved in an improvement program based on the principles of Lean Production.

The strategy that was adopted in order to improve the reliability of the findings is triangulation. Triangulation allows the use of multiple data sources for a deeper comprehension of the subject of study (Farquhar et al., 2020). Data was collected through open-ended interviews, direct observation and the independent analysis of different drawings and documents. In total, more than 20 hours of interviews and meetings were held, 4 visits to two construction sites and approximately 13 hours of observations of the production process of the modules in the factories. Interviews were conducted with multiple company representatives. The study commenced in July 2022. The development of the taxonomy was based not only on the analysis of the data collected, but also on the literature review about cost management challenges in the context of modular construction (see literature review). Table 1 displays the sources of evidence utilized for the study for the respective phases and stages.

Table 1: Sources of Evidence

Phases	Stages	Main Activity	Details of activities	Sources of evidence
Problem Identification and Comprehension	Stage 1	Exploring gap opportunity	Understanding a relevant problem from practical and theory point of view	Literature review; Participant observation (planning meetings)
	Stage 2	In-depth exploration	Understanding the production process at the factory and modular products	Direct observation (manufacturing plant)
Development of the Solution	Stage 3	Collecting and analyzing data	Understanding the budgeting process and information flow; Analyzing factory production, cost control and challenges; Exploring logistics costs and factory costs with other sectors; In-depth understanding of the budget process for modular solution Y; Analysis of various budgets for modular solution Y, cost breakdown and material spreadsheets; Analysis of design drawings	Open ended interviews (cost management system); Document Analysis (cost estimates, design); Direct observation (manufacturing plant)
	Stage 4	Development of a taxonomy of costs	Discussion and validation of information	Open ended interviews (cost management system)
Analyses and Reflection	Stage 5	Presenting and discussing the product	Discussions with company representatives; Validation of the taxonomy	Participant feedback (cost management system)
	Stage 6	Qualitative analysis	Using literature and previous stages to qualitatively analyze the research product	Open ended interviews (cost management system) Literature review

RESULTS

This paper presents the preliminary results of this investigation. The company prepared a cost estimate by using a spreadsheet, in which the costs of each modular product was calculated, through accounting data and standard cost of raw materials and the standard time of production for each product or product family. The cost management system employed by the company can be classified as the traditional standard costing method. The changes were monitored by costing by apportionment of the transformation cost categories. The change in specification cost and the total hours for incorporating the changes in manufacturing the unit were recorded. The cost of different Y solution modules categorized according to their complexity, direct material cost and estimated production time with its own labour. Four categories were used for generating and controlling costs associated with different types of modular solution Y; (i) complex, (ii) medium complex, (iii) simple, and (iv) circulation or the most simple. The analysis of the estimated costs and production cost control suggested that cost estimates were developed with some form of logic aimed at aligning them closely to the production cost, especially indirect manufacturing cost. Some modules were stored in an open space at the manufacturing plant before being transported to their respective construction sites.

The nature of the production process led to the categorization of the main phenomena that generates costs. The taxonomy of cost categories followed five distinct key stages of manufacturing and assembling the modules as shown in Figure 2; (i) design process, (ii) production of volumetric units, (iii) logistics process at manufacturing plant, (iv) transportation process and, (v) assembly of pre-finished volumetric units.

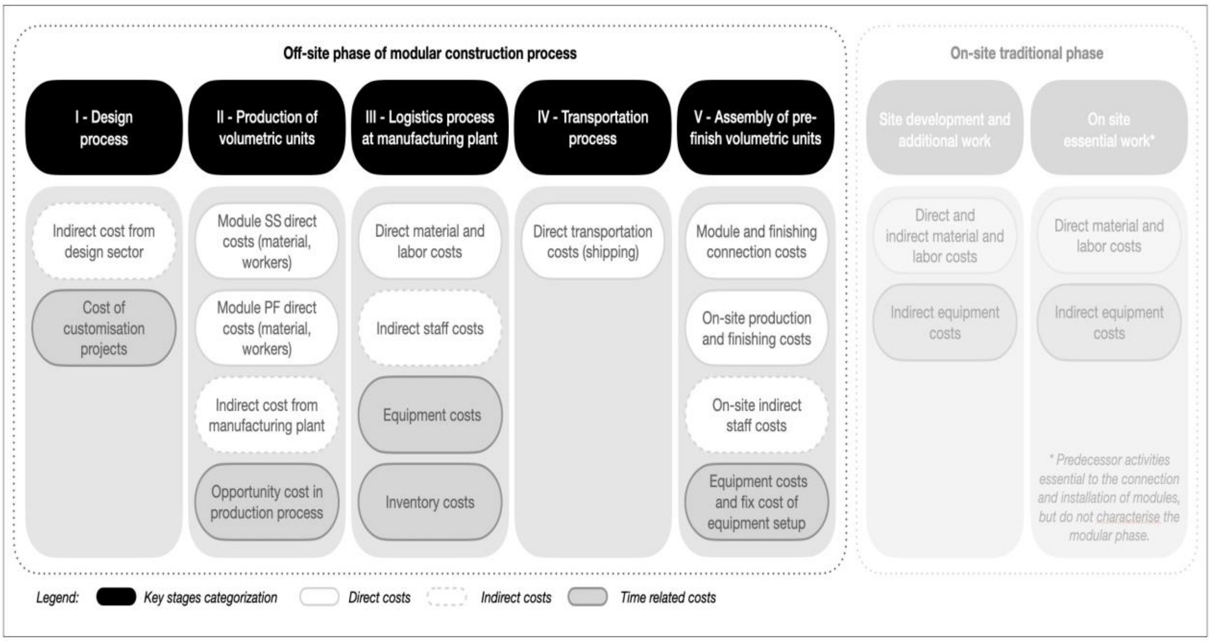

Figure 2: The Nature of Modular Construction Process and Associated Costs

Costs related to the design process can be divided into two main categories: indirect costs related to the design team, and project customization costs. During the production stage, costs arise from materials and labour of the structural shell (SS) and the pre-finished (PF) modules, indirect costs of the manufacturing plant, and opportunity costs in the manufacturing plant. Manufacturing indirect costs refer to transformation costs and other industrial costs such as indirect costs of energy, water, maintenance, rent and depreciation. The logistics process at the manufacturing plant incurs indirect and direct costs from the workers, equipment and inventory. The transportation process essentially includes the costs directly associated with freighting volumetric units and are estimated from the potential supplier or freighting company. The transportation costs depend on the number of modules and the distance to be travelled to the delivery point. The assembly of pre-finished volumetric units involves costs associated with materials used for connecting the modules, plant and equipment used during the assembly, and costs of the workforce.

DISCUSSIONS

The study has provided insights into the various stages of modular construction and the associated costs at each phase. It has shed light on the complexities of cost management in modular construction, emphasizing the need for innovative cost management solutions and the application of some lean methods to overcome the specific challenges posed by each stage of the process.

TAXONOMY OF MODULAR CONSTRUCTION PHASES

The reviewed literature does not provide an explicit description of the different stages that modular development goes through. Providing a taxonomy of the different phases of modular construction provides a point of departure for understanding different costs associated with modular construction. Taxonomy provides a good foundation for calculating operational costs for each category, which is usually disregarded when preparing cost estimates. Moreover, taxonomy provides a structured conceptualization and common language for communication among construction team members, aiding clarity. The structured conceptualisation makes it possible and easy to identify sources of cost deviations in case of cost overruns. Production planning can also be improved as the appropriate efforts and resources for cost control can be dispatched according to the requirements of any category.

REPETITION AND STANDARDIZATION OF COMPONENTS

Modularity allows repetition, which facilitates cost management. This repetition can lead to more accurate cost estimates and better cost control throughout project delivery. In addition, modularity provides opportunities for customization whilst maintaining cost effectiveness. The use of components that can be customized and combined in numerous ways provide opportunities to achieve cost advantages through repetition and standardization. This balance between repetition for cost efficiency and customization provides evidences of the potential positive impact of modular construction in improving project cost control.

There are some opportunities for improving cost estimating and control related to the use of digital technologies, such as the improvement of the existing cost database, and the use of 5D-BIM for quantity takes-offs. Through BIM, adjustments to the designs can be made at any given point in time and BIM can show real time changes and visual representation of cost data of different components of the modules. However, the impact of digital technologies tends to be very limited if traditional cost modelling, based on the standard cost method, is still used.

SYNCHRONIZATION OF ACTIVITIES

The management of inventories to avoid storage cost by the company is also a key change. The adoption of lean production techniques such as JIT and pull planning, are important for synchronising not only with the construction site but with the suppliers of materials for producing modules. As suggested by Bataglin et al. (2020), confirmation points (triggers) can be used as a mechanism for pulling components from manufacturing plants, according to the status of the system. Therefore, the implementation of lean techniques will reduce different types of waste as only necessary modules will be produced, workflows streamlined, as well as aligning on-site and off-site operations, ultimately reducing lead times and saving cost.

STRENGTHENED LOGISTICS SYSTEM

The transportation of modules from the manufacturing plant to different schools spread across the country may also impact the overall expenses of producing modules. Several strategies can be utilized to reduce those costs. Space utilization of the trucks used for transportation can be maximized through efficient loading processes, and leveraging economies of scale through bulk transportation and reducing the number of trips. The selection of transportation modes can also assist in controlling transport costs: an effective, adapted and strengthened logistics system is critical for cutting transportation costs incurred by the company (Hsu et al., 2017).

In overall, modular construction offers opportunities for reducing lead time, and consequently time-related costs, and also can improve reliability of cost estimates. The complexities associated with off-site manufacturing, transportation logistics, and on-site assembly require a re-evaluation of traditional cost control methods. The dynamic nature of modular construction projects needs proactive approaches that consider the intricacies of supply chain coordination, production scheduling, and site integration.

CONCLUSIONS

Modular construction is known for its efficiency and predictability. The streamlined processes of modular construction allows for waste reduction and shorter project lead times. Modularity also provides an opportunity for operational costs to be reduced as assembly line activities are much simpler. It allows for customisation while still maintaining cost effectiveness, making it possible to achieve cost advantages through standardization and the repeated use of components. This balance between repetition for cost efficiency and customization highlights the effectiveness of modular construction in managing costs in projects.

However, to a large extent, the unique characteristics of modular construction create distinctive cost control difficulties. The high costs in modular construction often stem from the initial investment in equipment and land for module production, the complexity of design and materials used. The primary cost drivers in modular construction emanate from transportation, warping and damage during transportation, and a shortage of specialised skilled workers. To address cost control in modular construction, it is crucial to use cost control methods that align with the unique features of modular construction.

The main conceptual contribution of this study is the development of a taxonomy outlining the different phases of modular construction. A structured framework for determining costs associated with each phase of modular development is provided through taxonomy, aiding better cost management custom-made to the requirements of each phase. The taxonomy of cost categories followed five distinct key stages of manufacturing and assembling the modules; (i) design process, (ii) production of volumetric units, (iii) logistics process at manufacturing plant, (iv) transportation process and, (v) assembly of pre-finished volumetric units. The development of this taxonomy is strongly related to some lean principles, such as elimination of the share of non-value adding activities, reduction of variability, pull production, synchronisation and takt time, and simplification by the reduction of the number of steps and parts.

Whilst this perspective paper sheds light on valuable insights and reflections on the current subject, there are a few notable limitations of the study that needs to be acknowledged. As this is an on-going study, the results of the study are partial thus limiting the depth of analysis of some aspects which have been explored comprehensively and in detail. Moreover, the lack of previously published information about the different stages of modular construction made it impossible to draw comparisons with prior studies thus making it difficult to build upon existing knowledge. Finally, there were some limitations related to the research method as the findings of the study are based on a specific company, and thus cannot be generalised to other situations because of the unique context and conditions.

Regarding future studies, the following suggestions emerged from this investigation: to develop additional prescriptive knowledge (e.g. principles and prescriptions) for designing cost management systems for modular construction, and to test the taxonomy of cost management categories by applying in the development or testing of cost management systems.

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DOUBLING THROUGHPUT WITH OPTIMIZED CYCLE-TIME FLOW (OCF) STRATEGY

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ABSTRACT

Despite the availability of advanced managerial tools and technologies for project planning and control, projects failing to meet schedules and budget targets remains a common phenomenon. We argue that a root cause for these failures is the absence of strategic planning. Optimized Cycle-time Flow (OCF) is a strategy developed by Intel Inc., that enables teams to plan portfolios of projects subject to resource constraints and the principles of flow, while avoiding the pitfalls of the planning fallacy and unnecessary time-extensions. This paper presents a thorough exploration of OCF through a case study in a typical installation project, one of the first OCF implementations. Practical applications of the principles of OCF are explored through analysis of construction plans and interviews with key personnel. The paper provides supplementary observations and validation of empirical findings regarding the effectiveness of OCF. The multi-project environment and the sense of urgency to reduce time-to-market are recognized as a catalyzer for OCF. The case study highlights the importance of critical production thinking as manifested in the first two OCF principles: "Plan and Integrate Strategically" and "Plan Tactical Targets".

KEYWORDS

Constraint Management, Design Science Research, Last Planner® System, Optimized Cycle-Time Flow (OCF), Production Control, Strategic Integration & Planning, Target Pull-Plan

INTRODUCTION

Significant progress has been made in recent years towards the realization of Lean Construction (LC) for installation projects in Intel Corporation (Gabai et al., 2023; Gabai & Sacks, 2020). First, an organizational learning process was carried out to assimilate the basic principles and tools of LC, including the Last Planner® System (LPS). Later, in light of growing awareness of waste and the need to enhance value in a predictable way, additional improvement attempts were made, leading towards the development of Optimized Cycle-time Flow (OCF) strategy.

The theories and tools expressed in OCF are diverse, including Transformation-Flow-Value (TFV) (Koskela, 2000), Portfolio, Process and Operations (PPO) (Sacks, 2016), Theory of Constraint (Goldratt 1997; Goldratt et al. 2004), and LPS (Ballard, 2000). Over the following years, OCF yielded significant results, including successful implementation of pull scheduling

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at the organizational level, reductions in projects' cycle-times, and improved resource flow. Human capital played a central role, thanks to the commitment throughout the entire value chain, from production floor workers to senior managers. In addition, an international learning group was initiated, the "OCF Industry Tribe", with participants from a variety of AEC backgrounds and at different stages of OCF implementation at their projects and organizations.

OCF was developed in a unique production environment: a multi-project organization with a clear value proposition, portfolios of similar projects, urgent installations needed to enable factories to begin production, and a "clean room" environment requiring accuracy and cleanliness.

Previous papers on OCF (Gabai et al., 2023; Gabai & Sacks, 2020) reported remarkable empirical results, including significant cycle-time reduction and enhanced throughput (TH). This paper provides an exploratory investigation and analysis of the empirical results, aiming to improve understanding of how the principles of OCF work in practice, and so to set the stage for a discussion regarding the applicability of OCF to other construction domains, in the context of portfolio or single project management. A case study for OCF implementation on a typical installation project is presented, attempting to identify how the principles of OCF were expressed.

LITERATURE REVIEW

Optimized Cycle-Time Flow (OCF) is a strategy that was originated to benefit both project stakeholders and project implementation teams. The seven principles of OCF are derived from various proven theories and methodologies, that are reinforced and synergized as they are combined. OCF principles are composed of six planning principles and only one execution principle, which emphasizes the importance of up-front planning to achieve 50% cycle-time (CT) reduction, and to double the organizational TH.

Figure 1: The OCF flywheel (Credit: Intel Corporation).

The OCF flywheel (Figure 1) begins with Principle I - ***Plan and Integrate Strategically***, and Principle II – ***Plan Tactical Targets***. These two principles are based on the Strategic Project Leadership® (PSL) approach to project management (Shenhar, 2015), that emphasizes business and strategic thinking at the project level, and guides managers how to translate strategy into practical activities within their project. SPL optimizes business outcomes by deploying strategies that effectively address project complexity and rapid changes, ensuring alignment between project and organizational objectives. In the context of multiple project organizations, and based on the Portfolio, Process and Operations (PPO) model (Sacks, 2016), these two first principles address the flow of trades and operations upon portfolios of projects and target an organizational throughput improvement. This is reinforced once integrated with Transformation-Flow-Value (TFV) theory (Koskela, 2000), emphasizing value generation to the customer, and efficient production flow. At the outset of implementation of these principles, the stakeholders develop a Target Pull Plan per project that must align with the strategic plan for 50% CT reduction and optimized organizational TH.

Principle III – ***Collaborate*** – This principle also stems from PSL and emphasizes a cultural environment that must show respect and develop trust and integration within the project team. It is also related to LPS implementation (Ballard, 2000) and emphasizes the importance of collaborative planning to improve reliability and stability of the production system. In a multiple project environment, this collaboration also leads to formation of organic high-performance teams, composed of trades from several subcontractors, that flow from project to project (ensuring CT reduction and completing projects on time).

Principle IV – ***Resolve Constraints***, and Principle V – ***Restructure Resources*** – are based on the Theory of Constraints (Goldratt 1997; Goldratt et al. 2004) and aim to identify and alleviate potential bottlenecks in the system. These two principles reinforce the implementation of LPS as they enhance lookahead planning and the make ready process, focusing on either physical or informational constraints that limit the production system (Ballard and Tommelein 2016). In the context of project portfolio management, these principles are applied to ensure constraint removal on projects that are pulled for construction. In the construction phase, continuous efforts are made to identify and remove constraints that may evolve in real time. This requires full support from the back office (for design issues etc.), and enhanced involvement of senior management when ad-hoc decision making is required (including resource allocation) to enable smooth production flow.

Principle VI – ***Control Project Start*** – and Principle VII – ***Ensure Project Flow*** originate from the Toyota Production System (Liker, 2001) and include pulling project to production just-in-time and according to client needs. Only once everything is set in place, work can be performed without stopping until completion. Thus, projects are batched according to customers prioritization and their maturity level, enabling to level the Work in Progress (WIP), and the availability of resources to reduce cycle times (each OCF batch is reduced by 50% CT).

RESEARCH METHOD

As presented in previous studies (Gabai et al., 2023; Gabai & Sacks, 2020) and as demonstrated in the next section, empirical data indicates the effectiveness of OCF in terms of cycle time reduction. This case study provides a supplementary observation and validation of the empirical findings, enabling a deeper understanding of the working mechanisms of OCF at the individual project level. The case study approach was selected, as it "…allows the questions of why, what and how, to be answered with relatively full understanding of the nature and complexity of the complete phenomenon" (Voss, 2008). As OCF is an emergent practice, there is great importance to present detailed examples that may enable industry practitioners to evaluate the applicability of the method in their organizations and projects.

Information for the case study was gathered from two main sources.

1. Review and assessment of construction plans, in the format of excel spread sheets exported from Primavera P6, and documentation of target pull plan meetings in which the durations of each task were re-examined, and a revised plan was developed.
2. Semi-structured one-hour interviews were conducted with key personnel, including the project manager, the piping subcontractor, and the owner representative (the tool owner). The interviews included open questions regarding the application and influence of each of the seven OCF principles at the project and organization level. Additionally, interviewees were asked to elaborate on the assumptions and actions that enabled CT reduction.

DOUBLING THE THROUGHPUT

To provide context for the case study, this section presents preliminary empirical results from OCF implementation on over 1,700 projects to date. The case study applies a magnifying glass to one of these projects.

At the organizational level, OCF implementation was done in a pincer movement: from one side, reduction of CT at the single project level (as detailed in the case study), and from the other side WIP management via “OCF batching”, to ensure only ready and required projects enter the construction phase, considering the demonstrated capabilities of the production system. Figure 2 illustrates a non-feasible baseline plan (in red) with extreme peak points regarding WIP levels, compared to an OCF batching plan (in green) which provides stable WIP levels. Figure 3 presents a non-feasible baseline Gantt chart that illustrates the number of projects under construction at the same time, compared to an OCF batching plan, with 24 batches of projects. Once OCF batching is combined with targeted 50% CT reduction at the single project level, doubling the TH becomes feasible.

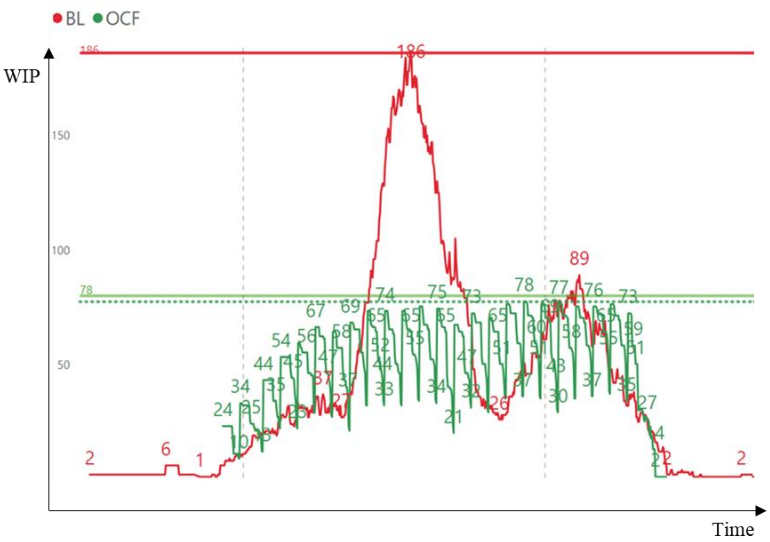

Figure 2: WIP levels of a non-feasible baseline plan compared to a OCF batching plan (Credit: Intel Corporation).

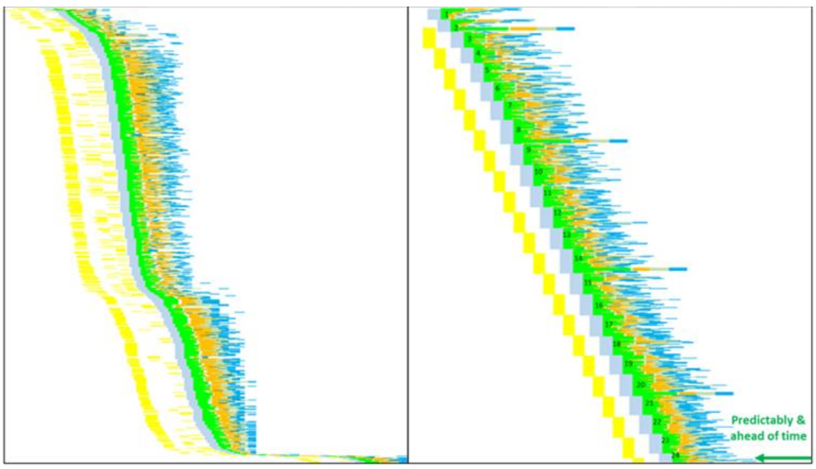

Figure 3: Gantt chart of a non-feasible baseline plan (left) compared to an OCF batching plan (right) (credit: Intel Corporation)

Figure 4 presents data analysis of 682 projects carried out from last quarter of 2018 till the mid of 2022. The red columns present the performance before OCF implementation (including accelerations taken in most of the projects). The green columns present the performance after OCF implementation, with a 242% improvement in TH and 59% reduction in CT.

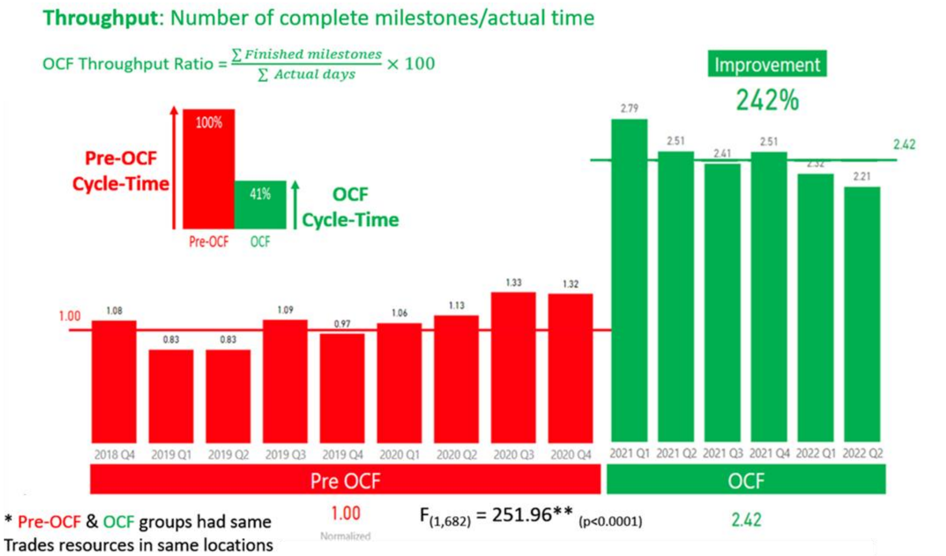

Figure 4: Doubling TH and reduction of CT by 50% after OCF implementation

CASE STUDY: OCF IMPLEMENTATION ON AN INSTALLATION PROJECT

BACKGROUND

This case study focuses on OCF implementation on a typical tool installation project in one of Intel's fabrication factories. The factory, which is spread over thousands of square meters, includes over one thousand tools that must be installed at a millimeter tolerance level and must enable efficient space usage. In these projects, the factory in general and specifically each "tool owner" is referred to as the client, and value is measured through their lenses. Thus, a project that provides most value is one that is pulled according to production needs, meets specifications, and is carried out in minimal cycle times and disruptions to the production process.

The location breakdown structure of the project included three locations where work was performed: Level 1 – the Utility Level – contains electrical panels, utility pipes and ductwork that feed up to the sub fab; Level 2 – the Sub-Fab – contains pumps, transformers, power cabinets and other systems that support the clean room; Level 3 – the Fab or "clean room" – includes the tool itself and the interface with the products and workers on the production line. Figures 5 and 6 illustrate the three locations of the project, and Figure 7 illustrates workers at the clean room level (they wear "bunny suits" to maintain the sterile production environment). The construction scope herein is being done in all 3 levels mentioned above. Four main trades, from different subcontractors, took part in the project: Electrical, Piping, Ductwork, and Architecture-Carpenters. The trades worked in close coordination with the tool owner, who was also required to take actions at several steps in the process.

In general, the work breakdown structure of a typical tool installation project includes three main phases: Phase 1 – connection of the lateral lines at the sub fab to the clean room, according to the location of the tool to be installed ; Phase 2 – tool installation works at the clean room, that involve only non-dangerous gases and electrical charging; Phase 3 – tool installation works at the clean room, that involve dangerous gases.

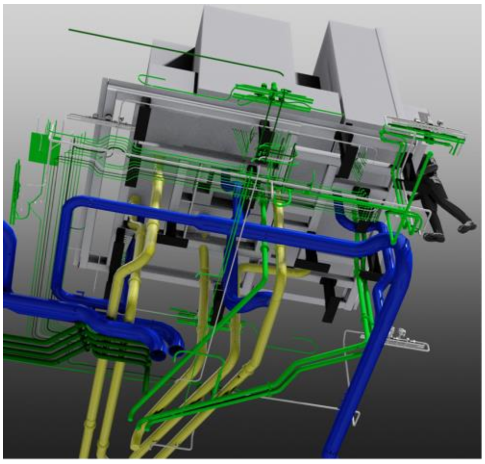

Figure 5: 3D perspective of the Sub-Fab and Fab level

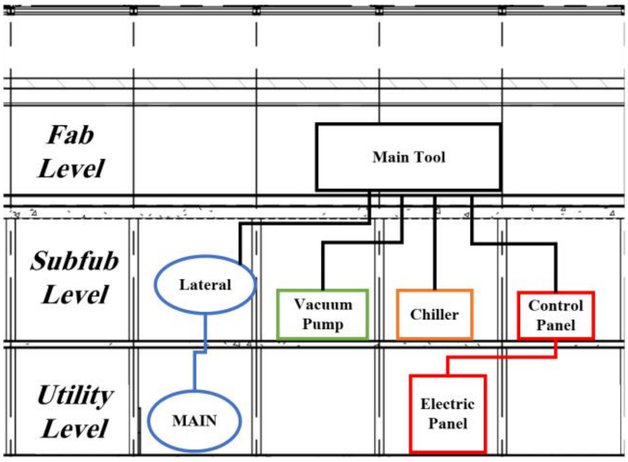

Figure 6: Location Breakdown Structure of installation projects at a typical Fab

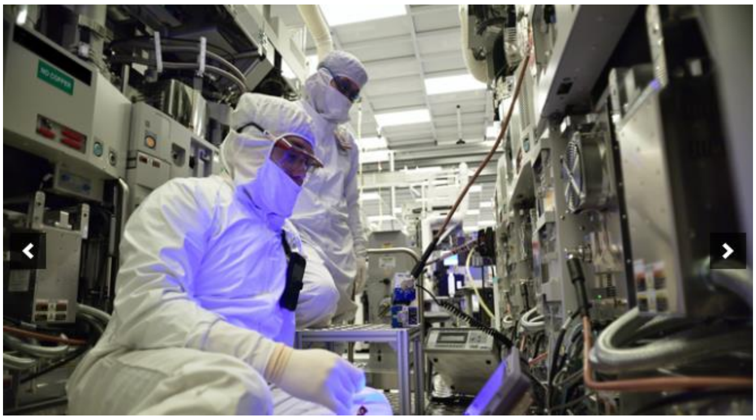

Figure 7: Installation workers at the clean room level of a Fab

CONSTRUCTION PLANS

The project was carried out using LPS and Pull scheduling, which were already implemented throughout the company's projects, and the teams were experienced in their operation. The preliminary plan, with a duration of 61 working days, is presented in Figure 8. During the application of OCF, a “Target Pull Plan” was collaboratively developed, to meet the company’s strategy to reduce installation projects cycle times. The Target Pull Plan, with a duration of 24 working days (CT reduction of 61%), is presented in Figure 9. Visual comparison between the plans highlights how the Target Pull Plan led a reduction in the duration and increased the work in parallel. It should be noted that the project was completed according to the plan, with a PPC above 90%.

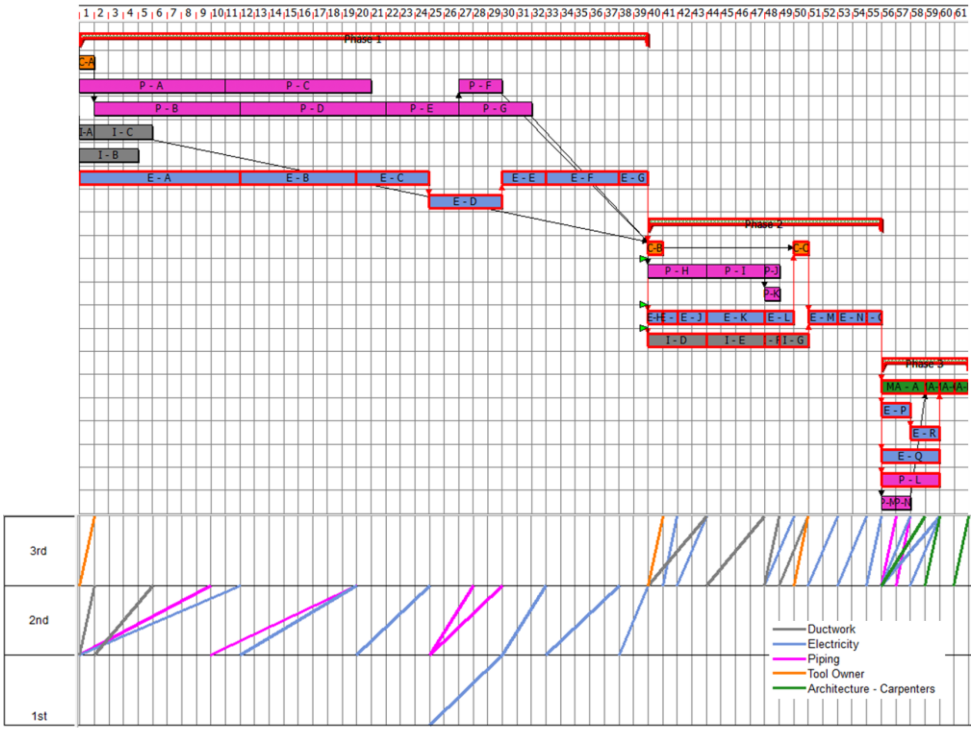

Figure 8: The preliminary baseline plan, before OCF implementation.

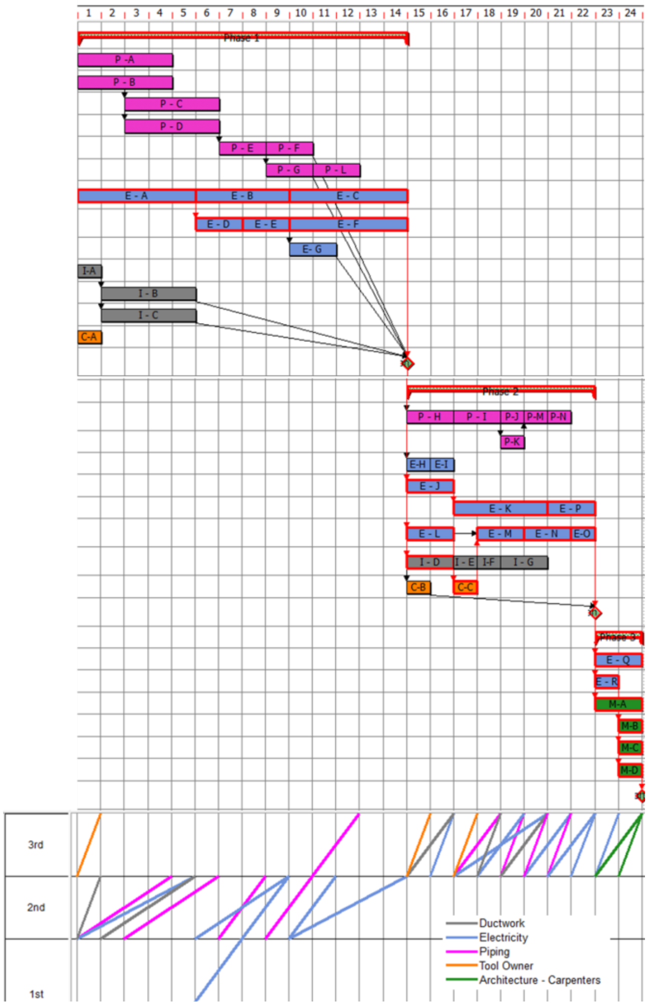

Figure 9: The 50% Target Pull Plan for OCF implementation.

IMPLEMENTATION OF THE SEVEN OCF PRINCIPLES

After the preliminary plan and the Target Pull Plan were compared, and illustrated the dramatic reduction in the project duration, semi-structured interviews were held with key personnel in the project to understand how the seven principles were implemented. The personnel interviewed included: the Project Manager (PM) from the construction division of the owner; the piping subcontractor (P-Sub), and the tool owner (the internal costumer). Interviewees were asked to elaborate on how each of the seven principles manifested at the project and organization level. In addition, they were asked to refer to the essential changes between the preliminary plan and the Target Pull Plan (Figures 8 and 9), and to describe how these changes were made possible. Highlights from the interviews, regarding each of the principles, are presented in the following sections.

Principle 1 - "Plan and Integrate Strategically": This refers to the organizational strategy to double the TH of completed installation projects, by OCF batching to control the WIP levels, and by setting 50% reduction target. Interviews highlighted that strategic planning was the core principle that initiated OCF implementation. The tool owner emphasized that completing the project with minimal CT, once all necessary preconditions are met, allowed early beginning of production in the Fab, thus increasing the competitive advantages of the organization.

The P-Sub admitted that at first, he thought this strategy would require investment of additional resources, but he took the leap of faith and "the results speak for themselves." In a pre-OCF environment, part of his business model relied on accelerations as projects were running late. With the long-term strategy, including OCF project batching (Figures 2 and 3), the piping company was able to maintain a stable, reliable cash flow, invest in well skilled trades, and undertake more projects per annum. He admits that "…with OCF and without accelerations, the profitability was improved and predictable".

All trades agreed that reducing the WIP enabled resources availability, and increased motivation to complete the project and move on to the next OCF batch. It also enabled them to generate greater value for the customer, who could start production earlier, and with minimal interruptions.

Principle 2 - "Plan Tactical Targets": The preliminary plan was revised, and a Target Pull Plan was collaboratively developed according to the strategy of doubling TH and reducing CT. As seen from the comparison of the preliminary plan and the target pull plan (Figures 8 and 9), a CT reduction of 61% was reached on this project. During the Target Pull Planning the trades were required to challenge the assumptions reflected in the preliminary plan, regarding both durations and feasibility to perform several tasks in parallel.

At the first stage, the team examined the feasibility that baseline duration estimates could be reduced if they could work on substantially fewer projects in parallel. Each trade was required to examine whether they could commit to shorten the durations by 33%, 50% or 80%. This approach led the trades to re-examine their work assumptions. In some cases, the answers were unequivocally negative. However, for a significant number of tasks, possibilities emerged as it became clear that long durations with inflated internal buffers were assumed in the preliminary plan.

At the second stage the logical connections between tasks were re-examined, possibilities for simultaneous work were considered, and an improved workflow sequence plan was developed. Once the trades let go of the limiting assumption that each trade must require a separate location for any work to be performed, the door was also opened for many opportunities to work in parallel. Thus, a "lean" production plan was established, relying on the targeted required durations, and sound logical connections. It should be noted that once the durations were reduced, some of the tasks gained a positive total slack, and buffer management became possible (Goldratt 1997; Goldratt et al. 2004). Additionally, production was shielded by limiting the number of concurrent projects (WIP) for each trade, allowing resource availability, enhanced motivation for early completion, and improved workflow for each trade, as well as earlier cash flows (because payments are approved upon completion of work).

Principle 3 - "Collaborate": This principle was brought up many times in interviews and in different contexts, highlighting its importance and lateral influence. Tight collaboration was shown by trades at the Gemba, senior management of the subcontracting companies, and by the tool owner. The PM demonstrated how trades coordinated their daily work at an hourly level of resolution, to enable a significant portion of work to be performed in parallel at the same location. Even lunch breaks were coordinated to enable trades to perform specific tasks that require the entire location, with minimal influence on other trades. Senior management collaboration was reflected by the back-office support, including agile ad-hoc design coordination when needed.

There were voices in the organization that questioned whether the extensive parallel work would align with the safety standards of the organization. However, as the P-Sub explained, the opposite was the case: the exposure to safety incidents decreased as the CT of the project was reduced; the collaborative approach led to an improved safety environment, as safety plans where tightened and coordinated; inputs were generated from the safety inspectors of each trade, enabling preventive actions ahead of time.

Collaboration was also the key for coordinating the work performed by the tool owner and the vendor, enabling them to perform their work in parallel to the installation team. The tool owner emphasized his presence and availability on site and his commitment to respond in real time to any constraint that may arise during the work (contrary to traditional RFI processes that may be untimely, sequential and cause work stoppages).

Principle 4 - "Resolve constraints": This principle integrates with the look-ahead plan and the make ready process in LPS. The P-Sub explained that traditionally each trade was required to provide its own working platform, that not only did not fit the needs of the other trades, but in most cases blocked their access. To resolve this constraint, the trades planned an integrative working platform, that would fit the needs of all trades and would enable them to work in parallel. As described regarding principle 3, the PM and the tool owner had substantial influence to resolve constraints in real time. This included providing design solutions at the Gemba, without triggering a cumbersome system of "design changes".

Principle 5 - "Restructure Resources": the preliminary plan clearly shows that the electrical works were on the critical path, and the electrical team was working at its full capacity, indicating the presence of a bottleneck. It was suggested to restructure the resources within the electrical team. The senior electrical team that worked on the project received a broader role, including mentoring of junior teams in a portfolio of projects, and a reinforced motivated junior team was assigned to the project enabling reduction of the bottleneck effect.

Principle 5 was also implemented by maximizing the potential for off-site pre-fabrications of the piping works, enabling dramatic reduction of the welding required on site. As a result, the piping trade was able to carry out more tasks in parallel, with improved safety and reduced disruptions to the other teams.

Principle 6 - "Control Project Start": In the pre-OCF environment, in general, tool owners would drive the system based on push strategy, meaning that projects would start as soon as possible, regardless of projects maturity levels, and even if the tool vendors' delivery dates were far off. In that situation, the project technically could not be completed, increasing the cycle times dramatically. Under OCF strategy, the tool owner shifted to a pull strategy that triggered the project only once it reached a suitable maturity level, and Just in Time regarding the vendor's delivery date. The tool owner explained that without this principle, "we may end up in situations where after installations are started, the trades can't complete their job and switch to start another installation, then when the prerequisites are met, the trades or the vendor are no longer available, and so on". Thus, the tool owner made sure to complete all prerequisites before the project was launched.

Principle 7 – "Ensure Project Flow": This principle refers mainly to the construction phase once the project is carried out. To ensure project flow, the entire supply chain must align with the project and provide full backup. This was achieved through the personal involvement of stakeholders, with direct communication to coordinate and resolve any issues that arose. The project was carried out with the "…touch the project once…" concept in mind of all trades, while fully focusing on the project, and without diverting attention to future or parallel projects.

DISCUSSION AND CONCLUSIONS

The case study demonstrates application of OCF at the single project level, detailing how it works through implementation of seven principles. The results reinforce the conclusions from empirical results that showed enhanced performance in over 1700 projects where OCF was applied.

Analysis of construction plans in the case study (Figures 8 and 9) revealed over 50% waste removal, in the form of inflated durations that were considered a cushion to absorb delays. We suggest that the presence of non-value adding times in such work scopes reflect planning failure, which leads to inflated internal buffers. It is likely that these types of waste can be found in many construction projects, even when planning is done using proven methods (e.g. LPS), as plans are ultimately based on motivations, constraints, and internal buffers of each individual trade. Thus, setting strategic and tactical goals to reduce durations, may initiate identification and removal of this type of waste. As detailed in the case study, work plans were coordinated on a half-day level of precision, with tight collaboration of the trades, to ensure optimal workflow and waste removal.

Critical production thinking manifests in OCF strategy through the first two principles: "Plan and Integrate Strategically" and "Plan Tactical Targets". These principles are the pillars of OCF and are a necessary condition to OCF strategy success. Once the first two pillars are set and an organization aims to double its throughput, the other principles of OCF should pave the way to the desired results. As presented in the literature review, the principles are deeply rooted in previous LC work, and thus enhance implementation of other methods as well (e.g. LPS).

The interviews highlighted the importance of vertical integration of all parties in the project. This was reflected as senior managers were present in the Gemba, emphasizing their personal commitment, and providing real-time solutions to remove constraints. This integration was reinforced once the WIP levels were controlled, allowing the focus required on the individual project.

The multi-project environment was recognized as a catalyzer for OCF. The trades adopted a macro perspective that enabled them to level the WIP and reduce the CT, and to enable continuous flow from one project to the other. This was also reflected by the relinquishment of the traditional reward mechanisms (e.g. accelerations), preferring stable cash flow, that allows investment in long term resources and human capital fed with continuous work (as reflected from the OCF batching strategy presented in Figures 2 and 3). We argue that a multi-project environment is not a "given condition", but rather a perspective that arises from critical production thinking, and a clear product and value proposition. Therefore, it may apply to a variety of construction environments. For example, a residential building can be examined as a multi-project environment, with each apartment being a sub-project with a different customer (Sacks & Goldin, 2007). Thus, reduction of CT and increasing TH will reflect completed apartments delivered to customers.

This study was limited to the context of OCF implementation on an installation project in a manufacturing plant environment. Further studies are required to test and evaluate the working mechanisms of OCF outside the factory walls and on non-repetitive projects.

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REDUCTION OF FLOOR CYCLE TIME VARIABILITY IN HIGH-RISE BUILDING CONSTRUCTION

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ABSTRACT

High-rise building construction projects, characterized by their inherent complexity and susceptibility to unpredictable variations such as complex logistics, weather, and resource availability, often face challenges in maintaining schedule reliability. Despite the potential for optimization due to the repetitive nature of high-rise structures, traditional planning methods struggle to address the cascading effects of variability, resulting in long cycle times for completed floors and frequent shifts in estimated completion dates. This paper presents the outcomes of implementing a Last Planner System (LPS)-based strategy for the structural frame of two high-rise buildings. Key performance metrics such as cycle time, production rates, and labor productivity were chosen to evaluate the impact. The findings demonstrate that detailed operational planning and interventions to support continuous improvement reduce the floor cycle time and its variability. Furthermore, the results offer tangible evidence of actual performance, providing practitioners with the necessary data to create more realistic master plans. This approach enhances the operational efficiency of high-rise construction projects and contributes to the broader understanding of effective strategies for managing schedule variability.

KEYWORDS

Phase scheduling, flow, variability, continuous improvement, standardization.

INTRODUCTION

The Last Planner System (LPS) is widely recognized for its effectiveness in improving production planning and control, steering projects toward their goals (Ballard & Tommelein, 2021). Despite decades of lean research and industry practice, many construction firms still rely on traditional methods like Gantt Charts and a transformational view of construction (Bølviken & Koskela, 2016). Previous research has investigated high-rise building construction, with a particular focus on the production planning of control for interior finishing work (Sacks et al., 2005), façade installation (Friblick et al., 2009), and formwork technologies (Abou Ibrahim & Hamzeh, 2015). Moreover, some studies in high-rise construction have explored the effect of learning curves on specific activities such as interior wall installation (Lee et al., 2015), formwork installation, and rebar fabrication and installation (Nguyen & Nguyen, 2013). Despite these efforts, there appears to be a notable gap in prior research concerning the

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assessment of floor cycle time performance for structural frames in high-rise construction and its association with overall project performance, including floor-level production rates and labor productivity (Murguia et al., 2022). Understanding the relationship between cycle times and project performance serves as evidence to advance the adoption of lean construction techniques in the sector further.

High-rise building structures face challenges such as resource availability, supply chain issues, complex logistics, and weather, leading to unpredictable cycle times and significant delays. To address these challenges, an LPS-based implementation strategy involving daily work planning, design of operations, and continuous improvement was implemented in this research during the structural phase of high-rise building construction. Two high-rise buildings in Mexico City using in-situ reinforced concrete structures with post-tensioned slabs were investigated as case studies. The structural frame contractor confronted the challenge of accelerating concrete structure delivery due to unforeseen delays, presenting an opportunity to introduce optimization tools to minimize cycle times and bridge the gap between plans and actuals. The paper details the specific tools implemented in the case studies, such as collaborative operation analysis, crew balance charts, and time-motion studies. The primary objectives were to manage variability in floor cycle time and quantify project performance metrics, including floor-level production rates and labor productivity. The results address current gaps in project planning and control for the structural frame in high-rise building construction. Furthermore, the findings contribute to planning more precise (and realistic) master schedules for clients, cost consultants, and contractors in agreeing upon project milestones. This research seeks to provide evidence of performance improvement and illustrate the possibilities when production planning and control are coupled with meaningful project control metrics.

RESEARCH BACKGROUND

Cycle time variability is prevalent in construction projects and necessitates effective management. Reducing and coping with variability is a key concept in lean construction (Thomas, 2002). The LPS was developed to protect construction operations from upstream flow variability (Ballard & Tommelein, 2021). However, variations in production systems can be reduced but never eliminated. Therefore, an LPS-based implementation strategy, including detailed work planning and design of operations, are required to absorb those variations and shield-protect targets. In addition, effective performance evaluation metrics are needed to assess the effectiveness of interventions.

CYCLE TIME AND VARIABILITY

Cycle time is defined as the cumulative duration of activities minus overlaps between activities plus the sum of waiting times (i.e. work discontinuities). Consequently, cycle times can be reduced by reducing waiting times and activity durations and increasing overlapping activities (Ballard, 2001). Gabai & Sacks (2020) provided strong evidence of cycle time reduction of up to 48% by implementing a lean-based method called "optimized installation flow" in industrial infrastructure installation in the semiconductor industry. In structural frame construction, the floor cycle time is the time elapsed between installing the first vertical element on a floor (start date) and the last slab concrete pour on that floor (finish date).

DAILY WORK PLANNING AND DESIGN OF OPERATIONS

A wealth of evidence, both in research and practice, supports the implementation of weekly work planning within the LPS. However, one of the least implemented components of the LPS is the design of operations at the daily planning level (Ballard & Tommelein, 2021). The design of operations entails collaborative planning among Last Planners (foremen or front-line supervisors) and craft workers responsible for executing the tasks. Operations encompass the steps to be carried out by one or multiple workers, specifying the steps, durations, sequence, individuals responsible for each step, and the pathways for workers, equipment, and materials (Ballard & Tommelein, 2021). Previous research has investigated productivity enhancement through detailed production planning, involving eliminating non-contributory work and increasing the Percent Plan Complete (PPC) (Ghio, 1997). The findings underscored the need for daily work planning to effectively manage change orders and devise efficient task completion strategies without escalating the workforce size. However, there is still insufficient evidence of the relationship between daily work planning and project performance metrics.

PROJECT PERFORMANCE METRICS

The expanding body of literature reveals a growing understanding of the relationship between production planning and control within the LPS, and its impact on project performance. Pérez et al. (2022) delved into key LPS metrics to evaluate project performance in high-rise buildings. Analyzing a dataset of 71 projects in Chile, they correlated production planning and control metrics, namely Percent Plan Complete (PPC) and constraint removal time (CRT), with output metrics such as the schedule performance index (SPI) at the planned completion point. The results indicated moderate correlations (between 0.3 and 0.4) between PPC, CRT, and SPI. Similarly, Liu & Ballard (2009) demonstrated the need for daily planning to enhance workflow reliability and labor productivity. Analyzing data from 592 working days, they found moderate associations between labor productivity and PPC with commitment plans and favorable weather conditions (correlations between 0.34 and 0.42). Arumugam & Varghese (2014) proposed a method to characterize flow in the reinforced concrete structure of high-rise apartment buildings, noting a floor cycle time of 6 to 8 days. However, as the floor area per level was not reported, benchmarking a floor-level production rate was not feasible. In contrast, Veran-Leigh et al. (2022) provided benchmark values for production rates of structural works of 63 m²/day and 73 m²/day but did not correlate PPC metrics with performance values.

RESEARCH METHOD

This research selected the case study approach to investigate the phenomenon (i.e., the case) in depth and within its context (Yin, 2014). Several sources of data were collected to achieve the research objectives: project documents (contractual programs, daily plans, design of operations), quantitative data (concrete pours, crew size, number of worker-hours), and qualitative data (on-site research observations) during the structural frame construction. Data were screened to ensure quality and analyzed using statistical tools. Based on Murguia et al. (2023), the following performance metrics were established: cycle time (days), production rate (m^2/day), and labor productivity (m^2/worker-hour). These metrics align with the research aim, which is to provide evidence-based project performance due to the implementation of daily work planning and continuous improvement strategies.

CASE STUDY DESCRIPTION

Project U, a 60-story residential development in downtown Mexico City, features 18 basement levels, a Total Gross Floor Area (TGFA) of 48,745 m² and a total height of 207 m. The typical floor has 847 m² of Gross Floor Area (GFA). Figure 1 shows the typical floor plan. The structural frame is a reinforced concrete structure with post-tensioned slabs and an average rebar density of 88 kg/m². Construction commenced in May 2021, and a single tower crane was part of the construction strategy. Project P, a 31-story luxury hotel project in a high-end residential neighborhood with a total height of 106 m, boasts a TGFA of 27,432 m², with floors averaging 945 m². Each floor was divided into two slab pouring events to accelerate the schedule (Figure 1 shows the typical floor plan with the division considered). Unlike Project U, the main structure had an average rebar density of 107 kg/m², reflecting higher structural safety standards demanded by the client. For both projects, the typical activities within the floor cycle included setting out, vertical rebar (columns and shear walls), vertical formwork, concrete pour of vertical elements, beam formwork, beam rebar, slab falsework and formwork, slab rebar and slab pours.

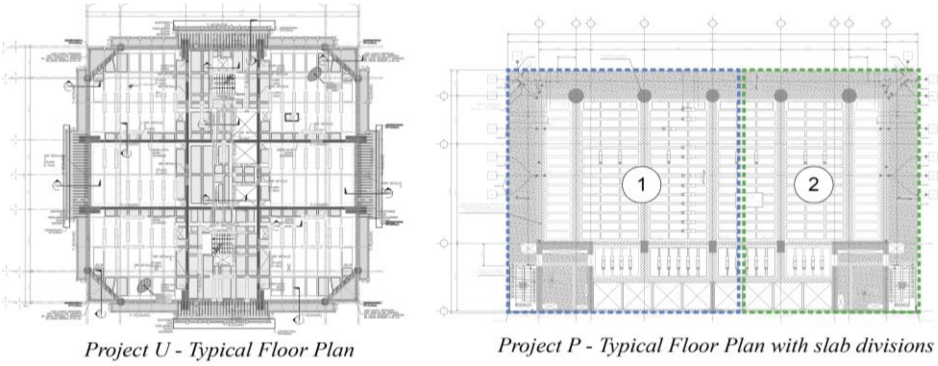


Figure 1: Project U and Project P's typical floor plans

LPS-BASED IMPLEMENTATION STRATEGY

Both projects implemented a lean-based approach led by the contractor's top management and an external lean consultant. Field engineers and crew leaders actively led daily work planning sessions, conducted collaborative operation analyses, and monitored crew balance charts. Figure 2 illustrates the key steps of the LPS-based implementation strategy.

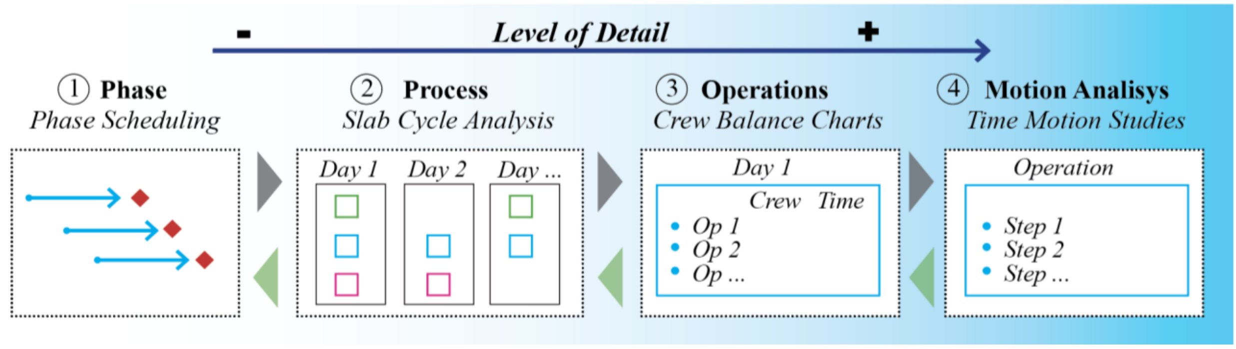


Figure 2: LPS-based implementation strategy

1. *Develop a phase schedule*: A collaborative schedule was developed by field engineers and project managers, incorporating milestones agreed upon with the developer. This step provided a robust framework for sequencing and monitoring progress.
2. *Slab cycle analysis – Daily operations by crew*: Through workshops with crew leaders, a collaborative approach was used to define the entire slab cycle for carpenters, steel fixers and concrete gangs. This ensured buy-in and alignment from all participants.
3. *Implementation and evaluation - Crew Balance Charts:* Operations listed on the corresponding day of the slab cycle analysis were handed to each crew using Crew Balance Charts and evaluated at the end of the day.
4. *Time-Motion Studies*: All the operations in the slab cycle, starting with the most repetitive, were analyzed using Time-Motion Studies. This allowed for a better understanding of all the steps involved in the operations and included suggestions from workers and field engineers.

RESULTS

The strategy was implemented from level 25 onwards on Project U and after level 3 on Project P, leading to different outcomes. In Project U, the structural frame reached the 25th floor with delays exceeding the contractual timeline. Further complicating matters, Project U experienced highly variable slab cycle times ranging from a swift 10 days to a staggering 54 days, primarily due to unforeseen disruptions caused by overlooked activities in the program, such as rebar bending or tower crane availability. On the other hand, the developer in Project P requested faster delivery times. However, Project P faced unique challenges, including the developer's control over the tower crane, which limited material availability for the contractor, especially rebar and falsework movement. Furthermore, Project P's spatial constraints needed off-site rebar cutting and bending, impacting additional processes such as pre-ordering and increasing inventory management efforts owing to large batches for reduced shipping costs. Moreover, the implementation strategy encountered significant organizational challenges, such as limited engagement from both crew and engineers, undefined roles, overlapping responsibilities, and communication problems. These issues required resolution before the implementation of the strategy, underscoring the critical role of robust on-site management in ensuring planning at the operational level and project success.

(1) Phase Scheduling

A collaborative planning session was conducted in line with pre-established milestones agreed upon with the owner's project managers, superintendents, and field engineers. This session brought together structural engineers with the construction team to thoroughly understand project constraints and determine the feasible number of slab partitions considering the structural design. In Project P, this analysis concluded that two pouring events were possible, while Project U could only accommodate one. This crucial definition directly informs the overall schedule and subsequent strategic decisions.

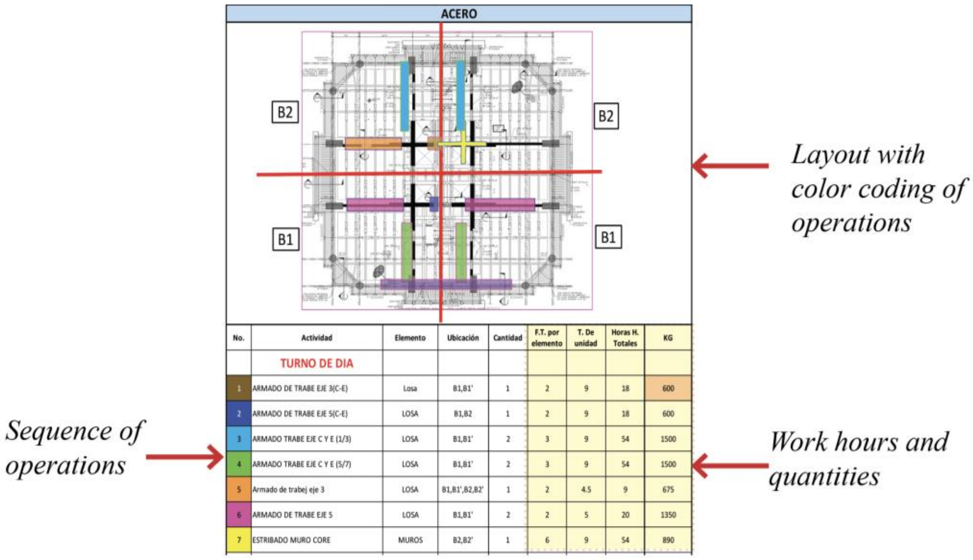
Additionally, these sessions established the general sequence and order of activities based on the specific site context. Factors considered included tower crane placement, personnel access, and material supply. This collaborative approach ensured optimal planning tailored to the unique conditions of each project.

(2) Slab Cycle Analysis: Daily Operations per Crew

At the outset of the implementation strategy, superintendents, field engineers, and crew leaders collaborated to develop detailed slab construction cycles for both projects. Project P achieved a 9-day cycle, while Project U required a 10-day cycle. These cycles outlined daily operations and responsibilities for carpenters, steel fixers, and concrete crews, highlighting critical interactions and potential constraints faced by each team (e.g., crane availability, dependencies on previous tasks, material availability, and post-tensioning requirements).

These slab cycles served as a starting point and were revised throughout the project lifecycle. Bi-weekly on-site reviews, led by the superintendent and lean consultant, incorporated lessons learned from time-motion studies and addressed execution challenges, such as overlapping activities and material handling issues.

Marked-up floor plans served as crucial visual aids in this process. Crews used these plans to map out the daily operation sequence, specifying required work hours, work quantities (kg, m2, m3), and specific locations for each task. Figure 3 exemplifies this concept for Day #3 of the slab cycle in Project U, focusing on rebar installation. It illustrates the operational sequence, labor resource allocation, and a color-coded layout to facilitate spatial coordination. This detailed planning process enhanced crew coordination and minimized unforeseen disruptions during construction.



No.	Actividad	Elemento	Ubicación	Cantidad	F.T. por elemento	T. De unidad	Horas H. Totales	KG
	TURNO DE DIA							
1	ARMADO DE TRABE EJE 3(C-E)	Losa	B1,B1'	1	2	9	18	600
2	ARMADO DE TRABE EJE 5(C-E)	LOSA	B1,B2	1	2	9	18	600
3	ARMADO TRABE EJE C Y E (1/3)	LOSA	B1,B1'	2	3	9	54	1500
4	ARMADO TRABE EJE C Y E (5/7)	LOSA	B1,B1'	2	3	9	54	1500
5	Armado de trabej eje 3	LOSA	B1,B1',B2,B2'	1	2	4.5	9	675
6	ARMADO DE TRABE EJE 5	LOSA	B1,B1'	2	2	5	20	1350
7	ESTRIBADO MURO CORE	MUROS	B2,B2'	1	6	9	54	890

Figure 3: Visual aid example for Daily Work Plan (Project U)

(3) CREW BALANCE CHARTS

At the end of each workday, and based on the corresponding slab cycle plan, field engineers and crew leaders convened to develop Crew Balance Charts (CBC) to assign activities to carpenters, steel fixers and concrete finishers. These CBCs were handed to each crew member, detailing the operations expected for the following day, specifying the allocated worker-hours, time of day, crew identification, material quantities, and its location within the slab (Figure 4). During these on-site meetings, field engineers evaluated the operations performed during the day and any challenges encountered. Based on this evaluation, the team adjusted the CBC for the following day, incorporating mitigation plans when necessary.

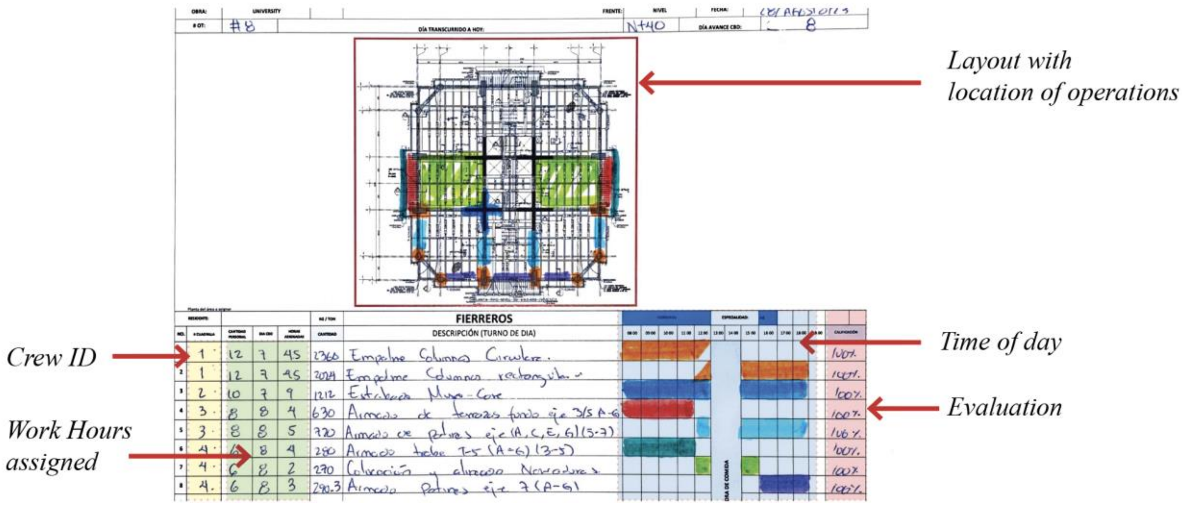
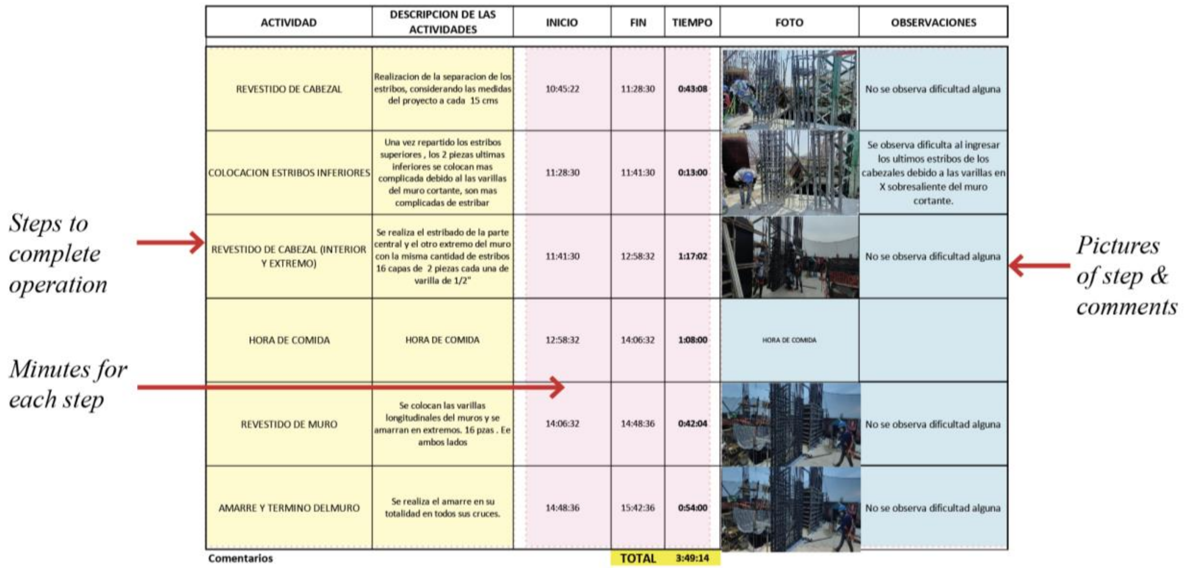


Figure 4: Crew Balance Chart for steel fixers

(4) TIME-MOTION STUDIES

To further refine the process and to validate the time considered in the slab cycle, time-motion studies were conducted by the lean consultants on most operations, starting with repetitive operations constituting up to 80% of the slab cycle, such as standard columns, shear walls and main beams. An illustration of one such study is depicted in Figure 5, focusing on rebar installation within a shear wall. The study outlined all necessary steps for completing the shear wall and the allocated time for each step, accompanied by a concise description, visual aids, and observations regarding potential improvements.

This approach fostered a collaborative environment by actively incorporating crew members and field engineers to suggest improvements for individual steps within each operation, ultimately enhancing overall slab construction performance. These studies not only validated execution times for future slab cycles but also highlighted opportunities for improvement, prompting targeted problem-solving efforts. Additionally, they served as valuable resources for training new crews on-site and standardizing procedures across all existing teams.



ACTIVIDAD	DESCRIPCION DE LAS ACTIVIDADES	INICIO	FIN	TIEMPO	FOTO	OBSERVACIONES
REVESTIDO DE CABEZAL	Realizacion de la separacion de los estribos, considerando las medidas del proyecto a cada 15 cms	10:45:22	11:28:30	**0:43:08**		No se observa dificultad alguna
COLOCACION ESTRIBOS INFERIORES	Una vez repartido los estribos superiores , los 2 piezas ultimas inferiores se colocan mas complicada debido al las varillas del muro cortante, son mas complicadas de estribar	11:28:30	11:41:30	**0:13:00**		Se observa dificulta al ingresar los ultimos estribos de los cabezales debido a las varillas en X sobresaliente del muro cortante.
REVESTIDO DE CABEZAL (INTERIOR Y EXTREMO)	Se realiza el estribado de la parte central y el otro extremo del muro con la misma cantidad de estribos 16 capas de 2 piezas cada una de varilla de 1/2"	11:41:30	12:58:32	**1:17:02**		No se observa dificultad alguna
HORA DE COMIDA	HORA DE COMIDA	12:58:32	14:06:32	**1:08:00**	HORA DE COMIDA	
REVESTIDO DE MURO	Se colocan las varillas longitudinales del muros y se amarran en extremos. 16 pzas . Ee ambos lados	14:06:32	14:48:36	**0:42:04**		No se observa dificultad alguna
AMARRE Y TERMINO DELMURO	Se realiza el amarre en su totalidad en todos sus cruces.	14:48:36	15:42:36	**0:54:00**		No se observa dificultad alguna
Comentarios			TOTAL	3:49:14		

Figure 5: Time-motion study example of rebar installation in shear walls

PROJECT PERFORMANCE

To visualize project performance, the master-level flowlines, as described in Murguia et al. (2023), were used to compare plans and actuals for both projects. Furthermore, production rates and labor productivity were estimated from the labor and concrete pour data. The flowlines in Figures 7a and 7b show that both projects missed the contractual completion dates for the structural frame. However, the strategy described in this paper was implemented from the 25th floor onwards on Project U. As shown in Figure 7a, this led to a noticeable acceleration in the cycle time, represented by the steeper slope of the actual line after that level. Had this strategy not been implemented, the project would have likely overrun the contractual deadline even further. The review of the actual performance results showed that the contractual dates for Project P were unrealistic because planners during the tender stage considered weekends or holidays within the contractual cycle times. These observations were evident in the unreasonably short timeframes, such as 7 days for completing 945 m^2 of work, creating a pace of 135 m^2/day, not very common in the industry for in-situ reinforced concrete frames with a single crane.

The boxplots in Figure 8 summarize the cycle time data. During the first stage of Project U (Floors 7- 25), the minimum cycle time was 10 days, whilst the maximum was 24 days (some outliers up to 54 are outside the boxplot). The median was 15 days. Additionally, the first and third quartiles were estimated at 12 and 17 days, respectively, suggesting an interquartile range of 5 days. During the second stage of Project U (Floors 26-50), the minimum cycle time was recorded at 9 days, whilst the maximum was 14 days. The median cycle time was 11 days. Furthermore, the first and third quartiles were estimated at 10 and 12 days, respectively, suggesting an interquartile range of 2 days. Therefore, substantially less variability was achieved. Finally, the minimum cycle time for Project P was recorded at 9 days, whilst the maximum was 19 days. The median cycle time was 14.5 days. Moreover, the first and third quartiles were estimated at 13 and 16 days, respectively, suggesting an interquartile range of 3 days, suggesting less variability.

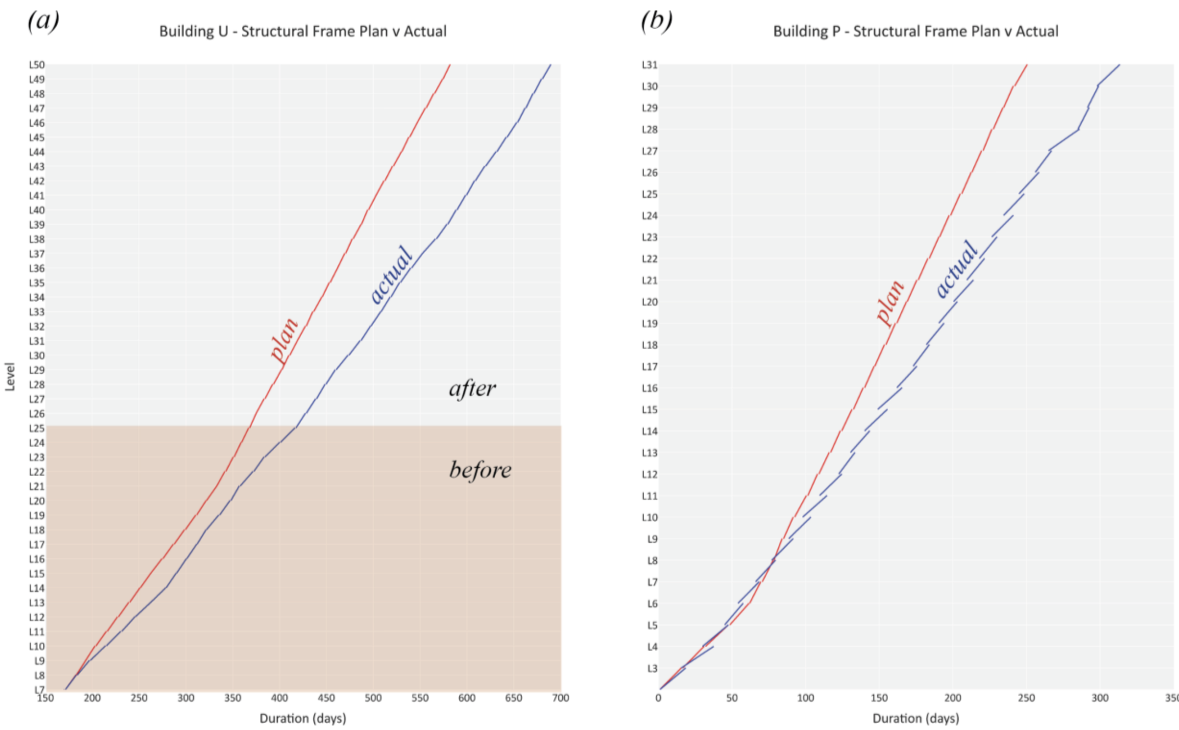


Figure 7a and Figure 7b: Flowlines (plan v actual) for Projects U and P

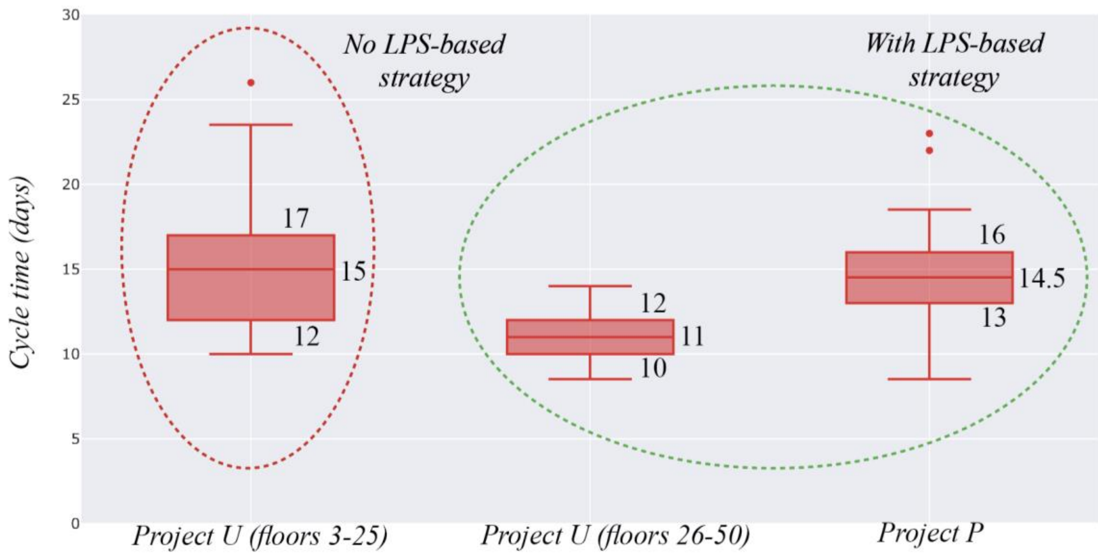


Figure 8: Cycle Time Boxplots for Projects P and U

TIME COMPRESSION AND WORKFORCE REDUCTION

Both projects experienced a significant acceleration in construction speed due to increased production rates, measured in square meters of GFA delivered per day. Notably, this was achieved while simultaneously reducing the number of workers required to complete each floor. For Project U (see Figure 9), the production rate before implementing the described LPS-based strategy (floors 7-25) was an average of 53 m²/day. In comparison, after implementing the LPS-based strategy (floors 25+), the average production soared to 79 m²/day, representing a **49% increase**, whilst **the number of workers had a reduction of 30%**. Overall, comparing phase 1 (levels 7-25) to phase 2 (levels 26-49), productivity increased from 3.5 m^2/100 worker-hours to 13.1 m^2/100 worker-hours, an astounding **274% increase**. In the case of Project P (see Figure 10), the production rate started at 67 m²/day and finished at 145 m²/day, marking a remarkable **116% increase**. In terms of the number of workers, there was a **29% reduction**.

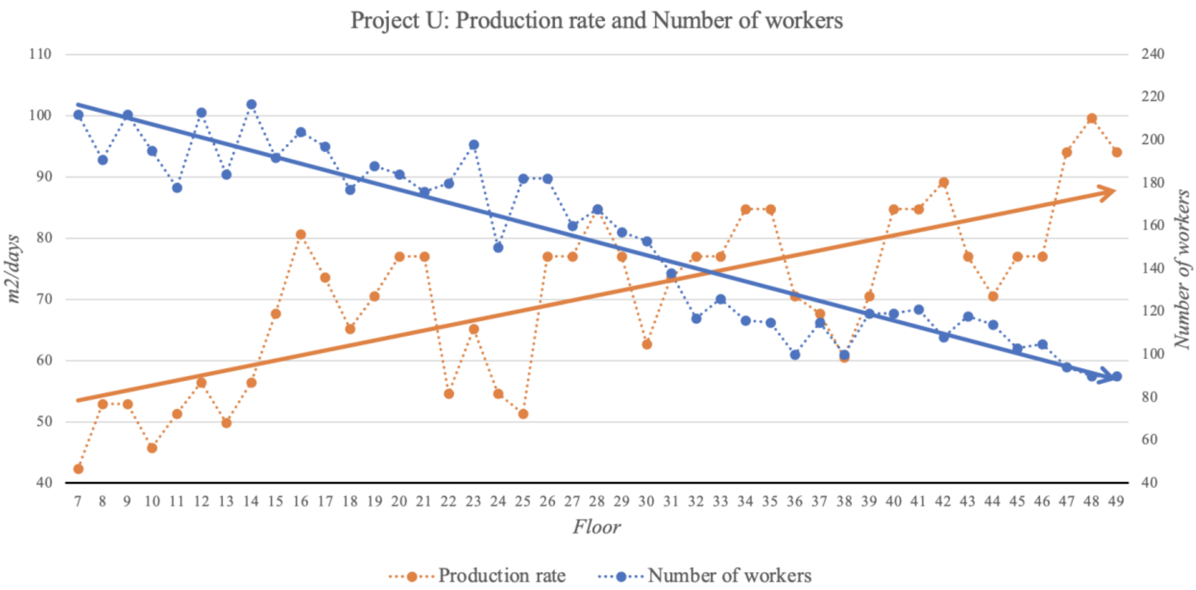


Figure 9: Productivity Metrics Project U

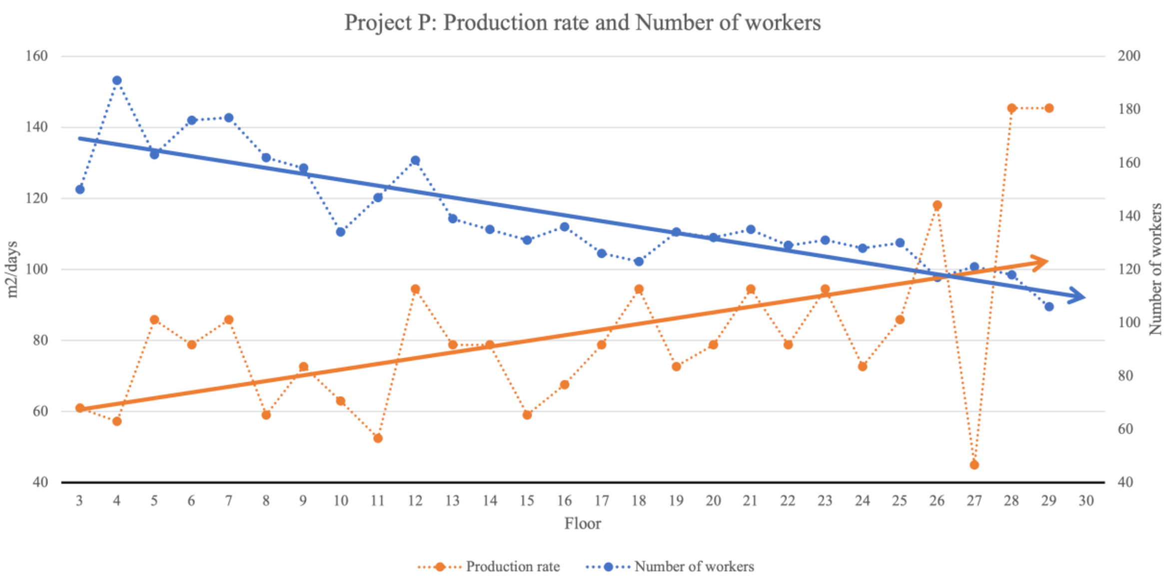


Figure 10: Productivity Metrics Project P

BEYOND PRODUCTIVITY: ADDITIONAL OUTCOMES

Building upon the productivity gains, both projects experienced **significant reductions in worker turnover.** Before the LPS-based implementation strategy, both projects faced substantial monthly worker rotation, averaging *41% for Project U and 43% for Project P*. These figures decreased to 18% and 24% on average for Projects U and P, respectively. The turnover decrease proved crucial for successfully implementing the LPS-based strategy by minimizing knowledge loss and the need for constant training of new workers. While a baseline level of worker turnover persisted, around 20% on average, on-site workers reported improved overall satisfaction. The initiatives described in this paper, including a 22% salary increase, likely contributed substantially to this positive shift in morale and commitment to continuous improvement.

DISCUSSION

UNREALISTIC CONTRACTUAL PHASE SCHEDULE

Despite operating in distinct contexts, both projects experienced significant benefits from the LPS-based strategy but did not meet the original contractual dates (Figures 7a & 7b). The contractor's planners developed these programs within the tendering team years before construction. It is worth noting that planners at the tender stage are typically unfamiliar with actual performance data or may inadequately consider the project context. Moreover, to secure contracts, a touch of optimism bias is introduced into the master plan. A data-driven, forward-thinking client would be prepared to procure projects that align more closely with actual performance. This approach to procurement would be crucial to avoiding misalignment between planned and actual timelines and, consequently, better predicting the overall duration of the structural frame.

WIN-WIN-WIN IMPACT AND FUTURE POTENTIAL

The LPS-based implementation strategy benefited all stakeholders: developers through reduced schedule variability, contractors through cost reductions, and the workforce through increased wages. Moreover, the incentive program is based on productivity gains, using CBCs and time-motion studies, effectively motivating crews and field engineers, demonstrating its potential for early adoption in future projects. Applying this strategy to subsequent trades such as façade, services, and fit-out in high-rise buildings holds immense promise. This could prevent gains in the structural phase from being negated by later trade bottlenecks, leading to overall project efficiency optimization. Further research exploring this application could pave the way for a more streamlined and cost-effective future for high-rise construction.

CONCLUSIONS

This study presented an LPS-based implementation strategy to support variability reduction of floor cycle time in the construction of high-rise building structures. The strategy included a master phase schedule, daily work planning, crew balance charts, and time and motion studies. The strategy was implemented in two live projects in Mexico City. The results showed a significant reduction in cycle time and its variability, leading to significant performance improvement for both production rate and workforce reduction. The significant gaps between plans (client's expectations) and actual (what is possible) need to be more aligned through a data-driven performance culture. This research uniquely presents performance data that can be used for benchmarking in future studies. This study has some limitations. PPC was not captured to correlate PPC performance and cycle time variability. Furthermore, the effect of learning curves was not considered in this study. Finally, future studies can examine other work packages, such as façade and interior work, along with the integration of lean and BIM.

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NO SINGLE TAKT PLANNING METHOD FITS ALL PROJECTS

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ABSTRACT

Takt planning methods have been used to plan and control production of a variety of construction projects that have been delivered in various contexts. Recognizing that projects vary by type based on different product- and process designs as well as contextual characteristics of relevance to project production, not one but several takt planning methods have therefore emerged. This paper presents the objectives pursued in takt planning and describes projects by type and context, based on their complexity, in relation to these objectives. It outlines several takt planning methods and then matches those methods to project types and contexts. It is clear that no single takt planning method fits all projects and also that takt planning may not be a suitable method to plan some projects. This paper aims to shed light on available takt planning methods and on choosing which one to use when considering the complexity of a given project and its context.

KEYWORDS

Takt planning, takt production, work structuring, complexity, uncertainty, variability, slack.

INTRODUCTION

Projects are complex socio-technical systems. Their complexity stems in part from the fact that they comprise a large number of elements that are interconnected in various ways and to various degrees (e.g., people, materials, equipment, activities, processes, economic conditions, and legal requirements). Complexity is exacerbated by expected and unexpected variability arising from internal processes (e.g., decision-making processes or production processes) and external factors. Articulating and managing project complexity is crucial for effective project planning.

Here we focus specifically on takt planning. Takt planning methods have been used to plan and control production of a variety of construction projects that have been delivered in various contexts. Recognizing projects by type based on different product- and process designs as well as contextual characteristics of relevance to project production, various takt planning methods have therefore emerged. Our aim is to shed light on available takt planning methods and on choosing which one to use while considering the complexity of a given project type and context.

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This paper is structured as follows. We first offer a literature review on takt planning, project- and contextual complexity, and slack. Next, we introduce takt planning, present its objectives, and describe project characteristics relevant to takt planning. We then characterize and compare five projects, using data from case studies documented in the Lean Construction literature, based on their complexity and in relation to the aforementioned takt planning objectives. Subsequently, we outline four takt planning methods and match those methods to project types and contexts. We conclude the paper with recommendations for follow-on research.

LITERATURE

TAKT PLANNING

Takt planning methods set a regular "beat" for production so that work can flow in time and space, in order to match customer demand. The application of takt production in manufacturing dates to at least the early 1900s (Baudin 2012b), however the application of takt in construction has become more widespread only in this millennium. Takt planning can be applied to an entire construction project, but it is likely that different parts of a project will each have their own takt, as is the case in manufacturing where different assembly lines typically have different takts.

Quite a few instances of takted projects have been reported in the Lean Construction literature. These reports show that takt planning can be applied to projects of various types across the construction industry. Among relatively recent examples, Fiallo and Howell (2012) described the application of takt in designing the production system for an infrastructure project. Frandson et al. (2013) described the use of takt planning for the installation of a hospital's exterior cladding system, and Linnik et al. (2013) described how takt planning was used on the same project to plan non-repetitive interior work. Heinonen and Seppänen (2016) described the use of takt planning for the refurbishment of cruise ship cabins. Dlouhy et al. (2016 and 2018) applied their "three-level method of takt planning and takt control" to plan the construction of two automotive manufacturing plants. Vatne and Drevland (2016) described how takt was used to plan interior construction of a student housing complex, whereas Lehtovaara et al. (2019) used takt to plan interior construction of a residential building.

Although these reports mention the use of takt, not all takt planning methods are the same. In fact, takt planning describes a broad category of location-based planning methods, and therefore comparison with other methods in this category is warranted. Frandson et al. (2015) compared and contrasted the underlying assumptions of the Location-based Management System (LBMS) with takt planning. They identified key differences in how these methods make use of capacity-, space-, and time buffers. Formoso et al. (2022) presented a location-based approach for using takt on linear infrastructure projects, allowing for flexibility in choosing when to start work in any one of several planned work zones. Tommelein (2022) presented the Work Density Method (WDM) for takt planning, a method based on the work density concept to determine work locations and set a time limit for the completion of activities. Tommelein and Lerche (2023) compared the use of takt planning methods on projects of two different types: (1) a wind farm infrastructure project and (2) a healthcare facility project, the first paced by rather unique and expensive equipment, the second more flexible in throttling up-or-down the number of resources involved. These applications and methods may be viewed according to characteristics relevant in this production-planning context, as will be described in this paper.

Because takt can be used to plan the construction of products in different contexts—i.e., to deliver projects and phases of projects of various scope and size—the methods used on any given project may vary with time as needed to result in an efficient and effective plan. This aligns with Shenhar's (2001) assertion that "one size does not fit all projects."

Questions that come to mind are: (1) What are the essential conditions to implement takt time successfully in construction projects? (2) When all these essential conditions are met, is it still possible to fail in applying the fundamental principles of takt and find no solution? (3) When is it not appropriate to takt a process? (4) When does takt planning [and control] fail and what alternative methods can then be used?" These questions were inspired by Casey Ng's questions on LinkedIn, as quoted in Baudin (2012a). In this short paper, we begin to address these questions, but we cannot provide extensive answers.

A study of project- and contextual characteristics that affect the suitability of using takt planning and the choice of method is in order. In the following section we present such characteristics that we think are fundamental to assessing the applicability of takt planning. These characteristics may be grouped into concept categories pertaining to project- and contextual complexity and the availability of slack as a coping mechanism.

PROJECT- AND CONTEXTUAL COMPLEXITY

As it is said that construction projects are becoming more complex over time, and Baccarini (1996) stated that complexity makes a difference in the management of projects, we must first define complexity. Then we can ask: How can knowledge of what makes a particular project more (or less) complex than others be used to plan and deliver that project using takt planning?

Complexity, as defined by the Cambridge Dictionary (n.d.), is "the state of having many parts and being difficult to understand or find an answer to." The degree of complexity of an entity (e.g., a project) is, according to Klir (1985), "associated with the number of recognized parts as well as the extent of their interrelationship; in addition, complexity is […] related to the ability to understand or cope with the thing under consideration." Williams (1999) argued that in the context of project management, complexity manifests in two dimensions: (1) structural complexity and (2) uncertainty. Whereas structural complexity relates to the number of distinct elements in a project and the degree of interrelatedness between them, uncertainty relates to how well-defined the goals are and the means to achieve them.

Geraldi et al. (2011) systematically reviewed project complexities and presented a timeline of the historical development of complexity frameworks since the 1990s, showing when new understandings emerged in the literature. They identified five so-called "dimensions of complexity" in projects, namely (1) structural complexity, (2) uncertainty, (3) dynamic [complexity], (4) pace [complexity], and (5) socio-political [complexity]. In the framework presented in this paper we include an additional dimension, namely organizational complexity. Although these dimensions appear to not be mutually exclusive, we use this framework—with adjustments tailored to the context of construction and takt planning—to expand on the nature of project- and contextual complexity. Using example projects delivered with takt planning and mapping them to the complexity framework, we illustrate that some takt planning methods may be better suited for certain project types than for others.

1. Structural Complexity: 1.1. Product Complexity and 1.2. Supply Chain Complexity

Projects with a variety of numerous, interrelated elements give rise to structural complexity. Structural complexity may be attributed to product complexity and supply chain complexity. Product complexity is determined by the number of systems and their constituent elements, and the interrelationships between those systems and elements. These interrelationships can involve various degrees of tight- or loose coupling (Howell et al. 1993). In the construction context, interrelationships refer to how elements within a system fit together, and how changes in the design of one system affect the design of other systems. Supply chain complexity is determined by the quantity and variety of products, people, and organizations, and their interrelationships. Whereas Williams (2005) lumps both organizational- and supply chain complexity together under the umbrella of structural complexity, here we lump product- and supply chain complexity together and we treat organizational complexity separately. The articulation of complexity dimensions is itself rather complex and not generally agreed upon.

2. Uncertainty

The prediction and control of system performance is particularly challenging in the presence of uncertainty (Böhle et al. 2016). Uncertainty defines a state where individuals have incomplete knowledge of a situation (Saunders et al. 2015), e.g., due to measurement errors or a limited understanding of cause-and-effect relationships. Uncertainty may be viewed as "unexpected variability" (Saurin and Werle 2017). It may arise from human and social influences or organizational conditions, and it can be influenced by both internal and external factors.

3. Dynamic Complexity

Dynamic complexity refers to changes over time, so it indicates a certain kind of variability. Hopp and Spearman (2011) characterized variability as the attribute of non-uniformity within a class of entities. Process variability emerges from variations and randomness in work procedures, setups, random interruptions, and quality issues. Flow variability results from the way in which work is released to the system or transferred between locations.

4. Pace Complexity, i.e., Pace of Project Delivery

Pace is related to speed and urgency associated with performance and completion of project activities, reflecting deadlines and pressure to deliver results (Geraldi et al. 2011). "Fast" projects require numerous resources and overlapping activities (i.e., work taking place in many locations simultaneously), increasing activity interdependence and making them more tightly coupled, and consequently increasing the complexity related to planning. Lindkvist et al. (1998) suggested that the use of deadlines, milestones, and other time-based controls not only helps to pace projects in relation to overall time limits, but also supports parallel (simultaneous) work by encouraging communication and reflection. Takt time is a time-based method of control (Hall 1998) that helps to pace projects and indeed provides such support.

5. Socio-political Complexity

Socio-political complexity pertains to the network of interactions between people, power dynamics, stakeholder relationships, and political influences within and around the project environment (Geraldi et al. 2011). This dimension of complexity is related to the alignment of interests among stakeholders and their negotiation of project objectives.

6. Organizational Complexity

Organizational complexity encompasses technical elements (e.g., skill- and tool specialization) and human elements such as decision making, interactions among individuals (employees) at different levels of the organizational hierarchy (e.g., teams, departments, and divisions), as well as factors such as organizational size, culture, expertise, and risk tolerance (Peñaloza et al. 2020). In contrast to supply chain complexity that relates to elements and interactions between companies, and socio-political complexity that relates to elements and interactions both within and around a project, organizational complexity focuses on internal project team dynamics.

Takt planners, and planners in general, will recognize these dimensions of complexity in their projects and the contexts in which their projects unfold. To manage complexity, they can use certain coping mechanisms, which we present next under the broad category called "slack."

SLACK

Slack refers to the use of resources in a planned or opportunistic way to cope with complexity (Formoso et al. 2021, Saurin et al. 2021). Here, resources refer to not only people, materials, tools, and equipment, but also time, information, production strategies and, more generally, the flexibility people have in devising new approaches and creative solutions. Slack does not necessarily imply the use of extra or idle resources: existing resources can be readapted in order to protect systems from uncertainty and variability. Bourgeois (1981) described three roles for slack: (1) spare resources to prevent ruptures in the face of a surge of activity; (2) resources that allow an organization to adjust to external changes; and (3) resources that allow an organization to experiment with new products or innovations in management.

Formoso et al. (2021) and Saurin et al. (2021) advocated for two uses of slack in construction: (1) to have enough resources for fulfilling demands or carrying our strategic actions, and (2) to manage complexity as projects are complex socio-technical systems. Although it is (generally) desirable to reduce complexity rather than manage it, it is prudent to devise management strategies—e.g., strategically plan the use of slack—to cope with existing complexity that is difficult to remove or reduce. Slack resources should be planned and deployed judiciously so as to add flexibility or redundancy to systems while ensuring that they will have positive impacts. These impacts can be measured in terms of system resilience, reliability, robustness, innovativeness, and output flexibility. When the use of slack is mostly opportunistic or not well-defined, it can impact the system negatively and generate waste.

The provision and use of slack resources in the context of takt planning can be realized through various approaches. One approach is to develop alternative takt plans, so that the most suitable one can be used when uncertainties in the project diminish. Another approach is to determine what aspects of the work (e.g., work zones, work instructions, process sequence) should be standardized in a takt plan and what should be left for qualified workers to figure out. This poses strategic questions: (1) What level of specificity is appropriate for takt plans at different levels of planning? and (2) How detailed should takt plans be at various points of a project's construction timeline?

PROJECT CHARACTERISTICS RELEVANT TO TAKT PLANNING

With this understanding of takt planning, characteristics of project complexity, and slack as a means for coping with complexity, we now focus on project characteristics relevant to identifying a suitable takt planning method. The success of applying a takt planning method depends on the ability of the planner (i.e., the person or team responsible for developing and maintaining plans) to structure the work of a project, or a phase of a project. Here, "ability" encompasses not only personal- and team competence, but also the degree of flexibility granted to the planner. This flexibility can arise from the manifestation of resilience of the planning method, when the method enables the planner to define and fine-tune various production system design elements to their desire. The following are examples of "throttles" or "adjusting mechanisms" (Binninger et al. 2017) that can be manipulated to shape a takt plan.

1. Use alternative breakdowns of the scope of work.

One throttle is to study alternative breakdowns of the scope of work. Takt planning requires a breakdown of work into "chunks" that can be done concurrently, creating process modularity, allowing for fast feedback, and ultimately aiming to reduce lead time. Work breakdown relates to product complexity, i.e., how tightly- or loosely coupled project physical elements (building elements, assemblies thereof, and systems) are. On the one hand, when they are loosely coupled, planners have more flexibility, e.g., to structure work into small (in scope and duration) process steps and divide work space into more zones to reduce cycle time. On the other hand, when projects are less flexible, i.e., when elements and systems are tightly coupled and process steps are larger (in scope and duration), planners may not be able to divide work space into so many zones but instead have to rely on other takt planning throttles to realize shorter cycle times.

2. Re-sequence work or add/remove work from a process step.

A second throttle involves the possibility of re-sequencing work or shifting work content from one process step to another, essentially redistributing the workload between steps in order to achieve more evenness (workload leveling or “heijunka”). This helps to reduce cycle time and work fragmentation, and it results in a reduction in the workload of one process step and possibly a corresponding increase in another process step. The feasibility of resequencing work or shifting work content may depend on trade jurisdictions (e.g., whether a trade contractor can perform the work initially assigned to another trade), specialty equipment requirements, personnel training needs, etc.

3. Define the resources that can be assigned to perform work.

A third throttle is to adjust resources in terms of their type, quantity, or capacity (e.g., augmenting capacity by providing skill training). When all constraints for a task have been removed, the pace at which work happens is dictated by the nature of the resources involved.

For example, operations such as percussive- and rotary drilling are equipment-paced, i.e., the operation is inherently tied to the capability of the equipment being used. Reducing cycle time would require allocating additional- or alternative equipment, i.e., equipment that gets work done faster. However, such equipment can be expensive, difficult to obtain, and logistically challenging to mobilize on site. Furthermore, even when under ideal conditions a certain level of predictability in equipment performance may be anticipated, that performance will be impacted by uncertainties stemming from the surrounding environment—known unknowns.

In contrast, for example, operations such as those involving interior work (e.g., painting, tile installation, window installation) are worker-paced. Provided that there is some kind of slack (e.g., capacity buffers, multi-skilled labor, or financial resources to hire additional workers), it is relatively speaking more straightforward and affordable to adjust the number of workers. Although the pace of work is dictated mainly by worker skills and speed of construction, the surrounding context can also introduce uncertainty. For example, retrofit work tends to have more known unknowns compared to new construction (e.g., “Does the ceiling have asbestos or not?”), in which case the additional complexity must be considered during planning.

4. Exploit flexibility in the use of space.

Spatial features and flexibility in the use of space influence the flexibility afforded to planners. In some projects, most of the work must be performed in situ, and this need for location-specific work may limit how much work can be scheduled concurrently using takt planning while avoiding trade stacking. Conversely, other projects may allow some or several elements or assemblies to be produced ex situ, with only the final installation taking place in situ. The possibility of working ex situ provides planners with flexibility in structuring in-situ work. By reducing the time needed to perform in-situ work (i.e., reducing the work density), the corresponding process cycle times can be reduced, ultimately shortening the overall project duration. Furthermore, defining larger zones for takted work can allow several crews to work shoulder-to-shoulder, requiring them to figure out who works where and when, while at the same time offering the flexibility of choice.

5. Acknowledge the distinction between operable takt vs. customer takt.

Projects must be delivered to meet the customer’s takt, but approval processes and externalities can introduce uncertainty into the delivery process. For example, projects situated in seismically active areas require rigorous inspections of both structural- and non-structural elements during construction. Takt plans must make explicit the handoffs from upstream- to downstream process steps, including those required for inspections, and include decoupling buffers where needed. Slack can be used to mitigate some variability, e.g., from delays in inspections or rework resulting from failed inspections. Other projects, such as those in the realm of infrastructure, may encounter unknown underground and site access conditions. A takt plan can help to delineate different zones where work can take place simultaneously, limiting the propagation of variability (Formoso et al. 2022).

The flexibility to adjust these throttles derives from the characteristics and constraints of each project. Understanding the general characteristics of the type of project being evaluated can guide the identification of the most suitable takt planning method(s). For example, planning the construction of a multi-family building or a hotel may be simpler in some regards than in others when compared to planning the construction of an offshore wind farm.

SELECTION OF PROJECTS FOR COMPARISON

To compare construction projects in terms of their dimensions of complexity and rationalize the takt planning methods used to deliver them, we looked at data from five case studies documented in the Lean Construction literature. These case studies—some of which conducted by the authors of this paper—describe a variety of projects, namely:

[1] Multi-family residential building (Barth et al. 2020)
[2] Cruise ship cabin refurbishment (Heinonen & Seppänen 2016, Makinen 2021)
[3] Overhead MEP work in a healthcare facility (Frandson & Tommelein 2014a, 2014b)
[4] Offshore wind farm construction (Lerche 2020, Tommelein & Lerche 2023)
[5] Underground linear infrastructure projects (e.g., sewer lines, fiber-optic cables) (Yassine et al. 2014, Formoso et al. 2022)

PROJECTS COMPARED ALONG DIMENSIONS OF COMPLEXITY

By adapting Geraldi et al.'s (2011) framework to the context of construction—here specifically takt planning—we illustrate how one might evaluate projects based on their complexity. Although their framework presented five dimensions of complexity, we present seven as we not only added organizational complexity but we also split structural complexity into product- and supply chain complexity.

Based on group discussions among the authors and our expertise in takt planning, we scored each project along each dimension of complexity, assigning the full range of integer values from 1 to 5 (Table 1). Admittedly this is a very crude way of assessing complexity but, as we were wondering if an approach like this might be promising in any way, it offered an initial attempt at categorization. To add: scores assigned to complexity in one dimension are not to be summed up with scores assigned to complexity in another dimension, as these dimensions are qualitatively rather different and overlap to some degree, as previously mentioned. Clearly, follow-on research must include selection of an assessment method that is more fit-for-purpose, comprehensive, and superior to what is presented here. Methods matter! For choice problems, for example, we have argued that Choosing by Advantages (CBA) is superior to Weighting-Rating-Calculating (WRC) and to the Analytic Hierarchy Process (AHP) (Arroyo et al. 2014a, 2014b).

Table 1: Projects Scored According to their Dimensions of Complexity

Type of Project	PRODUCT	SUPPLY CHAIN	UNCERTAINTY	DYNAMIC	PACE	SOCIO-POLITICAL	ORGANIZA-TIONAL
[1] Multi-family building	4	3	1	3	1	2	2
[2] Cruise ship cabin refurbishment	3	2	2	1	2	1	1
[3] Hospital overhead MEP work	5	4	3	5	4	4	5
[4] Offshore wind farm	2	5	5	2	5	3	4
[5] Linear infrastructure	1	1	4	4	3	5	3

Product complexity assesses the interconnectivity of physical elements (e.g., building elements, assemblies thereof, and systems). A score of 1 indicates low complexity due to loose interconnectivity, whereas a score of 5 indicates high complexity due to tight interconnectivity. We scored case [5] the lowest, considering that it has relatively few, simple parts, connected one-to-one linearly and therefore is the least complex of all 5 cases, and we scored case [3] the highest, considering that many parts of different shapes and sizes make up the mechanical, electrical, and plumbing (MEP) systems, all routed and tightly packed in the same overhead space. Table 1 reflects these scores and the scores given to the three other cases, but due to the 12-page restriction of this paper we could not spell out all our rationale in this write-up.

Supply chain complexity gauges the level of customization of construction materials. A score of 1 represents a project using mostly made-to-stock materials (not customized, simple, and readily available), whereas a score of 5 represents use of engineered-to-order materials (highly customized, complex, and procured with long lead times). We scored case [5] the lowest, considering that many of its parts are commodities and made-to-stock, and we scored case [4] the highest, considering that its parts are engineered-to-order to reflect the latest technological advancements, and that they are being supplied by geographically dispersed companies.

Uncertainty here measures, for example, the unpredictable nature of approval processes (e.g., permitting) and workers' ability to ascertain where (work locations) work can be performed in the short term (e.g., influenced by weather or other unforeseen subsurface conditions). A score of 1 indicates the least amount of uncertainty, whereas a score of 5 indicates the highest amount of uncertainty. We scored case [1] the lowest, considering the more routine nature of the work involved, and we scored case [4] the highest, considering the potential impact of weather and sea conditions on the project.

Dynamic complexity (often tied to uncertainty) relates to the flexibility planners have—based on project characteristics—to break down work into smaller chunks, divide work space into zones, and rearrange process steps. A score of 1 indicates planners have a high degree of flexibility in work structuring, whereas a score of 5 indicates minimal to no such flexibility. We scored case [2] the lowest, considering that work zones (cruise cabins) are independent from one another, and process steps can be rearranged to some extent, and we scored case [3] the highest, considering the interconnectedness and density of parts in MEP systems, which impose limits on how work can be broken down and what zones can be defined.

Pace (or speed) complexity evaluates the difficulty of adjusting the number of resources in a project, considering factors such as cost, availability, and required worker skills or equipment capabilities. A score of 1 indicates that it is relatively easy to adjust the number of resources, whereas a score of 5 indicates that it is challenging to do so. We scored case [1] the lowest and case [4] the highest.

Socio-political complexity refers to the context and environment surrounding the project, characterized by the influence of the voices of stakeholders and power dynamics among them, that ultimately impact the project. A score of 1 indicates a weak impact, whereas a score of 5 indicates a strong influence of stakeholders on the project and strong stakeholder interactions. We scored case [2] the lowest and case [5] the highest.

Organizational complexity measures the experience, skills, behaviors, and knowledge levels required for performing work within organizations involved in the project team. A score of 1 implies that work is relatively straightforward, whereas a score of 5 indicates that work requires more experience, skills, behaviors, and knowledge, as well as specialized processes and tools or equipment as needed to perform more demanding work. We scored case [2] the lowest and case [3] the highest.

Of note is that our discussions that resulted in these scores were based on comparing specifics of individual projects, rather than only their project type. Being specific is important because numerous flavors of complexity can be discerned among projects, even among those of the same project type.

To visually capture the assigned scores and use the complexity framework, we drew a radar diagram (Figure 1). The aim is to provide planners with insights into the diverse complexity profiles of different projects, informing the selection of what may be the most appropriate takt planning method for their project.

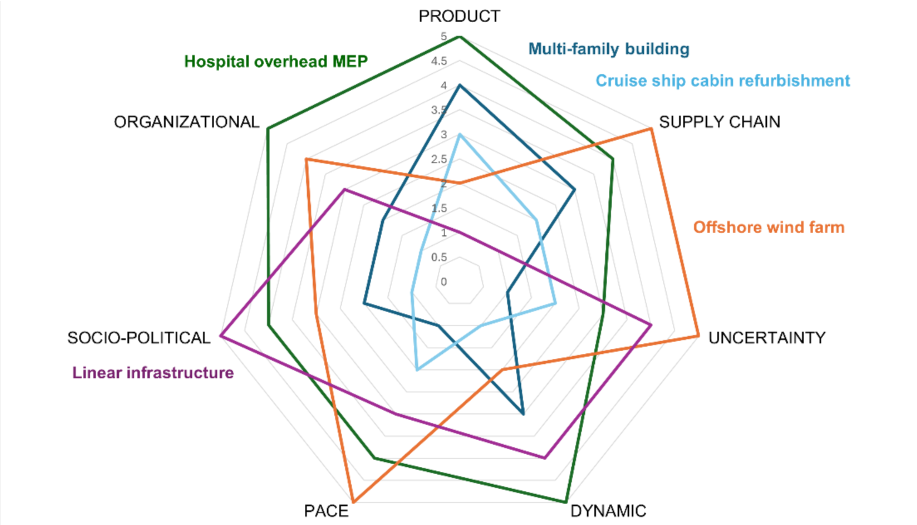

Figure 1: Radar Diagram Depicting Projects by their Dimensions of Complexity

TAKT PLANNING METHODS

The takt planning methods in use on projects around the world may be categorized as Methods A, B, C, and D. Method A is to define sequences of process steps and work zones a priori (i.e., before hiring trade specialists), typically based on some repetition in the physical product (e.g., rooms), and then use existing production data to compute the takt. An early promoter of a version of this method was Porsche Consulting (Gardarsson et al. 2019); Dlouhy et al. (2016, 2018) and Binninger et al. (2017) describe their own versions. This method of managing variability at the highest level of planning by creating a takt plan and then freezing it, while managing adaptations as needed at lower planning levels, applies to cases [1] and [2].

Method B is the Work Density Method (WDM) (Tommelein 2022). The method is to consider alternative work structures and develop work density maps showing how much time will be needed to perform certain scopes of work in different areas on site. It requires collaboration of the trades involved to decide on process steps, sequencing, and then zoning based on leveling of workloads (cumulative work density). This method applies to case [3].

Method C is to specify takt(s) and zones, but to defer deciding when to work in each zone until certain project uncertainties get resolved. This method is to define a hierarchy of locations, and exercise certain project control at each hierarchical level. It applies to case [5].

Method D stems from recognizing that certain resources have capacity constraints, i.e., they are bottleneck(s) in the system. The method therefore is to maximize the bottleneck's utilization and pace other work based on that (as is done in the Theory of Constraints). The other work can then be structured with its own takt (perhaps using one of the other methods mentioned), informed by the required pace. This method applies to case [4].

Looking at cases [1] and [2] in Figure 1 we see patterns of complexity that appear to be similar and we note that both projects used some version of Method A. This is also the method that we (based on our considerable expertise in takt planning) would recommend using for these projects. Similar analyses were conducted for Methods B, C, and D.

DISCUSSION

Takt planning enforces clarity and simplicity by defining small chunks of work, clearly delineating what is to be done where, when, and by whom and what the expectations are for the handoff to the next trade. However, different methods achieve these objectives in different ways. Based on our scoring of five projects using seven dimensions of complexity and the four takt planning methods as described, we see alignment between a project's scores according to these dimensions of complexity and the takt planning method selected.

Our findings are highly speculative at this time. However, further research may indicate that the proposed characterization of project attributes, thought to be relevant to takt planning according to certain dimensions of complexity, may help choose which takt planning method to deploy for a particular project or phase of a project. It may also become clearer in which circumstances it is appropriate to use location-based planning and control, yet not takt planning in full, or when takt planning is not a suitable method at all.

CONCLUSIONS

Various takt planning methods can be identified in the Lean Construction literature. No single method appears to be universally applicable to all projects. Our premise was that deciding which method to use requires consideration of the complexity and context of the project to be planned with takt. This paper started by describing the objectives pursued in takt planning and it listed references to illustrate the use of takt to plan projects of various types. The section that followed shed light on different dimensions of project- and contextual complexity, and outlined various project characteristics that are relevant to takt planning.

The extension of Geraldi et al.'s (2011) complexity framework to the context of construction- and takt planning offered a practical approach to assess project complexity based on seven dimensions. The authors scored different projects based on their product- and supply chain complexity, uncertainty, dynamic complexity, pace complexity, socio-political complexity, and organizational complexity. The scores depicted in a radar diagram indicated differences between projects that helped to rationalize why one takt planning method or another might have been used on a certain project. This rationalization can inform planners when choosing a suitable takt planning method, considering the unique characteristics and challenges posed by each project. Follow-on research will describe each project in more detail regarding its dimensions of complexity and how the takt planning method was formulated, so that the matching of complexity with the appropriate takt planning method can be refined.

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A REVIEW OF POKA YOKE IN CONSTRUCTION PROJECTS: CLASSIFICATION, BENEFITS AND BARRIERS

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ABSTRACT

The construction industry is a critical sector in the economy of countries; however, it has low productivity and is associated with errors and rework. In response, poka yoke or mistake-proofing devices have been developed to avoid errors or reduce the possibility of committing them. Their application has been documented in manufacturing and, to a lesser extent, in the construction sector, where the literature on this subject is scarce. Therefore, the following article aims to develop a literature review of poka yoke in the construction sector. To this end, a literature review was conducted using PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis). Twenty-five articles related to poka yoke were analyzed. From the literature review, it was obtained that the main poka yoke found corresponds to the principle of facilitation; the main benefits reported were improvement of quality and performance and reduction of errors, and the main barrier is the lack of training on the subject. The following article will contribute to professionals and researchers in the construction sector to have a better understanding of the applications of poka yoke.

KEYWORDS

Poka yoke, mistake-proofing, Lean Construction, PRISMA

INTRODUCTION

The construction industry is critical for economic strengthening and unemployment reduction (Bajjou et al., 2017). However, it faces significant challenges due to low productivity (Widjajanto et al., 2020), cost overruns, and low quality (Ramírez et al., 2021), among others. Challenges in the construction industry are often caused by errors during construction, making construction defects the main concern (Hosseini et al., 2012). Errors in the construction industry

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manifest themselves at various project stages, from planning to maintenance, affecting financial, safety, and human life aspects (García et al., 2015). These errors can be related to higher levels of the organization, such as problems in design, poor specifications, inadequate control and supervision, and a lack of specialization or training in the workforce (Peralta & Serpell, 1991). Others may be associated with operational work, such as incorrect proportions of water in mortar preparation (Dos Santos & Powell, 1999) and failures in construction machinery (Bashir et al., 2011).

To counteract errors, a technique called mistake-proofing or poka yoke generated in Japan was developed to help reduce errors in the manufacturing industry through devices (Shingo, 1986), and has been successfully applied in other industries, including the Architecture-Engineering-Construction industry (Tommelein, 2019) and has been shown to have multiple benefits in this industry, such as variability reduction, quality improvement, work safety (Baijjou et al., 2017), reduction of rework, production of more added value, improved productivity and increased customer satisfaction (Zavichi et al., 2010). Despite the benefits shown in the literature, no previous literature review study on poka yoke in the construction industry has been recorded. That is why the following article aims to review articles recorded in the literature and evaluate the types of poka yoke and the benefits and barriers to construction projects.

BACKGROUND

POKAYOKE IN CONSTRUCTION

Although poka yoke has its origins in the manufacturing industry, its use in construction is also possible (Tommelein, 2019). Koskela (1992), is one of the pioneers in mentioning the term poka yoke in the construction industry, where he proposes poka yoke as an alternative to reduce variability and thus avoid performing activities that do not generate value. Then, Dos Santos & Powell (1999) show its application in 6 construction projects in England and Brazil, showing benefits such as: reduction of variability and improvement in the quality of the final result. Also, Tommelein (2008) mentions the application of poka yoke in the design stage, which consists of using different colors for the walls of a design plan, to denote that they are different and thus avoiding a mistake at the time of construction.

In addition, in Chile, Zavichi et. al (2010) propose a poka yoke device for the transport of materials between floors of buildings to reduce accidents. One of the guides that proposes many poka yoke devices is the one developed by Tommelein and Demirkesen (2018), where different poka yokes applied in the construction industry are compiled. Also, Tommelein and Yiu (2022) present several examples of poka yoke devices that seek to solve problems such as manual welding and measurement errors.

POKAYOKE PRINCIPLES

Tommelein (2019) states that the error-proofing methodology, known as Poka Yoke, is based on six principles: eliminate, prevent, replace, facilitate, detect and mitigate. These principles are organized according to the degree of desirability of error correction, from the most preferable to the least desirable, but no less valuable. When scheduling an operation before its initiation, the risks associated with the steps that make up the operation and their possible consequences are identified. Subsequently, their possible occurrence is "designed" to avoid them altogether.

The 6 types of poka yoke set out in Tommelein and Demirkesen (2018) will be explained below:

1. Eliminate: Eliminate involves eradicating the probability of an error occurring in a specific task, step, or sequence of operations by reconfiguring the product or operation so that the task (or associated part of the product) is no longer required. Zavichi et. al (2010) exemplify the removal of scaffolding in the construction industry, proposing the use of elevators with appropriate protective measures instead of scaffolding to ensure worker safety.
2. Prevent: Preventing involves designing and engineering the product or operation in such a way that no individual can make mistakes. Tommelein and Demirkesen (2018) present an example related to junction boxes in electrical installations, expressing concern about the possibility of faulty connections and the risks associated with the work at the height required to wire luminaires. As a poka yoke measure, they propose the installation of clips on each luminaire during the wiring process in a workshop environment. These clips, being designed to fit in only one way (asymmetry), ensure that the cables are always connected correctly. This practice significantly reduces the time required for overhead installation by electricians.
3. Replace: Replacing consists of substituting a task with a more reliable alternative to improve consistency. Tezel et al. (2010) give as an example a device that can virtually eliminate the need for statistical process control. They allow self-inspection in repetitive tasks by the line operator (which requires some vigilance and memory) by preventing errors using relatively simple and inexpensive mechanical, electrical and visual mechanisms.
4. Facilitate: Facilitate implies the use of resources to simplify the execution of a task, making it more affordable. Bajjou et al. (2017) provide a representative example of how water addition is commonly performed manually during mortar production without any strict control, which affects mortar quality, thus proposing strict monitoring of the added measurement as poka yoke.
5. Detect: Detect involves the quick identification of an error to correct it before it becomes a defect. Tezel and Aziz (2017) propose sensors in work helmets that vibrate or emit a sound to alert the worker of a work hazard.
6. Mitigate: Mitigate consists of using resources to minimize the impact of an error, especially in critical construction projects. Hosseini et al. (2012) provides an illustrative case where one of the critical errors in reinforcement operations involves improper delivery, cutting or bending of reinforcing bars. To prevent such errors, they propose a poka yoke method that involves coloring the ends of the tied bars, thus reducing the possibility of misuse.

METHODOLOGY

In the following research, a literature review was conducted on the application of the Poka Yoke method in construction projects using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology. The PRISMA method has been used previously in Lean Construction literature reviews such as the study conducted by Erazo et al. (2023) in which after collecting data under the PRISMA method they conducted their research on the benefits of applying Lean Construction, during the pandemic era. In addition, Lee et al. (2022) mention that this type of review facilitates the authors to become familiar with the primary knowledge retrieved in the selected articles thus developing a research model through a solid approach, thus exploring future research directions with greater precision.

For the literature review, a search for publications related to the application of Poka Yoke in construction was conducted using Scopus, the IGLC database and the Web of Science database. This because Scopus is one of the databases with a wide domain in research on the topic of construction compared to other databases (Galaz et al., 2021); IGLC hosts most publications on the application of Lean Construction worldwide (Daniel et al., 2015); and Web of Science because it is one of the most recognized international multidisciplinary references (De Filippo, 2013).

In the first identification phase, the search was performed using 9 keywords from year 1998 to 2024, because the first paper that addresses poka yoke in construction is (Dos Santos et al., 1998). The keywords and their combinations are shown in Figure 1. Likewise, 112 results were obtained based on all the keywords. For the next phase of eligibility, after having the combinations of articles found from I to XXIV, 61 duplicate publications were eliminated from the reviewed articles and relevant articles were filtered for evaluation. A total of 33 articles were excluded through title and abstract review, articles were excluded because they were considered not to refer to the application of Poka Yoke in construction projects or were far from the topic in question. A total of 18 articles were left, which, in the next phase of exclusion, were filtered again through a complete reading, thus excluding 6 articles that did not meet the criteria to be considered in this study: They do not mention at least one application of any of the 6 types of Poka Yoke in construction projects, and 13 articles belonging to snowball were added because they were centrated in the topic showing at least one application of Poka yoke in construction, leaving a total of 25 articles that were considered for this research.

The above steps are described in Figure 1.

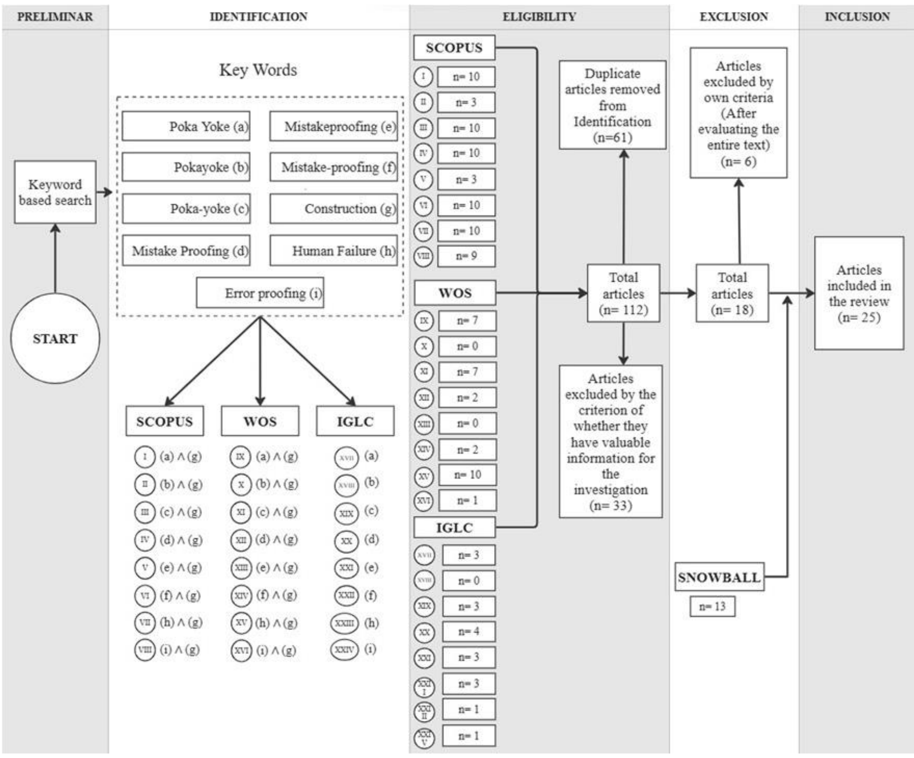

Figure 1. PRISMA flow diagram for the systematic review.

RESULTS AND DISCUSSION

PUBLICATIONS BY YEAR

In this section, the publications by year were divided into two graphs in Figure 2, an initial one where the number of articles per year is shown, and another one with the accumulated graph of poka yoke publications over time.

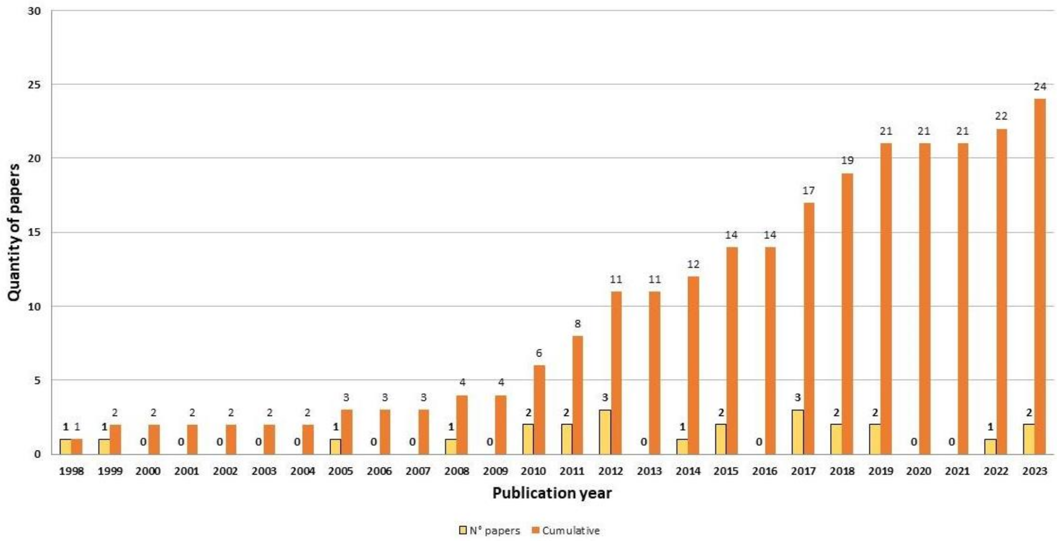

Figure 2. Number of poka yoke application papers in construction and their cumulative quantity vs year of publication.

From Figure 2, the first article dedicated to poka yoke, according to the review, was prepared by Dos Santos et al. (1998). This article explores the concept of Poka Yoke in the implementation of the principle of transparency in the construction sector. In this context, the use of an elevator control board is described as it prevents the elevator from moving if the door is open, thus constituting a PREVENT type of poka yoke. Later, in the following year, Dos Santos & Powell (1999) published an additional article, focusing exclusively on Poka Yoke devices under construction, being pioneers in addressing this topic in depth in this industry.

Between the years 2000 and 2009, there was little research on the topic, since only two articles were registered in that period: the research by Marosszeky et al. (2005) focusing on the use of quality control mechanisms to improve workflow reliability, and the article by Tommelein (2008) detailing the application of poka yoke in the manufacturing industry construction, providing a variety of examples and detailing different poka yoke devices. This work generated an increase in the production of research related to poka yoke, as reflected in the graph.

From 2010 onwards, a greater number of publications related to poka yoke in construction have been observed, addressing different topics such as: improving productivity in construction (Sadri et al., 2011), total quality management (Laguna et al., 2014), its relationship with Six Sigma (Vinod et al., 2015), safety (Bajjou et al., 2017), variation reduction in construction projects (Uhanovita et al., 2023b), among others.

Although the publications have been analyzed by year, Figure 2 also shows the cumulative analysis of publications. It is observed that until 2010, publications have been limited to slow growth. However, in the period from 2010 to 2020, there has been a significant increase in publications, going from 6 articles to 21 articles in 2020. This increase is attributed to the contributions of Tommelein (2008) and Zavichi (2010), who exhaustively explored the benefits of using Poka Yoke in the construction industry and provided various examples in their articles.

Likewise, as of 2020, 5 articles have been registered. In that sense, from the graph we can notice that there is a growing interest in the application of poka yoke and poka yoke principles in construction projects.

CLASSIFICATION OF POKA YOKE TYPES

In Table 1, the reviewed articles have been classified according to the 6 types of poka yoke presented in Tommelein & Demirkesen (2018):

Table 1: Number of examples of poka yoke principles found in the review.

Id	Principles	Examples in literature	Number of references	References*
P1	ELIMINATE	15	6	1, 3, 4, 5, 9, 11,16
P2	PREVENT	20	17	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 15, 16, 18, 22, 23, 24
P3	REPLACE	12	8	2, 3, 4, 6, 11, 16, 19, 23
P4	FACILITE	30	13	1, 2, 3, 4, 5, 7, 11, 14, 15, 16, 20, 23, 24
P5	DETECT	17	12	1, 2, 5, 6, 7, 11, 12, 15, 16, 17, 21, 24
P6	MITIGATE	14	8	4, 5, 11, 13, 16, 19, 24, 25

*1. (Zavichi et al., 2010), 2. (Tommelein, 2008), 3. (Uhanovita et al., 2023a), 4. (Tommelein & Yiu, 2022), 5. (Tommelein, 2019), 6. (Rubio et al., 2019), 7. (Bajjou et al., 2017), 8. (Schmidt, 2013), 9. (Dos Santos & Powell, 1999), 10. (Dos Santos et al., 1998), 11. (Tommelein & Demirkesen S., 2018), 12. (Bajjou et al., 2017), 13. (Bashir et al., 2011), 14. (Hosseini et al., 2012), 15. (Laguna et al., 2014), 16. (Marosszeky et al., 2005), 17. (Mollo et al., 2018), 18. (Saurin et al., 2012), 19. (Tezel et al., 2010), 20. (Tezel & Aziz, 2015), 21. (Tezel & Aziz, 2017), 22. (Vinod et al., 2015), 23. (Sadri et al., 2011), 24. (Uhanovita et al., 2023b), 25. (Mollo et al., 2019)

From Table 1, the poka yoke principle most frequently cited in the literature for its application in the construction sector is the FACILITE (P4) principle, which was found in 13 articles and 30 examples of this type of poka yoke. Tommelein (2019) mentions that this principle is one that AEC practitioners tend to use the most because it is not a principle that consists of poka yokes designed to avoid errors. For example, Tommelein (2008) addresses design quality in construction systems and mentions examples of FACILITE type poka yoke, such as color coding for different types of walls on plans. Hosseini et al. (2012) discuss the implementation of Lean Construction in the Waste Management of construction processes and provides an example of FACILITE type poka yoke, which consists of coloring the end of grouped bars to prevent improper cutting or bending.

In second place in terms of mentions is the PREVENT (P2) type principle, where 17 related articles and 20 examples of this type of poka yoke were found. Tommelein (2008) provides two examples that belong to the PREVENT type, thus representing most of the examples identified in the present study. Examples of PREVENT type presented include the use of a connection plug to ensure proper wiring and the use of a sealant and return leg to ensure proper performance of the ceiling panels. Furthermore, Tommelein and Yiu (2022) point out an additional example of the PREVENT type, where CIVIL 3D software is used to link a 3D model with a 2D plan and prevent design mismatches and errors. On the other hand, Rubio et al. (2019) mention a specific example of the application of poka yoke, which consists of the use of safety railings to prevent falls from heights, also being an example of the PREVENT type.

The DETECT (P6) principle is documented in 12 references in the literature and 17 examples were identified in the analyzed articles. One of these examples consists of the implementation of an RFID detection system, which activates an alarm when an unauthorized worker accesses a dangerous area (Rubio et al., 2019). Additionally, another example is illustrated that involves the use of a dynamic information panel, which workers update in case of errors to alert their colleagues. Likewise, the use of understandable Squirter DTIs washers is mentioned, which indicates when a bolt reaches its target tension and becomes functional (Tommelein, 2019).

From Poka yoke principle of ELIMINATE (P1), 15 examples were found in 6 references. For example, Zavichi et. al (2010) provide as an example the change from the traditional work method (use of scaffolding) to a safer and more efficient alternative (use of an elevator with sufficient protection), this eliminates the possibility of errors or accidents associated with the use of scaffolding. and improves worker safety. Uhanovita et al. (2023b) illustrate some examples of ELIMINATE type poka yoke, among which is ensuring that the detailed designs provided to bidders are clear, precise and complete, as this would help avoid misunderstandings and errors during the pricing process and tender. Dos Santos and Powell (1999) illustrate an example of ELIMINATE by proposing an implementation of electronic and mechanical devices to avoid errors in the manual addition of water during mortar production, guaranteeing quality and efficiency on the job.

The MITIGATE (P6) principle was the second with the fewest examples that the literature provided, with only 14 examples in the literature in 8 references. Examples include the use of PPE to reduce the impact in the event of accidents that occur on site (Bashir et al., 2011), the use of SawStop saws which detect the moment in which human skin comes into contact with blade making it instantly hidden and thus causing the least possible damage to the user (Tommelein, 2019), the creation of protrusions with some nails on the heads of the tubes for a more precise installation, thus mitigating the possibility of incorrect installation (Tezel et al., 2010).

The REPLACE principle was the one with the fewest examples found, with only 12 examples in 8 references. Tezel et al. (2010) suggest an example of REPLACE-type poka-yoke, which is manifested through the implementation of adjustable metal struts designed to hold the benches in place during the construction process, replacing traditional struts to improve precision, safety and productivity in the work environment. Tommelein and Demirkesen (2018) propose a REPLACE-type poka-yoke to address the concern of potential worker falls from the edge of the roof. The solution involves installing a parapet along the perimeter as part of the permanent structure. This measure not only improves safety by mitigating the risk of falls, but it also replaces temporary protection, generating economic benefits throughout the life cycle of the building. Rubio et al. (2019) suggest dynamic information panels such as poka-yoke to improve static signs on construction sites, providing updated safety information and allowing remote updates by workers and the safety manager.

There are also potential poka yokes that are based on a combination of principles. For example, Tommelein (2008) mentions that design specialists use a color code as a type of pokayoke that facilitates and prevents. It prevents in the sense that they use it for their specific work and phase of a project to avoid confusion. And, it facilitates because color coding can be used to distinguish various types of walls, which makes it easier to clarify and categorize specified design requirements and helps better organize planning and cost.

BENEFITS AND BARRIERS OF ITS ADOPTION

In this section, the barriers and benefits that poka yoke generates in construction projects are described, which is why two summary tables have been developed: Table 2, where the benefits of poka yoke are seen, and Table 3, with the barriers found in the literature.

Table 2: Benefits of poka yoke in construction.

Id	Benefits	Absolute frequency	Relative frequency (n=45)	References*
B1	Improves quality and performance	8	17.78%	1,2,3,4,5,6,7,8
B2	Reduction of errors	8	17.78%	2,7,9,10,11,12, 13,14
B3	Reduction of rework	5	11.11%	6,9,10,15,16
B4	Reduction of time	3	6.67%	3,9,17
B5	Improves efficiency and minimizes resource usage	3	6.67%	3,13,20
B6	Continuous flow	3	6.67%	18
B7	Better customer satisfaction	2	4.44%	7,18
B8	Low investment cost	2	4.44%	10,18
B9	Reduction of variability	2	4.44%	3,8
B10	Reduction of interference	2	4.44%	7,19
B11	Improves profitability	2	4.44%	11,15
B12	User-friendly	2	4.44%	8,11
B13	Personnel reduction	1	2.22%	1
B14	Reduction of incompatibilities	1	2.22%	1
B15	Improves safety	1	2.22%	3

*1 (Tommelein & Yiu, 2022), 2 (Tommelein, 2019), 3 (Bajjou et al., 2017), 4 (Marosszeky et al., 2005), 5 (Tezel & Aziz, 2017), (Sadri et al., 2011), 7 .(Burlikowska & Szewieczek, 2009), 8 (Dos Santos & Powell, 1999), 9. (Zavichi et al., 2010), 10. (Tommelein, 2008), 11. (Bashir et al., 2011), 12 (Hosseini et al., 2012), 13. (Tezel & Aziz, 2015), 14 (Tezel et al., 2010), 15 (Laguna et al., 2014), 16 .(Li & Liu, 2016), 17 .(Bajjou et al., 2011), 18 .(Uhanovita et al., 2023a), 19 .(Dos Santos et al., 1998), 20 .(Saurin et al., 2012).

From Table 2, 15 benefits were identified from the literature, where the two main benefits were found with a frequency of 8 articles, which are “improvement of quality and performance” (B1) and “reduction of errors” (B2). Benefit B1 refers to the improvement in worker performance and processes. Uhanovita et al. (2023a) mentioned that Poka Yoke provides the opportunity to increase your ability to carry out a quality construction process, reducing variations that allow the parties to work collaboratively and help increase productivity and project success. Likewise, they also recommend that before starting the design stage, the requirements of the end users must be identified through the Poka-Yoke principles, and after that, the projects can be completed without variations in the stage. construction increasing productivity.

Benefit B2 is equally often about “reduction of errors” (B2), maintaining the idea that errors decrease thanks to the timely detection of their cause and in some cases preventing them from occurring. The goal of error reduction is to achieve a better system by avoiding more defects in the product and process by eliminating waste, trying to reduce variation, and not tolerating poor quality (Tommelein & Demirkesen S., 2018). For example, Marosszeky et al. (2005) mentioned that thanks to the implementation of Poka Yoke, the possibility of changes in requirements can be prevented in the design stage since the client must be given a complete idea about the design and once the client realizes Depending on the form, type and functions of the construction project, design changes and identified requirements will not arise during the construction phase.

The third most cited benefit is the “reduction in rework” benefit (B3), which has a positive effect since it prevents the error from getting worse. Through poka yoke, unnecessary use of personnel to correct an error can be avoided, which has the benefit of a “reduction of time” (B4), a “continuous flow” (B6) and a “personnel reduction” (B13). By avoiding the production of a defect in the product with a better one with no defect and in a shorter time, it produces “Better customer satisfaction” (B7). Moreover, the implementation and development of these mechanisms have a “low investment cost” (B8).

The use of these mechanisms produces a “reduction in variability” (B9) and a “reduction in interference” (B10). The reduction in errors, time, rework, interference and variability produces “improves efficiency and minimizes resource usage” (B5) which produces “improved profitability” (B11). Furthermore, poka yoke mechanisms often are “user-friendly” (B12).

On the other hand, Table 3 shows the 9 barriers obtained from the literary review of poka yoke.

Table 3: Poka yoke barriers in construction.

Id	Barriers	Absolute frequency	Relative frequency (n=10)	References*
C1	Lack of training	2	20%	5,6
C2	Uncertainty in the nature of construction	1	10%	3
C3	Tool immaturity	1	10%	5
C4	Resistance to change	1	10%	5
C5	Difficulty in identification	1	10%	1
C6	Lack of consensus	1	10%	2
C7	High investment cost	1	10%	5
C8	On-site work pressure	1	10%	5
C9	Limited research	1	10%	4

*1. (Tommelein & Yiu, 2022), 2. (Tommelein, 2019), 3. (Rubio et al., 2019), 4 .(Dos Santos et al., 1998), 5. (Uhanovita et al., 2023a), 6. (Tezel & Aziz, 2017)

The literature on barriers to implementing poka yoke in construction is sparse compared to the manufacturing industry, where detailed studies have been conducted, such as (Lazarevic et al., 2019), which identified obstacles such as high costs and lack of training. In construction, the review shows that most of the barriers are derived from the study of Uhanovita et al. (2023a) on the construction industry in Sri Lanka.

The most cited barrier is "Lack of Training" (C1), indicating that there is little knowledge about poka yoke and its benefits in the works. Tezel and Aziz (2017) highlighted the importance of management being well-trained for successful implementation. Given the uncertain nature of construction, identified as the "most uncertain industry" (C2) due to its unique characteristics (Ilyas & Ullah, 2019), it becomes a barrier as it implies a continuous change in the conditions of risks and defects in construction (Rubio et al., 2019).

The barrier "Lack of maturity of the tool" (C3) refers to the professionals' perception that poka yoke is a new tool, generating fear of not obtaining good results (Uhanovita et al., 2023a). "Resistance to change" (C4) is also observed, as in other lean tools such as LPS (Alarcón et al., 2002), indicating that professionals are reluctant to abandon traditional work practices.

CONCLUSIONS

From the present research, it was noted that the literature regarding poka yoke has increased in the last 10 years, due to greater research and interest in the topic of reducing errors. Likewise, it has been observed that one of the most used principles is facilitate, followed by prevent, and noticing few applications in mitigate and replace. Furthermore, the main benefits of using poka yoke devices have been improvement of quality and performance, and reduction of errors; and also, barriers to its use have been observed such as: lack of training, construction uncertainty, immaturity of the tool, among others. The authors recommend exploring the adoption of new technologies such as poka yoke devices and conducting workplace studies that will identify a greater number of poka yoke devices, identify the benefits observed in the field, and explore the barriers associated with their implementation on site. of construction.

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ABOUT TIME-COST TRADE-OFFS IN TAKT PLANNING

Iris D. Tommelein[1]

ABSTRACT

Time-cost trade-off problems in construction scheduling are well known and described in the literature, but time-cost trade-off problems pertaining specifically to takt planning have received little attention to date. Previous papers have introduced concepts and applications of takt planning (aka. takt production) in construction. They addressed production systems design questions and presented various takt planning methods. Quite a few of those papers also mentioned how takt planning helps cope with variability that is known at the time of planning and with the manifestation of variability when it is encountered during plan execution. Coping methods include the use of capacity- (people and their means of production), materials- (inventory), space-, and time buffers. These buffers—and of course money too (financial buffers or contingencies)—come at a cost. This paper explores various costs to be considered in the takt planning process and it presents trade-offs that can be made to meet selected objectives. The goal is to initiate discussion on this topic and help spur further quantification of the advantages of using takt when designing project production systems.

KEYWORDS

Takt planning, buffers, slack, direct cost, indirect cost, fixed cost, variable cost, cost management, buffer management.

INTRODUCTION

While time-cost trade-off problems in construction scheduling have been studied extensively for many decades, time-cost trade-off problems pertaining specifically to takt planning have received little attention to date. To investigate the latter, this paper revisits the assumptions that underlie basic time-cost trade-off formulations and then scrutinizes those assumptions in light of the application of the lean concept "takt" used in the development and control of construction schedules. Note that the terms planning and scheduling are used interchangeably in this paper.

This conference paper is not a formal literature-review or research-based paper but rather a white paper reflecting the author's thoughts on time-cost trade-offs in takt planning. Essential parts of a formal study (e.g., an in-depth literature review) are therefore not included here but deferred until a later time. A white paper is meant to be thought provoking.

This paper is structured as follows. First, the literature section describes the basic formulation of the time-cost trade-off problem in construction scheduling. It then describes key concepts pertaining to takt planning in construction. The body of the paper elaborates on tangible and intangible time-cost benefits of takt planning. This is followed by a discussion on time-cost trade-off considerations, and conclusions with recommendations for further research.

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LITERATURE

TIME-COST TRADE-OFFS IN CONSTRUCTION SCHEDULING

The time-cost trade-off problem in construction scheduling has been studied since the early days of the critical path method (CPM) (e.g., Kelley 1961) and has become a fundamental topic in project management textbooks (e.g., Ch. 10 in Harris 1978, Ch. 11.4 in Hendrickson et al., 2024). Numerous variations of this problem have since been formulated, based on different assumptions with resource- and other constraints added, and using various mathematical programming- or heuristic optimization methods.

The problem is formulated by means of activities networked using precedence relationships (e.g., finish-to-start links) to make up a construction schedule (essentially a directed graph). Each activity is given a duration (e.g., modelled using a deterministic value). Each activity comes at a cost (e.g., also a deterministic value) in function of what it takes to perform the associated work using a certain resource allocation (workers with tools, equipment, materials, etc.) so that the activity can be completed within the specified duration with reasonable certainty. By definition, direct costs of an activity are costs that would not be incurred if the activity were removed from the schedule. A (piecewise) linear relationship is assumed between the so-called normal duration at the normal cost of an activity and its crashed duration (shorter than the normal) at the crashed cost (higher than the normal).

Given the network's precedence relationships and activity data, the project's direct cost and duration defined by the so-called critical path(s) can then be computed. An activity is said to be on the critical path—it is a so-called critical activity—when, if delayed in finish time, the entire project would be delayed. A critical activity has no float.

Starting from the normal duration and normal cost for each activity, the project duration can be shortened while its direct cost will increase. A heuristic method for doing so is to stepwise shorten the duration of the critical activity (or several critical activities in parallel) that is the least costly to shorten. For example, the order in which to crash activities shown in Table 1 is F, C, C, B and C, A, and finally B and C.

Table 1: Example activity network with time- and cost data (Tommelein 2023)

Activity	Finish-to-Start Predecessor	Normal Duration [days]	Normal Cost [$]	Additional Cost/Day Shortened [$/day]	Minimum Duration [days]
A	-	3 days	$1,800	$800/day	2 days
B	A	4 days	$2,000	$200/day	2 days
C	A	5 days	$1,000	$150/day	1 day
D	C	1 day	$400	--	1 day
E	A	3 days	$1,500	$500/day	1 day
F	B, D, E	2 days	$700	$100/day	1 day

In addition to direct costs, projects also incur indirect costs. Sometimes called general conditions costs, these are not straightforward to attribute to only one or a few activities, but instead are more related to the project as a whole (e.g., the costs of project supervision, gate access and fencing around the site, provision of temporary utilities). They tend to accrue in direct relation to the duration of the project and are typically modelled as a linear function of time, expressed as cost per time unit (e.g., $300/day). Accordingly, they decrease (or increase) with the decrease (or increase) of the project duration. A project's total cost is the sum of its direct- and indirect costs.

Figure 1 depicts the direct- and indirect costs for different durations of the project. It shows that the plot of the project's total cost vs. time—called the time-cost trade-off curve—may exhibit a minimum rather than steadily increase or decrease. That minimum total cost point is the optimum duration for the project (indicated on Figure 1 at 8 days and $10,200) in the sense that the project will cost more when scheduled to be of any other duration, longer or shorter.

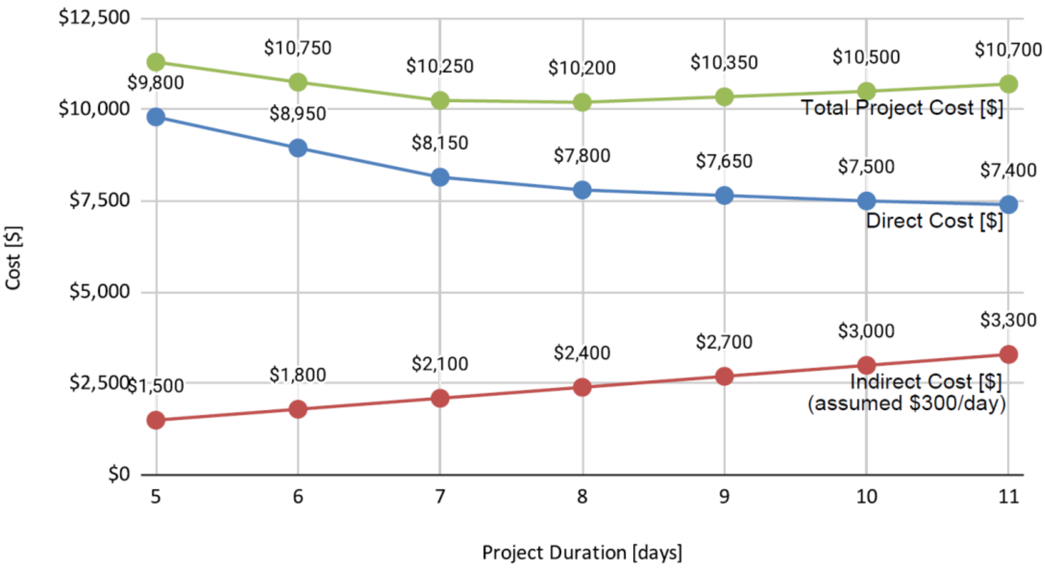

Figure 1: Time-cost trade-off in CPM scheduling (Tommelein 2023)

Note that the classification of a cost as direct or indirect depends on one's point of view and choices informed by the commercial terms of a project, including the cost accounting system in use. Figure 2 illustrates contributors to a company's and its projects' direct- and indirect costs. General and administrative (G&A) expenses are direct costs for the company, i.e., if the company did not exist, these costs would not be incurred. As they must be paid for in some way, they may be treated as indirect costs by accounting for them as an overhead charge on each project the company performs (e.g., as a percentage of a project's direct- plus indirect costs).

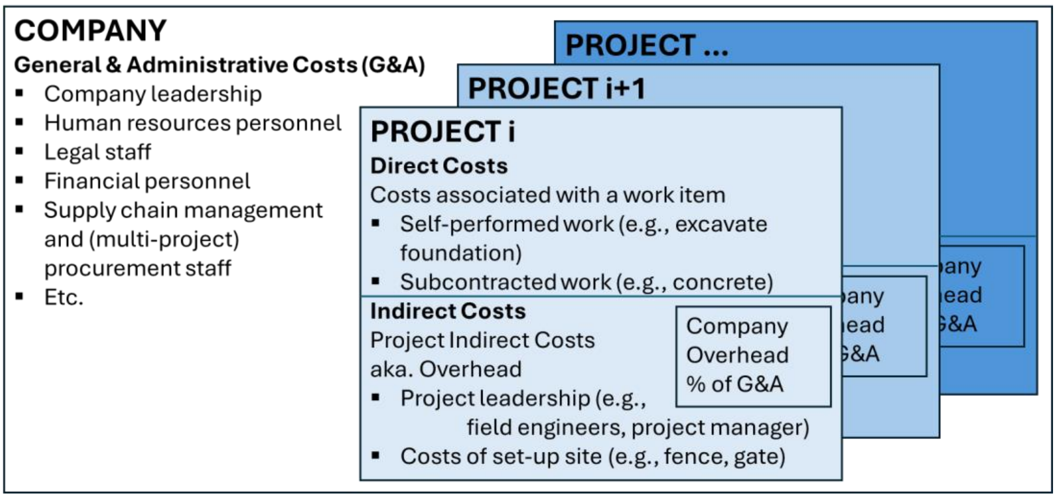

Figure 2: Contributors to direct- and indirect costs for companies and their projects (Tommelein 2023)

With this basic description of the time-cost trade-off problem and cost-related definitions pertaining to construction schedules in general, we next focus on takt planning, before we get into time-cost trade-offs related to takt plans (aka. takt schedules), a specific type of construction schedules.

TAKT PLANNING (AKA. TAKT PRODUCTION)

Practitioners and scholars alike have taken interest in defining a takt when planning construction processes (e.g., Frandson et al., 2013; Linnik et al., 2013; Heinonen & Seppänen 2016; Dlouhy et al., 2016, 2018; Binninger et al., 2017; and Lehtovaara et al., 2019). Despite this interest and the occasional mention of cost in takt-related papers (e.g., Vatne & Drevland, 2016), time-cost trade-offs problems pertaining specifically to takt planning have received little attention to date. In fact, a search for “time-cost” in papers posted on IGLC.net identified only a single one (O'Brien et al., 1997). It pointed out that the basic time-cost trade-off problem formulation ignores capacity constraints (e.g., resource availability, resource utilization, and site conditions) encountered when a schedule gets accelerated or delayed. We were unable to locate any prior studies on the specific topic of time-cost as it relates to takt planning.

In takt planning, the work to complete an entire construction project or a phase thereof is broken down into processes, with each process comprising steps arranged finish-to-start in linear order. The scope and sequence of these steps is decided while considering where work is to be done and avoiding trade stacking. Then the work space is divided into zones so that each step can be completed in each zone within the same, fixed amount of time, defined based on the duration needed to meet customer demand (T), aka. the “customer takt”. The work is structured so that only a single trade is working in any one zone at any given time while aiming to achieve continuous flow (e.g., Formoso et al., 2022).

Flow (i.e., a smooth progression of something, said to be “continuous” when there are no interruptions) manifests itself in multiple ways (Tommelein et al., 2022) which can be measured (e.g., Singh et al., 2020; Singh and Tommelein, 2023a, 2023b), e.g., (1) When a step is completed in one zone, the succeeding step of the same process can start there, and (2) At the same time, the trade that completed their work moves to start work in the next zone, etc. Thus, trades flow from one location to the next (Tommelein et al., 2022 called this “trade location flow”) and work in each zone gets done in the process order of successive steps (“process location flow”).

By creating concurrency of steps, the project can be completed faster than it would be otherwise (Figure 3). The cost for shortening the schedule duration will be a function of the trade location flow, process location flow, and many other metrics, and their costs. Using these, takt planners can then make trade-offs as needed to balance the degree to which they can meet their objectives.

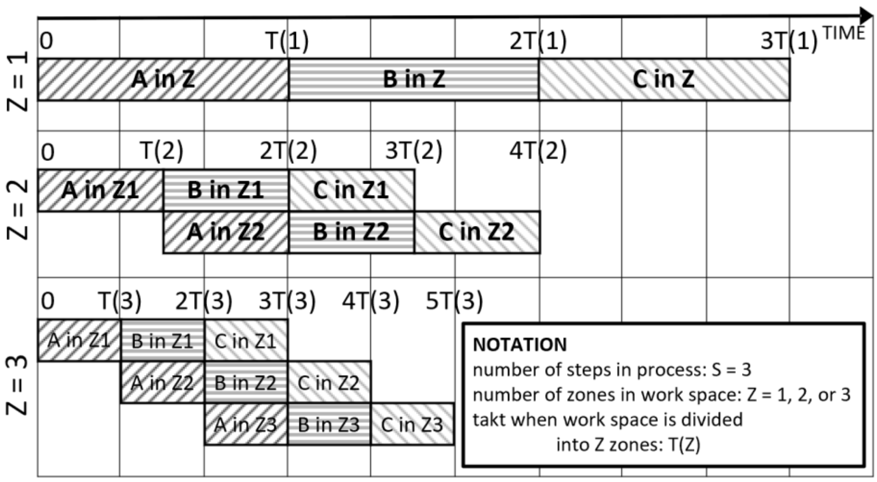

Figure 3: Duration of 3-step process (steps A, B, and C) when the work area

is divided into respectively 1, 2, and 3 zones Z (after Figure 1 in Jabbari et al., 2020)

Because workloads will exhibit some variability, any individual workload (i.e., the actual time needed by a trade to complete a certain scope of their work in a given zone) should be less than the time T allotted. How much less is a function of a workload's variability: trades must reasonably ensure that each step-worth of work will be completed by time T. This ensurance is obtained by underloading resources and thereby creating a capacity buffer, i.e., by scheduling resources to work below 100% utilization. The use of right-sized capacity buffers makes it possible to achieve plan reliability (Frandson et al., 2015).

In any case, at least one trade will have a workload greater than everyone else's and that is called the workload peak, aka. the "operational takt." The workload peak must be smaller than or at most equal to the time T allotted or the customer demand will not be met. As this workload peak is a function of the way zones are defined, it is labelled T(Z), with Z referring to a specific zoning of the space where work is to take place. Thus, the zoning and takt plan must be structured so that $T(Z) \leq T$.

Once the workload peak (possibly with an allowance to account for variability) of a process is known for a certain zoning of the work space, the shortest duration D of that takted process can be computed mathematically:

$$D = (S + Z - 1) \times T(Z) \quad \text{(Equation 1)}$$

where S is the number of process steps, Z the number of zones, and T(Z) the workload peak. An increase in the number of zones Z typically results in a decrease in the duration D, as zones get smaller in area and T(Z) tends to go down (up to a point, as noted in Jabbari et al., 2020).

Several methods exist to zone a work space. For example, as a tool to support the use of the Work Density Method (Tommelein 2017, 2022), Jabbari et al. (2020) described a mathematical algorithm, the Workload Leveling and Zoning algorithm aka. WoLZo. WoLZo uses a given distribution of workloads for each trade in the work space and the number of zones dividing the work space, to calculate the optimal boundaries for zones (constrained to be either rectangular or L-shaped), i.e., the zoning that results in the minimum operational takt T(Z).

Given this brief review of the literature on the time-cost trade-off problem and on takt planning, the following section opens the discussion about time-cost trade-offs in takt planning.

TIME-COST TRADE-OFF CONSIDERATIONS IN TAKT PLANNING

Float in a Takt Plan?

Now return to the basic description of the time-cost trade-off problem with solution methods that stepwise reduce the duration of one or several critical activities. Note that all steps in a takted process follow each other sequentially as in a Parade of Trades and they all are given an equal duration (Tommelein et al. 1999; Tommelein, 2020). Unless an explicit time buffer is incorporated in the process (e.g., a 1-takt delay, perhaps to allow for make-up work), there is no float from start-to-end of a process: all steps are critical. Time-cost optimization methods must therefore be rethought.

Indirect Cost when Shortening the Duration of a Process or Project

The argument may still hold, given the previously stated assumptions about overhead rates, that shortening the duration of a project will result in less indirect cost. Whether shortening the duration of a process (presumably one of several processes in a project) will also shorten the duration of the project depends on how that process fits into the project network.

We can extend the notion of criticality of an activity and identify critical processes in a project. However, it is common practice in takt planning to strategically include time buffers not only within- but also between processes to prevent any delays from reverberating through the schedule (Binninger et al., 2017). Teams pursuing takt planning must proactively manage their work to prevent a Parade of Delays (Dahlberg and Drevland, 2021) and should be cognizant of slack in their production system available to help them cope with unforeseen circumstances (Formoso et al., 2021). The practice of adding time buffers to a takt plan is similar in spirit to adding feeding- or project buffers to a schedule when using the Theory of Constraints (TOC) (Goldratt, 1990), or to adding a schedule contingency before the project completion date. When time buffers are added, then all processes have float.

Revisiting the assumption about the overhead rate, note that shortening a project or process by creating more concurrency in the schedule increases the schedule density (schedule density is a term used in construction claims; see for example Finke, 2000 or Ottesen and Hoshino, 2014). Otteson's (2019) thesis is that an increase in schedule density is a predictor for productivity loss. More activities underway in multiple locations at the same time and greater interdependence between them may result in greater complexity that in turn may require more managerial attention. Consequently, an increase in the need for managers could warrant an increase in the overhead rate.

However, the structure of the schedule, in and of its own, captures only a small part of the reality of a project. Team engagement and managerial practices play a role in project delivery! On takted projects, the shared understanding developed among trades during the takt planning process, and the visual- and structural clarity of the takted schedule (e.g., Figure 3) could be such that no additional managerial attention will be required when the schedule density increases. We speculate that research might even indicate that successful execution of a takt plan demands less managerial attention.

Cost of Shortening the Duration of a Process

The duration D of a process can be shortened in several ways, as indicated by the terms in Equation 1, namely by:

- Reducing the number of steps S in the process. This may be possible by moving work from one step to other steps (or combining steps) in the same process, by moving work to another activity or process step elsewhere in the project schedule, or by taking scope out from the on-site work and moving it off-site. A reduction of D in this way can either increase or decrease the project cost depending on capacity constraints (e.g., O'Brien et al., 1997), network characteristics, and the related economics.
- Increasing the number of zones Z to allow for more concurrency, if doing so indeed reduces T(Z) and has the effect of lowering D. The indirect cost implications in this case already were discussed in the previous subsection. As for the direct cost implications, in a first-order approximation, shortening the duration may be cost neutral as each trade's total amount of work and resources stay the same. In a second-order approximation, however, consideration must be given to costs stemming from work interruption or remobilization penalties. These are discussed later, in the subsection Cost of Logistics.
- Reducing work densities (e.g., by adding more resources) to lower the workload peak in a process, so that T(Z) can be lowered either in and of its own or by rezoning. Adding resources clearly comes at a cost. However, knowing which process step(s) essentially determine the workload peak also reveals which trade(s) in which zone(s) have a much smaller workload than others. These trades can use the process workload data to identify when and where they can slow down without jeopardizing the duration of the process. By assigning fewer resources, they can lower their cost while increasing their work density (not to exceed the workload peak) in certain or all zones. In combination, such cost changes due to increases and decreases in resources can have a positive or negative impact on the cost of the process.

When the workloads of all steps in a process are more-or-less balanced across trades and zones, resources presumably are used efficiently, and a near-continuous trade location flow and process location flow will be achieved.

Cost of Capacity Buffers (Underloading)

Whereas all steps in a takted process are critical, looking closer at the workload for each step in each zone it is noted that resources are underloaded. This is so by construction. Indeed, the intentional use of capacity buffers is what sets takt planning apart from other planning methods such as the Location Based Management System (Frandson et al., 2015). Underloading means that resources have a modest amount of extra capacity to do more work if needed, e.g., due to the manifestation of variability, and still finish each step on time. The whole point of takting a process (underloading resources at each step) is to allow handoffs to occur like clockwork, so as to prevent delays from occurring and impacting follow-on work.

Underloading comes at an increase in cost directly tied to a process step. Arguably, paying for intentional underloading is the greatest challenge to overcome when introducing takt planning to a team that is narrowly focused on productivity. Underloading brings benefits to the schedule, such as robustness, by creating slack time for trades to respond to disturbances encountered during plan execution.

Cost of Time Buffers within and between Processes

As was mentioned in the section on shortening the duration of a process or project, time buffers can be added anywhere in a takt plan, e.g., in or towards the end of a process, or in-between processes. Whereas all steps in a process are critical (they must be done within the takt), the process itself can be decoupled from preceding or subsequent processes by means of a buffer, and thus at that level have float.

While the use of a time buffer itself may appear to be free (a no-cost option), the buffer may extend the project duration and therefore result in an increase in indirect costs. Time buffers can also cause resources to be idle, having to wait for work, resulting in increased direct- or indirect costs depending on how the accounting is done. Trades involved in takt planning must duly consider how to use their time on site waiting until the next zone becomes available, e.g., by judiciously creating learning opportunities or workable backlog, in order to avoid otherwise unproductive wait times.

Cost of Space Buffers

Like time buffers, space buffers may appear to be free (a no-cost option), but that is not the case. They indicate a wasted opportunity to complete a process faster as work is waiting on workers. The availability of open spaces may tempt people to use them and as a result, materials handling and work practices may not be as well thought-out as they could be. Moreover, space buffers may not be free even when left open, e.g., when completed work requires protection or conditioning.

Cost of Logistics

Concern about the cost of logistics is often expressed when people hear about just-in-time production with its frequent deliveries of small batches of products—highly relevant to takt planning, especially when a work space is divided into many zones—because their minds are set on efficiencies of scale when producing and transporting large batches of products. It is also brought up in the context of kitting—likewise highly relevant to takt planning (e.g., Tetik et al., 2019, 2021; Gschwendtner et al., 2021). The concerns are valid when new practices are being contemplated. Lean practices such as those mentioned require engagement early on in a project and an up-front financial investment for their implementation. Cost accounting for logistics is complicated, and even more so when logistics is interpreted broadly (e.g., Mossman, 2007, Seppänen & Peltokorpi, 2016).

To illustrate, Figure 4 offers an example of a lean logistics cart used by a mechanical and plumbing contractor. This contractor invested in the development of this mobile, adjustable rack, that will serve not only the current project it is used on, but also future projects. The cost of this rack may be charged to the project for example on a per-use basis. Gschwendtner et al. (2021) accounted for such costs in their study of supply- and reverse logistics to support a takt plan, however they failed to obtain data describing the efficiencies gained by the installation crews that were supplied with kitted materials. Logistics costs are incurred by one group of people and the benefits reaped by others; when too narrowly accounted for, they will not pen out. This is where accounting (e.g., Horngren et al., 2012) and lean accounting systems have a role to play (e.g., Cunningham et al., 2003; Maskell & Baggaley, 2006; Maskell & Kennedy, 2007; and Maskell et al., 2011), to take a broad view on the production system and attribute costs appropriately, as needed here in the context of takt planning.

Figure 4: Example of lean logistics - cart with pre-assembled fixtures
(Source: I. D. Tommelein, 20 April 2016)

DISCUSSION

Taking a step back from these time-cost considerations, it will be clear to the reader that the intuition they may have developed about basic time-cost trade-offs in CPM-type scheduling does not exactly hold for takt planning.

The time-cost trade-off problem was originally formulated in the context of CPM, which is used at the master level of scheduling (using the terminology of the Last Planner® System (Ballard & Tommelein, 2021)). The time-cost trade-off problem as discussed in this paper, however, pertains to takt planning, which affects planning at multiple levels in the Last Planner® System, from master level scheduling all the way down to execution and control. Takt planning is production focused and therefore demands consideration of various kinds of variability in the system given its context, dedicated and shared resources, capacity utilization and allocation, production throttles that can be adjusted in the planning process, etc. All of these affect the cost of the takt plan and may thus be relevant to time-cost trade-offs.

In an effort to instil regularity in a takt plan (e.g., by means of defining process steps and balancing workloads) and aiming to achieve reliability in the execution of each and every step, some costs will have to be incurred (e.g., underloading of resources). This notwithstanding, such investments are expected to pay off and, if not immediately, then certainly in the long term reduce cost. Reliability and visual clarity in the takt plan create the possibility for project participants to tune their resource allocation to systemic needs, rather than exclusively to their own resource availability and company optimization strategy. Furthermore, the clarity in a takt plan's definition creates the stability that makes it possible for team participants to learn and improve their work over time in the course of a single project (e.g., Vatne and Drevland (2016) mentioned that crews were able to reduce their crew size as they speeded up), but also going from one project to the next one (e.g., increase their process capability) (e.g., Tommelein, 2020).

Further study is in order of existing algorithms for time-cost trade-offs—there are so many! It may be possible to use some parts of existing problem formulations (e.g., Feng et al., 2000, Al Haj & El-Sayegh, 2015) to study time-cost trade-offs in takt planning, and it certainly is possible to develop fit-for-purpose computer-based simulation models to allow for experimentation with alternative plans (e.g., Tommelein, 2020; Gschwendtner et al., 2021). Whatever problem formulations and algorithms exist, they will require extensions, e.g., to model various resource types, variability, work density, and other concepts specific to takt planning.

Besides the need to develop new algorithms and computer-based support tools to help takt planners make time-cost trade-offs, more fundamental is the development of lean construction cost accounting systems. This topic is worthy of greater study in our IGLC community, informed by publications on lean cost accounting as it is used in manufacturing and elsewhere.

CONCLUSIONS

Starting from the recognition that problems pertaining to time-cost trade-offs specifically in takt planning have received little attention in the scholarly literature to date, this paper explored various costs that are to be considered in the takt planning process. It raised a number of concerns and recognized a lack of knowledge; knowledge that will be needed to make informed time-cost trade-offs to meet selected objectives.

Only a few of the specifics related to time-cost trade-offs were presented in this paper. An in-depth study of the literature is needed, and formal cost models should be developed to support takt planners, e.g., using lean accounting methods. Our hope is that this paper's exposition of theoretical concepts related to the time-cost trade-off problem in takt planning will initiate discussion on this topic and help spur further quantification of the advantages of using takt in project production systems.

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RIGOROUS 2-HOUR TAKT REVEALS UPSTREAM UNDERPERFORMANCE

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ABSTRACT

The primary purpose of this study is to demonstrate that rigorous production control requires high quality and flawlessness in the upstream production process. The research approach is a quantitative case study. One-piece flow forms the theoretical framework combined with the "sea of inventories" logic. The empirical material is collected from the case company's renovation projects' data, documentation, meeting minutes, and training material.

The definition, modelling, and analysis of the production system are fundamental to continuous improvement in construction. Systematic analysis, documentation, quality control, and quality assurance enable fact-based improvement and control of the production system. Our study, following the logic of continuously tightening requirements for control variables in the production flow, reveals upstream underperformance and drives the elimination of the problems, thus improving efficiency. In our case, company evidence shortening the takt from 4 hours to 2 hours reveals hidden problems in upstream flow, resulting in continuous improvement in production quality. Overall, our study provides evidence of the applicability of one-piece flow in construction.

KEYWORDS

One-piece flow, Toyota Production System, JIT, Takt

INTRODUCTION

The construction industry has used the Toyota Production System (TPS) and Lean methods since the 1990s. Still, results in increased productivity have not been rooted in the industry despite numerous successful Lean interventions (Pekuri et al., 2011; Da Rocha et al., 2022). Lately, Riekki et al. (2023) suggested that takt production could work as a ground-up driver towards implementing a Lean-based production system for construction.

Research has shifted to takt production and flow to increase the construction industry's productivity. At least four schools of thought can be distinguished from takt production: Takt Time Planning (e.g., Tommelein and Emdanat, 2022), Takt Planning and Takt Control (TPTC) (e.g., Binniger et al., 2017), Takt Time Planning (Gardarsson et al. 2019) and "hourly takt", takt production based on one-piece flow (e.g., Riekki et al., 2023). Research has tried hard to define the construction physics (Bertelsen et al., 2007) and flow of construction (Sacks 2016). Still, it has ended up where so many things flow that there is no unambiguous name or definition for

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all identified flows (Tommelein et al., 2022), or the flow is just not flowing in the construction industry (Rocha et al., 2022).

In addition to the inability to formulate a theory for a holistic approach to a lean construction production system (Riekki et al., 2023), the research in the construction industry has not recognised products (different types of buildings), upstream processes or their importance as part of the production system. In contrast to TPS in the automotive industry, product development plays a minor role in the construction industry (Pekuri et al., 2014). Instead, construction companies typically outsource product development to subcontractors without realising that the construction and the assembly phases are some of the most critical stakeholders in setting the product requirements for industrial manufacturing (Stevenson, 2021, p. 165; Hopp and Spearman, 2011, p. 4; Fujimoto, 1999, pp 112-113). Without systematic product development, there is no systematic production capability creation, which would result in systematic production development (Annunen and Haapasalo, 2022; Annunen and Haapasalo, 2023). This underlines the observation that craftsman production (Womack et al., 2007, pp.19-24) is the predominant product design and production form in the current construction industry ("prototype production"). The focus of productivity development in the construction industry should be to transfer the design and construction from artisanal production first to the beginning of the industrial era. Then, we can take it further step-by-step and not, as is currently the case, transfer the characteristics of highly developed production methods in companies to a system based on craft production.

Based on the above, this article examines the basis of a construction production system and the enhancement of the production system in a case company, which brings previously hidden problems to the fore and their root causes. Thus, the main goal of this article is to show that rigorous control of production requires flawlessness of the upstream production process and thus causes a continuous improvement in the production quality as the more stringent control is moved. This goal is pursued through the following research questions:

1. RQ1: How is the one-piece flow used in the 2-hour takt case project to reveal the problems of the production system when compared to the previous 4-hour takt project?
2. RQ2: What are the problems and the root causes in upstream flow revealed by shortening the takt (4h takt to 2h takt)?

In this paper, we first review the literature to understand the relation between one-piece flow and eliminating disruptions (poor design, procurement, prefabrication, logistics, quality), resulting in quality and productivity improvement. Second, we describe our case study production system and analyse how the change from 4-hour takt to 2-hour takt has revealed more detailed failures. Also, we identify their respective failure mechanisms in the upstream process, leading to improved performance in the production system. We deliver case evidence on the applicability of one-piece flow in construction when carefully applied.

LITERATURE REVIEW

ONE-PIECE FLOW

The just-in-time (JIT) concept is part of TPS which creates a pull flow to the production, which forces the previous part of the process to do what the next part of the process (customer) needs. Part of the JIT is one-peace flow which brings the problems to the surface if implemented meticulously. The benefits of one-piece flow are undeniable: it builds in quality, creates natural flexibility due to shortening lead times and creates higher productivity since it reduces the cost of inventory and unleashes people's creativity. Simultaneously, it improves safety and morale (Liker, 2020, 71-73). If a problem surfaces, the entire production line is forced to shut down. This, in turn, forces everyone to stop and fix the problem so production can continue. This way, the crew and the process evolve. The one-piece flow with a short lead time enables higher quality because there is no large buffer of faulty parts when the defect surfaces. Also, part of the one-piece flow is that the next part of the process acts as an inspector for the previous part, and the defects are quickly found (Liker, 2020, pp. 61-76).

SHOP FLOOR CONTROL AND PRODUCTION SYSTEM

Hopp and Spearman (2011, p. 481) define Shop Floor Control (SPF) as the point where production planning interfaces with processes. They suggest that production control works best under stable conditions, which is precisely what TPS aims for. Unfortunately, creating such an environment can conflict with business requirements. As a result, in industrial production, part of the production is carried out in production systems, where some of the methods highlighted in Toyota's TPS research either do not fit well or do not fit at all (Irani, p. 36, Table 2.2). When classifying production systems and assessing their usability, one must understand the product being produced, its volume, and its variation—i.e., how many articles of the same product are intended to be manufactured. This product volume (Low vs High Volume) – product variation (Low vs High Mix) forms a product-process matrix. A low-volume, high-variation (LVHM) product can be considered more demanding to manufacture than a product with high volume and low variation (HVLM). Therefore, every Toyota facility is engaged in improving with Lean the productivity of HVLM assembly lines, which are very inflexible production systems (Irani, 2020, pp. 26-34; Chryssolouris, 2006, pp. 332-334; Hopp and Spearman, 2011, pp. 6-11).

The Bill of Materials is an essential part of the information maintained and processed by Manufacturing Resource Planning (MRP) for managing material flows in industrial production (Hopp and Spearman, 2008, pp.116-119). During the design phase, the designed parts, materials, subassemblies, and other objects combined with their part hierarchy can produce the Engineering Bill of Materials (E-BOM). Actual manufacturing requires the Bill of Materials at the purchasable part number (Manufacturing BOM or M-BOM) level and the corresponding article hierarchy (Sheng-Hung et al., 1997, Stevenson pp. 562-564).

The smaller the batch size, the more flexible the production system must be. As Lean focuses on cost reduction through waste elimination, the Theory of Constraints (TOC) provides a competing manufacturing strategy (Irani, 2020, p. 25) as its goal is to maximise flow through the entire system by identifying bottlenecks, balancing the flow and eliminating constraints (Stevenson, 2021, p. 715). Yet another production strategy is controlling the production system via Work in Progress (WIP). A pull system can be implemented with Kanban, but it is far easier to limit the amount of WIP to a constant level and use a Constant WIP (CONWIP) production system for pull production (Hopp and Spearman, 2011, pp. 363-368). All these strategies can be used for implementing a production system, and the question arises of which would be compatible with construction.

RESEARCH APPROACH AND LOGIC OF THE PAPER

Our research follows a case study approach, defined by Yin (2009), aiming to utilise the research material of one company. The target company of the case study was chosen because it has been developing production efficiency in two business units simultaneously using the same method, i.e., one-piece flow. The study chose between two business units and their different applications of one-piece flow based on the management and maturity of the manufacturing process. In the project selected for the study, 1) the manufacturing process was more comprehensive and 2) described in greater detail at the task level for workers. Also, the manufacturing process 3) utilised more prefabricated components and 4) employed a documented and trained management system for daily and weekly management. In other words, the selection criteria for the study were the extent of systemic change in product, design, procurement methods, contract models, the extent of one-piece flow usage, management of the manufacturing process, and team management. The research team also considered the significance of the takt duration for the study. It concluded that a 2-hour takt (implemented three times a day, leaving 2 hours as a daily buffer) is more significant than a 4-hour takt, where, based on observations, the wagons had more built-in buffer than in the selected project.

This research also shows how the one-piece flow principle of the TPS applies in the construction process, where effort is put into controlling variation in the production. This, in turn, has required and will require significant improvement in the quality of the upstream process in the studied business unit. Here, we apply the logic from the "sea of inventories" to more rigorous time control of the system. The empirical part is two-phased, based on first the description of the case project and details of the 2-hour takt. The quantitative study focuses on which deviations emerge after moving from a 4-hour to a 2-hour takt. The system's capacity can be utilised comprehensively only by analysing and eliminating the causes of disruptions, and therefore, design, procurement, design for the prefabricated parts and elements, off-site prefabrication, delivery, site-logistics and the construction process itself are studied as a production system.

The focus of the empirical analysis has been the implementation of our case company's refurbishment process of bathrooms. The model of the 2-hour production system was created together with the production team as they prepared for their next project, and the documents and organisational instructions were used as a reference. Our data was collected from the backlog of the previous 4-hour and 2-hour projects (contracts, planned and performed schedule), financial final accounts and deviation accounting maintained during the implementation phase of the projects, as well as defect/deficiency lists made in the projects and approvals of implemented repairs from the quality management system. The research team also accessed the project organisation's schedule analysis after the 2-hour project concluded. The most critical part of the study was the event data on deviations produced by the day-to-day management model of the last two projects, which the research team used as the starting point for quantitative analysis. This event data was classified and supplemented using WhatsApp records and analyses produced by three lean interventions on the implementation problems of one-piece flow. As a result, a comparison of the deviations in the 4-hour and 2-hour production systems was obtained and categorised data from the 2-hour project was integrated into the production system model. Using this framework, the aim was to formulate improvement suggestions to utilise one-piece flow and reduce production variability more effectively.

DEVELOPMENT AND DESCRIPTION OF THE PRODUCTION SYSTEM – CASE STUDY

The researched business unit primarily renovates residential buildings constructed in the 1960s and 1970s using a concrete element frame system. These renovations typically involve replacing water, sewage (occasionally also heating), and electrical systems, necessitating the dismantling of bathrooms and toilets down to the concrete framework in the apartments. Also, projects include the dismantling and renewing of the corresponding systems in the basement and the required connections to the municipal water, sewer and heating systems at the plot. Therefore, renovations vary depending on the surrounding city infrastructure, the size of the residential complex (number and type/size of buildings), and the geological conditions of the site. The organisation aims to achieve a lasting competitive advantage in the HVLM market by industrialising its production system and portfolio-based business model as described in Portfolio/Process/Operations-model (PPO, Korb et al. 2017, pp.165-167).

From Theory of Constraints (ToC) to Takt Production

The pipeline renovation business unit encompasses two distinct business models based on one-piece flow and subcontracted work. The studied organisation has systematically developed its production system to manage manufacturing. The organisation initiated the transformation from the traditional subcontracting method to partnering. Initially, the projects were subdivided, and subdivisions were tendered, repeatedly purchasing them as cheaply as possible from ever-changing subcontractors (black-box tendering) using the customer's design for HVAC.

The first step of the business unit towards developing an industrial production system was establishing a production Alliance. This objective was to standardise the production method by maintaining a consistent team and striving for longer-term collaboration with trades, employing the Alliance project delivery method starting in 2015 (Korb et al. 2017). However, the recurring problem on sites was the persistent variation, which led to applying ToC to identify and address workflow bottlenecks. Nonetheless, poorly designed details make the renovation process susceptible to variation. In the Design-Bid-Build (DBB) project delivery method, which the clients widely use in the Finnish bathroom refurbishment market, the main contractor is not adding value to HVAC designs. Instead, the main contractor uses the exact customer-originated 2D drawings in tendering for separate trades. As a result, the subcontractors are responsible for creating the implementation design and selecting the parts and materials, often while the work progresses. The Alliance method proved to be ineffective in solving various production-related problems. The project manager summarised that the production bottlenecks shifted faster than they could be identified and controlled. In 2019, the team moved to use the CONWIP model to gain control over the design and production processes to standardise products and work in some form. At the same time, the organisation transitioned to a partnership model with selected subcontractors, conducting business together based on the open-book principle.

The use of CONWIP as a core of the production system shifted the responsibility for completing plans, products, and materials, as well as understanding the execution of work, to the main contractor's organisation. Gradually, the organisation's ability to create and manage the housing manufacturing process as a whole grew to an exceptional level for a leading contractor in the market. Moving from a zero-sum game business to partnering enabled the transition to takt production, initially implemented with 4-hour takt and takt logistics. Project by project, the organisation improved its manufacturing planning expertise towards an LD400 level in each wagon. This led to more precise parts lists (M-BOMs) for procurement and logistics while simultaneously refining the standard product and standard work (manufacturing process). Continuous ambition to refine design towards the LoD400 level, increased design precision to form M-BOMs for each wagon, and the ensuing opportunity to meticulously plan and execute the production process down to the minute raised the maturity of the production system to its current level. During the last three projects, the organisation has systematically transferred material processing and assembly to a separate production facility, a "factory", causing the prefabrication level to increase drastically.

The continuously improved takt production system aims to execute construction using a one-piece flow. Because the renovation projects vary across the market area, each project is divided into two parts: the process and the project part. The process uses takt production, and its design is refined to LoD400. The project part is executed using a traditional management model influenced by the LPS. From the manufacturing industry production systems perspective, the unit has separated the recurring renovation of similar residences into a one-piece flow based on product and process standardisation, referred to as the HVLM production system. Over six years, the production system has been developed to increase production flow from 150 apartments in 2018 to 330 apartments. Meanwhile, the organisation and direct costs have grown by approximately 15% during the same period.

THE PRODUCTION SYSTEM IN THE CASE PROJECT

The core of the production system is the manufacturing process and its management. The organisation believes managing the manufacturing process necessitates control over the products (apartments) and their production. Consequently, the organisation of the business unit focuses on two principal tasks: 1) product design and 2) manufacturing planning. Since changes in the product invariably affect manufacturing, and alterations in manufacturing methods impact the product, the studied organisation has formed a single, cohesive and interactive team to implement their production system without hierarchical or organisational boundaries. The objective of designing the production system is the capability to plan all necessary materials and then required tasks from the beginning of manufacturing (a bathroom dismantled to concrete) to the finished product (a zero-defect delivered apartment). The studied organisation has set itself the goal of transitioning to industrial production, where the organisation is responsible for the product, all its materials, parts, tasks, work techniques, tools and procedures from design to installation. The responsibility also includes transitioning to hourly work, using the employer's unilateral right of supervision, and superseding subcontracting.

The project was implemented using the DBB method, where the client commissioned what is incorrectly known in the market as a feasible 2D design. The business unit had won the tender based on price. During contract negotiations, the implementation organisation developed the design so that the project could use as many established solutions and materials as possible that are known to be compatible with a one-piece flow production. Hence, the production system consisted of three segments: A) product/manufacturing process design and procurement, B) apartment manufacturing process and C) off-site prefabrication and supply chains. The production system is depicted in Figure 1. The design was an iterative process, and it consisted of the following subprocesses: 1) product design, i.e. apartment HVAC design; 2) pre-fabrication design; and 3) manufacturing process planning: creating M-BOM per apartment type, work breakdown structuring and formulating task lists per apartment type and staging and levelling the wagons. Since the design created and maintained M-BOMs, it also controlled the 4) procurement and takt logistics. The apartment manufacturing process was separated from the project on-site management, and the 5) daily operations and management included daily huddles for team members (TMs) and team leader (TL). The group leader (GL) met daily with TLs following the standard management procedure and problem-solving process. These meetings were also attended by design, prefabrication, procurement and project management. TLs and GL managed 6) logistics on-site and took care of 7) call-offs for JiT deliveries for both prefabricates and materials.

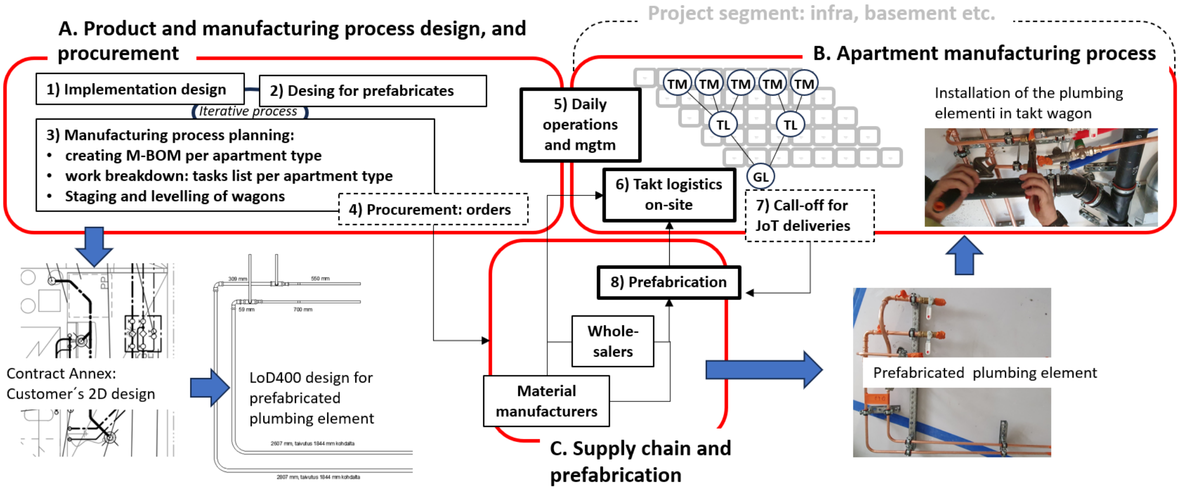

Figure 1: The modelled production system, which uses one-piece flow as a core

Timewise, the project was divided into two main phases: the production preparation phase and the production phase. The production preparation phase focused on prefabrication design, material selections, procurement planning and JiT-logistics. The prefabrications were designed to be millimetre precise for manufacturing, and simultaneously, M-BOM was formed for each apartment. Depending on the apartment type, the number of items in the M-BOM varied between 280 and 300 separate articles. The prefabrications reduced the number of parts and material items delivered to and built on-site by about 50-70 items per apartment. The apartment-specific parts and prefabrication list were the basis for planning takt-logistics, scheduling, and placing orders. It was also used to update the manufacturing process task list, which the organisation aims to shorten and specify with each project. There were 246 defined tasks in the studied project, for which duration estimates at the minute level and worker competency requirements were empirically defined. Using the task list created with the help of the plans and the M-BOM, a 2-hour takt train was formed, in which tasks were distributed and levelled across the wagons based on estimated task durations. The design principle was to leave a 15 – 30-minute buffer depending on the expected variation in each wagon and the daily 2-hour buffer. In levelling, the aim was to manage and balance execution time at a minute level, concentrate on specific tasks according to competency requirements, and consider staff capabilities. For prefabrications, the decision criterion in product design was the smoothness of the 2-hour takt and the reduction of throughput time. The manufacturing time of prefabricated components was not considered in the decision-making process, as there was insufficient data on actual manufacturing times.

The formation of the takt train created the prerequisites for resource allocation and the formation of teams for implementation. The structure and organisation of the production system were arranged by dividing the manufacturing process (adjacent wagons) into three teams: demolition and installation of vertical HVAC lines (wagons 1-3), casting, installation of horizontal HVAC lines, and tiling (4-11), and installation of fixed furnishings and finishing works (12-21). In each team, a team leader was responsible for team members implementing their wagons, daily supervision of workers, problem-solving and escalation, and work safety.

RESULTS AND DISCUSSION

The two-layer daily management model, which was adopted from TPS, was designed based on experiences from the 4-hour takt to control the manufacturing process and resolve problems arising in manufacturing. Based on interviews with management, the goal was for the team members of the three teams to be at the top of the hierarchy. Other levels of the organisation, team leaders, group leader, planning, procurement, and prefabrication, were supposed to support the team members, the actual operators implementing the manufacturing process. The project shifted to a 2-hour takt, similar to previous projects that used a 4-hour takt, prefabricates, standardised parts and materials, and established daily management practices. The team members were mainly the same as in the 4-hour takt, but the task contents were changed while the degree of prefabrication was increased. The product was expected to become more straightforward regarding prefabricated components, which resulted in a shortening of the manufacturing process and throughput time. In numbers, the shift from a 4-hour takt to a 2-hour takt changed the execution so that instead of the previous 40 units in a 4-hour wagon, the manufacturing process aimed to be implemented in 37 units of 2-hour wagons, of which 15 units had one or more prefabricates. Consequently, the throughput time for an apartment was reduced from 160 hours to 74 hours. Each day included an empty wagon as a buffer, so the calendar time for apartment throughput was decreased from 20 weekdays to 12,4 weekdays. The hours spent on factory work were not tracked for the prefabrication part, except for individual trial installations, which showed a time saving of 30-70%.

The project personnel conducted a more detailed internal evaluation based on the actual takt schedule for the part of the project they deemed most important (the C and D staircases, with 24 apartments, which they considered too large batch size after analysis). According to this assessment, there were start delays of 2 working days and completion delays of 5 working days, which meant that the throughput time for this project batch was extended to 17 working days. The same analysis also revealed that reducing the batch size could shorten the throughput time for the entire staircase by 4-5 working days. By moving the vertical HVAC installations out of the bathroom to the staircase, the throughput time for the bathrooms could be reduced by 4 working days when looking at the entire batch of apartments produced. However, the schedule review did not reveal any continuous deviations or the root causes of delays, so alongside the traditional schedule review, a quantitative analysis of deviation information produced by day-to-day management was included in this study.

How is the one-piece flow used in the case project to reveal the problems of the production system? (RQ1)

In the researched case, the implementation of 2-hour Takt production based on a LoD400-level plan specific to each apartment type, which 1) standardised materials into pre-cut parts, 2) defined prefabricated components, and 3) fixed the predefined number of parts and materials to be installed according to the M-BOM per location, revealed the weaknesses of upstream processes. This is because, in a 2-hour takt, there is no time for a redesign, acquiring additional parts or materials from the off-site factory or hardware store, or fabricating suitable parts from materials, as was possible in a more stable 4-hour takt in the previous case. Additionally, the precise dimensioning of the prefabricated components and the solutions chosen for tolerance management were not sufficient for all apartments. As a result, workers had to modify and alter prefabricated elements. This led to deviations in dimensions exceeding the tolerances, resulting in either a shortage of parts or materials in that specific takt wagon or a later wagon(s). The skills or available time of the team leaders did not allow for error detection, leading to a build-up of problems. Incorrect decisions made by the workers were caused by a lack of training, lack of printed instructions, and/or design errors due to mistakes made in the upstream processes.

Additionally, there were more takt wagons and workers at the site simultaneously during the project than in the previous one. Each worker had to implement a wagon in three locations equipped with prefabricated elements, parts, and materials. With three 2-hour daily cycles, the worker had to switch workstations (apartments) three times instead of two, as in the previous case. As a result, the team leaders encountered more errors in a day than before. The potential number of errors was also increased due to changes in personnel, alterations to prefabricated elements, partial changes in individual workers' wagons, reorganisation of team leadership, and the addition of new personnel to the order process, as well as the necessity of creating project-specific plans for installations, orders, and prefabrication.

The hierarchy of team leaders, group leader and support organisations were supposed to solve quickly escalated problems. However, the records from the meetings showed that problems began to accumulate from the start of the project, and the root causes of these issues were not resolved; instead, they began to recur. In other words, the one-piece flow highlighted problems. Still, the management arrangement could not conduct adequate root cause analysis or allocate sufficient resources to solve the root cause. The arrangement could only find a temporary solution to the problem and enable work to continue.

Another clear challenge in implementing a one-piece flow was that the latent interdependencies went unnoticed by team members and leaders. This became particularly evident when installing prefabricates, as incorrect installations were made in several apartments before the error was later discovered. A practical example involved installing water pipes in the ceiling, which were implemented as prefabricates. From the ceiling, the pipes continued as surface installations to fixtures such as shower taps, and the error was not detected until wagon 27. However, the incorrect installation was made in wagon 11. In the meantime, 15 incorrect installations have been completed. Various errors forced the project to undertake three Lean interventions. In the first two, the prefabricate installation method was thoroughly reviewed, and team members were defined and trained with precise instructions. In the third, a method for reporting defects was established, and problem sources were identified to make the WhatsApp channel more effective in communicating and resolving defect reports. The first two interventions impacted the number of defects, whereas the third did not appear beneficial, with defect numbers remaining the same despite the intervention.

What are the problems and the root causes in upstream flow revealed by shortening the takt (4h takt to 2h takt)? (RQ2)

The quantitative analysis of the day-to-day management log file revealed that the transition from a 4-hour takt to a 2-hour takt did not go smoothly, with the defect frequency (calculated as the ratio of deviations to the number of takts carried out during the review period) rising from 1,3 defects per takt to 1,9. The categorisation of deviations in the 2-hour takt project is presented in Figure 2. When examining the distribution of deviations, the shift to a 2-hour takt increased the number of product shortages (from 57 to 79 pcs), work errors (54 to 76), and design errors (13 to 20). Still, at the same time, resource allocation (11 to 8) and process errors (42 to 22) decreased. The shorter review period explains the reduction in deviations caused by absences.

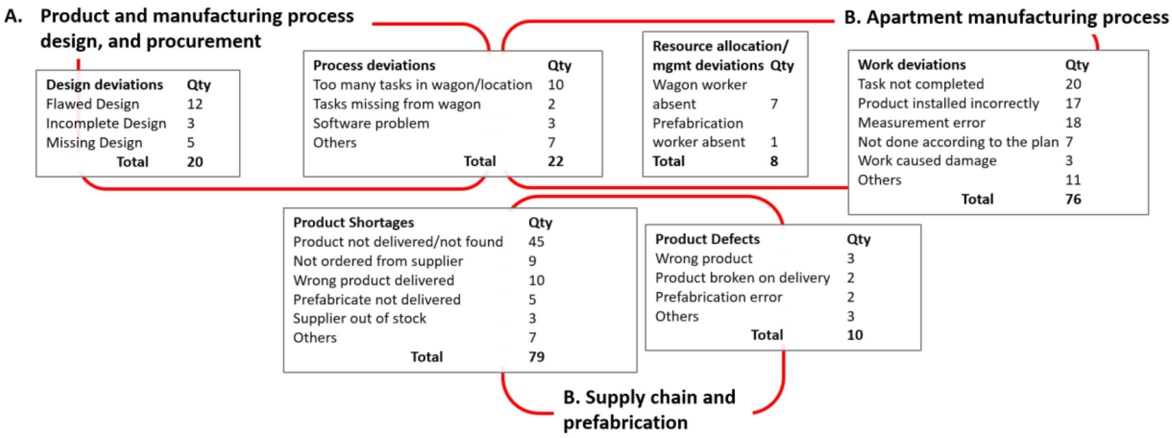

Figure 2: The results from quantitative analysis in the framework of the modelled production system

Process errors decreased because the manufacturing process was shortened in terms of the number of wagons and tasks as prefabrication increased. In other words, the design assumption that the manufacturing process would simplify due to the increased prefabrication seems correct. This is supported by the observation that the majority of process deviations were caused by an excessive number of tasks in individual wagons (levelling failure).

The primary root causes of work-related upstream underperformance can be divided into two categories based on the quantitative analysis of deviations. Work deviations stem from two leading causes: either the work standardisation is inadequate, the guidance is incomplete, or the guidance has not reached the worker responsible for the implementation in the wagon. In such cases, the team member is unaware of the installation instructions, their skill level is insufficient to follow and carry out the installation, or they have decided not to follow the instructions and instead carry out the installation as they consider best.

The supply chain was the weakest part of the production system in terms of the errors that were analysed. The reason is that parties involved in the supply chain lack communication, situational awareness, and verification opportunities in the studied project. Fundamentally, the material is missing because it has been 1) left undelivered to the correct apartment, 2) the wrong material has been delivered instead of the correct one, 3) not ordered or an ordering error has been made, 4) missing because the measurements of the apartment's bathroom exceed the planned tolerance, or 5) the material has already been used elsewhere.

The root cause of design errors is that the 2D drawings are inherently unfeasible, meaning the wagon has been misdesigned. The design may become unviable if a previous wagon has deviated from the implementation plan. Additionally, the drawing may be unfeasible because a measurement deviation in a particular apartment exceeds the established tolerance limits.

When examining process deviations, the most significant factor was the variation in task durations caused by different locations (bathrooms of various sizes). This resulted in what seemed like random overloading of specific wagons. Another reason was that the person did not follow the installation method or could not perform the tasks. At the start of the project, it became apparent that some of the wagon's tasks had been incorrectly planned or were unrecognised and unscheduled. These issues were partially corrected during the commissioning phase of the train by relevelling the wagons.

Based on the root cause analysis, the two most valuable improvements to the production system are transparent management of the supply chain and training team members for their installation tasks. In practice, managing the supply chain means managing the MBOM at the apartment and wagon level, from planned parts through procurement to final installation. For training purposes, the team leaders must study each wagon and its installation tasks themselves to train their team members for wagon-specific implementation and, especially, to lead the work and solve problems effectively. The third area for development is the prefabricates, whose installability must be ensured as part of the training. Since training is challenging to conduct before production starts, the training phase in a 2-hour takt system (i.e., the project start, where the train is brought into a new site) must be resolved either by implementing it at a slower takt, such as a 4-hour takt, or by over-resourcing the teams with additional trainers in the initial phase. The fourth area of development is takt logistics: Just-in-Time (JiT) deliveries divided the shipments into too small batches to track them manually or digitally. Batch size of deliveries should be increased and visual management added to detect deficiencies in delivery contents.

CONCLUSIONS

The primary purpose of this study is to show that rigorous production control requires high quality and flawlessness of the upstream production process. Through a literature review and case study, we formed a one-piece flow production system model from an example project.

The empirical material collected from the case company's renovation projects reveals that modelling the production system made visible the logical components of the production system. Similarly, it made visible the functions associated with these components, the implementation of these functions as processes, and the required and produced information, preconditions for systematic continuous development. This allows the identification of errors and their root causes, whether they need to adjust the product development, the operational model (necessitating correction of the production system), or the dysfunction of the model (necessitating staff training).

In our case study, implementing a 2-hour Takt production from a 4-hour takt revealed a list of new challenges to be eliminated. Therefore, it is validated that the logic of the "sea of inventories", continuously tightening the requirements for the control variable in the production flow, reveals upstream underperformance and drives the elimination of the problems, thus improving efficiency. Overall, our study provides evidence of the applicability of one-piece flow in construction. However, we have only studied a few renovation projects, and further studies need more cases to validate our findings fully. In this context, it is essential to note that the studied business unit and its organisation, which utilises a one-piece flow, is focused solely on executing repetitive projects that inherently involve a lot of repetition. The organisation refers to implementing a one-piece flow as a "housing factory" that flows through projects. Since the one-piece flow is a production system for HVLM products, its applicability to different construction business units is a fundamental topic for further research. Also, various construction project delivery methods must be studied to strengthen the external validity.

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SHORT TAKT IN CONSTRUCTION: A SYSTEMATIC LITERATURE REVIEW

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ABSTRACT

Over the past decade, Takt planning has steadily gained ground as a production system design scheme in construction projects. The approach entails organising trades as wagons in a train and running that train through a set of designated work areas in a building, with the train making regular stops and the wagons spending a fixed amount of time – the takt – in each area. The most common takt in construction projects is weekly takt. While using a shorter takt in combination with smaller work areas yields a shorter overall execution time, there is limited research on the actual consequences and feasibility of reducing takt time in practice. This paper conducts a systematic literature review on using short takt in construction projects, seeking to consolidate existing knowledge and suggest avenues for future research. From searches in the Scopus and IGLC.net databases, the paper identifies 13 articles related to using short takt in construction projects. The articles are analysed using thematic coding, revealing seven themes: maturity, planning and preparation, production monitoring, visual management,mock-ups, logistics, and collaboration. Key insights include the importance of rigorous follow-up during production and the advantage of experience in managing short takt times. The paper concludes that the sum of existing knowledge on short takt times in construction is limited, offering minimal practical guidance for implementation. This identifies an urgent need for further research to fill this significant gap.

KEYWORDS

Lean construction, production system design, takt, short takt

INTRODUCTION

The construction industry has evolved significantly in the past few decades, with an increased focus on enhancing efficiency. This shift has seen the adoption of Lean principles to reduce waste and deliver better value. Recognised for their vital role in modernising construction processes, lean methods contribute to achieving superior outcomes (Kuenzel et al., 2016; Lohne et al., 2022). Over the past decade, one method that has gained particular traction is takt planning (Andreassen & Drevland, 2023; Halttula & Seppänen, 2022).

Takt planning is a method for planning and executing projects, strongly influenced by Lean and the Toyota Production System (TPS) (Linnik et al., 2013). Key principles in Lean and TPS include continuous improvement, elimination of waste, and optimal workflow (Power et al., 2023). Takt time is a central part of the Just In Time principle in TPS, which focuses on producing the product at the right time (Linnik et al., 2013).

A train metaphor often illustrates Takt planning (Dahlberg & Drevland, 2021; Haghsheno et al., 2016). A train comprises several wagons, each representing a trade's work (for example,

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electrical, HVAC, carpentry). In a construction project, the building is divided into work zones with an equal amount of work for each zone. The train moves through the building and stops in each zone at a specified rhythm – the takt. The most common takt time in construction projects is weekly (Binninger et al., 2018), meaning the train wagons stay in each zone for a whole week before moving on to the next zone. This cycle is repeated until all wagons have visited all zones.

By adjusting the size of work zones, it is feasible to significantly shorten the execution timeline of a takt (Binninger et al., 2018; Jabbari et al., 2020). Smaller zones necessitate reduced workloads within each, thereby permitting a decrease in takt time. This strategy can potentially lower both production times and project costs substantially. However, it also introduces new challenges, necessitating adjustments in logistics, coordination, and the frequency of work zone turnovers.

There is limited research on the actual consequences of reducing takt time in practice. Some smaller projects with limited scope have conducted such tests (Apgar et al., 2022; Binninger et al., 2018), as well as some larger construction projects (Apgar & Smith, 2023; Keskiniva et al., 2021; Riekki et al., 2023). However, the literature in this area is relatively limited, and there is a need for further research to gain more knowledge on how shorter takt time affects the practical execution of projects.

Adjusting the size of work zones offers a strategic means to significantly reduce project timelines, as smaller zones require less work per segment, thus allowing for shorter takt times. This approach can lead to notable reductions in both production times and costs, albeit introducing challenges related to logistics, coordination, and the management of work zone transitions (Binninger et al., 2018; Jabbari et al., 2020). Despite its potential benefits, there is a notable scarcity of research exploring the practical implications of reducing takt time, with limited studies focusing on both small-scale experiments and larger construction endeavours (Apgar et al., 2022; Apgar & Smith, 2023; Binninger et al., 2018; Keskiniva et al., 2021; Riekki et al., 2023). This gap highlights the necessity of exploring the impact of shorter takt times on project execution in real-world settings. Consequently, further research is essential to deepen our understanding of the effects of shorter takt times on the practical implementation of projects and to identify strategies for ensuring the successful execution of projects with short takt durations.

This paper presents the findings from a systematic literature review focused on the use of short takt in construction projects. The review served as a preliminary step to an empirical case study examining the implementation of 1-day takt. The aim was to consolidate current knowledge and identify potential avenues for future research.

The paper starts by outlining the methodology for selecting and analysing pertinent literature, leading to the identification of twelve studies that shed light on the implementation of short takt times. The thematic analysis reveals seven themes relevant to projects with shortened takt times: maturity, planning and preparation, production monitoring, visual management,mock-ups, logistics, and collaboration. Notable findings highlight the necessity of diligent follow-up during production and the benefits of experience in short takt management. The review finds that the sum of existing documented knowledge on short takt times in construction is minimal, with little practical guidance available for implementing short takt in projects – underscoring the pressing need for additional research to address this substantial knowledge gap.

METHOD

To identify literature, Scopus and IGLC.net were selected for their extensive coverage of relevant research. Scopus provides a broad range of curated peer-reviewed literature across disciplines, including construction, offering access to journals, books, and conference papers. The IGLC.net database contains all papers published at the IGLC's annual conferences.

The search used "takt" and "construction" to encompass the literature on takt planning. Searches conducted on Scopus and IGLC.net yielded 110 and 97 hits, respectively. Scopus searches included "construction" to narrow down the scope to construction-specific literature. In contrast, IGLC.net searches used only "takt" due to its focus on the construction industry.

The article selection process, illustrated in Figure 1, involved removing duplicates and excluding articles unrelated to takt planning with shorter takt durations. This process resulted in the final selection of 12 relevant articles, primarily case studies.

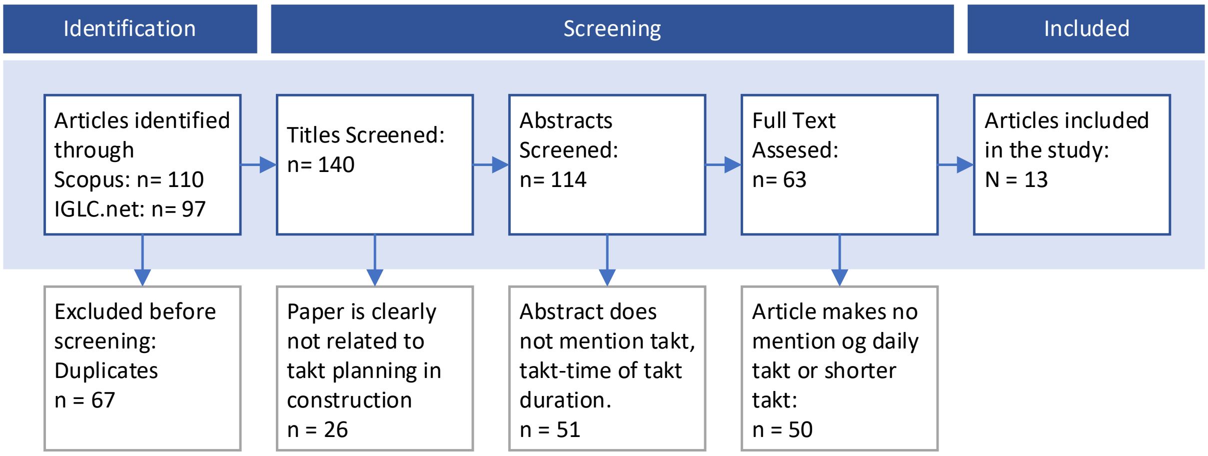

Figure 1: Flow chart for literature search and selection

The included papers were analysed using thematic analysis as described by Robson (2002), aided by an Excel sheet that organised the articles for a concise overview, including details about publication, content, and relevance. This structured approach facilitated easy identification of key points and themes across the literature.

LIMITATIONS

This review has several limitations worth noting. First, it focuses exclusively on peer-reviewed research literature. As a result, potentially valuable insights from non-peer-reviewed sources such as trade magazines, which might discuss practical applications and industry trends, have been omitted.

Secondly, the review did not include PhD dissertations. These works are often rich sources of detailed research but are challenging to integrate into a systematic review due to the lack of a unified database for global PhD theses. This makes a structured and comprehensive search challenging.

Finally, the literature screening process also presents limitations. Relying on skimming full texts to identify mentions of short takt times may result in oversight. This method depends heavily on the authors' ability to detect relevant details, which can be subjective and potentially inconsistent.

RESULTS

This section presents the results from a thematic analysis of the identified literature pertaining to using short takt in construction projects. The study defines *short takt* as any schedule tighter than a weekly cycle, including daily and hourly takt. The main goal was to pinpoint key factors influencing project outcomes when takt times are shorter than the commonly used weekly takt.

Out of the 13 identified and included articles, only one specifically explored the effects of reducing takt time (Binninger et al., 2018). However, 11 of the remaining 21 articles were case studies from projects – with short takt times – that investigated different issues. For instance, examining the general implementation of takt production (Lehtovaara et al., 2019), research on logistics handling during takt production (Heinonen & Seppänen, 2016), and comparing projects with varying takt times to assess effective implementation of takt production (Lehtovaara et al., 2021).

The studies reviewed reported takt times ranging from 25 minutes to 2 days, with many projects opting for a 1-day takt. Short takts were mainly used in the finishing stages of highly repetitive projects, like residential and hotel constructions. Most of the research came from Finland, with additional studies from Norway, Germany, Ireland, and the USA. Table 3 summarises each study’s focus.

Table 1 Overview of included studies

Reference	Country	Case Projects	Takt Time	Project Type
Apgar and Smith (2023) [Conference paper]	USA	1	1-day takt	Data centers
Apgar et al. (2022) [Conference paper]	USA	1	1-day takt	Roofing system
Binninger et al. (2018) [Conference paper]	Germany	1	1-hour takt	Retail space
Frandson and Tommelein (2014) [Conference paper]	USA	1	2-day takt	Health care facility retrofit
Gardarsson et al. (2019) [Conference paper]	Norway	None (Literature review)	Varying, discusses shorter takt	Not applicable
Heinonen & Seppänen (2016) [Conference paper]	Finland	1	25-minute takt	Boat cabins
Keskiniva et al. (2021) [Journal paper]	Finland	1	2-day takt	Residential renovation
Kujansuu et al. (2019) [Conference paper]	Finland and USA	4	From 1-day to weekly takt	Residential
Lehtovaara et al. (2021) [Journal paper]	Finland	6	Varying takt. From 1-day to weekly takt	Hotel and residential
Lehtovaara et al. (2020) [Conference paper]	Finland	24	Varying takt. One project with 1-day takt	Residential
Lehtovaara et al. (2019) [Conference paper]	Finland	1	Varying takt. From 1-day to weekly takt	Residential
Riekki et al. (2023) [Conference paper]	Finland	1	4-hour takt	Hotel
Tetik et al. (2019) [Conference paper]	Finland	2	1-day takt and 40-minute takt	Boat cabins

The thematic analysis of the articles revealed seven themes related to effectively implementing shorter takt times in construction projects: 1) Maturity, 2) Planning and preparation, 3) Production monitoring, 4) Visual management, 5) Use of Mock-up, 6) Logistics, and 7)

Collaboration. The following sections explore each of these areas in detail, shedding light on their significance and the role they play in the success of projects utilising short takt times:

MATURITY (EXPERIENCE)

The literature often emphasises maturity in the context of implementing shorter takt times, referring to organisations with extensive experience and advanced practices in takt production. While several Finnish studies explicitly mentioning 'maturity'(Lehtovaara et al., 2021; Lehtovaara et al., 2020; Tetik et al., 2019; Kujansuu et al., 2019), other studies hint at maturity issues, such as overestimating work capacity (Binninger et al., 2018) or a lack of preparation for takt production's pace (Lehtovaara et al.(2019), without directly mentioning the term. Maturity is often associated with experience in these discussions, though this perspective may overlook other important aspects, such as organisational culture and leadership.

Lehtovaara et al. (2021) emphasise maturity's role in managing short takt times and work zones, noting challenges in projects with low maturity levels due to inexperience with takt production. Despite planned efforts, these projects struggled with workflow efficiency, contrasting with higher maturity ones, which saw benefits from longer, weekly takt times. Lehtovaara et al. (2020) introduced a maturity model for takt production, identifying three maturity levels from basic takt planning to advanced, socially integrated practices.

Tetik et al. (2019) compared takt production maturity in shipbuilding and construction, finding ship cabin production more advanced in integrating takt and logistics solutions. However, it did not explicitly define maturity, viewing it as developing efficient takt and logistics practices in construction.

PLANNING AND PREPARATION

The literature emphasises the necessity of thorough planning for the success of construction projects employing shorter takt times (Apgar & Smith, 2023; Apgar et al., 2022; Binninger et al., 2018; Frandson & Tommelein, 2014; Lehtovaara et al., 2021; Lehtovaara et al., 2020; Lehtovaara et al. 2019; Riekki et al., 2023; Tetik et al. 2019). A study by Riekki et al. (2023) on converting an office building into a hotel with a four-hour takt highlighted how advanced and detailed planning, including a preparatory workshop, dedicated management efforts, and logistics coordination, was critical for project efficiency. Their findings align with the findings of Lehtovaara et al. (2019), which pointed to the importance of detailed planning, takt principle training, and careful production startup.

Additionally, the research notes the common issue of inadequate project definition prior to construction commencement, as seen in Tetik et al. (2019), where plan maturity affected procurement and delivery planning. Lehtovaara et al. (2021) and (2020) further discussed the benefits of early obstacle identification and integrating takt requirements in the design phase for enhanced collaboration and smoother production. They also warned against the pitfalls of minimal buffer areas, highlighting the balance needed to manage delays and unforeseen events in projects with tight schedules and high process variability.

PRODUCTION MONITORING AND CONTROL

The literature underscores the crucial role of rigorous production monitoring, including active management and daily coordination meetings, to adhere to takt times once construction starts. Studies reveal that effective workflow supervision, especially with shorter takt times, is key to maintaining efficiency (Apgar & Smith, 2023; Frandson & Tommelein, 2014; Riekki et al., 2023; Lehtovaara et al., 2021; Gardarsson et al., 2019). In cases like Riekki et al. (2023), where a project adopted a four-hour takt, the intensive monitoring required by management proved essential for project success, offering flexibility and control. Similarly, Binninger et al. (2018) demonstrated that close oversight and proactive management support were vital, particularly after startup challenges in a project with an hourly takt, leading to significant improvements in coordination, efficiency, and project duration reduction from ten to three days.

Several studies highlight the need for additional resources, as well as active production management and daily follow-up in managing projects with short takt times (Keskiniva et al., 2021; Lehtovaara et al., 2019; Apgar & Smith, 2003). With short takt times, limited time is available to address production disruptions. Lehtovaara et al. (2021) point out the need for more resources, particularly in site management and among technical leaders during the planning and startup phases. This increased resource requirement is mainly due to the need for more frequent coordination and management of takt production.

Daily Coordination Meetings

Daily meetings are deemed essential for the day-to-day management of short-take projects. According to Riekki et al. (2023), such meetings help create a shared situational understanding and enable quick responses to work challenges. Other studies support this. Kujansuu et al. (2019) found daily meetings an effective way to start the workday, share information, and evaluate progress from the previous day. Lehtovaara et al. (2019) made a similar observation, highlighting it as a learning point due to the absence of good routines and daily meetings.

Buffers and Plan Adjustments

Buffer management is an approach in production or project management that uses reserves or buffers to handle uncertainty and variations in the workflow (Gonzalez et al., 2008). It involves allocating extra time, resources, or materials to manage unforeseen events without disrupting progress.

Gardarsson et al. (2019) point out that shorter takt times limit the time available to handle delays or unexpected project challenges. Dividing into smaller work zones may reduce total production time and costs but increase the risk of delays. Keskiniva et al. (2021) support this, noting that takt planning with shorter takt times can be rigid, making it challenging to adapt to changes and maintain the pace. Keskiniva et al. (2021), therefore, emphasise the necessity of daily monitoring and adjustments to avoid delays.

Lehtovaara et al. (2021) highlight that short takt times demand a more proactive role from tradespeople in managing capacity and resources, deviating from the buffer of extra time and materials often available in longer takt projects. Effective coordination and resource planning become essential skills for tradespeople to navigate the constraints of shorter tasks successfully.

Riekki et al. (2023) demonstrate that projects with short takts, such as one with a 4-hour takt, can maintain flexibility and manage adjustments effectively with careful planning, including adjustments in work steps, wagon sequence, the addition of new steps, and buffer wagons.

However, Lehtovaara et al. (2019) caution against a “hard start” without a gradual pace increase, as it can lead to subcontractor disengagement and a lack of thorough error inspection. This underscores the importance of a balanced pace and resource allocation from the project’s outset to mitigate potential issues and fully leverage the benefits of shorter takt times.

VISUAL MANAGEMENT

Visual management, utilising digital tools and physical markers, is reported by several studies as beneficial when implementing shorter takt times, enhancing workflow and communication (Lehtovaara et al., 2021; Lehtovaara et al., 2019; Riekki et al., 2023). Digital aids like Building Information Modeling (BIM) are crucial in reporting progress and managing discrepancies. Digital tools help keep schedules aligned with production, support accurate work tracking, and facilitate real-time updates, making them critical for efficient takt management (Riekki et al., 2023; Lehtovaara et al., 2019). However, adjusting takt plans can be challenging and time-consuming, indicating the need for more automated solutions to enhance adjustment efficiency (Lehtovaara et al., 2021).

In addition to digital tools, physical visual aids such as printed takt plans and floor markings significantly improve on-site management and teamwork, as demonstrated in a hotel project employing a 4-hour takt (Riekki et al., 2023). These strategies foster a collective understanding and ease the integration of personnel, underlining the combined value of digital and physical visual management methods in optimizing construction processes.

MOCK-UPS

The hotel project detailed by Riekki et al. (2023) included efforts to create a mock-up of a hotel room outside the actual construction site as part of its planning phase. This initiative aimed to gain early insights into potential work process challenges and opportunities. Unfortunately, the mock-up was not finished before construction commenced, significantly restricting the learning opportunities it could have provided. The study highlights that such attempts can provide valuable insights into potential challenges and opportunities for details in work processes; however, it stresses that such mock-ups need to be completed to benefit from potential advantages during the planning and project phases.

LOGISTICS MANAGEMENT

Logistics management, especially in conjunction with shorter takt times, is crucial for maintaining project momentum, as evidenced by various studies. Riekki et al. (2023) emphasize the necessity of synchronizing material deliveries with the takt plan to ensure smooth progress. The study details a project using a four-hour takt in a city centre, where logistics strategies for different materials—external storage for large items and on-site storage for smaller items—helped maintain low inventory levels and streamlined material flow.

Tetik et al. (2019) and Heinonen & Seppänen (2016) discuss adopting industrialized logistics strategies from the shipyard industry, such as material sequencing and Just-In-Time (JIT) deliveries, to enhance takt production in construction. These approaches – including organizing materials on trolleys for specific cabins and ensuring daily delivery schedules – minimized inventory and optimized logistics management.

COLLABORATION

Two main areas of collaboration recur in several studies as crucial for the successful implementation of projects with short takt times. The first is collaborative planning among design teams, main contractors, subcontractors, and suppliers related to both the takt plan and the logistics management (Apgar et al., 2022; Heinonen & Seppänen, 2016; Riekki et al., 2023). The second concerns the importance of contract models that effectively support takt implementation and facilitate good collaboration. A greater focus on collaboration in contract models is essential to address challenges related to tight deadlines and complex work methods (Heinonen & Seppänen, 2016).

Studies by Kujansuu et al. (2019) and Lehtovaara et al. (2019) highlight the challenges of conflicting contract models and the negative impact of non-collaborative contract terms on project trust and efficiency. These findings suggest a need for contracts that promote openness, manage changes effectively, and support Lean management principles. Moreover, adopting new contract forms that encourage collaboration and innovation could address these challenges, aligning project stakeholders towards common goals and facilitating the successful execution of projects with short takt times.

SUMMARY OF FINDINGS

This literature review has systematically explored the existing knowledge on implementing short takt times in construction projects, identifying seven key themes: maturity, planning, monitoring, visual management, mock-ups, logistics, and collaboration. Table 2 summarises the insights from each of these themes.

Table 2 Summary of findings

Maturity	• Project organizations with higher takt maturity navigate shorter takt times more effectively.
Planning and Preparation	• Thorough planning and preparation are crucial for projects to succeed with shorter takt time – including detailed planning, early integration of takt production requirements, and training in takt principles. • Proactive planning is important to avoid obstacles, reduce the risk of quality errors, and minimize the need for rework.
Production Monitoring and Control	• Short takt requires more active follow-up in the production phase. • Daily coordination meetings are crucial. • The startup phase should facilitate learning and adjustment to shorter takt times. • Continuous plan adjustments and buffer management are essential.
Visual Management	• Digital tools like BIM simplify workflow and communication • Visual tools such as paper takt plans and floor markings enhance on-site management and communication.
Mock-up	• Development and testing in a mock-up can provide valuable insights for planing and executing the takt plan.
Logistics	• Aligning deliveries with takt schedules is crucial for material flow and project progress. • Efficient strategies include systematic planning, material sequencing, Just-In-Time deliveries, and supplier integration. • Advanced inventory management systems minimize time loss.
Collaboration	• Collaborative planning among design teams, main contractors, subcontractors, and suppliers is crucial for short-take-time projects, impacting both takt plans and logistics management. • Conflicting contract models can hinder collaboration, affecting project trust and efficiency. • Contracts should foster openness, effectively manage changes, and adhere to Lean management principles.

DISCUSSION AND CONCLUSION

This paper delivered a systematic literature review focused on using short takt times in construction projects, aiming to synthesize the current body of knowledge and highlight areas for future investigation. A notable discovery is the scarcity of detailed research on short takt times, with just 13 articles addressing the topic. Among these, only one explicitly delves into short takt times, with the rest incorporating short takt cases in their studies, without short takt being the focus of the research. This scarcity raises questions about the specificity of findings to short takt times versus general takt production in construction.

Nevertheless, certain insights emerged distinctly related to short takt times, such as the need for intensified follow-up during production and the observation that organisations with greater experience in takt planning are better equipped to manage short takt times. These points serve as foundational insights for understanding other findings. For instance, while visual management tools are beneficial across takt projects, their value is likely accentuated in projects with short takts. Their use fosters greater transparency and should thereby reduce reliance on managerial oversight.

The study highlighted seven key themes relevant to executing short-take time projects, suggesting these areas as fruitful directions for future research. Although not exclusive to short-take-time projects, they underscore critical considerations in execution, revealing a more complex relationship among them that warrants deeper exploration.

While the themes were presented separately in the results, it is important to recognise the overlap and inherent connections between them. For example, *Maturity*, *Planning and Preparation*, and *Production Monitoring and Control* are closely interrelated. Mature organisations, i.e., those with expertise in takt production,, often have planning processes that anticipate issues and provide early solutions. Mature organisations are better at production monitoring and control, which helps them efficiently manage short takt times, leading to improved workflow and resource utilisation through effective daily coordination and supervision. Thorough planning, including logistics coordination, is essential for managing short takt times. Without it, production monitoring becomes difficult, leading to frequent adjustments that complicate project execution.

The uneven geographical distribution of the studies, with two-thirds originating from Finland, warrants discussion. Why is this the case? There are several reasons. Firstly, the Finnish construction industry has seen a significant rise in the use of takt construction, and Finland has been quicker to adopt shorter takts than other regions. Industry sources indicate that a takt of 2.5 days is now the norm for Finnish projects. Secondly, Finland's research community is very active in takt production research. Over the past five years, Finnish researchers have contributed 30% of all construction-related takt studies, underscoring their significant influence in this area.

Although these factors explain the Finnish dominance in the study, they raise questions about the generalizability of the findings to other regions. While none of the seven themes don't seem directly influenced by cultural factors, future research should consider this aspect.

A notable limitation in the current literature is the lack of in-depth case studies on using short takt times in construction projects. To address this gap, future research should delve into these case studies to better understand how the themes identified in this paper manifest across different regions and project types. This will provide a clearer, more nuanced understanding of the challenges and best practices of implementing short takt times in diverse construction environments.

In conclusion, this paper aimed to consolidate existing knowledge on short takt times in construction through a review of the literature. However, it became evident that the available information is limited. As a result, there isn't enough evidence to offer comprehensive, practical guidance on effectively implementing short takt times in construction projects. Nevertheless, the identified themes serve as a valuable foundation for future empirical research to address this gap, offering insights to guide the development of best practices and strategies in the construction industry.

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APPLICATION OF THE WORK DENSITY METHOD TO IN-SITU PILE PRODUCTION IN HEAVY CIVIL ENGINEERING

Anne Fischer[1], Philipp Baumgartner[2], Iris D. Tommelein[3], Konrad Nübel[4] and Johannes Fottner[5]

ABSTRACT

The Work Density Method (WDM) is used in takt planning for defining zones with equal workload. To date, this method has been applied mainly to building construction. This paper investigates the WDM's applicability to equipment-driven processes in heavy civil engineering, specifically to the in-situ production of foundation piles for a highway infrastructure project. Two existing computer-based programs that support the application of the WDM, WoLZo and ViWoLZo, were used to find a suitable grid size based on data from a real-world project. The results show the potential of using the WDM (1) to define zones with equal workloads, given that pile groups are irregularly distributed over the construction site space, (2) to compare different scenarios based on work density as a metric (e.g., scenarios with different uses and sequencing of equipment), and (3) to derive a takt time and process duration when using multiple pieces of equipment that must coordinate their efforts and work in sync. Compared to the building construction application, the heavy civil engineering application reveals new requirements when using the WDM and takt planning in general, regarding the geometrical and logistical needs of equipment-driven operations that constrain how zones can be defined.

KEYWORDS

Production system design, takt planning (TP), Work Density Method (WDM), heavy civil engineering, work structuring, workload leveling, foundation piles, infrastructure project.

INTRODUCTION

As part of heavy civil engineering, in-situ pile production is highly complex due to its variety of variabilities (Fischer et al., 2021). Especially uncertainties related to soil conditions make it hard to plan the piles' production line. The intent of defining a takt plan is to demarcate clear handoffs between predecessor and successor trades, i.e., in-situ pile production followed by the above-ground structure they support, by harnessing variabilities within the production line so that the line's output will reliably meet the customers' target dates (Tommelein, 2020).

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The Work Density Method (WDM) was created to methodically support the use of takt when developing construction process plans (Tommelein, 2017, 2022). The method builds on the concept called work density "defined as the time a trade will require to do their work in a certain area, based on (1) product design, (2) scope of the trade's work, (3) specific steps of the operation in their schedule, (4) means and methods the trade will use, and (5) accounting for crew capabilities and size" (after definition in Tommelein et al. (2022)). While this method was first applied to deliver single- and multi-story buildings, it potentially has broader application across the construction industry. Here, we describe how the WDM can be rethought and adapted to suit the specific requirements of heavy civil engineering projects which, in particular in regard to takt planning, differ in several ways from building projects.

Fundamental distinctions between building construction and heavy civil engineering pertain among other things to the number- and specializations of trades involved, the sharing of resources, and the interdependences among them. In heavy civil engineering, major work requires in-situ production, the simultaneous involvement of specialists, and work space requirements that depend on the equipment being used. On projects with earthmoving processes (Kirchbach et al., 2012), considerable variability will likely be encountered. Such variability and other complexity dimensions of heavy civil engineering projects makes characterizing work densities challenging when creating a takt plan.

Our research objective was to determine whether, despite these differences, the WDM can be applied to the specialized field of in-situ production of foundation piles for bridges in a highway infrastructure project, a type of heavy civil engineering projects. The specific research questions were: (1) how to define the grid cells depending on the space the equipment needs to fulfill the work, (2) how to combine these cells into zones while balancing workloads in order to define a takt for the process involving multiple trades, and (3) how beneficial is the WDM when construction work in distributed irregularly over the construction site space?

To answer these questions, we studied the potential application of the WDM using two different computer-based support tools, namely WoLZo by Jabbari et al. (2020) and ViWoLZo by Singh et al. (2020) and Singh & Tommelein (2023a, b). We assessed the suitability of these tools to model the in-situ pile production process while identifying modeling assumptions made for the implementation of these tools that affect the successful use of the WDM in this context. In general, this paper contributes to knowledge by describing the application of the WDM for takt planning of projects of different types and complexity.

LITERATURE REVIEW

Takt planning has been applied to infrastructure projects (e.g., Fiallo & Howell, 2012, Tommelein & Lerche, 2023), on a variety of phases of building projects such as exterior cladding, interior overhead work, and finishes (e.g., Frandson et al., 2013, Linnik et al., 2013), hospitals and hotels (e.g., Riekki et al., 2023), and other types of projects. These projects are characterized by repetitive work and high fragmentation of the work as they require- and due to the involvement of specialized trades. Coordinating these trades to finish the project within the given time, quality, and budget is challenging.

Takt helps to create concurrency in the schedule, thus resulting in shorter delivery times. Takt planning aims to equalize the time each trade needs to complete their scope of work in each zone to achieve a more-or-less continuous flow of work and trades through space. Trades follow each other sequentially, forming a sequence of process steps called a "Parade of Trades" (Tommelein et al., 1999, Tommelein, 2020) or "train of trades" (a term used in the German-speaking areas). Each wagon in the train represents the scope of work fulfilled within one takt time unit by one (or sometimes several) trade(s). In execution, the takt plan may require the use of adjustment mechanisms (Binninger et al., 2017) also known as "throttles" in production system design, e.g., changes in the number of assigned resources.

Figure 1 illustrates the creation of concurrency using takt planning. The top row shows a process with three trades, one following the other, working in a single zone (Z = 1). Each trade needs a specific time to complete their process step, the so-called workload. The workload depends on the scope, means-and-methods selected, capabilities and quantities of resources, and zoning. The maximum amount of time across all trade steps in the process is called the workload peak. In this example, the workload peak, referred to as T(1), is assumed to be six time units/zone. If one can divide the work space into multiple zones, e.g., into two (Z = 2) or three (Z = 3), and correspondingly divide the step of work done by each trade into smaller steps, then the workload peak T(Z) as well as the duration D of the process can likely be reduced. In theory, increasing the number of zones would mean that the duration can get shorter. In practice, however, there is a limit to how small zones can get and still allow for work to take place. The practical size and shape of a zone will depend on the space each trade needs to effectively complete their step of work within the allotted time.

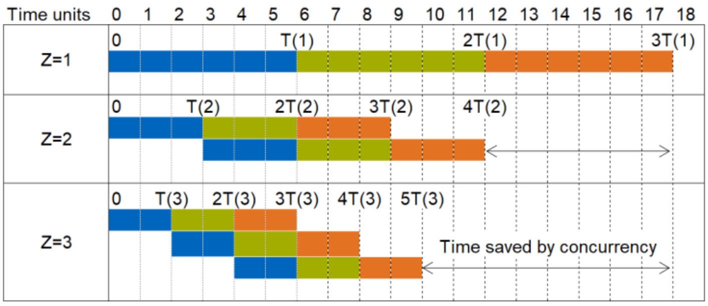

Figure 1: Process with three consecutive process steps, when the work space is divided into one (Z = 1), two (Z = 2), or three (Z = 3) zones to allow for concurrent work (Z: number of zones; T(Z): workload peak) (based on Tommelein (2022))

Formal methods exist to help takt planners with sizing and shaping zones of work. From a workload leveling point of view, data can be used to mathematically determine the work space zoning that minimizes the maximum time any trade in the process needs to complete their work zone by zone. Unlike other space scheduling methods, such as the line-of-balance method, which starts with an *a priori*-defined location breakdown structure, the WDM does not start with *a priori*-defined space units. Instead, it computes each trade's workload in a given zone.

Previous research used the WDM to schedule trades working on interior finishes of building projects. With that type of work in mind, Jabbari et al. (2020) developed a mathematical algorithm, called the Workload Leveling and Zoning (WoLZo) algorithm, to calculate the optimal zoning assuming that the calculated zones would be either rectangular or L-shaped. They defined a zoning to be optimal when it minimizes the workload peak across all steps in all zones. Singh et al. (2020) and Singh & Tommelein (2023a, b) developed a simple visualization of work densities shown in a grid overlaying the work space, programmed in Microsoft Excel. Their Visual Workload Leveling and Zoning (ViWoLZo) program allows users to create zones of any shape. ViWoLZo makes it easy to manually adjust the boundaries of zones, including their size and shape, and compare the workload peak of the process T(Z) to assess whether that process can meet the customers' demand.

METHODOLOGY

APPLIED METHODOLOGY

Since the body of literature relevant to scheduling in-situ pile production processes is limited, we adopted a case-study research methodology. This study was conducted in the context of the master's thesis of Philipp Baumgartner (2023), a co-author of this paper.

To gain fundamental understanding of the study topic, the first and the second authors conducted three semi-structured interviews, 1.5 h each, with four project leaders from three construction companies. These project leaders were considered to be experts in the field, and had been selected on the basis of their local experience and their management position. The interviews centered on understanding the requirements and the details of the Kelly drilling process for pile production in order to document process steps and space needs (Figure 2). The Kelly drilling process is widely used for the production of piles with a large diameter, ranging from 0.6 m to 3 m and up to 125 m deep (Bauer group, 2024). Its flexibility meets various engineering requirements and soil conditions.

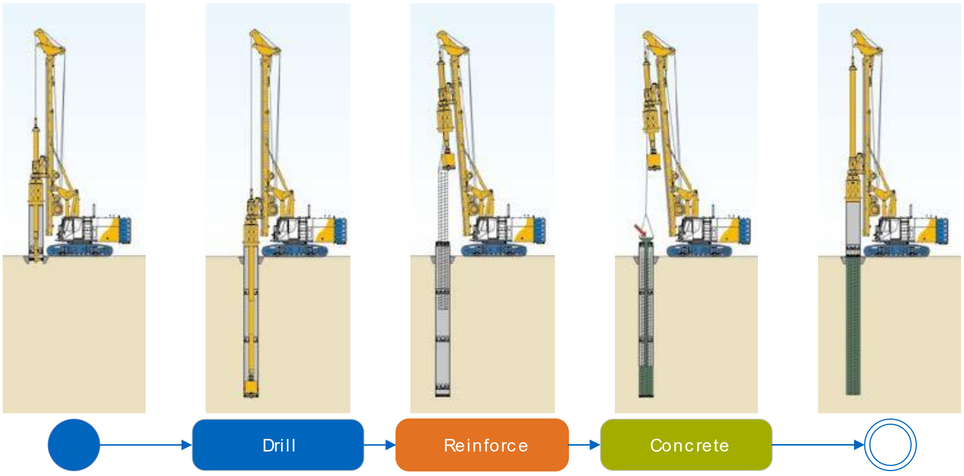

Figure 2: Kelly drilling process: (1) drill, (2) reinforce, (3) concrete
(after image from Bauer group (2024))

To assess the feasibility and effectiveness of using the WDM for process planning of heavy civil engineering work, we obtained input data from a real-world highway infrastructure project. Specifically, we focused on the process pertaining to the in-situ production of bridge foundation piles. This project had unique requirements to accommodate challenging soils conditions: single piles had to be produced in a specific order. Detailed records including extensive datasets were available, detailing production times for each process step in every pile. At the time of our study, all piles had already been produced. We thus mapped the as-built construction process using historical data from this project, informed by the interviews we had conducted previously. We used this data later to calculate the work density corresponding to the grid we chose to superimpose over the construction site (work area). The interviews helped with the evaluation of the results.

IN-SITU PILE PRODUCTION

We next describe the pile production system and compare it with the interior finishing phase of building construction (Table 1). As is the case for materials installed as interior finishes in building construction, the product of heavy civil engineering is installed in well-defined locations. In-situ pile production is characterized by the repetitiveness of the process steps to produce the product, but each product can be unique (e.g., in terms of its geometry and material composition). The process resembles linear assembly line production. The pace-setting resource is the Kelly drilling rig. After the drilling rig is positioned, piles are produced in three main steps: (1) drill, (2) reinforce, and (3) concrete (Figure 2).

In contrast, there are differences in the resources. Building construction is typically done by workers organized in trade crews moving flexibly from one work zone to the other, carrying or carting their tools and materials as needed, and relocating relatively small-sized equipment. Heavy civil engineering is dominated by its equipment with an operator and its support crew.

Movement of the drilling rig and its setup takes times and effort. Besides its sluggishness, the drilling rig needs a specific space to work and allow for a safety clearance, and all its auxiliary devices must be kept within reach. Auxiliary devices include temporarily installed casings to stabilize the drilled hole, oscillators to support the drilling and removal of the casings, and tools to drill in different soil conditions. Small front-end loaders or excavators support this heavy equipment by handling its auxiliary devices and material. Even though the equipment is well-instrumented with sensors to assist the operator, (e.g., automated release of a tool), the quality of pile production depends on the operator's and the supporting crew's know-how and skill.

The differences in the resources lead to differences in the type and degree of digitalization used in the process. Whereas building projects may make use of digital standards and Building Information Modeling (BIM), the process of data collection during execution is still highly manual, in part because people mainly do the work. In contrast, the latest civil engineering equipment is instrumented to support with operator-assistance systems and automatically collect large amounts of sensor data during execution for later process analysis (e.g., Fischer et al., 2023). However, the data describing boundary conditions may be uncertain. For example, digital models may not accurately capture the exact depth of soil layer interfaces, boulders, or groundwater levels. Not knowing the soil characteristics makes it hard to automatically select the optimal tool for the equipment or to determine the tool's optimal soil filling level, so that the operator's and support crew's expert knowledge and intervention is still needed (Fischer et al., 2021). Considering the trend of adoption of construction robotics (Brosque et al., 2020) for equipment-intensive processes, our study can inform how the operations are planned of such systems involving human-machine interaction.

Table 1: Comparison of production systems of interior finishing in building construction with pile production in heavy civil engineering

Characteristics	Interior finishing	Pile production
Product	Rooms	Piles
Process	Process steps are performed by many different trades	Process steps are executed mainly by the same trade crew
Resources	Trade crews with tools and relatively-small equipment	Large equipment and auxiliary devices, operators, foreman, 1-2 construction workers
Flow interruptions	Coordination between the trades	High uncertainty due to the soil conditions
Digital technologies in practice	Collaborative planning using BIM; material tracking with barcodes, RFID, cameras, or notification.	Use of GIS (less use of BIM); material tracking with GPS; digital delivery notes; highly automated equipment with operator-assistance systems.

ADAPTION TO THE WORK DENSITY METHOD

To demonstrate the application of the WDM, we adapted Tommelein et al.'s (2022) example to pile production and rethought how one would partition the work space in zones for takt planning. The objective of this rethinking was to find the number and shape of zones that would balance the workloads of steps in the pile production process, and to possibly create concurrency to reduce the process duration. This potential of rezoning to reduce the duration is stated mathematically:

$$D = (S + Z - 1) \times T(Z) \qquad \text{(Equation 1)}$$

where D is the duration of the process, S the number of process steps, Z the number of zones, and T(Z) is the workload peak, defined as the maximum of all trades' workloads in every process step and every zone. The workload is expressed by trade and in time units (e.g., hours) to complete a certain scope of work in a certain zone, so it could be expressed, e.g., or h/m² or h/pile, with the caveat that zones will likely vary in terms of their physical area (Figure 3).

On the theoretical side, Figure 3 depicts the work density maps referring to the production of two single piles (black circles) installed in three consecutive steps, (1) drill (blue), (2) reinforce (green), and (3) concrete (orange). The number in each cell indicates the work density for that cell, and the darker shade of color in a cell indicates a higher work density.

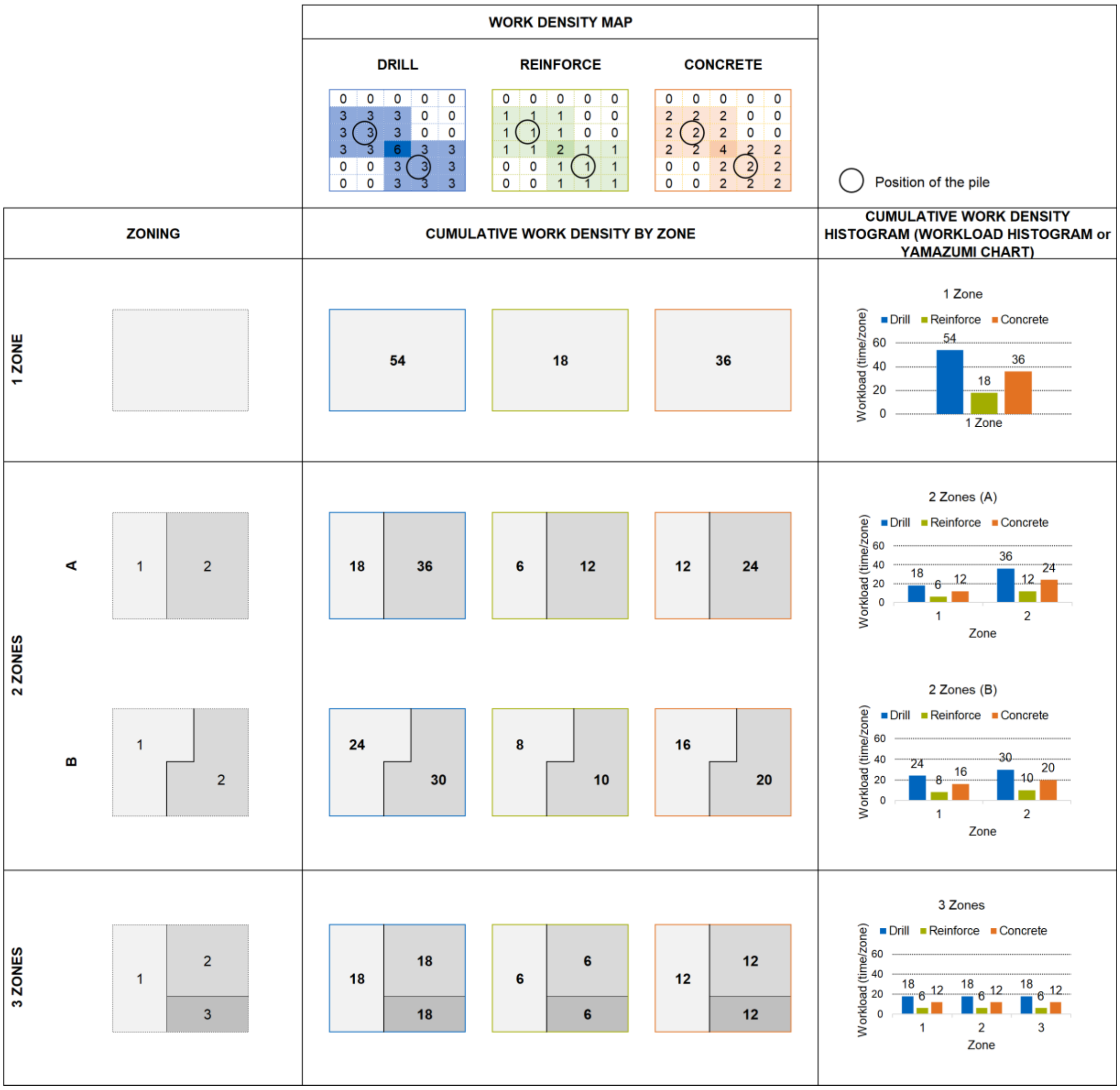

Figure 3: Work density maps and workload histograms for four different zoning alternatives to produce two single piles (after Figure 5 in Tommelein (2022))

For Z = 1, the trade defining the workload peak is the drill trade with T(Z) = 54. In this case, the duration of the process is D = (3 + 1 – 1) × 54 = 162.

For Z = 2, the workload peak may decrease. As the zoning influences the workload, alternative partitions must be considered when trying to even out workloads for any trade, or to reduce the workload peak of the process. The middle of Figure 3 shows partition A with a workload peak of $T(Z_A) = 36$ compared to partition B with $T(Z_B) = 30$.

For Z = 3, the workload peak may decrease further. The bottom of Figure 3 shows one such zoning. In this exceptional circumstance (where the work density maps of drill, reinforce, and concrete are multiples of each other), it is possible to achieve workload evenness within each trade, although there is still unevenness across trades. Evenness across trades can be achieved by combining the reinforce- and concrete trades into a single step.

On the practical side, a certain zoning may be rendered infeasible due to overlapping: if the distance between the piles is too narrow, the space the equipment needs to produce the piles overlap (darkest cells). The space needed depends on the swing radius of the drilling rig (production line) and the auxiliary devices or vehicles (logistics), e.g., casings, tools, a wheel loader for material supply and disposal, or a concrete mixer. Relatively speaking, partition B follows these restrictions best; nevertheless, it is still infeasible due to the overlapping of the zones.

In the case of building construction processes when workload unevenness occurs across trades, it is common to assign more (or fewer) people to trade crews to decrease (or increase) their workload. In the case of the pile production, where the dominance of the drill process step is obvious in all zoning alternatives, the workload per zone cannot be decreased by increasing the number of human resources (but it may be decreased by increasing the skill level of workers, in particular the skill of the equipment operator). One alternative for speeding up the process is to decouple the process steps, so that they are executed by different equipment trades, e.g., (1) drill: for the upper layers of a hole use a drilling rig smaller than the rig needed to drill the deeper layers; (2) reinforce: free up the drilling rig by installing the rebar cage by crane; (3) concrete: pull out casings during concreting by using an oscillator installed in front of a drilling rig.

To sum it up, first, an increase in the number of zones Z can lead to a decrease in the workload peak T(Z) for a certain zoning and, therefore, in the duration D. Second, the workload peak depends on how zones are defined. As mentioned, there is a limitation on any zone's size and shape depending on the space the work practically needs (Jabbari et al., 2020). In the case of pile production, the process is dominated by a highly specialized piece of equipment with a fixed crew. The pile production process duration can be shortened by using multiple pieces of equipment working concurrently in multiple zones.

CASE STUDY

OVERVIEW

The input data are from a completed highway infrastructure project in Rosenheim, Germany. This project involved the construction of a bypass road including two bridges near the German-Austrian border. The project consists of 32 bridge piers, each including any number from 5 to 17 large-diameter bored piles of the same type and ranging from 26 m to 50 m in length. Data from 232 piles in total was used for the case study, including their location on the construction site as well as their production rate. This data was used to test out both computer-based programs, (1) WoLZo and (2) ViWoLZo, made available by the third co-author.

WOLZO

First, we used WoLZo to apply the WDM to the case study. Figure 4 shows the construction site layout overlayed with a grid mesh. We experimented with different grid mesh sized but chose this grid mesh to include multiple piles (independent of their pile groups), allowing the experts enough work space within a grid cell for adjustment during planning and operation.

The production times for all piles within each cell were summed up to create three work density maps, one for each process step. These maps were input to the WoLZo algorithm. The algorithm groups work density grid cells into zones, balancing the cumulative work densities (aka. workload) by zone and by trade to minimize the workload peak of the process and, consequently, determine the achievable takt. The algorithm, constrained to rectangular shapes, achieved optimal results when dividing the area into 14 zones (Figure 5). Figure 6 shows the corresponding workload histogram of the three-step process (S = 3). The workload peak is T(Z) = 41 h and the duration of the process is D = (3 + 14 – 1) × 41 h = 656 h (rounded up to 66 work days of 10 hours/work day).

This first result indicated that: (1) A limit was reached regarding the division of the work space into more zones, as the workload peak was found to correspond to a single grid cell, namely Zone 7 (Figure 5). This high workload is due to the presence of many work-intensive piles in this central location on site. (2) Despite WoLZo's calculation of the optimal zoning, the workloads in the different zones are still uneven. (3) The analysis revealed uneven workloads between process steps across zones.

This unevenness prompted us to combine the reinforce- and concrete step. In theory, the workload is distributed more evenly (Figure 7). In practice this combination is possible, indeed, since the equipment trade of the concrete step uses a drilling rig, and that drilling rig can install the rebar cage. The results show a more even workload histogram across trades (S = 2). The workload peak remains the same, however, the reduced number of process steps results in a reduction of the duration of the process: D = (2 + 14 – 1) × 41 h = 615 h (62 work days).

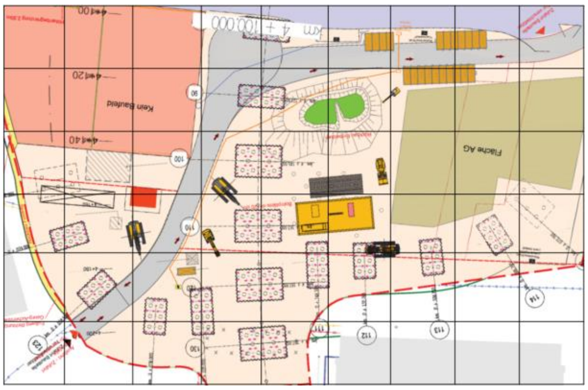

Figure 4: Construction site layout of the case study project overlayed with grid mesh

Figure 5: WoLZo optimal zoning with rectangular shapes for Z = 14

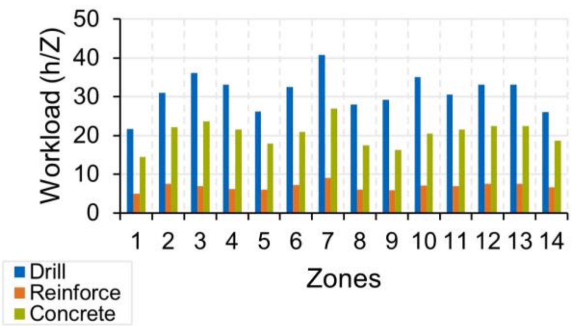

Figure 6: Workload histogram of process steps by zone for three trade steps (S = 3)

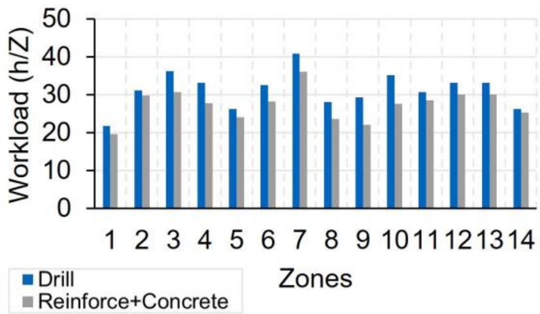

Figure 7: Workload histogram of process steps by zone for two trade steps (reinforce and concrete combined) (S = 2)

VIWOLZO

To further level the workload histogram, the same grid mesh and two work density maps (S = 2) were input to ViWoLZo. Using trial and error, the ViWoLZo user found a better result by going from 14 rectangular zones in the WoLZo calculation to 11 zones (Figure 8). "Better" here means that the distribution of the work densities is more balanced (Figure 10). The new workload peak is T(Z) = 47 h and the duration of the process is D = (2 + 11 – 1) × 47 h = 564 h (57 work days). Compared to the WoLZo results, the process duration is reduced by 51 h which is more than a work week. Despite this improvement, one single grid cell still hasa very high work density (Zone 7). Furthermore, the manually calculated zones are irregular and Zone 5 is split, which may be impractical. Whether to allow zones to be spit, and what shapes zones might take on, are modeling questions (e.g., see Figure 5 in Jabbari et al., 2020).

In pursuit of further improvement, knowing that a finer mesh might enable a zoning with a lower workload peak, the final model focused on the grid mesh size of a cutout of the construction site area, including only four pile groups (frame with dashed lines in Figure 8). Figure 9 shows this cutout with a grid where each cell contains one single pile. It also shows the result of the manual zoning process of this cutout using ViWoLZo, considering the work space needed. The nine zones achieved the most even workload distribution (Figure 11). The workload peak of this cutout is T(Z = 9) = 20 h and the duration D = (2 + 9 – 1) × 20 h = 200 h (20 work days). This final model illustrates the importance of defining a suitable grid mesh and giving careful consideration to process step sizes in order to ensure that zones can accommodate all equipment.

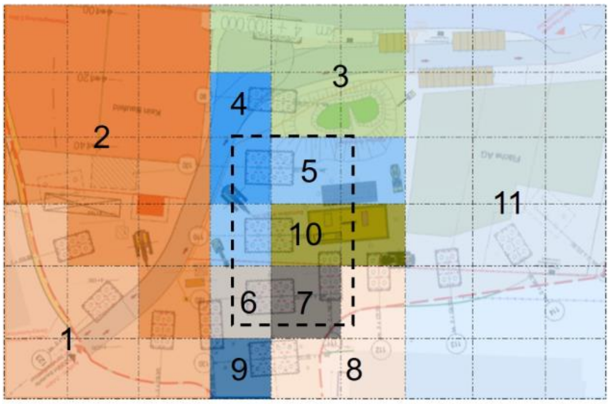

Figure 8: ViWoLZo optimal zoning with manually chosen shapes for Z = 11

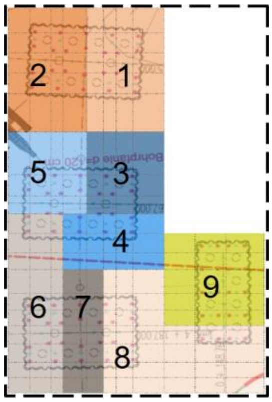

Figure 9: ViWoLZo optimal zoning with one pile per cell for cutout pile groups

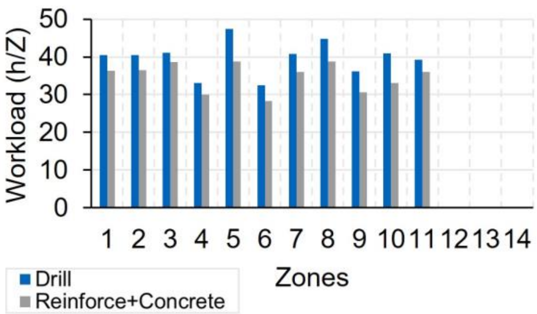

Figure 10: Workload histogram of process steps by zone for two trade steps (reinforce and concrete combined)

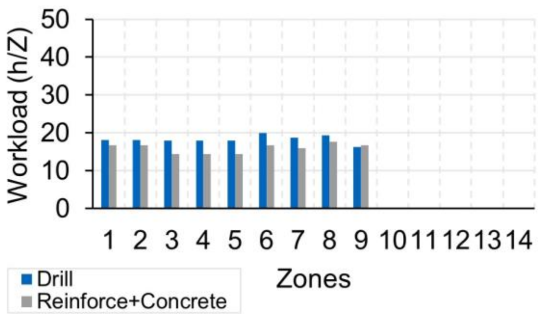

Figure 11: Workload histogram of process steps by zone for selected pile groups (cutout)

RESULTS AND DISCUSSION

The case study showed that the WDM can be applied to in-situ production of foundation piles for a highway infrastructure project, which requires consideration of equipment dependencies. Using a process defined by its steps and the corresponding work density maps as input, two computer-based programs, WoLZo and ViWolZo, were used to zone the work space while achieving a more-or-less even workload distribution for all process steps. Constraints put on the grid mesh regarding work space, the number of process steps, the shape of each zone, and the number of zones all affect the total duration of the process.

The WoLZo algorithm calculated the optimal size and shape of the zones, restricted to rectangular and L-shapes. The resulting zones' workload distributions revealed unevenness, especially per process steps across the zones: the workload for installing the rebar cage (reinforce), and for concreting (concrete) is lower relatively speaking than the workload for drilling the hole (drill). The process steps, reinforce and concrete, were therefore combined in the follow-on study. ViWoLZo gives the flexibility to manually size and shape zones in order to find a more even workload distribution. The zoning obtained show a reduction of the process duration by about 5 work days out of 60, or about 8%.

The study confirmed two notable observations regarding the definition of the mesh size of the grid used in any model. The smaller the grid cells (here one pile in one grid cell), (1) the more flexible the zoning is, and thus the ability to find a lower workload peak (or other process optimum), but (2) the less constrained the zoning is in regard to ensuring that all space requirements are satisfied (e.g., the zone must be accommodate the area of the equipment footprint and requisite surrounding work space).

The case study results reflect the use of a single equipment trade for drilling, reinforcing, and concreting. Further study might consider multiples of that single equipment trade, e.g., using a single equipment trade for a single process step (one for drill, and one for reinforce and concrete), working sequentially from one zone to the next. Decoupling of process steps should allow for a smooth and stable handover from one- to the following step. This further study could be conducted, e.g., through experimental modeling using simulation (Abdelmegid et al., 2022). Practical challenges, such as soil disposal and excavation management, underscore the importance of considering logistics in takt planning. One must balance multiple flows (trades, material supply and removal, equipment, etc.) instead of one flow with a single criterion (here trades) (Tommelein et al., 2022). Besides process requirements, organizational requirements must also be addressed to enable a continuous assembly flow between different trades (Kujansuu et al., 2019). In the presented case study, the zoning was based only on spatial and process constraints. Cost and other resource requirements were not considered.

The case study results significantly underestimated the actual duration of the pile production process, which took 119 work days. Reasons are that the models based on work density did not account for work breaks (e.g., overnight breaks between process steps, with a step ending before the end of a 10 hour work day), nor for the movement and installation of the drilling rig from one pile location to the next. Furthermore, no disturbances or irregularities were considered. However, regularity was embedded in the actual schedule (though it was not takt plan) to facilitate the coordination between specialists, e.g., concrete delivery was scheduled for a specific time each day, even though that resulted in waiting time for the drilling rig.

CONCLUSION AND OUTLOOK

This study's aim was to assess the applicability of the Work Density Method (WDM) in heavy civil engineering projects, demonstrating its requirements within a specific case-study project. Applying a takt planning approach seemed promising for synchronizing the use of resources and process duration planning. The case study showed that takt planning applies to equipment-driven processes. It did so by illustrating the use of the WDM, one method to zone the work space by equalizing workload. Two different computer-based programs, WoLZo and ViWoLZo, were used.

Compared to building construction projects, heavy civil engineering projects have different dimensions of complexity; they can be equipment-driven with a single piece of equipment setting the pace for the overall process. The highly specified equipment trade seems to act like a one-piece workflow, which makes it hard to throttle up and down the pace. This notwithstanding, the case study showed that zoning according to WDM helps even out workloads to reduce the process duration.

Regarding the research questions 1 and 2 on how to define and combine grids and zones, the answer is that equipment space needs as well as logistics must be added as considerations in new models that could build on algorithms such as WoLZo's. In its current implementation, WoLZo constrains zones to be rectangular or L-shaped, and the cells in zones must be contiguous. In contrast, in its current implementation, ViWoLZo allows for flexibility by allowing zones to be split and irregularly shaped (research question 3), but it too needs augmentation to address the aforementioned considerations. Further model extensions could provide support to better represent space needs for equipment, pile groups, etc., and to investigate concurrency by multiple pieces of equipment.

The case study highlighted the need to adapt the WDM to the unique characteristics project types. Further research can look into optimizing crew- and equipment coordination, developing logistics strategies, considering sustainability factors, and integrating the WDM with project management software to enhance project delivery. Validation through benchmarking, education, and training is in order to facilitate the WDM's adoption and success in the heavy civil engineering sector.

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IMPROVING REASONS FOR NON-COMPLIANCE DOCUMENTATION USING UAV ON CONSTRUCTION PROJECTS

Mauricio J. Toledo[1] and Brian E. Sánchez[2]

ABSTRACT

Most Last Planner System® (LPS) research focused on finding the Reasons for Non-Compliance (RNC) and their origins come from indirect means such as perception surveys, therefore, registered RNC are based on opinions and not facts. This situation causes an incorrect categorization of RNC, and consequently, these RNC remain unsolved and they would probably happen again.

The aim of this research is to create a formal registry of RNC on construction building projects during rough works for improving RNC documentation, using photos taken by an unmanned aerial vehicle (UAV). We performed 3 case studies: one using a traditional planning method, and two other projects using partial LPS implementation. We took aerial photos with the UAV to register unfulfilled Work Commitments (WC), their RNC and to propose a Corrective Action (CA) that would solve the RNC. This registry is supported by analyzing the RNC with an Ishikawa Diagram and using the 5 Why 2 How method (5W2H) to systematically propose a CA. We documented all this information in a "RNC Form" for each RNC detected. We took photos once a week for the project with a traditional planning method and twice a week for the projects with partial LPS implementation. We created 22 RNC Forms, which we shared with the project team professionals to receive feedback.

The results are a methodology that accounts for a standardized process on how to carry out the UAV flights, photo taking and subsequently, how to document the RNC creating a RNC Form. This shows a more objective and visual record of the RNC, from which a process of continuous improvement is encouraged, by proposing a CA that solves the identified problem. The methodology and the RNC Form were validated with surveys on a Likert scale, from 1 (strongly disagree) to 4 (strongly agree). We interviewed 7 construction field professionals from the three projects. The composition of the RNC Form and the future use of the proposed methodology reached a score of 4.0 and 3.9 respectively; therefore, they were highly valued by the field professionals.

KEYWORDS

Reasons for non-compliance, RNC, UAV, LPS, corrective action.

INTRODUCTION

Since its introduction by Glenn Ballard and Greg Howell at the end of the 20th century, the Last Planner System® (LPS) has proven to be an efficient tool in project management, evolving from short-term planning and problem solving to a unified, continuous process improvement system for planning and control of projects throughout their entire life cycle (Ballard & Tommelein, 2020).

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Despite the adoption of LPS, a large majority of construction projects implements only partial LPS, and they usually focus on short-term planning. The Percentage of Plan Completed (PPC) and Reasons for Non-Compliance (RNC) are the most used metrics on LPS projects (Daniel et al., 2015). However, RNC, which are recorded to generate a Corrective Action (CA) and thus prevent future recurrence, usually come from single case studies or indirect means such as perception surveys (Lagos & Alarcón, 2021). This indirect process may result in failure to identify the real source of the RNC, causing the proposed CA to be incorrect and not providing an adequate solution to the problem. Thus, our research question is: What should be the procedure to improve RNC documentation?

Therefore, this research proposes a methodology for documenting the RNC. We propose to use a type A3 document (Gupta et al., 2019; Koskela et al., 2020) called "RNC Form" to visually document site conditions related to detected RNC. The RNC Form provides background information about the Work Commitments (WC), it describes the RNC type and its impacts and once the problem is identified, it recommends a CA, which provides a solution to the problem. Site photos taken using an unmanned aerial vehicle (UAV) support this process. We also use the project schedule, and the construction methodologies to visually show the unfulfilled WC for short term planning. Our aim is to standardize the proposed methodology, indicating the relevant parameters for an adequate documentation and the required time to carry this out. We expect to replicate this procedure in future projects.

LITERATURE REVIEW

Reason for Non-Compliance (RNC) is defined in the Last Planner System® (LPS) literature as the reason why short term Work Commitments (WC) are not fulfilled (Ballard, 2000).

Most of the RNC are caused by the general contractors (construction companies) and subcontractors in high-rise building projects (Lagos & Alarcon, 2021). The lack of workspace is a frequent problem that construction companies must constantly coordinate and review to avoid site congestion and interference among trades that affect the work performance for the rest of the team (Sabbatino et al., 2011). Subcontracts fail in what is generally the most frequent RNC in the construction industry: lack of labor (Sabbatino et al., 2011).

Registry of RNC usually comes through third parties (Lagos & Alarcón, 2021) or indirect means (Daniel et al., 2015), which can lead to erroneous registry and consequently to persistent unsolved construction problems. This deficiency of current LPS practice should be addressed. According to López (2013) the average PPC in construction projects does not exceed 70%, therefore this represent a big problem. The lack of an accurate RNC registry can be addressed using the Ishikawa Diagram analysis to visually identify the root causes of RNC in 6 generic categories of idea generation (Tague, 2005).

We identify the RNC to understand the causes of the problem and to generate a corrective action (CA). Thus, we create a continuous improvement process and we avoid the repetition of RNC for subsequent WC (Ballard, 2000). We used the 5W2H method for this purpose (Tague, 2005) and we asked 7 structured questions to briefly explain the proposed CA, to describe the procedure to follow and justify its cost. As input, we use all relevant information about the detected RNC (problem).

The use of a camera-equipped UAV provides an unprecedented opportunity for inexpensive, easy and fast documentation of the execution of on-site planning (Ham et al., 2016) and this information allow us to find of a large number of spatial interferences (Zapata & Sánchez, 2020). UAVs have been used in the construction industry for different purposes, such as: safety inspections (Irizarry et al., 2012), applications in construction management like land surveying, logistics, on-site construction, maintenance and demolition (Li & Liu, 2019). They have even been used for progress tracking (Álvares & Costa, 2018). However, commercial use of UAVs has experienced an exponential growth in recent years, which has consequently led to an increase of aerial incidents recorded in the last decade (Pérez & Ortiz, 2020). Therefore, we need an UAV flight strategy adequate to each project´s site conditions.

Bordin et al. (2018) noted the use of A3 reports as a Kaizen tool to provide context of a problem, describe the current situation, the improvement objective, provide an analysis, and an action plan that addressed the situation to be improved. According to Gupta et al. (2019), A3 documents have a great potential to improve the effectiveness and communication of information in the construction industry. Therefore, we standardized the format to describe the information gathered in the field and to present the analyses performed using an A3 document as a single page report.

METHODOLOGY

We followed the CIFE Horseshoe (Fischer, 2006) to guide our observation of a practical problem, to develop a plan to address it. In our literature review, we identified the lack of objectivity in the registration of RNC as a problem and we found that UAV use might facilitate visual information to perform such registration (Chica et al., 2019; Zapata & Sánchez, 2020). The most common RNC in Chilean construction projects during rough construction are: lack of labor, lack of workspace and missing prerequisites (Sabbatino et al., 2011), therefore that will be our initial research focus. Then, we will document non-compliance of work commitments (construction activities) using UAV pictures.

We carried out three case studies on Chilean building projects during the rough works stage. One of the projects used traditional planning, while the other two had a partial LPS implementation. We conducted on-site monitoring for a maximum of 6 weeks per project. We planned UAV flight strategies for each project to take high-resolution photos of workspaces and to avoid possible accidents both on the field and on its surroundings. Figure 1 shows the three case studies. Figure 1a shows a 2-story building in a low-density neighborhood. Figure 1b and 1c show cases 2 and 3, both midsize residential buildings on high density neighborhoods.

We analyzed the RNC using the visual information of unfulfilled work commitments (WC). We briefly explained the factors causing non-compliance using an Ishikawa Diagram. After analyzing the RNC, we proposed a Corrective Action (CA) using the 5W2H methodology, providing a brief explanation of the procedure. We created a RNC Form that documents the analysis and visualization of the detected RNC and we shared it with the field office to receive feedback.

Figure 1: Case Studies: (a) 2-story reinforced concrete and confined masonry building (384 m2); (b) 7-story reinforced concrete building (approx. 2,000 m2); (c) 7-story reinforced concrete building (approx. 900 m2).

Finally, we applied validation surveys to the project team members for each case study to quantify the impact of this research. 7 construction professionals (civil engineers and construction managers with 5-10 years of construction experience), answered our survey after a 30-min presentation of our methodology. Their familiarity with the project, with our work and the weekly feedback received during the on-site monitoring brought valuable feedback to our proposal. The validation survey had 11 question and we used a Likert scale, from 1 (strongly disagree) to 4 (strongly agree) to receive feedback about the proposed methodology, the structure of the RNC Form and the future use of the proposed methodology.

RESULTS

We created 22 RNC Forms that we shared with project team members for each case study to validate our hypothesis about the need of an objective RNC registry. At the end of the 6-week construction project monitoring, we showed our RNC Forms and methodology to each field office team and asked them for feedback with a validation survey. The purpose of this survey was to demonstrate the usefulness of the proposed methodology, the adequate visualization and understanding of the RNC Form structure and to test the potential adoption of this process in future projects.

PROPOSED METHODOLOGY

Figure 2 summarizes the main three components of the methodology: (i) Creation of a flight strategy in a simulated environment (steps in light blue); (ii) Weekly site visits (steps in gray); and (iii) Creation of the RNC Form (steps in orange). The time required for the execution of the proposed methodology is divided into two categories:

1. One time processes: They establish the flight strategy for each case study. They have a total duration of 4:30 hours and we show them in light blue in Figure 2.

2. Periodically executed processes: Steps that are executed every week. Total execution time depends on the number of weekly site visits and the number of RNC Forms made. The site visit includes the request of the weekly planning, thus, we know the weekly work commitments and workspaces beforehand and we plan the UAV flight strategy and capture pictures accordingly. The RNC Forms register the unfulfilled WC and their RNC, according to the weekly planning. Figure 2 shows that each site visit takes 45 minutes (grey steps), and that the estimated time to create a RNC Form is 1 hour (orange steps).

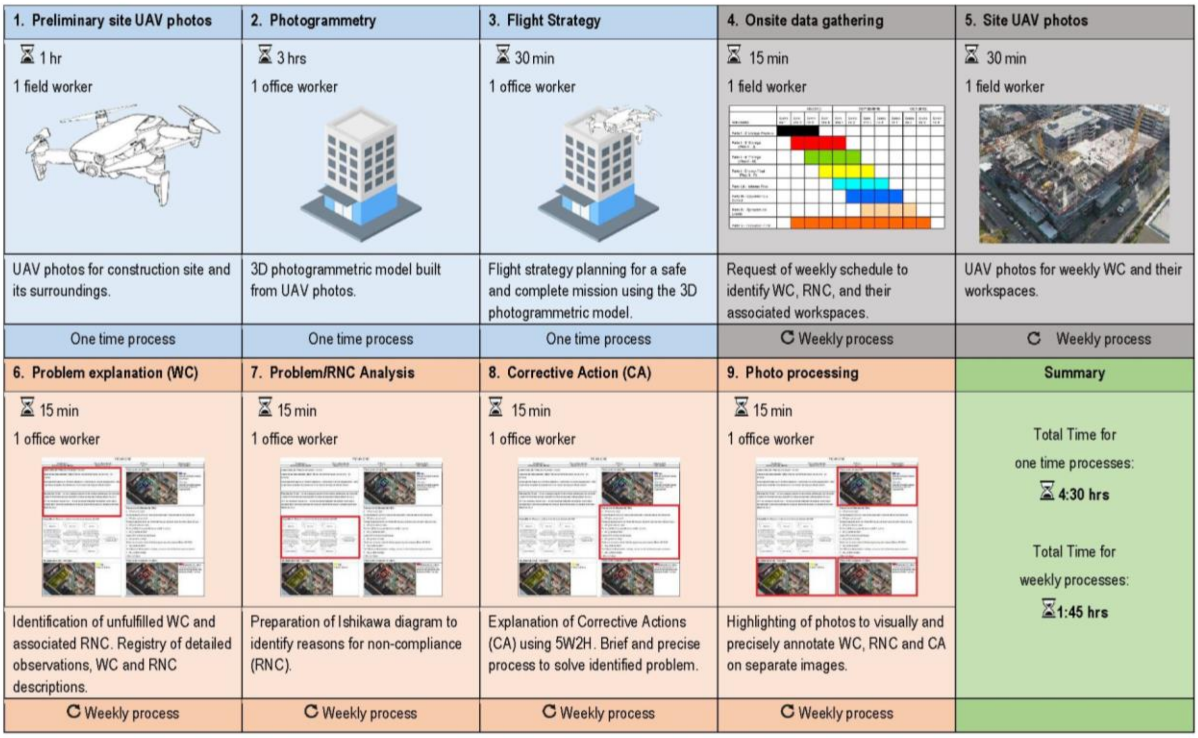

Figure 2: Proposed methodology and execution time summary.

Flight Strategy

We created photogrammetric 3D models to develop a flight strategy for each project. These models, shown in Figure 3, allowed us to explore the construction site and its surroundings for each case study, in order to plan the weekly UAV photo shooting and avoid obstacles. We built the photogrammetric model from a single grid flight mission around each project site. Each model is approx. 100 m by 100 m. These parameters allowed us to generate photogrammetric models with a GSD of less than 2 cm/pixel. On these 3D photogrammetric models, we planned/tested the flight strategies. In most cases, we chose circular flights around fixed points on site, with a target flight height of 40 m and a radius of 30 m (as shown in Figure 3).

Case study 1: The project size is approximately 12 m by 32 m, so our flight strategy captured the entire project with a single circular UAV flight, as shown in Figure 3a.

Case study 2: The largest project required 3 circular UAV flights to cover the entire project site, as shown in Figure 3b. Unlike the other case studies, this project was near completion of the rough works during our research, thus we only spent 4 weeks on-site and consequently we built fewer RNC Forms.

Case study 3: The buildings surroundings and the presence of a tower crane in this project, forced us to reduce the flight strategy to a semicircle (as shown in Figure 3c) and to elevate the flight height from 40 m to 60 m to avoid collision with the crane.

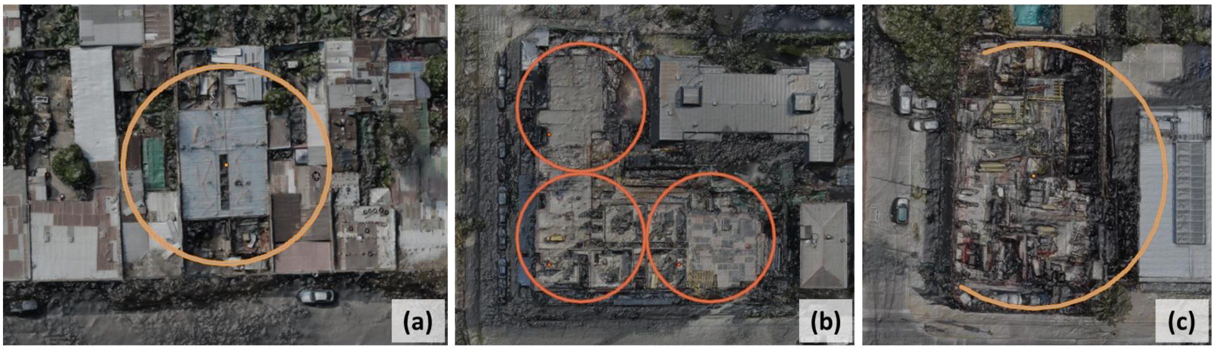

Figure 3: Flight Strategies: (a) Case study 1: single circular flight; (b) Case study 2: large project footprint demands 3 circular flights; (c) Case study 3: obstacles and tower crane presence force a semicircle flight.

Weekly Project Visit

We visited each project twice a week during the construction project monitoring. We executed our UAV flight strategies to take site photos. We asked about the construction processes and WC for each case study, and we gathered information about the weekly planning. We also showed the RNC Forms from past weeks to the field professionals. The visits were at least 1 day apart, to be able to notice significant changes between one visit and another. Case study 1 was the smallest project and it used a traditional planning method. It did not show much weekly progress, thus we reduced the site visits to once per week.

RNC FORM

The RNC Form is divided into 2 main parts: left and right. The left part seeks to describe and provide context to the unfulfilled WC, the identification of the associated RNC and its analysis using the Ishikawa Diagram, and an illustration of the WC and its location in the field. The right part seeks to illustrate the RNC, how to achieve the CA using the 5W2H method and a picture showing the CA location. Figure 4 shows a RNC Form that has 7 major sections: (1) General Information about the construction company, date and time of photos for the CNC Form, and the UAV operator's name; (2) Background about the name, description, and explanation of the WC and RNC; (3) Ishikawa Diagram that explains the factors causing unfulfilled WC; (4) WC

Visualization that shows an annotated (yellow) photo of the WC location, and a brief text description; (5) RNC Visualization that shows an annotated photo (blue) of the RNC location and type; (6) Corrective Action (CA) that describes the solution to the RNC according to the 5W2H method; and (7) Visualization of the CA that shows an annotated photo (red) of the CA location, accompanied by a brief explanation.

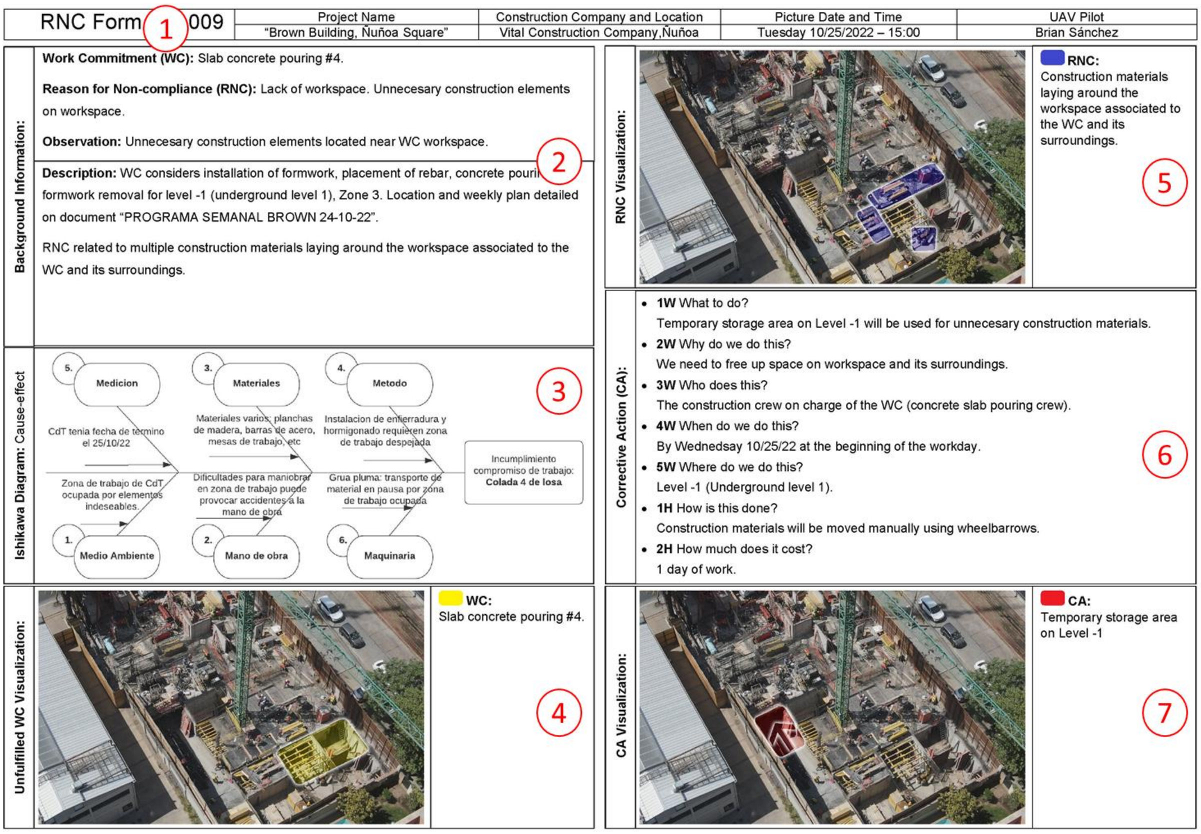

Figure 4: RNC Form 009, Case Study 3 – Brown Building, Ñuñoa Square.

We analyzed the photos taken during the week to identify and describe the unfulfilled WC and to identify and classify the observed RNC.

RNC are different in nature, thus for each type of RNC studied, we built a detailed definition of the 6 categories of the Ishikawa Diagram: Measurement, Materials, Method, Environment, Labor and Equipment. For instance, *RNC lack of workspace* refers to any undesirable element that prevents the realization of the WC. This can be dirt, debris and/or disorganized storage of materials. In this case, *Environment* is the most relevant aspect for the RNC (what can I find in the workspace? and why it hinders WC?). We list each category according to its importance for each case: 1 is the most important factor in the diagram and 6 the least important. This ranking varies for each RNC type. However, for the same RNC type, the main category is always the same. *Labor* is the most important factor for *RNC lack of labor* and *Measurement* is the most important factor for *RNC missing prerequisites.*

For each recorded RNC, we proposed a corrective action (CA) to solve the problem using the 5W2H method (Tague, 2005). After defining the CA, we searched among the UAV photos to find the one that best visually depicts the site conditions. We use yellow, blue and red annotations in the picture to highlight the location of the WC, RNC and CA respectively. We highlight them in separated pictures to avoid annotation overlapping, as shown in Figure 4.

We prepared at least 1 RNC Forms for each site visit and we showed them to the field professionals for each project the following week. We shared the RNC Forms in A3 format as shown in Figure 4 in both electronic (PDF) and printed form.

We prepared and shared 22 RNC Forms for the 3 case studies with the field professionals and we periodically received their feedback and validation regarding the RNC, its depiction, and the associated CA. Several of our suggested CA were actually implemented. We did not find *RNC lack of labor*. We found 9 instances of *RNC missing prerequisites*, 8 instances of *RNC lack of workspace* and we had to define a new type we called *RNC lack of materials* (5 instances). We created 6 RNC Forms for Case Study 1 (our guinea-pig project), 6 RNC Forms for Case Study 2 and 10 RNC Forms for Case Study 3.

VALIDATION

We applied a validation survey to 7 field professionals from the 3 case studies. The survey has three major groups of questions. First, we asked whether the proposed methodology is adequate as a tool for creating an objective RNC registry for short term planning. We asked about the suggested procedure and the time required for its execution. Second, we asked whether the RNC Form structure is clear. We asked if the RNC Form adequately explains, analyzes and visualizes the WC; and if it adequately describes and visualizes the RNC; and if it adequately explains the proposed CA and its visualization. Third, we asked about the future use of the proposed methodology for construction projects during rough works. We used a Likert scale for the validation survey with multiple-choice answers ranging from 1 to 4, where: strongly disagree (1), disagree (2), agree (3) and strongly agree (4). The validation results are shown in Figure 5.

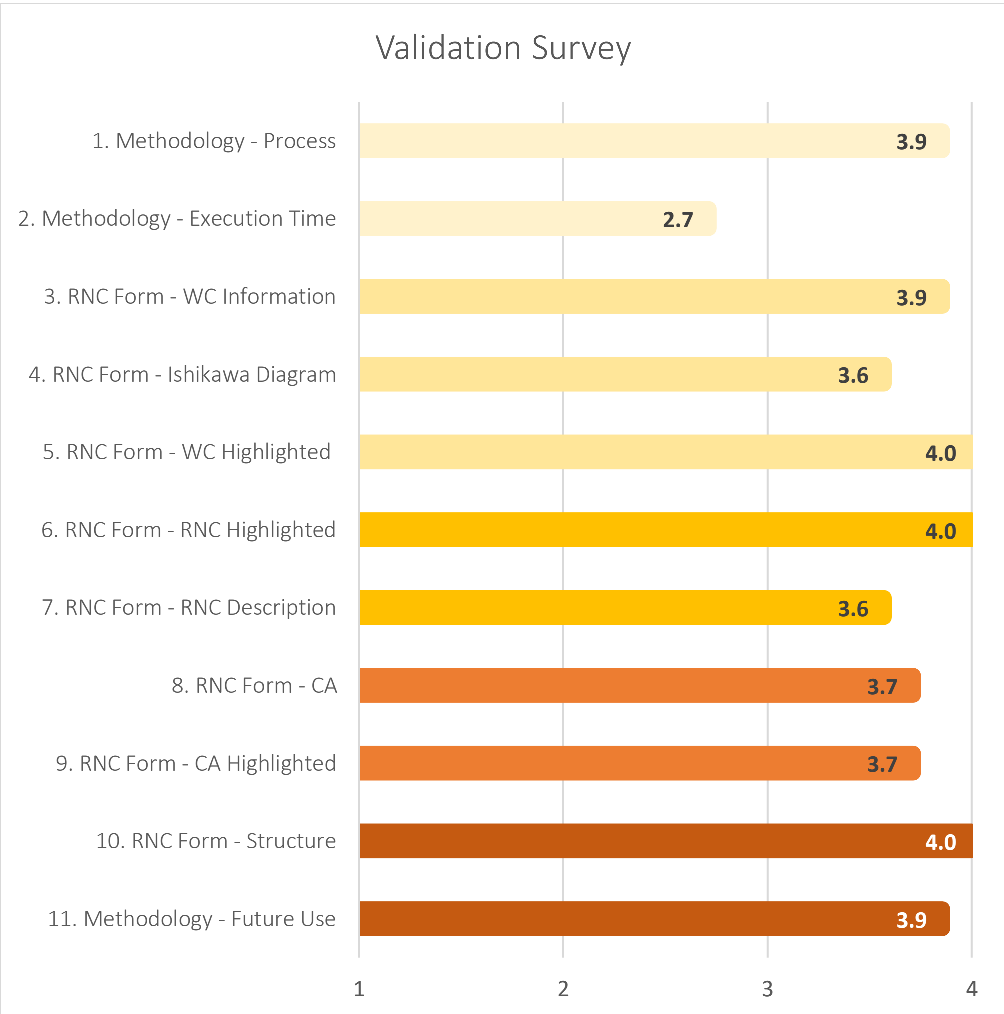

Figure 5: Validation Survey Summary Results.

In the first group of questions, we asked about the proposed methodology and it was well received with an average score of 3.3 (Q1 & Q2). For the second group of questions we asked about the RNC Form and its structure as a registry for RNC. We received a high level of approval with an average score of 3.8 (Q3 to Q10). In the third group of questions, we asked about future use of our methodology and we obtained the best results with an average score of 3.9 (Q11). Thus, as a whole we obtained an overall score of 3.7 in the survey, which means that our methodology was highly valued by the field professionals.

Respondents liked the proposed research with an average score of 3.9, but they pointed out that was a lengthy process with a score of 2.7, as shown in Figure 5. Regarding the RNC Form, respondents valued the WC section, and they rated the WC background context, the explanatory Ishikawa diagram and the WC visual annotation with scores of 3.9, 3.6 and 4.0 respectively. They also valued the RNC visualization and the explanation for each annotated picture, with scores of 4.0 and 3.6 respectively. Respondents also valued the CA proposed using the 5W2H method and its annotated picture, where both received a score of 3.7. Finally, the respondents had a positive feedback about the structure/organization of the RNC Form and they were willing to use the methodology in future projects, with scores of 4.0 and 3.9 respectively.

DISCUSSION

In our literature review, we identified the "lack of labor" as a relevant RNC during rough works projects; however, we could not capture this type of RNC in our UAV flights for the three case studies. We took photos during our site visits centered on the workspace for each WC, but the crews of construction trades were constantly moving throughout the construction site and we could not document missing workers. Therefore, we were not certain that unfulfilled WC were due to lack of labor.

Depending on the project scheduling sophistication, the project team valued differently our proposed methodology. Team members from Case Study 1 (traditional planning) valued the suggested CA for unfulfilled WC. For instance, in our 1st RNC Form we suggested the implementation of a temporary staircase that would provide safe access to the 2nd floor. Our RNC Form documented the problem and CA proposed and the project team built such staircase (on a different location though). For Case Studies 2 and 3 (partial LPS planning), the project team particularly valued the usefulness of the RNC analysis shown in the Ishikawa Diagram of the RNC Form. As no formal RNC registry existed, they valued the RNC analysis, which complemented the weekly planning and project PPC metric (Percentage of Plan Completed).

Our RNC Form arose from the need to summarize the analyses of the proposed methodology in a compact format and using weekly visual information from the UAV pictures. The RNC Form final version corresponds to the 7th iteration of this process. We modified preliminary versions of the RNC Forms, both by incorporating the feedback obtained in each project from the field professionals and by continuous improvement.

CONCLUSIONS

The purpose of this research was to create an objective RNC registry, based on actual weekly site conditions. We proposed a methodology that standardized the analyses for the WC, the RNC and its associated CA, and that is visually supported by photos taken using an UAV. We called it the RNC Form. We built 22 RNC Forms for the 3 case studies. We received feedback and validated the RNC Form and our methodology with field professionals.

Our methodology has an estimated execution time of 1 hour per week per RNC Form and can be summarized in three parts:

(1) Flight strategy in a simulated environment: We use a 3D photogrammetric model to create a safe and efficient UAV flight strategy for each project. This process is done only once per project and has an estimated duration of 4:30 hours.
(2) Weekly site visits: We gather site information to build a RNC Form. We asked for the project weekly planning and used the flight strategy for taking UAV photos of the workspace associated to weekly work commitments (WC). This weekly process lasts approximately 45 minutes.
(3) RNC Form: Given the weekly schedule, the unfulfilled WC and the RNC, we built visual RNC Forms that proposed a CA. This weekly process lasts approximately 1 hour per RNC Form.

Our validation survey shows that field professional valued our visual RNC Form (The overall score of 3.7). They considered adequate the explanation and description of the WC, the RNC analyses, and the suggested CA (with an average score of 3.8). They are willing to use the RNC Form in future projects (average score of 3.9).

FURTHER RESEARCH

Our methodology aims to work in support of field professionals, i.e., we do not want to interfere in the construction processes or planning used in building projects. We want to enhance the scheduling process, using an LPS-based tool to document RNC that interrupt the workflow and propose a solution (CA) that eliminates waste.

We see opportunities for future research implementing RNC Forms on different types of construction projects as well as exploring other types of RNC. We applied the methodology on 3 case studies during the rough works, but we see potential for use during other construction phases such as excavation. We worked on an urban environment, but we could also explore the application of our RNC Forms on other building types on rural or/and remote environments.

Finally, if we are able to systematically create RNC Forms for ongoing projects, which seems plausible given the acceptance and willingness to use them by field professionals, we could perform a better categorization of RNC Forms, beyond the three types we found with our UAV-pictures (*RNC missing prerequisites, RNC lack of workspace* and *RNC lack of materials*). Once we have a large number of RNC Forms, we could perform statistical analyses of RNC or explore the effectiveness of CA to avoid recurrence of RNC.

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QUANTITATIVE INDICATORS IN TAKT PRODUCTION CONTROL: AN EMPIRICAL ANALYSIS

Jaakko Riekki[1], Olli Seppänen[2], Joonas Lehtovaara[3] and Antti Peltokorpi[4]

ABSTRACT

Takt production has improved lead times and stability of lean construction projects. There are several studies about takt planning but research on takt control is scant. Although some quantitative indicators have been proposed for assessing how well sites are able to follow the plan, there are no studies which have used these indicators on real projects on a work package and daily level of detail.

This paper investigates through a case example how previously proposed quantitative indicators of takt control work on a detailed level. We also discuss how the indicators can be interpreted for understanding plan adherence, control actions, and improvement opportunities.

Studying takt control aims to learn why and how production deviates from the plan and how management should act to get the intended production realized. Quantitative analysis with progress data and indicators calculated from them can be used to measure deviation from the plan and the performance of the production system. This paper shows how takt control can be analyzed with flow efficiency and punctuality indicators. Indicators reveal improvement opportunities in outlier trades and takt areas in flow efficiency, the relationship of product and operations flow and go-back work areas.

KEYWORDS

Takt production, production control, quantitative indicators, progress tracking, improvement

INTRODUCTION

Takt production in construction has seen increasing attention from lean construction scholars. So far, the focus of takt production development has been on takt planning, but studies such as Lehtovaara et al. (2021) have qualitatively assessed the effects of takt production in execution. Their results indicated that takt projects tend not to follow the plan exactly but did not elaborate on the nature of issues encountered. Takt control has also been qualitatively touched by Binninger et al. (2017) in the form of proposing a set of possible adjustment mechanisms.

However, studying takt control with quantitative methods could increase understanding on detailed level. The challenge is that quantitative analysis requires gathering data by tracking and recording progress of the schedule on a detailed level. Detailed progress tracking and

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recording can be tedious for the site management team although it can be aided by technology (Keskiniva et al., 2021). Zhao et al. (2021) showed how tracking workers and materials and linking them to schedules can be done with indoor positioning, but this technology is not yet very prevalent.

Despite the challenge, quantitative methods have been used previously for production control in construction in several settings. Hamzeh et al. (2019) proposed a set of metrics and a dashboard aimed at evaluating the performance of the Last Planner® System (LPS) of production planning and control on the team and project levels. These metrics measure the reliability of planning of future work and whether the system is on track towards milestones, but not adherence to a set schedule per se. In location-based management system (LBMS) studies, quantitative methods have been used for assessing production flow. Seppänen (2009) analyzed three LBMS cases quantitatively in detail. Sacks et al. (2017) proposed a quantitative construction flow index (CFI) and tested it in a number of LBMS case projects. For takt production, methods for calculating quantitative flow efficiency measures have been published by Binninger et al. (2019). Binninger (2021) also quantitatively showed the flow properties of an aggregated set of takt cases on a project portfolio level. Further, Alhava et al. (2019) showed with data, how takt production does not always follow the plan but did not analyze the data in detail. Conceptually, Keskiniva et al. (2023) suggested several indicators for takt production performance assessment. However, none of the above-mentioned studies have analyzed takt production quantitatively on a daily and work crew level of detail. This motivates further quantitative analysis in the takt production control context with finer granularity to better understand the actual performance of takt production in execution.

The aim of this paper is to investigate through a case example: (1) How do previously proposed quantitative indicators of takt control work on a daily and work crew level of detail? and (2) How can these indicators be interpreted for understanding plan adherence, control actions and improvement opportunities?

To achieve the aim, a detailed set of progress records of a takt phase of a case project was analyzed. A set of pre-published indicators were used to investigate how they behave with real project data.

METHOD

We first briefly describe the case project and the method of data gathering and extraction, because it has implications on choices that were made for the calculation of the indicators. After that, we introduce the indicators and explain how they were calculated from the data.

CASE PROJECT DESCRIPTION

The case project was a 3-year new construction site that included several phases. One of the phases, the focus of this study, consisted of 178 hotel rooms that were built using takt production. The hotel rooms were small (about 24 m^2) and very repetitive which motivated planning the phase with a two-hour takt time. Each work package, i.e. work done by one trade in a takt area at a takt time, formed their own takt wagon so that the terms work package and wagon are interchangeable, and the term work package is used in this paper. Hotel rooms were done with the takt time of two hours. Production speed was therefore 4 rooms per day since a working day was 8 hours.

The first author participated in the case project in the planning phase and at the beginning of the control phase but was not part of the management team. The first author visited the site and discussed with the management team frequently during the project and occasionally after it had been finished.

SCHEDULE AND PROGRESS DATA

The takt schedule was created in a spreadsheet. The schedule was updated with modifications and progress records by working in one master file. A site manager made the progress record updates daily by marking each work package either started or done. Partial progress rates were not used due to the short takt time. In addition, the site manager modified the plan as required. Copies of the master file were taken daily, and the date was added to the filename. This resulted in a set of 90 schedule version files that represented the current state of plan and progress for each date. Since the progress was recorded daily instead of per takt time, the per takt progress during a day is not distinguishable in the data. This leads to the progress records showing up in batches of four takt times. This has implications for calculating the indicators, which are explained in the following subsection.

The schedule version files were read with a custom program into a custom data structure that contained the progress record for each work package in each takt area at each takt time as well as the planned time of each work package in each takt area at each date. The indicators presented in the following subsection were calculated using custom algorithms that used this data structure. The custom program and algorithms were created by the first author.

INDICATORS

The following indicators were chosen for the analysis: (1) Flow efficiency from product perspective, (2) Flow efficiency from operations perspective and (3) Punctuality. How they are calculated is explained in the subsections below. The flow efficiency (FE) indicators were chosen because they are important measures of value creation and waste and have already been established in previous research by Binninger et al. (2019). Punctuality, as conceptualized by Keskiniva et al. (2023) was chosen because it measures plan adherence, which is also important, but which the FE cannot describe. Other indicators such as continuity, sequence adherence and work in progress are also of interest and require investigation in future studies.

Indicators 1 and 2: Flow efficiency from product and operations perspectives

The general formula for calculating flow efficiency is presented in equation 1. It is the ratio of value-added time to total time such that any non-value-added time between segments of value-added times is added to the divisor (Binninger et al., 2019).

$$FE_i = \frac{t_{i,\text{value added}}}{t_{i,\text{ value added}} + t_{i,\text{ non-value added}}} \tag{1}$$

This can be calculated from two perspectives and separately for planned and actual as presented by Binninger et al. (2019).

The product perspective looks at a single takt area or row in the takt schedule. The times any work package is planned in the takt area are planned value-added times. The times between the value-added times, where there is nothing planned are planned non-value-added times. Takt times before the first or after the last value-added time in the takt area are not considered.

The operations perspective looks at a single work package through takt areas. The times the work package is planned in any takt area are planned value-added times. The times between the value-added times where the work package is not planned in any takt area are planned non-value-added times. Times before the first value added time or after the last value-added time, when all planned takt areas for the work package are finished, are not considered.

The actuals are calculated similarly but instead of looking at the planned times the times recorded with progress are considered.

The flow efficiencies are first calculated for all takt areas and work packages. They can then be averaged over the takt areas for the average product flow efficiency and over the work packages for the average operations flow efficiency. The flow efficiencies can also be calculated in a time series that shows how they change over time. At any given time, the flow efficiency can be calculated as a cumulative value up to a selected time or as a moving average of a chosen time period before the selected time. With a moving average the local behavior of flow efficiency can be understood better compared to the cumulative value.

Also, the total planned flow efficiencies of the schedule can be calculated in a timeseries by considering the active schedule version at each time point. Any changes in the planned flow efficiencies in the timeseries indicate plan changes.

The batch size i.e. how big or small the combination of takt time and takt area is may have a drastic effect on the value of the flow efficiencies, as explained by Binninger (2021). A schedule of the same scope of production planned with a one-day takt time tends to reveal buffers that are implicit in a schedule planned with a one-week takt time. These implicit buffers are calculated as non-value-added time in the flow efficiency equation only for the smaller batch size. For this reason, only schedules with a similar batch size can reasonably be compared directly. In the case of this paper progress was recorded daily instead of per the planned two-hour takt. For the planned flow efficiencies to be comparable with the actual flow efficiencies, the planned flow efficiencies were aggregated to batches of four takt times.

Indicator 3: Punctuality

Based on LBMS delay indicators (Seppänen & Kankainen, 2004) Keskiniva et al. (2023) defined punctuality (P) as the difference between planned and actual work package start (and finish) takt times. The start and end punctualities are calculated by subtracting the ordinal number t_{ordinal} of the planned start or end takt time from the actual start or end takt time for each work package i and takt area j. The general formula is in equation (2).

$$P_{i,j} = t_{\text{ordinal},i,j,\text{actual}} - t_{\text{ordinal},i,j,\text{planned}} \tag{2}$$

This results in two values (the start and the end punctuality) for each work package in each takt area. These can be charted in several ways, for example by showing the punctuality of a work package in each takt area. A negative value indicates delay.

The batch size affects the unit of time that the punctuality is calculated in. For a two-hour takt, the punctuality could be calculated as two-hour units. In the case of this paper the batch sizes of planned and actual do not match and comparing plan with actual with different batch sizes would be misleading. Because of this the planned time of a work package was mapped from the takts to the days that they are in. This leads to a time unit of one day for the indicator.

FINDINGS

A visualization of the schedule and progress record data presented in Figure 1 (interpretation inside the figure) was generated to get a general understanding of how the work progressed. The plan is shown as it was at the end of the phase. There were plan changes during the phase, so the plan would look different depending on the chosen date. The schedule analyzed is also of a limited scope of the phase. Concrete floor drying times caused a delay of several weeks and considerable disturbance for the latter portion of the phase. This was ruled out to not cause unnecessary difficulties for interpretation of the analysis.

Some work packages in front of the train were planned faster than the takt, and some of them were completed faster than planned. This was possible because the limiting factor for starting work was getting water tightness at the top of the building, after which there was plenty of space for the first faster work packages.

It is clear from Figure 1 that the progress tracking breaks down during and after the break planned for two weeks to account for holidays. After the break, there were two large and several smaller batches of tracking data. After those batches, regular updates were resumed. The large batches do not represent reality because they represent several days' worth of progress but are recorded in one day. Due to this, the analysis was done in two parts: (1) a general analysis on the whole schedule with averaged indicators and (2) a more detailed analysis on a segment of the schedule in the beginning of the phase (shown with a dashed line in the bottom left of Figure 1) where production was relatively stable. In the latter we investigate indicators representing individual takt areas and work packages.

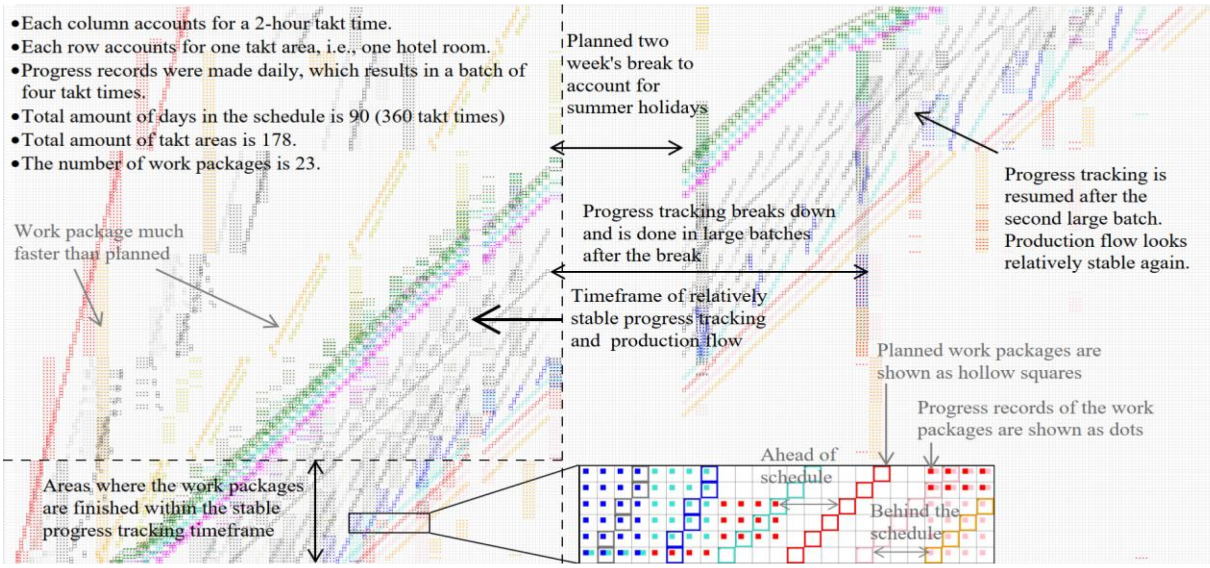

Figure 1: Visualized overview of the schedule and progress record data.

ANALYSIS OF THE WHOLE SCHEDULE WITH AVERAGES

From the schedule visualized in Figure 1, overall flow efficiencies were calculated by averaging over the 178 takt areas for the product perspective and over the 23 work packages for the operations perspective (Figure 2). The planned flow efficiencies represent the average planned flow efficiency of the schedule at the point in time.

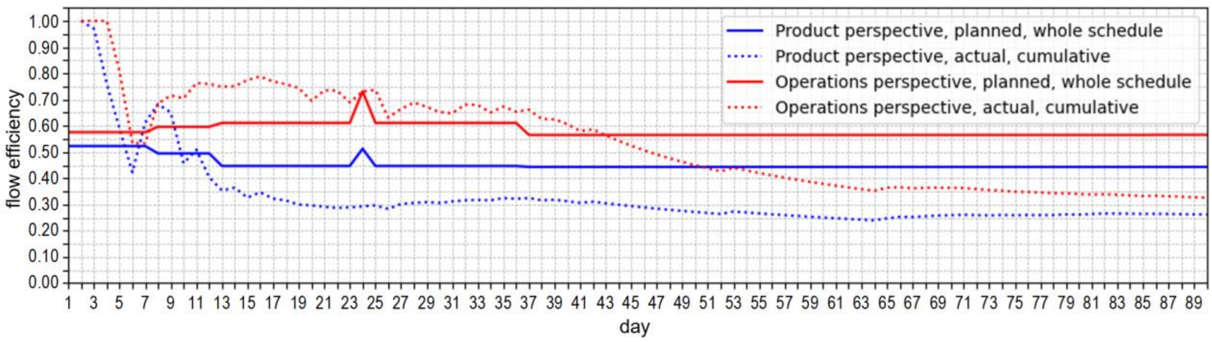

Figure 2: General flow efficiencies averaged over all work packages or takt areas.

The indicators show that plan changes were made at 8, 13, 24, 25 and 37 days. The change at the 24th day seems to have been retracted at the 25th day. In the first plan changes, the operations flow has increased whereas the product flow has decreased. Here some of the faster work packages in front were moved closer together. This decreased the non-value adding times in the operations flow but increased the non-value-adding times in the product flow.

The actuals in the Figure 2 were calculated cumulatively from the start of the work package for the operations flow and from the start of the takt area for the product flow. In the beginning they fluctuate heavily because even one non-value adding time unit will decrease the ratio when the total accumulated time is still short. The further in time the cumulative average is calculated, the more stable it becomes as it approaches the final value at the end of the phase. Both actuals start to decline at about the 42nd day. Here the progress tracking broke down, which caused big gaps in recorded value adding times. The actual indicators lose meaning at that point, but they can show a problem like this. Before breaking down and after the initial fluctuations, the flow efficiencies fluctuate somewhat but stay at a relatively steady level. For product flow the actual is mostly lower than planned, whereas for operations flow the actual stays above the planned before the 42nd day. On average, the work packages have less gaps in their flow relative to what was planned whereas the takt areas were not being worked on as often as was planned.

In the timeframe before day 42, the visualization shows, and site observations confirm, that despite the actual product flow efficiency being below the planned, the phase was mostly able to meet the schedule. Even if there were more gaps than planned in the product flow, the overall flow was good enough. Through the visualization and discussions with the management it was discovered that in some cases one worker had two adjacent work packages and worked on them at double speed but alternating between the two every day. This way they made the same takt but the planned operations flow for both of the work packages was only 50 %, although for the worker the planned flow efficiency was 100 %. This is an effect that was not but should be accounted for when calculating the flow efficiency, and it may be a cause for the higher than planned operations flow efficiency.

The punctuality indicator was calculated by averaging the punctualities of work packages in each takt area. The averaged start and end punctualities of the work packages in the takt areas are presented in Figure 3. The takt areas were worked on in order from left to right. The planned time was aggregated from the two-hour takt to a day.

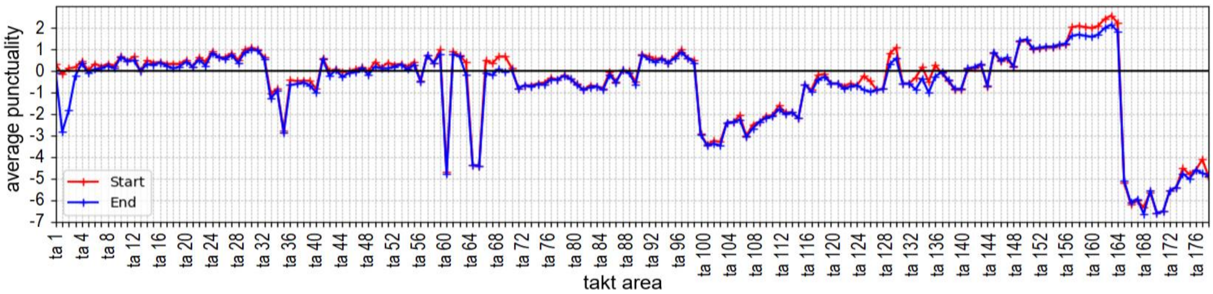

Figure 3: Punctuality at takt areas averaged over all work packages. On the horizontal axis are the takt areas in order from 1 to 178. On the vertical axis is the punctuality in days.

In the second and third takt area from the left, there is a large gap between start and end punctuality. This was due to one work package that was started on time but finished very late because of go-back work in those takt areas. From the third takt area onwards, the punctualities show that the work packages were started and finished ahead of schedule and very close in time to each other. Being ahead of schedule builds up to takt area 33, after which there is a dip to below zero. This is because the last work packages in those takt areas were planned to be finished before the break but were recorded finished in one of the big batches after the break. In takt area 36 that goes deepest below zero, there was a similar kind of go-back work problem as in the second and third takt areas, only this time, the work package was not even started in time. Takt areas 61, 65 and 66 are also outliers of this kind. If outliers are not considered, there is an upward trend in the punctuality after takt area 36, which is expected because the big batch of records is getting nearer in time in each subsequent takt area. In the middle segment of the graph there is more erratic behavior that can be traced to the progress record batches but are not studied here in detail. After the clearest example of batch recording at takt area 100, there is again an expected upward trend. The big dip at takt area 165 on the other hand corresponds to the start of the last floor of the building where the layout was different from the previous ones. Site observations confirm that the production flow was affected by this. The punctualities show that production falls quickly several days behind schedule, but that progress continued after that. Disregarding the progress record gaps, the punctuality clearly indicates whether production is ahead or behind the schedule.

ANALYSIS IN MORE DETAIL DURING THE STABLE TIMEFRAME

More detailed analysis is limited to the takt areas that are finished within the stable timeframe. For the operations flow, the focus limits only to the timeframe. The number of days in the analysis is 41, the number of takt areas is 33 and the number of work packages is 23.

Product flow of takt areas is presented in Figure 4. The cumulative values fluctuate in the beginning and gain stability as they approach the final value at the end. Fewer disturbances are shown by the cumulative indicator at the end of the time series. In contrast, the moving average shows how the flow efficiency behaves locally.

The graphs in Figure 4 show that in general the actual flow efficiencies of the takt areas are at a lower level than planned. The actuals also continue further in time than planned because they were finished later than planned. By visual inspection, there also seems to be more variation in the flow efficiencies both in the cumulative and the moving average. The indicator also shows that the actual flow efficiencies seem to get lower towards the end of the phase. Based on discussions with the site management team, this may be due to the last work packages in the work queue having a lower work content compared to their predecessors. To optimize operations flow, the crews wait for several takt areas to be available so that they can finish them in a bigger batch. This also explains why some of the takt areas are finished later than planned.

The large spread in the first half of the planned moving average is explained by the early faster work packages that create a gap of non-value adding time before the next work packages. This gap is small for the first takt areas but gets larger for the subsequent takt areas. Moving average eliminates this effect after day 20.

Holidays, especially when close to the beginning of a work package, cause a disturbance in the cumulative flow efficiency. Holidays were planned breaks, but work was allowed as extra buffer and therefore they were not removed from the schedule and analysis. Plan changes also cause difficulty for interpretation, especially if they happen retroactively.

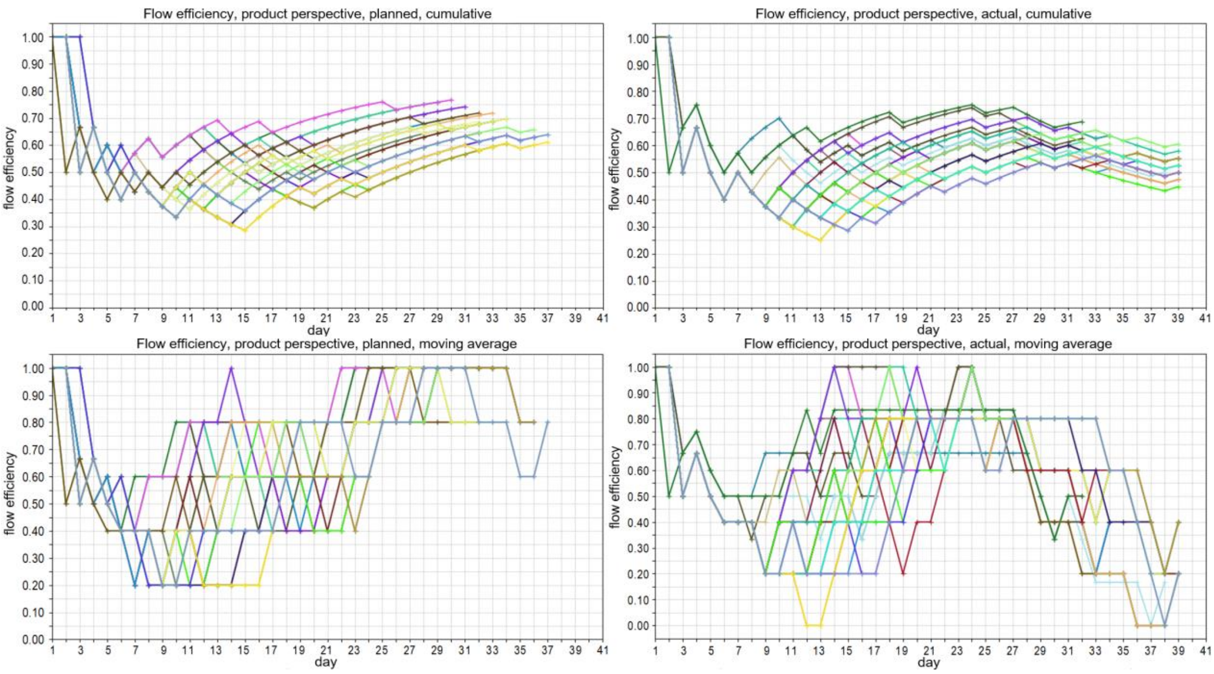

Figure 4: Flow efficiency from product perspective of 33 takt areas. Each line represents one takt area. Top left planned is cumulative, top right is actual cumulative, bottom left planned moving average, bottom right actual moving average.

An example of operations flow of work packages is presented in Figure 5. By visual inspection, the variation in the actual flow efficiencies of different work packages is bigger than planned. Some of the work packages have lower than planned actual flow efficiency, but others have a higher than planned actual flow efficiency. As the averaged analysis suggested, the actual operations flow seems to be on a higher level than planned for most of the work packages, which could be caused by two work packages assigned to one worker. Others however had more gaps than planned, which could be due to them having waited for a batch of takt areas before coming to finish them in one go. The root causes for this kind of variation should be investigated to better understand how to balance the schedule.

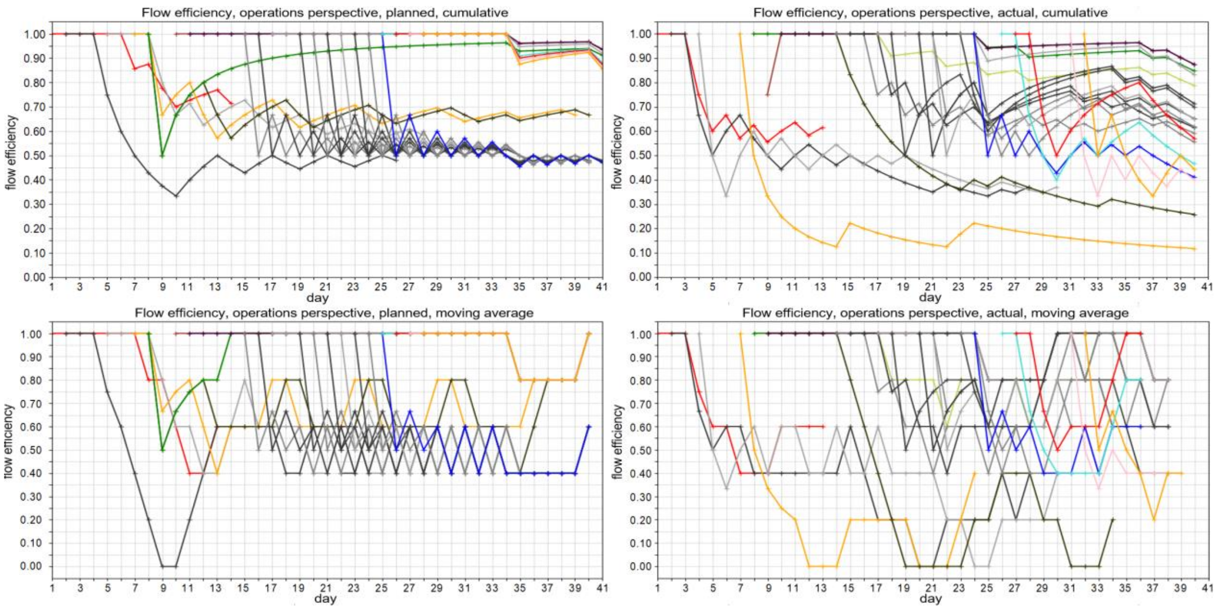

Figure 5: Flow efficiency from operations perspective of 23 work packages. Each line represents one work package. Top left is planned cumulative, top right is actual cumulative, bottom left is planned moving average, bottom right is actual moving average.

The start and end punctualities of the work packages in the 33 takt areas are presented in Figure 6. For the most part, the start and end are close to each other, which means that work was finished quickly after starting. The punctualities fluctuate around zero but seem to be more ahead than behind. This suggests that production was mostly able to keep to the schedule even though it was not followed rigorously. In the end punctuality, the outlier that falls out of the figure caused the drop in the averaged case. The yellow line with chronically low punctuality is the last work package (closing the lowered ceiling drop) in the phase considered. By investigating the individual work packages the causes for effects in the averaged analysis can be narrowed down. The single outlier point in takt area 14 is due to a work package that was not planned in its adjacent takt areas.

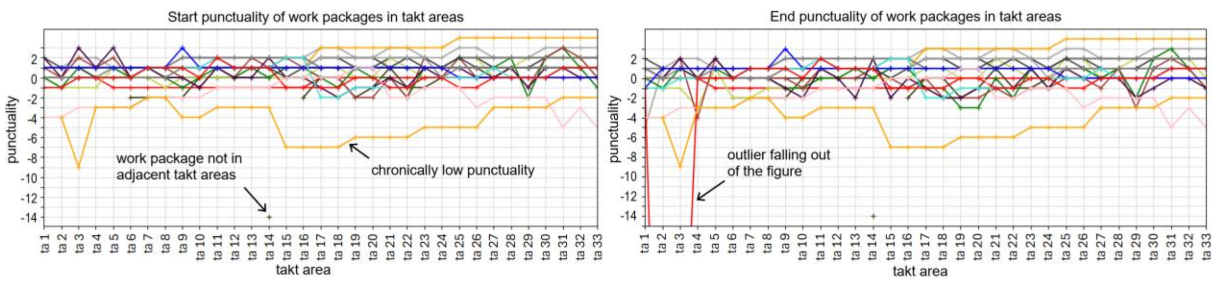

Figure 6: Start and end punctualities of each of the 23 work packages. Each line represents one work package. On the left is the start punctuality, on the right is the end punctuality.

Figure 7 shows how the flow efficiencies behave when looking at individual takt areas. Takt areas to look into were chosen from the punctuality graphs in Figure 6. Takt area 2 was outlier related to end punctuality, but its effect is not visible in the flow efficiency of the same takt area. On the other hand, takt area 8 seemed like one of the least problematic from the point of view of punctuality, but it shows more fluctuation in flow efficiency compared to the takt area 2. This tells us that the indicators do not predict the behavior of the other and indicate different qualities of the production system. In both takt areas, the actual product flow is again mostly lower in efficiency than planned. But it can be noted that there are also periods where the actual flow efficiency is higher than planned. This indicates that the time periods where production is not planned are still used to do work in the takt area. The effect of having a lower flow efficiency at the end is visible here also.

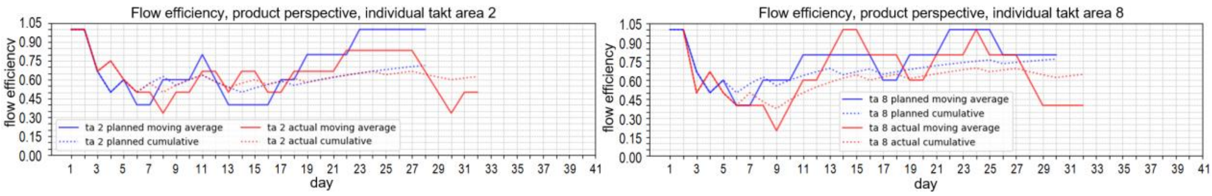

Figure 7: Flow efficiency from product perspective of two individual takt areas. Takt area 2 on the left and takt area 8 on the right.

Figure 8 shows in more detail the flow efficiency of individual work packages. These were chosen to investigate what the difference between two adjacent work packages may look like. The work package 8 was before the work package 9.A in the work queue. Work package 8 has very stable and high flow efficiency with only one interruption on day 25. This does not, however, indicate that the work package necessarily worked the takt areas in the order that was planned, only that the work crew worked somewhere at almost every takt time. Since the product flows were, in general, lower than planned, it is highly probable that this work package took advantage of any free takt areas to prevent interruptions. This could be taken as evidence of adjustment mechanisms being used. Although 9.A has lower flow efficiency, here it is seen for a single work package, how the actual operations flow is higher than planned. This seems like an example of a work package that was planned every other day. The visualization confirms this and that it was planned at double speed to keep following the takt. Through discussions with the management team, it was found out that the worker assigned to this work package was indeed assigned to the adjacent similar work package to work on in the in-between days. The operations flow efficiency indicator as it was calculated here for a work package of this kind is therefore misleading and should be modified to account for the workers used.

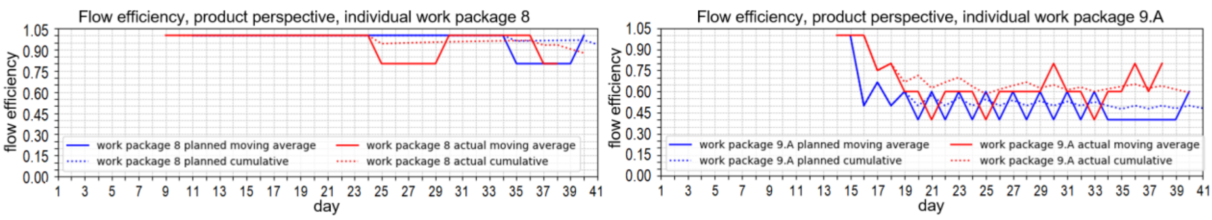

Figure 8: Flow efficiency from operations perspective of two individual work packages. Work package 8 on the left and work package 9.A on the right.

DISCUSSION

The punctuality shows that the schedule was mostly met even with lower than planned product flow. That takt production can provide sound production control even if the plan is not followed exactly has been found in previous qualitative studies such as in (Lehtovaara et al., 2021). The higher than planned operations flow efficiency could be caused by workers alternating between two double speed work packages but also by its prioritization over the product flow as suggested by Binninger et al. (2019). The calculation method could be modified so that it considers the flow efficiency of workers instead of work packages.

Seppänen and Kankainen (2004) found in LBMS studies that discontinuities were the main disturbance that caused late finishes although tasks were started early. They also found that time buffers decrease interruptions. Here in contrast time buffers were minimal but tasks were mostly finished close to starting, which suggests few disturbances. Also, strong signals of cascading delays as described by Seppänen (2009) in LBMS case studies were not found. This supports the interpretation that time buffers recommended by LBMS are not essential to avoid trade collisions and production slowdowns in takt production.

It must be noted that the study focused on a limited single phase in a single 2-hour takt time case. The limitation was intentional to be able to focus on investigating the indicators. Had the whole scope of the phase or the project been considered, the results would have been more difficult to interpret. Therefore, although the discussion above does indicate the applicability of the indicators for studying takt control, it does not, however, allow for generalization.

Other indicators such as continuity used by Seppänen and Kankainen (2004) in LBMS studies or the proportion of work performed out of sequence parameter of the CFI (Sacks et al., 2017) could also be adapted to takt production. In addition to the punctuality, Keskiniva et al. (2023) conceptualized six more indicators to evaluate takt production performance. These could be further investigated to find out their value and applicability.

Also, as Binninger (2021) pointed out, the connection between different levels of planning and control (so called macro, norm and micro levels) have different perspectives. A 2-hour takt time is very close to the micro level and the way the indicators translate to the norm and macro levels should be investigated. One issue of this sort was run into in the discussion above about whether to track a worker or a work package. Further, affirming the findings of Binninger (2021), this study also indicates that there is much room for improvement through improved control practices and methods.

CONCLUSIONS

Returning to the research questions, it was shown in this paper that with progress record data, quantitative indicators such as flow efficiency and punctuality can be used to understand the nature of production on a daily and work crew level of detail. The indicators can show how the production system works overall and trace deviances to individual work packages or takt areas. For example, outliers and peculiarities can lead to relevant conclusions about takt control. They can also reveal plan changes and variabilities involved in production flow. There is plenty of opportunity for more research with more case projects in different settings and with a wider range of indicators. For example, understanding better the question of flow perspective prioritization and how and why takt production reduces the disturbances expected by LBMS could be some of the goals. Also, with such a short takt time as two hours the indicators relate to individual workers but with longer takt times such as one week the interpretation will probably be different. Expanding to other settings such as these warrants for future research.

In future research, setting up a link between the production control indicators and project delivery outcomes could be valuable. Companies should be able to set quantitative project level objectives and use the indicators to assess and direct improvement towards them across projects. This could also reveal common pain points to focus management attention.

Also, forecasts of the indicators could be developed to highlight the impact of problems, to set policies and to help commit to control actions. Dashboards of real-time indicators could allow site management to get focused information of deviations.

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REVISITING THE TAKT MATURITY MODEL AFTER THREE INTERNATIONAL TAKT FORUMS

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ABSTRACT

Takt production has gained wide interest as a change agent for systemic change in recent years. A maturity model for the adoption of takt production based on and validated with Finnish case projects was published in 2020. However, that maturity model has not been validated internationally and companies have continued their development of takt-based operations. In this paper, we suggest updates of the maturity model by reviewing the best practices presented in three international takt forums. We also validate the model using international case projects presented in the takt forums. Industry participants have taken routes to takt production implementation other than those assumed in the initial model. Some have advanced to levels that were not included in the original model. Our suggestions consist of adding four new requirements and modifying the descriptions of eight existing requirements. A modification to the description of one of the levels in the model and the model itself are also suggested. The contribution to knowledge is a new maturity model to use for benchmarking and as a roadmap for improvement of takt production.

KEYWORDS

Takt production, maturity model, takt forum, driving change

INTRODUCTION

The use of takt production as a production planning and control method is becoming more common in the architecture-engineering-construction (AEC) industry. A range of practices and variations thereof can be observed on projects around the world. At the same time, certain companies are advancing the state-of-the-art practices of takt production, (1) to refine its use on the types of projects where proof-of-concept has already been delivered, (2) to extend its range of application from specific phases of construction, to applications upstream in design and downstream in commissioning, and (3) to change the whole company based on takt production principles, rather than consider individual projects only. A lot can be learned from

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these practices and their characteristics, and lessons learned can be compiled into levels of maturity.

In this paper we build on the maturity-level model for takt production introduced by Lehtovaara et al. (2020). The original maturity model can be found in Table 2 at the end of this paper for reference (black text is original, modifications are in green). This model was developed based on 24 Finnish takt production cases. It includes 15 requirements structured at three levels into (1) technical takt planning, (2) social integration & takt control, and (3) continuous improvement levels. According to the model, companies can start takt production implementation using existing contractual structures, but higher levels of maturity require wider engagement of stakeholders in the supply chain (SC) and learning between projects. As the model was created after just a few years of experience in the Finnish market, further validation and development is needed.

To hear how leading AEC practitioners are deploying takt production, P2SL, Vison, Aalto University, and RIL (Finnish Association of Civil Engineers) have been organizing online forums for practitioners around the world to share their knowledge about takt production. Three such forums have taken place to date, a 1.5-day forum on 18-19 August 2022, and two 0.5-day forums respectively on 9 November 2022 and 23 May 2023. The presentations and discussions at the forums give reason to revisit the takt maturity model.

This paper presents insights the forum organizers gained as they relate to the maturity model. Suggestions for updates to the maturity model are extracted through revisiting the recorded presentations and discussions. Validation of the maturity model with the international case examples is also discussed.

METHOD DESCRIPTION

Three takt forums were held with sessions addressing 8 themes, including 23 15–20-minute presentations and an additional 5-minute Q&A. For each theme, the organizers gave a 5–10-minute introduction and led a 10–25-minute discussion and Q&A. Small group discussions for each theme took place in breakout rooms, but these were not recorded and are therefore not part of the analyzed data. The breakout room discussions informed the theme discussions that were recorded. During the presentations and break-out rooms, Menti.com (an online interaction platform) was used for gathering questions and comments from participants, which facilitated the discussion. Menti was also used to survey participants about their familiarity with takt production and the Last Planner® System (Ballard & Tommelein, 2021). Table 1 presents the forums, sessions and presentations. The second, third and fifth author were organizers of all of the forums, and the fourth author was an organizer in the first one only. The selection of session topics and presenters was a result of discussions amongst the organizers while they were planning the forums. The aim was to invite the most mature state-of-practice companies to present their experiences.

A qualitative thematic analysis was carried out to synthesize the data. All authors were familiar with the data from the three live forums they participated in. As a first pass, the first author skimmed through the recordings to extract tentative topics (e.g., supply chain management (SCM)) for analysis. After identifying these tentative topics, the first author rewatched all the recordings and noted in a table the points of discussion that relate to the topics. The tentative topics and the most prevalent notes related to them were then discussed among all the authors, which resulted in three categories, presented in the following section. All authors then discussed the key findings and topic-related suggestions. The resulting topics were discussed and connected to the maturity model requirements in Table 2 of (Lehtovaara et al., 2020). Some discussion points noted in relation to the topics do not, however, correspond directly to maturity-level requirements. These connections and differences are discussed in the findings.

Table 1: Takt forum sessions and presentations

Session	Presentation
Forum 1, day 1: 2022-08-18	
1. Strategic takt planning and using takt in design	1. Aleksi Heinonen (Vison Oy, [F])
	2. Adam Frandson (DPR [US])
	3. Cory Hackler (DPR [US])
2. Takt plan development and supply chain management	1. Van Kristensen (Turner [US])
	2. Marco Binninger (Weisenburger bau [G])
Forum 1, day 2: 2022-08-19	
3. Takt control including daily takt plan management and change management	1. Jukka Rannisto (Haahtela [F])
	2. Samir Emdanat (vPlanner [US])
4. Future of takt production in construction	1. Olli Seppänen (Aalto University [F])
	2. Iris Tommelein (UC Berkeley [US])
	3. Kim Lindholm (HOAS [F])
	4. Digby Christian (Sutter Health [US])
Forum 2: 2022-11-09	
1. Cultural change with takt production	1. Takt production in Skanska Nordics – We are better together (Pekka Kujansuu and Magnus Vissebråten, Skanska Norway/Finland [F], [N])
	2. Takt as a production system: Business portfolio flow and situational awareness (Kasperi Koivu, Fira [F])
	3. Takt method in everyday life of the SME company – journey to get there (Mikko Hirvonen, Respect Project [F])
2. Client involvement in project delivery with takt	1. Delivery of a megaproject with 1-day takt: Helsinki airport terminal 2 (Jasmiina Hietala, SRV [F])
	2. Why a superintendent uses takt even when the owner does not ask for it (Dan Murphy, Turner [US])
	3. Industrial owner's strategy with takt (Janosch Dlouhy, BMW [G])
Forum 3: 2023-05-23	
1. Learning takt production from other industries: manufacturing, marine refurbishment and construction	1. Lean cruise ship cabin refurbishment (Jaakko Mäkikalli, Makinen [F])
	2. Plan for every part (Ari Viitanen, Carinafour [F])
	3. Concept of takt time in construction and other industries (Peter Meijnen, Denkyu Consulting [G])
2. Takt beyond phase planning in building construction	1. Application of takt production in underground linear infrastructure construction projects (Veronica Ksiazenicki, Stiler [U] and Carlos Formoso, UFRGS [B])
	2. Takt in design at the Life Science project / The journey of applying takt (Hans Thomas Holm Statsbygg [N])
	3. Takt – LPS connection (Spencer Easton, Mortenson [US])

Notation: Presenters reported on projects in the following countries: B: Brazil, F: Finland, G: Germany, N: Norway, U: Uruguay, US: United States.

FINDINGS

The authors grouped the findings in three categories to emphasize what was deemed novel and controversial, and to de-emphasize repetition of points that have previously been discussed in takt production research. The goal was to suggest how the maturity model could be improved.

The three categories are (1) Strategic takt planning, which refers to an early holistic conceptual approach of applying takt production; (2) Supply chain management, which covers preconditions to be met before production (tasks) can happen on site, such as the design process, trade partners, procurement, prefabrication, and material flow, and (3) Driving change, which refers to using takt production to identify potential production system improvements (e.g., Tommelein & Emdanat 2022). These categories connect many detailed requirements together and can be seen as "change agents" towards successful takt production implementation.

In the following, the contents of the forums are discussed in light of the maturity model divided into these three categories. The data is referred to with the following notation: F: Forum, i: introduction to session, p: presentation, d: discussion and Q&A of the session, with the numbering of the forums, sessions and presentations as presented in Table 1.

CATEGORY 1: STRATEGIC TAKT PLANNING

Strategic takt planning is defined here as engaging in takt planning early in the project while taking a holistic view of the whole scope of production. Approaching takt production as a project's operations strategy has previously been introduced in Lehtovaara et al. (2021). A similar view of planning in levels of detail is also found in the three-level method of takt production (Dlouhy et al., 2016) and was introduced much earlier in the planning levels of the Last Planner® System (Ballard & Tommelein, 2021). The key idea about strategic takt planning is to enable early responsible commitments and create a concept that sets targets for future development of the plan. The early concept should be based on data such as historical knowledge of production rates. (F1.1.i), (F1.1.p1), (F1.1.p2)

An early concept, i.e., a generic idea of a takt plan where takt production principles are applied, enables choosing and integrating supply partners who are willing and able to deliver to the takt. This may affect the cost structure and business plan of the partners and is therefore important to know before signing a contract. The early takt concept can set requirements for the supply of design, labor, and materials before they are procured. It enables the potential partners to evaluate whether they can conform to the plan and speak up about their concerns. This is also a tool for gaining client involvement since the plan is built to their targets and crucial decision-making points can be identified early. Strategic takt planning can drive takt production on an organizational level. Integration of trade partners with an early concept is at the same time an opportunity for training. It is a way to build organizational competence for aligning everything that has to come together for a stream of projects to work, to get better across projects, and to enable sustainable profits for all companies involved. (F1.1.p2), (F1.1.d), (F1.2.p1), (F1.2.p2), (F1.4.p4), (F1.4.d), (F2.2.p3), (F2.2.d), (F3.1.p3)

Strategic takt planning is not mentioned in the maturity model although the requirements R1 (The production plan fits the client's requirements) and R2 (Takt areas, takt time and wagons with resourcing are unambiguously determined) on level i) (Technical takt planning, project-level) of the model can be interpreted to have a similar intent. The SC integration view is on level ii) (Social integration & takt control, project and organization level) with R5 (The logistics are integrated and takted with the production plan) and R6 (The design process is integrated and takted with the production plan) but there is no clear connection to the strategic planning level. The organizational level of continuous improvement is the intent of level iii) (Continuous improvement, organizational and regional level) but, again, the maturity model lacks explicit reference to the strategic planning level.

The early takt concept should show how the flows of work in different phases of construction are connected to create an overall flow. The aim is to meet the client's demand even at the expense of loss of capacity in the short term in some parts of the system. Different phases may have different kinds of variabilities and challenges. For example, they may have different location breakdowns, different buffering strategies and different batch sizes, i.e., takt time and takt area combinations. Unique areas of the project that do not fit well into the production system of other phases should be identified and pulled to the overall flow of the project. Possible workable backlog areas should be identified as they can be leveraged to make up for low density work in other areas. The phase breakdown can also be used to divide management responsibilities. The early overall takt plan should give an anchoring point to the project. As the project advances towards the execution phase, the strategic takt concept is developed into a takt plan where the details are filled in to meet the targets. (F1.1.p1), (F1.1.p2), (F1.1.p3), (F1.1.d), (F1.2.p1), (F1.3.d), (F2.1.p2), (F2.2.p2), (F2.2.d), (F3.1.p3)

Breaking up the project into phases and connecting them to an overall project flow is not explicit in the maturity model. Requirements R1, R2 and R3 (Effective visual management is ensured) on level i) include this intent but it is not clearly visible.

Historical knowledge of past projects should be gathered and used when shaping the early strategic takt plan. Reusable production steps and work packages (i.e., standardized operating procedures for construction) are created and developed on the execution level, but knowledge of indicators that describe them can be used for setting goals on the strategic level. These may also vary depending on the geographical area and on the trade partners to be considered, so understanding the variabilities involved would be useful. The historical data could be used to set up a production strategy in new projects early and to guide improvement activities. The mathematics of takt production on a strategic level can be simple but the ability to handle the complexity that comes with integrating the SC and the large amount of data requires digital tools. (F.1.1.d), (F1.1.p1), (F1.1.p2), (F.1.1.d), (F1.2.p2), (F1.3.d), (F1.4.p1), (F1.4.p2), (F1.4.d), (F2.1.p3), (F2.2.p1), (F2.2.p3)

Leveraging data is mentioned in R14 (Standardized, takt-based work quantity libraries) and R15 (Improving through KPI's and data-driven decision making) but the use of data to create an early strategic takt concept and to manage the complexity is not clearly visible.

Suggestions for augmenting the maturity model:

- S1: Level i) should be modified to consider only one phase and to the second level a requirement should be added that most or all project phases are considered.
- S2: To level ii) of the maturity model, a requirement should be added for the ability to form a takted production strategy before supply-partner contracts are signed.
- S3: On level iii), requirements R14 and R15 should be modified to include the ability to leverage historical knowledge of production rates and other indicators.

CATEGORY 2: SUPPLY CHAIN MANAGEMENT

A takt production environment creates a clear and stable demand for products and services to be supplied as needed for production. It enables delivery of smaller batches following the just-in-time principle. Proper SCM requires attention at the early strategic planning level and is crucial at the project execution level. (F1.2.p1), (F3.1.p1), (F3.2.p3)

Delivery strategies for different types of material flows must be planned strategically. Strategic takt planning changes the conversation in the SC from describing general needs to defining more understandable chunks. It also enables standardizing the SC processes to a takt plan and helps in mapping out the whole SC. Creating an overall vision of the flow of the project depicted in a strategic takt plan is important because the complexity of SCM can grow very quickly. (F1.2.p1), (F1.2.d), (F2.1.p2), (F1.3.p2), (F2.2.p1), (F3.2.d)

SC integration is mentioned in the maturity model in R5 and R6 on level ii) and in R13 (Industrialized logistics and material flow) on level iii). They do not clearly show how SCM should be considered early in a project on the strategic level.

Design development is better done by setting milestones and defining points of design deliverables based on the takt plan instead of managing design activities directly. Defining the milestones and deliverables should start with defining the functionality of the building; the design deliverables can then be packaged to supply the project by pulling to the takt plan. This also enables the decentralization of the design process to create flexibility for the design teams. The milestones and deliverables should match defined design-value steps that follow a model of design maturity for defined purposes in a takt plan. At each point of design development, the designers need to understand what is fit for purpose (aka. 'good enough') for the next customer in the SC to use their deliverables. Standardizing design and taking full advantage of Design for Manufacturing and Assembly (DFMA), prefabrication, and industrial construction must also be done at the early strategic level, with continuous improvement across projects.

Planning design to a takt in smaller batches is a problem, because designers are not used to thinking about the design process in such a way. The execution-phase design work (aka. construction documents) should be attuned to the takt plan and be made responsive to any issues encountered on site, especially in a project where information required for the final design is discovered only during construction. This is why designers should also understand the principles of takt production. (F3.2.p2) (F2.2.d), (F3.2.p2) (F2.1.p2) (F3.2.p2), (F3.2.d)

Design process integration and its connection to the takt plan is included in the maturity model in R6 on level ii). The connection to strategic takt planning is however not clear. The execution level of design process management covers many smaller steps that are not detailed in the maturity model.

At the execution level material delivery strategies such as designated logistical routes, the use of off-site buffers for just-in-time deliveries of large materials and on-site buffers (supermarkets) for smaller materials must be planned in connection with the takt plan. To make the just-in-time deliveries in small batches to suit the takt plan, logistics operations and material flow should be separated from trade work. Although the takt plan defines the logistical process, logistics can be used to control production by delivering the materials to be installed to work areas according to the takt plan. Smaller material and WIP buffers require better management of prerequisites, but they also enable better management by bringing clarity to the delivery needs. Any data that accumulates in a digital material handling system offers a way to learn about production flow. (F1.3.p1), (F2.2.d), (F3.1.p1) (F3.1.p3) (F1.3.d), (F2.2.p1), (F2.2.d) (F3.1.p2)

The requirements R5, R6 and R13 cover the intent of these viewpoints. However, the use of logistics for controlling production and leveraging data in material management systems are not described in the maturity model.

Execution-level design and material planning are a crucial part of a takted production system although they are not directly a part of the production system on site. The design must be developed to serve detailed material planning to meet the planned needs. Just-in-time material deliveries to the takt plan in small batches require detailed bills of materials, especially when striving for greater production speed. The bills of quantities used for cost estimation and workload calculations are not detailed enough for industrialized material flow management. In addition to providing the design documents for the trades following the takt plan, the design process could be connected to the takt plan to deliver the bills of materials as required by the material procurement lead times. (F.1.1.d), (F1.3.p1), (F1.3.d), (F2.1.p1), (F2.2.p1), (F3.1.p1), (F3.1.p2), (F3.1.d), (F3.2.p1), (F3.2.p2), (F3.2.p3) The maturity model does not consider the dependence of material flow management on design maturity.

Client decision making is also considered here as a part of the SC. Takt production speeds up construction, which sets new requirements for the client's ability to make timely decisions. Client decision-making delays have been brought up as a cause for delays and they may also amplify the risks of trade partners who have resources committed on site. However, a takt plan is also a tool for guiding the decision-making process by bringing clarity to the required decision-making points at the last responsible moments. Decisions to be made need not follow the takt plan directly but understanding the decision-making time is important for alignment to site requirements. (F1.2.p2), (F1.2.d), (F1.4.p4), (F2.1.p3), (F2.2.p3), (F3.1.d), (F3.2.p1), (F3.2.d) The client decision-making process is not considered in the maturity model.

SCM is referred to in the maturity model in the requirements R5, R6 and R13 but the emphasis on the subject in the takt forums gives reason to highlight its importance even more. The points of view of design and material flow warrant maturity models of their own or could be detailed with sub-requirements to the existing requirements.

Suggestions for augmenting the maturity model:

- S4: The project production strategy view to SCM should be considered in the maturity model with a new requirement on level ii). This can be combined with the earlier suggestion S2.
- S5: Description of R6 should be updated to consider maturity of design to milestones set by the takt plan and to require understanding of takt principles from designers.
- S6: To level iii), a requirement should be added for the ability to standardize and continuously improve the design process and design handoffs to improve efficiency through Design for Manufacturing and Assembly (DFMA) and prefabrication.
- S7: Description of R5 should be augmented with detail of different types of material flows. Description of R13 should be updated with the use of logistics and material deliveries to control production, and the use of material handling system data for improvement.
- S8: To level ii), a requirement should be added for the ability to manage client decision making. Description of R11 should be augmented with requirements for the client.

CATEGORY 3: DRIVING CHANGE

Takt production can be a gateway to lean. Its implementation requires structuring everything in the production system, standardizing processes, and developing tools and methods to overcome problems. Takt production requires many other lean principles to be in place to work well. The journey advances in stages, first the project level, second the production system across projects, and third the corporate view, culture, and leadership. (F1.2.p2) (F2.1.p1), (F2.1.d)

While takt planning can be a gateway to lean, for many project teams especially in the US, the segue into lean came with implementation of the LPS (Ballard & Tommelein, 2021). In the LPS, takt production (called operational takt planning) was first seen as a work structuring and production method applied on the phase planning level. Work structuring is the process of breaking work into pieces to promote flow and throughput, and production strategy includes an optimization process of planning the project in interconnected but separate phases. The case study by Tommelein and Pak (2019, Figure 6) then pointed to the strategic importance of trade partner- and SC alignment to takt planning on the master schedule level (called strategic takt planning). The route to takt production via LPS is however not mentioned in the maturity model.

Previous publications also suggest that takt production can drive change (Peltokorpi et al., 2021), (Tommelein & Emdanat, 2022). The maturity model itself is built to drive change by showing takt implementation as a journey. Adding a fourth layer to the maturity model aimed at driving cultural change was conceptually suggested in (Peltokorpi et al., 2022), although it was not discussed in detail.

The maturity model implies that takt production starts with technical takt planning on site on the project level. After getting good initial results, developing social integration of the SC and takt control begin on the organizational level. Going forward with the requirements should increase benefits until the third organizational and regional level of continuous improvement is achieved.

The maturity model was based on and validated with only with Finnish cases. Of the forum presentations, the cases (F1.3.p3) (Finnish), (F1.2.p2) (German), (F2.1.p1) (Norwegian), (F2.1.p3) (Finnish) and (F2.2.p1) (Finnish) seemed to have followed a journey similar to what the maturity model suggests. But cases (F1.1.p3) (US), (F1.2.p1) (US), (F2.1.p1) (Norwegian), (F2.2.p2) (US), (F3.2.p1) (Uruguay) and (F3.2.p3) (US) referred to LPS as a starting point to their takt journey. The Norwegian case (F2.1.p1) cited both LPS and the maturity model in their presentation. However, in all these cases, the general structure of the maturity model still seems to have been followed. This suggests that the maturity model has some international validity.

Presentations (F1.2.p4) (US), (F2.2.p3) (German), (F3.1.p1) (Finnish, cabin refurbishment instead of construction) and (F3.2.p2) (Norwegian, design process management in construction by the owner) suggest that owner demand can also function as the driver for starting a takt implementation journey. The reasons for owner demand are manifold. (F1.4.p4) and (F3.2.p2) addressed the owner's desire for clarity of milestones in a takt plan, (F1.4.p3) and (F3.1.p1) aimed for speed of production, and (F2.2.p3) pursued increased stability and flexibility in addition to speed. Owner demand as a driver was also discussed in (F2.2.i), (F2.2.p1) and (F3.2.d). One case (F1.1.p3) (US) mentioned, in addition to referring to takt production as a part of their LPS journey, an organizational lean leadership training program as a starting point. One case (F3.1.p2) (Finnish, ship building) focused on a "plan for every part" philosophy, where managing the material flow is regarded as the first step. These examples suggest that the maturity model outlines but one progression for companies to implement takt production.

Shifting people's mindsets is an important and difficult step in implementing takt production. Thinking in smaller batches, especially in the design process, is not something that people are used to and the takt principles may seem counterintuitive and constraining for people who are used to traditional production management methods. Gaining alignment with the people involved in a project can be a bigger problem to solve than creating technically sound plans. To overcome this barrier people should be prepared before they embark on takt planning. Preparation would include lean leadership training, teaching the terminology and definitions of takt production, simulation games, and showing the mathematics of takt production. On a hopeful note, it was mentioned that by bringing clarity, takt production can help with making the construction industry a less toxic environment for people to work in, which should make it more attractive to new talent. (F.1.1.d) (F1.1.p2) (F1.1.p3) (F1.2.p1) (F1.2.d), (F1.4.p4) (F1.4.d) (F2.2.p1), (F2.2.p3) (F2.2.d) (F3.2.p2) (F3.2.d)

The required mindset shift is implicit in the model in R4 (Training and involvement of the project participants is ensured) on level ii) and in R10 (Formulation and development of teams) on level iii). The need for learning new and unlearning old habits is not, however, emphasized.

Integrating the SC implies developing partnerships. Supply partners all the way to the worker level should see the benefit of takt production so that they want to come back to takt projects. The value on sites is created by companies, many of which may be small and medium-sized, so to change the industry, they must be involved in developing the production system. Organizations on higher levels of maturity should provide support for the newcomers through training and building partnerships. Lean enabled by takt production can provide structure for managing different levels of hierarchy in the organization, including sharing knowledge and sustainable problem-solving at the right levels. Building a more holistic production system with takt principles should not lead to more centralized management but better onboarding, more involvement, and more transparent risk management. Building partnerships around takt production may lead the market to segregate groups of companies willing to adopt takt principles from those who are phased out because of lack of interest. Takt production will start to dissolve trade boundaries so that the overall system can be balanced better. (F1.1.p2), (F.1.1.d), (F1.2.p1), (F1.2.p2), (F1.2.d), (F1.3.p1), (F1.4.p3), (F1.4.p4), (F2.1.p1), (F2.1.p3) (F2.2.p1), (F2.2.p3), (F2.2.d), (F3.1.p1)

Partnership building is not explicit in the maturity model, although R4, R5, R6 and R8 (Barriers are tackled through continuous and collaborative improvement) on level ii) and R10 and R11 (Contractual integration) on level iii) can be interpreted to have the same intent.

Technology is seen as a part of the takt journey. Software tools are required to handle the information flows and data that comes along with detailed planning, smaller batches, and the upstream SC processes. Digital data handling leaves a footprint that can be structured around the takt production system and leveraged for improvement. Sensors, automated monitoring, and visualization tools built around the takt production system can improve situational awareness, inform workers of site conditions such as humidity and temperature, and support data gathering for improvement metrics and control (including replanning). Prefabrication and robotics may change the way work is done, and sites planned with takt can help to reveal the best opportunities to serve the overall system. (F1.1.p2), (F1.2.p2), (F1.3.p2), (F1.3.d), (F1.4.p1), (F1.4.p2), (F1.4.d), (F2.1.p2), (F2.1.p3), (F2.2.p1), (F2.2.p3)

Technological competence is not considered in the maturity model. Including a requirement for adoption of technology in the maturity model was discussed among the authors. It is however left for future research because the practical case presentations in the takt forums did not show sufficiently detailed examples to make relevant suggestions.

Suggestions for augmenting the maturity model:

S9: To the description of the maturity model should be added that there can be starting points for takt production other than an urge from the site, projects where the Last Planner® System is used, and client demand.

S10: A more explicit requirement for development of people should be included by modifying the description of R4 to include general lean leadership training, changing of habits, the use of simulation games, and the mathematics of takt planning to shift mindsets.

S11: A requirement for building partnerships between companies should be added by modifying R10 to include the formulation of partnerships in addition to teams, and by emphasizing in its description that this should happen across companies. R10 should also say that more mature organizations should help build the capabilities of the runners-up.

DISCUSSION

The maturity model updated with the suggestions is presented in Table 2. In the model's description, it should be added that takt production implementation can have several starting points such as (1) urge from construction sites (2) as a part of LPS, and (3) client demand. The description modifications of requirements denoted with an asterisk (*) are not included but the authors intend to publish an updated model with this detail in the future.

In the process of writing this paper, a discussion came up regarding the importance of legal and commercial terms between the owner, trade partners, and labor, to drive change in the behavior of companies and people implementing their takt production journey. This was touched upon in (F1.4.p3), (F1.4.p4) and (F2.1.p3) but warrants further study with more data.

All requirements of the model except R7 (The common situational awareness during production is ensured), R8, R9 (Quality control is systematic and takted) and R12 (Systematic waste elimination over projects) are impacted by the suggestions. However, the intent of R7 might be impacted by new requirements addressing technology adoption. R8 and R12 relate to building partnerships and R9, that quality tends to improve in takt production, was touched upon in (F1.4.p3) and (F2.1.p3). Updates of these requirements also deserve further study.

Based on the takt forums, the maturity model seems valid for the most part, but note that companies that presented in these forums would not necessarily gain from meeting the requirements of the model exactly in the order presented, level-by-level. Every company is on its own journey; nevertheless, this raises the question whether some requirements should be characterized differently or reassigned to different levels. This also warrants further study.

Finally, we propose two additional avenues for future research. First is to expand the model to include relevant metrics to assess the organizations' advancement through levels and requirements; and second is to explore longitudinally how implementing the model impacts an organizations' effectiveness in advancing takt production and its related benefits.

Table 2: The updated maturity model (changes in green, (*) denotes description update)

Level i)	**TECHNICAL TAKT PLANNING IN ONE PROJECT PHASE (project-level)**
R1	The production plan fits the client's requirements
R2	Takt areas, takt time and wagons with resourcing are unambiguously determined
R3	Effective visual management is ensured
Level ii)	**SOCIAL INTEGRATION & TAKT CONTROL (project and organizational level)**
NR1	All or most of the phases of the project are takted and connected
NR2	The strategic takt concept is formed before the selection of supply chain partners
R4*	Training and involvement of the project participants is ensured
R5*	The logistics are integrated and takted with the production plan
R6*	The design process is integrated and takted with the production plan
R7	The common situational awareness during production is ensured
R8	Barriers are tackled through continuous and collaborative improvement
R9	Quality control is systematic and takted
NR3	The client decision-making process is systematic and takted
Level iii)	**CONTINUOUS IMPROVEMENT (organizational and regional level)**
R10*	Formulation and development of teams and partnerships
R11*	Contractual integration
R12	Systematic waste elimination over projects
NR4	The design process and design handoffs are standardized to meet Design for Manufacturing and Assembly (DFMA) and prefabrication requirements
R13*	Industrialized logistics and material flow
R14*	Standardized, takt-based work quantity libraries
R15*	Improving through KPI's and data-driven decision making

CONCLUSIONS

In this study, we revisited the takt production maturity model formulated in 2020. This was done by analyzing recordings of three online takt forums held in 2022 and 2023. These forums provided insights into the most recent industry advancements of takt production implementation, thus providing grounds for validating and updating the model.

When revisiting the model against the forums' insights, even though the models' initial levels and requirements reflected the industry's experiences quite well, we found several interesting areas where the model could be updated to reflect the current state of practice. Through three formulated categories (strategic takt planning, supply chain management, and driving change) 11 suggestions (numbered in the findings section) were presented to update the maturity model. Following these suggestions an updated version of the maturity model table was presented.

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IMPLEMENTING DIGITAL VISUAL MANAGEMENT: A CASE STUDY ON CHALLENGES AND BARRIERS

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ABSTRACT

The construction industry (CI) has an increasing interest in achieving better situational awareness (SA) in complex projects, by focusing on sharing real-time information among project participants, allowing decision-making based on the project development's up-to-date situation and status. The implementation of digital visual management (DVM) tools as means of communication to increase SA in CI projects has the potential to simplify information dissemination. This paper identifies the challenges and barriers faced during the implementation of a DVM tool. The authors interviewed nine project management professionals who were part of the client organization in a complex infrastructure project of the western part of the Metro in Helsinki and Espoo, Finland. The findings show that the lack of digital tools for collecting and analyzing project data, the focus of the DVM on the top management, and the lack of trust among the actors involved in the project undermine the success of DVM implementation. Thus, digitalizing data collection, increasing trust among project participants, and disseminating information are crucial for successful DVM implementation.

KEYWORDS

Visual management, digital visual management, situational awareness, construction reporting

INTRODUCTION

The complexity of construction projects requires information sharing to increase and spread situational awareness (SA) among project participants. An important component of lean philosophy is the visualization of the flow of production activities, which also allows waste identification and elimination (Koskela, 1992). Shared SA in complex projects in the construction industry (CI) results in a better understanding of the task flow and an easier identification of problems, combined with a more efficient decision-making process. In recent years, the academic community and practitioners have increased their interest in studies and applications of SA models and systems in the CI (Lappalainen et al., 2021). Such interest stems

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from the fact that the information bottlenecks, as well as the costs and time involved in collecting, updating, and sharing data, are also symptoms of the lack of SA in construction projects (Akinci, 2014).

During military operations, SA began to be defined as the perception of environmental elements in time and space, comprehension of their meanings, and projection of outcomes in the near future (Endsley, 1995). In the CI, SA was initially related to safety management (Gheisari et al., 2010), but the term has also been applied to the construction phase of projects, with different areas of focus, such as the role of building information modeling (BIM) in SA (Li et al., 2018), location-based construction planning and controlling (Dror et al., 2019; Reinbold et al., 2019; Görsch et al., 2020), and construction logistics management (Seppänen & Peltokorpi, 2016; Tetik et al., 2020).

To increase SA, visual communication, and visual management (VM) have been successfully implemented and documented in distinct phases of construction projects (Tezel, 2011; Pedó et al., 2022). As part of the Toyota Production System, VM focuses on the visual representation of information that can be retrieved at a glance during the execution of tasks and is often connected to Lean Management (Koskela, 1992; Galsworth, 1997; Liker, 1997; Formoso et al., 2002).

Controlling the status of complex projects is an essential element to create and distribute SA. Usually, projects rely on the use of key performance indicators (KPI's) to share the current situation among project participants. Performance indicators are compilations of information applied to measure and assess performance (Edwards and Thomas, 2005). The indicators used can be leading or lagging. Lagging indicators represent realised outcomes of a process. Leading indicators represent likelihood of a particular outcome (Moore, 1983).

The use of performance dashboards to display and share KPI's had been continuously applied during complex projects, creating an important link between the project controlling activities and the use of VM in the distribution of shared SA. Through a dashboard, staff members can stay in touch with the strategic direction of the company and present their contribution to it (Shermach, 2005). Effective dashboards provide important data that can be rapidly read and understood (Few, 2006; Middleton 2005).

Other promising tools capable of increasing SA in construction projects are related to digitalization and information technology (Olivieri et al., 2017; Dror et al., 2019; Pica & Abanda, 2019). These tools allow system-to-system, human-to-system, and system-to-human communication, enabling more effective data collection and sharing with the right person at the right time (Dave et al., 2015). These tools have different areas of focus and applications, including 3D laser scanning, location-based information from construction crews, and display and management information systems.

Naturally, with the progress of research and application of VM and digital tools in the CI, the possible connection between both approaches has also raised interest among scholars and practitioners, opening the field to digital visual management (DVM) concepts and tools. Previous research has found that to select the right mobile computing strategy for managing information in construction sites, it is necessary to clarify the information management process, create an overview for mobile computing, and choose the appropriate technology (Chen & Kamara, 2008). A set of VM requirements applicable to digital support and control during the design phase has also been examined (Pedó et al., 2022). Nevertheless, the investigation into the challenges of and barriers to DVM adoption in CI projects continues to be limited (Reinbold et al., 2022).

Current developments show DVM's potential to both provide information in a visual manner and allow more effective data collection and display in the CI's complex projects. However, so far, mostly the benefits of DVM have been discussed. Because these systems are not yet widely used, there is a need for more knowledge about the challenges and barriers related to implementing such systems.

This paper aims to identify the challenges of and barriers to the adoption of such tools and to understand the current stage of DVM adoption in the CI. This investigation is conducted in the context of a case study that explores the adoption of DVM during the reporting of a complex infrastructure project in Helsinki and Espoo, Finland. To identify the challenges of and barriers to DVM implementation, the researchers analyzed the visual reports produced by seven different contractors and interviewed nine project management professionals involved in the project.

METHODS

The chosen research method was a case study of a Finnish subway construction project encompassing seven separate sites. Case study involved a public project company building a subway project. The case was selected because the project had experienced considerable difficulties in managing the project status information in the previous stages of the construction. Disruption and recovery are often research opportunities worth documenting and analyzing since the findings often reveal insights into general processes (Yin, 2018). The project management team, which had progressed to its second phase, had been involved in developing a system to combine the collected data into a central dashboard and use it to manage the whole project.

In the prevailing literature, increasing the availability of visual information is a significant contributory factor for operations in complex and dynamic systems (Beynon-Davies & Lederman, 2017; Koskela et al., 2018). According to Beynon-Davies and Lederman (2017), VM systems are associated with concrete artifacts designed for informational purposes, the possibility to manipulate them for information and choice, and the location of the function in a physical space. The selected case addresses all these essential elements of VM, with the addition of digitalization.

A physical control room had touchscreens displaying the main Key Performance Indicators (KPIs) of the project, updated at 1–2-week intervals, depending on the data source. The data were collected mainly by the project management contractors working on site and a separate five-member status team, mostly using spreadsheets and web-based data, with no software integration or automation of data collection or use of sensors. A team ensured the quality, availability, and analysis of the data for the biweekly management sessions. During the sessions, the project management team assessed the situation and made decisions accordingly. The DVM system focused on the schedule, cost forecasting, and health and safety level of the project. At the time of this study, the system was used to manage the status of the final documentation and testing. The project had an 8-year duration and a budget of M€ 1,200.

The case study's location in Finland allowed the researchers access to the research data and enabled them to conduct face-to-face semi-structured interviews with DVM users. The preferred method of interviewing in this study was face-to-face, which the researchers considered a more effective way of observing body language and facial expressions than digital interviewing (Irvine et al., 2013). These observations were made during the interviews to the extent practicable. One of the factors that influenced this was whether or not the interview occurred in a room with VM tool/system access. Observations were documented during the interview. The informants were also interviewed in their familiar work environments. All interviews were conducted in Finnish by two researchers, one interviewing and the other observing and taking notes. Interviewees were asked to describe the DVM they use, including its functions, applicability, and the information it provides. They were also asked to describe the connections between the DVM and different aspects of the project, such as design, procurement, and logistics, and to identify any functionality that was automated. Interviewees were also asked to describe recent cases where they or someone else had used DVM in a user role. Table 1 provides background information of the interviewees.

Table 1. Informant description.

NO.	ROLE	EMPLOYER	INTERVIEW DURATION (MINUTES)
1	Project director	Consulting company	107
2	Construction director	Owner	107
3	Site manager	Owner	76
4	Project engineer	Consulting company	77
5	Project engineer	Consulting company	82
6	Project engineer	Consulting company	74
7	Scheduling manager	Consulting company	78
8	Financial director	Owner	62
9	Project manager	Consulting company	50

The durations of the responses reflect the fact that the research project included also other questions and themes than DVM. The durations of the interviews include all themes, not just the time spent by the respondent on the DVM theme.

The research data thus consisted of visual reports generated by the digital system and the interviews. The approach used in this study aims to gain an in-depth understanding of the use of DVM in project management (Fellows & Liu, 2021). Data triangulation was employed, utilizing both interviews and observations during the interview as sources of data. The crucial aspect in this case was to have two interviewers, allowing one to concentrate on doing the interview while the other focused on observing. Before the interviews, a methodology for observation was created, consisting of two sections: descriptive observation and reflective observation. The observations were documented in interview notes, which consisted of handwritten records that contained both the notes taken during the interview and the observations made. To effectively triangulate, careful analyze of any inconsistencies or similarities between the statements by the interviewees and the observations were made by the researchers.

DVM REPORT

Considering the complexity of the project and the communication channels among the seven contractors and the project owner the involved understood the need for standardizing the reporting of construction site key performance indicators (KPI's) as a tool to improve and increase the stakeholders SA sharing.

The chosen type of report was a dashboard and the efforts resulted in a standard reporting system that followed up seven lagging KPI's:1) the percentage of work planned, 2) the percentage of the work completed, 3) the deviation between planned and executed work in percentage, 4) planned costs in million euros (M€), 5) executed costs (M€), 6) health and safety in percentage, and 7) collaboration work in percentage. Concerns were raised about ensuring the report's comprehensibility and accessibility to all stakeholders. Consequently, elements that enhance visualization and colour codes were implemented.

The report adopted is represented in Figure 1. If there were no delays, the schedule report had a green circle. If the work was delayed, the circle was red. A Finnish method was used to measure occupational health and safety. The measure is based on the share of successful health and safety observations of total observations. For this health and safety KPI (Key performance indicators) green colour was used for indicator values above 95%, otherwise the KPI was red. Collaboration was measured via a questionnaire responded by those involved in the project, and the KPI measured the share of positive answers. For the collaboration KPI, the circle would be represented in green colour for indicator values above 80%, otherwise the circle would be represented in red colour. Other KPI's related to quantity of work executed and quantities were also followed. The report adopted is represented in Figure 1.

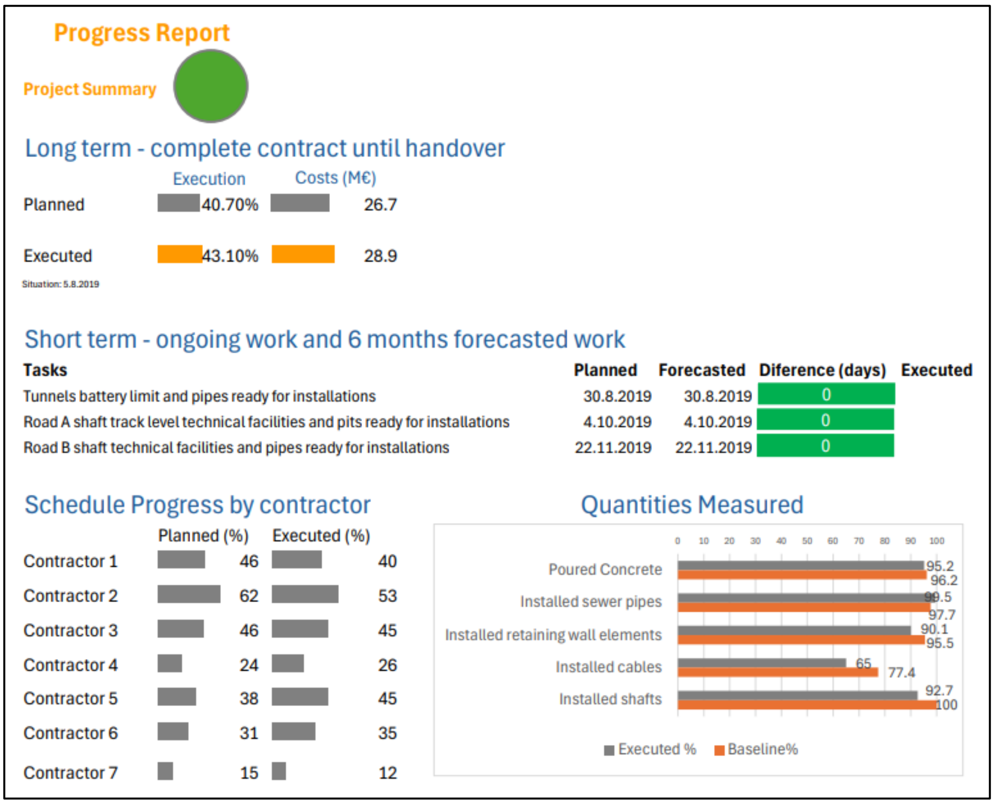

Figure 1: Visual Report of KPI's adopted during the project (source: adapted and translated from Finnish to English by the authors)

Having in mind the shared SA, the reports were displayed digitally in a "War Room", a management room for the project, that was accessible to the stakeholders. A picture of the digital displaying of the reports is seen in Figure 2.

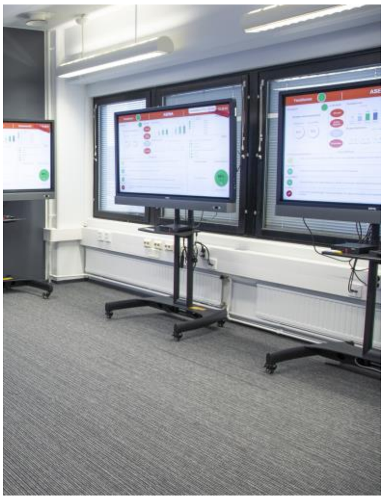

Figure 2: Digital display of visual report (Original photo: Timo Kauppila, NDAV)

BARRIERS AND CHALLENGES OF DVM IMPLEMENTATION

The interviews were transcribed, and the quotes were open-coded and categorized using Atlas.ti software. The authors then selected the quotations that mentioned reporting, automation of data collection, and collaboration. From this first handling of the quotations, 73 were subcategorized.

The authors created the following subcategories: 1) information and communication technology (ICT) and tools, 2) process and 3) people and culture. The following sections provide descriptions and examples of the categories with quotations from the interview transcripts and categorization. Some of the quotations were assigned to more than one subcategory. For example, the quotations that mentioned data collection and lack of trust in the reported data were categorized as *both* ICT and tools *and* people and culture because they pointed to the lack of digitalization in the data collection and analysis and emphasized that the data reported and collected were not always trustworthy.

Lack of ICT tools leading to manual workload

All quotations that mentioned tools for data collection and analysis, adoption of new tools and systems, information systems, information silos, and interoperability issues were classified under the ICT and tools subcategory. In total, 50 quotations were linked to this subcategory.

Several interviewees expressed their concern that the lack of a standard and unified tool for reporting increased the workload for this function, as illustrated in this quote:

“Well, yeah, there are, there are clearly flaws in the thinking, that no one had thought through to the end, all those reporting templates…”.

The adoption of a standardized DVM report required training of the project members involved in the reporting phase, their work tools and processes adaptation and adjustments in the reporting process. These points created resistance to the adoption of DVM reporting. The change process was not considered a smooth transition but a contractual obligation.

Two other significant barriers to the adoption of the DVM report were manual data collection and analysis. Different systems are used to follow up on the various aspects of the construction progress. An interviewee mentioned the use of five different data collection and reporting systems, one each for financial reports, schedule monitoring, health and safety data and reporting, and tracking the quantities completed on the construction site. To consolidate all the information into the DVM report, the data were extracted manually from different systems, which required time and was considered inaccurate by the interviewees.

It was clear that the systems used were not interoperable and the extraction and exchange of information had to be processed manually, which is an important challenge to be addressed when digitalizing reporting and implementing DVM approaches in construction projects.

“From what you’ve heard, the situation picture is quite manual, and its updating has evolved a lot during the time I was involved. Initially, I was involved in maintenance, and then quite quickly, also in development, both technical solutions and things like, well, I don’t know, maybe not so much in processes, but if you think about quantity tracking and KPI tracking, in their deployment, the contractors didn’t have information about what it practically means and how it works”.

Inconsistent process of collecting and publishing data

This subcategory includes mentions of necessary changes in both the data collection and reporting processes. Reporting process issues such as the contractors’ neglect and delay in publishing information and the increased workload in processing the reports are covered as well. With the implementation of the DVM reporting system that was new to the project participants, the processes for creating reports and collecting data were not well defined, and their development occurred simultaneously with the implementation phase.

The processes for creating the DVM reports were only developed due to the contractual obligations to produce and update such reports, which generated negative feedback related to project reporting. Many of the interviewees stated that the DVM reports contained unnecessary information, the updating of the information was often inaccurate, the same status was repeated over the weeks, and the reporting was not prioritized.

"When facing a tight schedule, reporting is often the first thing to be neglected. People just try to get through each day, and reporting is seen as an extra task."

"They often feel like, 'Why do we have to create this report?' And if your response is, 'Because it's in our contract that you provide it,' it immediately becomes additional work for them."

This resistance to the implementation of DVM reporting was also often perceived by an underrating about the utility and importance of the report. Some of the interviewees involved in the DVM reporting perceived it as an extra task to repeat the same information that had been reported previously, but in a different way. This reflects the lack of standards in the CI, as well as how management and tools differ from one project to another.

As project organizations change from one project to another, the implementation of DVM tools and reporting is not a standard process, which poses a barrier to the consolidation of the adoption of such approaches.

Culture of mistrust and resistance

All mentions of resistance to the implementation of a new process, mistrust in the reporting partners, the belief that someone was hiding information, the lack of information sharing with others, and the change of behaviors toward the DVM after its implementation were classified under the *culture of mistrust and resistance* subcategory.

In the interviews, the mention of the resistance to the implementation of the DVM reports was identified for different reasons. The resistance to the adoption of a new process and a novel manner of reporting, which belongs to the *people and culture* subcategory, concerns matters that need to be addressed. The changes should be dealt with before the implementation phase, and the discussions must clearly state the importance of the DVM and its benefits to the project. The contractual obligation is not enough to ensure the success of the implementation and can even contribute to the resistance to it, resulting in an attitude of adoption only due to contractual enforcement.

The most common mention regarding people and culture is related to the lack of trust. The existing culture of mistrust in the CI was also identified in this project by the authors. Several interviewees brought up the issue that contractors concealed information or tried to do so while manipulating the shared data and information. This mistrust encompassed how data were collected and by whom; the interviewees stated that when the data were collected and analyzed manually, the reports often contained outdated information, or the published information did not reflect reality. It came to light that mistrust also originated from people's behavior, with the interviewees admitting that they had also hidden information in some situations.

The mistrust culture is a major barrier to be overcome during DVM implementation, as it undermines trust in both the information and the SA shared. It also raises doubts about the decision-making process since the parties involved might make decisions based on outdated and mistrusted information.

Counterbalancing the mentions of the barriers and challenges during the DVM implementation, several interviewees identified two positive aspects that can be classified (under the people and culture subcategory) as enablers of the implementation. The first one was that when the project stakeholders were committed to the DVM implementation, the positive feeling about such adoption increased, and it was more often recognized as successful.

"In my opinion, it's important that if you go through it together, you can get the contractor more easily committed to it. So, we agreed that we would go through it together and streamline it in a way. In my opinion, it's a good commitment model in that sense then."

The second positive aspect was that after implementation, the interviewees felt that the DVM report facilitated their work, information sharing, and understanding of the project, thus increasing the SA of the project participants.

"In that, I feel that there was a very good, very strong; if we didn't have such a system, we would have been completely lost there, where those specific sites [were] going. Perhaps, with the traditional model, we wouldn't have obtained so much [information]."

These two points emphasize that involving the stakeholders and assuring their commitment to the DVM implementation create an environment conducive to making the transition and overcoming the initial struggles. The DVM implementation also increases the trust and understanding of the project SA.

Table 2 summarizes this study's findings.

Table 2. Identified barriers and enablers to DVM adoption.

Category	Barriers	Enablers
ICT and Tools	- Lack of standards for information sharing; - Use of different systems for different data; - Lack of interoperability among systems.	-
Data Collection and publishing	- Increased work for manual data collection and analysis; - Publication of outdated data; - Lack of clear understanding of the report utility.	-
Culture and People	- Lack of trust among project members; - Mistrust on data collection methods; - Lack of commitment from the project actors towards the reporting; - A shared culture of hiding information; - Resistance to the adoption of new methods and tools at work.	- The commitment of project stakeholders to the DVM adoption increased the positive feeling about the process and it was more often considered successful; - After the initial struggle with the report implementation, participants felt that the DVM report facilitated information sharing, project understanding and increased their SA.

DISCUSSION

This study aims to bring clarity to the barriers and challenges encountered while implementing DVM in a complex infrastructure project. During their research, the authors realized that the data were collected and analyzed manually for the purpose of generating the DVM report. Although the creation and sharing of a standard report facilitated the understanding and dissemination of information using DVM, there was noticeable mistrust in the data quality and the data reported. This is not a new discovery; despite the modest progress made in the digital evolution of construction projects, there remains a lack of trust in digital workflows (Soman & Whyte, 2020).

The lack of interoperability among the systems, which emerged from the interviews in this case study, requires much more advanced digital infrastructure and interoperability (Shibeika & Harty, 2015). For example, the traditional monthly reporting schedule and compilation of the data in the DVM reporting system used in this study appear to constitute a process that lags behind the digital era. The lack of interoperability among the different systems used could be addressed through digital systems that have the ability to connect and exchange information with one another. However, specialization in the construction sector continues to be a trend in terms of both professional roles and systems, and the integration of different systems and skills cannot be avoided (Turk, 2020). Therefore, the critical comments of the interviewees in this study can also be assessed as opportunities rather than just threats.

In this study, the process of creating and standardizing reports with a DVM approach, involving seven different contractors, provides evidence that systems lacking interoperability considerably increase the time required for reporting. This issue creates barriers to the adoption of such an approach, resulting in the neglect of the reporting when the project activities are urgent. Another interesting finding is that with information scattered in different systems, the increased time for reporting also hinders the implementation of DVM approaches. The underlying reason is that the involved parties might analyze the situation as entailing additional work without financial compensation. This perception reflects DVM practices' limitations regarding their simplicity and presentation of excessive information, as well as the lack of prioritization of information (Pedó et al., 2022).

This study's findings corroborate previously noted challenges in the adoption of DVM during construction projects. The DVM report followed an analog logic, where the data were collected and handled manually, with the digital format used only to display information (Reinbold et al., 2022).

The cycle of mistrust in the CI was a barrier to the implementation of DVM applications. This mistrust was also expressed as a lack of confidence in the reported data. Once a new process and a novel approach to reporting are implemented, engaging in constant work, with the commitment of the parties involved, as well as taking actions to increase trust among the participants in the process of data collection and reporting, become essential for the successful implementation of DVM.

CONCLUSIONS

In this paper, the authors have investigated and analyzed the impacts of creating a DVM process when reporting different KPIs for a complex infrastructure project, involving seven different contractors and client representatives.

The commitment of the stakeholders involved in the project is paramount for the success of DVM implementation. The present culture of mistrust in the CI is fueled by the lack of digitalization of processes. If data are analyzed and reported manually, even when generating a digital report, there is constant mistrust that the data are incorrectly collected or gathered at the wrong time. Due to such manipulation of data and reporting, there is also a persistent suspicion that contractors hide information.

In the studied case, the project stakeholders' resistance to the implementation of the DVM tool diminished after they overcame the initial challenges, identified the increase of shared SA, and acknowledged that the report supported their work.

This paper was limited to one complex infrastructure project in Finland and focused on the implementation of a specific DVM report, the generalization of results should be carefully considered. Further investigation of the information needs from users and the disparities between those and the information displayed is necessary.

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UNVEILING THE HIDDEN HIGH VARIABILITY IN PROCESSES WITH STABLE AND GOOD PPC RESULTS

Omar A. Samaniego[1]

ABSTRACT

Despite high and stable Percentage of Plan Completed (PPC) values obtained in projects where Last Planner® System (LPS) was implemented, construction processes often conceal variability, undermining true completion. Likewise, LPS metrics rely on a deterministic approach for measuring the performance of processes without contrasting them with non-deterministic variables, which can provide a new perspective and new room for improvement. This is why, this paper introduces four new metrics – Percentage of Plan Completed+ (PPC+), Percentage of Plan Completed++ (PPC++), Percentage of Plan Completed+ based on random scheme (PPC+r), Rate of Waste (Rw), and Rate of Planning Assessment (Rpa) – to unveil hidden variability around activity daily schedule, rework, excess capacity, and planning. Further, utilizing statistical modeling to define the pioneering stochastic indicator Rpa, the study presents an important leap from traditional LPS deterministic metrics. Thus, by also conducting one survey among LPS practitioners on PPC conception and usage, it illuminates how seemingly stable estimated PPC values can misrepresent process performance.

These metrics offer a transparent brand-new assessment way, revealing new opportunities for improvement aligned with lean principles. The study also provides foundation and directions for further research on hidden variability which can propel the current LPS approach.

KEYWORDS

Lean construction, Last Planner® System, PPC, metrics, stochastic indicator.

INTRODUCTION

This approach introduces a novel method for evaluating hidden variability within the context of the variability research field on PPC results, addressing existing gaps in this field. This becomes apparent when the study quantitatively shows that even when a process maintains a consistent PPC of 100%, variability may persist unnoticed.

The newly introduced PPC+ and PPC++ metrics scrutinize daily fluctuations within weekly PPC assessments, revealing variability in activity leaps and its impact on deliverable completion, respectively. Completion, within this framework, pertains to fulfilling technical requirements, distinguishing it from mere quantity or activity execution. Similarly, Rw highlights the waste of hidden resources employed to address unnoticed variability.

Moreover, taking note that randomness can be explained as out of control variability (Hamzeh, 2009), and adhering to the principle that planned results are diametrically opposed to random outcomes, and the closer planned results align with random outcomes, the poorer the planning execution, Rpa serves as a stochastic indicator utilizing a random variable (PPC+r)

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obtained by estimating the most probable PPC+ value within a random scheme for a particular process model. For defining this, the author conducted a simulation with a constant 100% PPC while varying PPC+ values.

The author doesn't assume that the basis of LPS approach takes completion as independent of meeting technical requirements. However, he asserts that there are signs that in Peru LPS practitioners understand PPC as an outcome of finalized activities, assuming that these activities result in deliverables meeting the technical requirements. As a result of this assumption, there could be a distortion in the PPC, as certain packages assumed to be finished may still require additional work subsequently. As LPS does not explicitly include formal procedures for quality control, relying on existing quality management systems to ensure the quality of completed work packages (Ibarra et al., 2022), there is a need to define indicators aligned with the LPS approach regarding completion.

TERMINOLOGY

Completion

The project scope's completion is assessed in accordance with the project management plan, whereas the product scope's fulfillment is evaluated based on the product requirements (PMI, 2017). In this paper, completion is accomplished only when deliverables meet technical specification, and since defects are not part of the specifications, completion also means free of defects.

Deliverable

Any unique and verifiable product, capability or result to perform a service that is required to be produced to complete a process, phase, or project (PMI, 2017).

Requirement

The term *requirement* is defined as a capability or condition that is required to be present in a product, service, or result to satisfy an agreement or other formally imposed specification (PMI, 2017).

PURPOSE

The aim of this study is to propose new metrics PPC+, PPC++, PPC+r, Rpa, and Rw, which collectively unveil hidden variability in regular high-performance and low-variability PPC results. Likewise, this paper presents Rpa as a pioneering stochastic indicator for LPS approach, opening the door for further indicators of this kind.

METHODOLOGY

Observation and Hypothesis

Describe regular construction process characteristics, how they are understood and measured by LPS practitioners, and provide possible explanations.

Literature Review and Foundations

Conduct a comprehensive literature review on the LPS key metrics, establishing the theoretical foundations for new metrics, including the understanding of completion, deliverables, and requirements.

Assessment of PPC Understanding

Conduct a poll among LPS practitioners to explore their understanding on completion. Evaluate emerging insights to identify potential misconceptions to later assess the necessity of introducing supplementary metrics to address these misconceptions

New Metrics Definition

Define the PPC+, PPC++, PPC+r, Rpa, and Rw metrics in detail, explaining the rationale and formulas for each. Describe the underlying assumptions and constraints applied.

Simulation and Theoretical Results

Assess selected metrics through simulation modeling and analyze results to uncover hidden variability despite a consistent 100% PPC. Obtain statistical values for PPC+ in a random scheme, describe its theoretical relation with Rpa.

Site Research Project

Propose starting points, procedural steps, and recommendations for conducting on-site research to validate the theoretical findings.

Conclusions

Synthesize theoretical and practical findings on PPC understanding and completion. Assess new metrics' utility in uncovering hidden variability and improving PPC estimation.

OBSERVATION AND HYPOTHESIS

In Peru, LPS practitioners commonly evaluate variability by monitoring PPC and other LPS metrics' behaviour, relying on measured resultant data, which unveils a prevalent deterministic approach. While this practice illuminates processes and guides actions, inherent biases may prevent thorough examination of resultant data upstream, alongside to misconceptions about key definition of completion in terms of deliverables rather than solely activities.

LITERATURE REVIEW AND FOUNDATIONS

PPC stands as the predominant metric in LPS, typically associated with effective weekly work planning and successful LPS implementation. It serves as a *post-production* gauge of the reliability of weekly work planning (El Samad et al., 2017). Likewise, other well-known metrics are the now called Tasks Anticipated (TA) and Tasks Made Ready (TMR) (Ballard, 1997) which can be used to align the weekly work plan assignments with the lookahead plan. On the other hand, Planned Work Ready (PWR) is a metric used for assessing the quality of the lookahead process; this metric serves as a forecast and can provide a better evaluation of schedule performance when complemented with PPC (Mitropoulos, 2005). In terms of quality of the deliverable resulting from activities, Sukster (2005) proposed the Percentage of Packages Concluded with Quality (PPCQ) determined by the ratio of packages concluded with quality to the total number of packages concluded, and the Percentage of Packages Really Concluded (PPCR) determined by the ratio of packages concluded with quality to the total number of planned packages. Jang and Kim (2007) proposed Percent of Constraint Removal (PCR), to measure the performance of the make ready process. Alarcón et al. (2014) observed that for successful projects, it is not sufficient to possess high values of PPC and PCR; it is also essential to control their variability.

The above is a sample of the most relevant LPS metrics which, in all cases, are deterministic and do not arise from statistical modeling. In terms of variability assessment, Emdanat et. al. (2016) proposed the Percent Required Completed or Ongoing (PRCO), which evaluates the percentage of required activities completed by their promised dates, encompassing ongoing activities projected for completion by their original promised dates after team members update remaining durations to align with remaining work. Additionally, they introduced the Milestone Variance (MV), denoting the gap in days between the anticipated completion date for all pending tasks and the milestone's prescribed deadline. Although these last-mentioned indicators are an attempt to analyze activity variation, all of this still remains within a deterministic estimation realm.

When it comes to simulation experiments, studies are founded on simulating process behavior to offer valuable insights, though new specific stochastic indicators are not provided. In this regard, Tommelein (1997) conducted a simulation that enabled experimentation through modeling push- and pull-driven sequencing of resources. Likewise, Hamzeh and Langerud (2011) conducted a simulation to study the relationship between increasing Task Anticipated (TA) and PPC increase, and the concerning impact on project performance. The study results showed that even a small change in TA may significantly affect PPC. More recently, there have been approaches to simulation games such as that proposed by Alves et al. (2022), who presented an analogue simulation game concerning Takt Time Planning (TTP) and Takt Control (TC) and showed, employing a case study, one way in which Lean Construction and Building Information Modeling (BIM) can be linked through QR codes. In author's opinion, concerning BIM models can serve as a graphical base for running future stochastic analysis.

ASSESSMENT OF PPC UNDERSTANDING

POLL RESULTS ON PPC UNDERSTANDING

The term *completion* is commonly used in LPS literature, typically in relation to activities. Therefore, *activities completion* implies that there is nothing more to add to those activities. However, there is a trend among Peruvian LPS practitioners to measure this in terms of quantities related to finished activities instead of completed deliverables. In this paper, a deliverable is considered complete only when technical requirements are met, signifying that the presence of defects indicates a lack of requirement compliance.

In this context, a survey was conducted with the aim of assessing the knowledge of PPC estimation among Peruvian LPS practitioners (see Table 1). To achieve this, a survey database built in Peru was selected, indicating that a majority of the emails correspond to this country. In this regard, preliminary observations derived from the results might be mostly applicable to Peru. The survey question was intended to replicate the common questions raised when estimating the PPC, and it includes a section regarding defects, stating that it has a delimited impact. The question was as follows:

"Considering that PPC is the percentage of plan completed, answer the following: There are 10 concrete slabs, each with a volume of 5m3. If you plan for 10 concrete-cast activities in a week and 9 of these activities are done within that time period, what is the value of PPC? Taking into account that the strength of the slabs is satisfactory; there are pending corrections, but they impact a maximum of 10% of the time or resources."

Table 1. Survey specs on PPC estimate

Location	Peru	**% Peru responders**	52.2%
Size	45	**% other countries**	47.8%
Mean	Emailing, WhatsApp	**Dates**	15 to 26 Jan, 2024
Tool	Google Forms	**LPS Years Exp. (LPSYE) Avg.**	4.13
Source	Database built in Peru	**LPSYE Standard Deviation**	3.31

To answer this question, it should be note that an activity finalized with a slab with pending corrections is actually *not completed*, then it remains as *work in progress*. The correct answer to the question above is *Need More Data*, as the number of not completed slabs (resulting from unproperly finalized activities) can vary and is not mentioned.

Figure 1 helps to explain why we need more data to answer the question. Here, NS means *not started*, WIP means *work in progress*, indicating either started activities not yet finished or the presence of defects, signifying incompleteness. Finally, OK means *complete*, denoting full technical requirement compliance. The first alternative indicates a real PPC equal to 90% as there are no defects, and activity finalization did not result in incomplete slabs (there is no pending corrections); here, the nine resulting slabs are OK. On the other hand, the rest of the possible alternatives show concrete-casted slabs, but there are defects affecting a different number of slabs tagged as WIP; those defects have the same impact in any alternative, as the impact is measured in terms of time or resources (10% impact as per the question), not in terms of deliverables. PPC estimates are based on activities and will differ from deliverable-based estimates if those activities are *wrongly assumed to be finalized with defects-free slabs*.

Figure 1. Number of slabs at different completion states related to the answer for the Poll on PPC estimate

Thus, to respond to the poll question, we require data regarding the number of deliverables associated with activities. Furthermore, considering the Lean Philosophy's emphasis on delivering value to the client, the inclusion of deliverables in PPC assessment is crucial, as they encapsulate the value created by the project. The results in Figure 2 shows the value of 90% as the most selected answer to the poll. Yet, the sample size is statistically not representative and need to be increased, these results are very consistent with the hypothesis that, in Peru, PPC is solely assessed based on activities without delving into the results, wrongly assuming that the results (deliverables) are in accordance with requirements. As quality is defined as the degree to which a set of inherent characteristics of an object fulfils requirements (ISO, 2015) then quality, in essence, is assumed, not assessed when estimating PPC for this population.

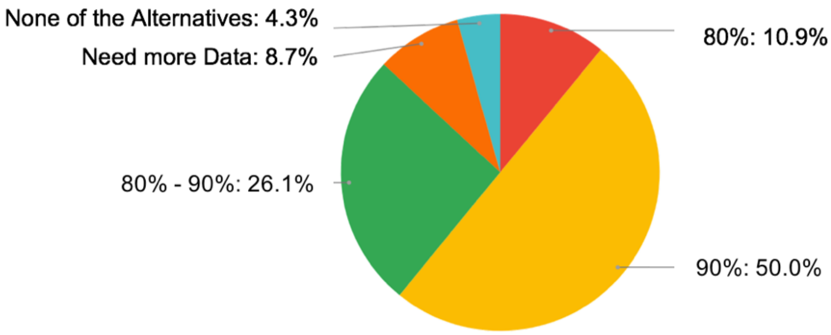

Figure 2. Proportions in answers for the poll on PPC estimate knowledge

A more extensive poll, displaying the same pattern, would suggest that common LPS practitioners make no further analysis of activities' results and consequently fall into wrong assumptions about completion and planning. The author doesn't claim that LPS practitioners usually wrongly estimate PPC but states that there might be a bias in the first glance assessment of PPC that may lead to wrong PPC estimates in Peru.

NEW METRICS DEFINITION

PPC+ AND PPC++

Percent Plan Complete (PPC) is the percentage obtained by dividing the number of completed planned activities by the total number of planned activities (Ballard, 2000). PPC is a well proven way for measuring schedule reliability and is used as a basis for an additional set of metrics introduced in this paper called PPC+ and PPC++. PPC variability may reduce and average PPC value may also increase in a given set of periods of time converging to 100%. Then, assuming that it consistently reaches the 100% for a set of periods, intuition may lead us to believe that there is no more variability to address; however, another kind of hidden variability remains, and can be out of control yet. The hidden variability is related to daily changes (back and forth leaps) in scheduled activities execution and reworks required at deliverables level, compromising completion; all of this is not measured by PPC. In some situations, changes in the sequence can result in poor quality, which might affect subsequent work, potentially necessitating the need for rework at later stages of the project (Fireman et al., 2013).

In the figures of this section the author explains these situations. Here, every activity is independent of one another, and there is no constraint to reschedule any of them ahead of or after the schedule. Furthermore, all activities are carried out in the same shown week.

Figure 3 illustrates five scheduled activities, each of them pertaining to a specific deliverable (e.g., concrete casting for one column). The assignment of two laborers for one activity every day is taken into account. In this scenario, the expected performance of two laborers is estimated to be *well*, achieving the completion of one column per day. It is noteworthy that in this example, no additional deliverable-related activities are introduced. In Figure 3, it can be also observed that when each column is completed on the respective day, the PPC equals 100%. This value remains consistent even if activities are rescheduled during the same week.

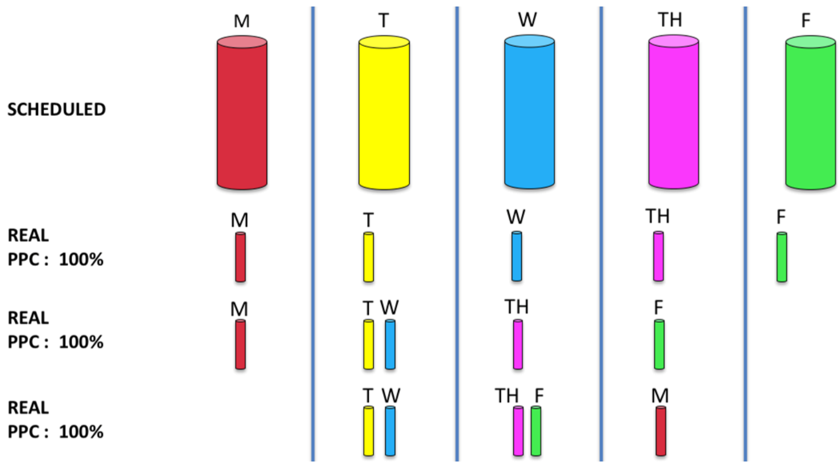

Figure 3: Common PPC estimate in Peru as per author's observation (Samaniego, 2021)

In Figure 4 PPC+ is estimated by taking into account only concrete casting activities done when scheduled. Thus said, there are only three activities completed when required, then PPC+ equals to 60%. In Figure 5, for obtaining PPC++ only concrete casting activities are taken into account if the resulting deliverable (column) is completed as daily scheduled – that means according to requirements and then free of defects; in this sense, as there are only two successful activities, then PPC++ equals to 40%.

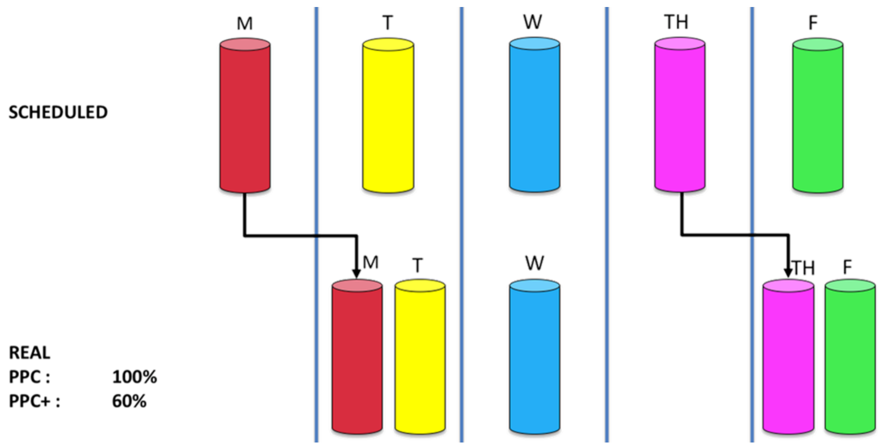

Figure 4: Application of PPC+ (Samaniego, 2019)

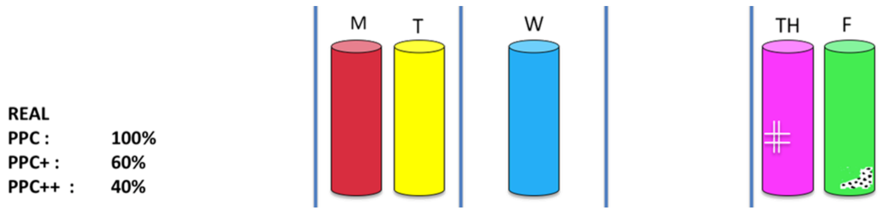

Figure 5: Application of PPC++ (Samaniego, 2019)

The author anticipates that both PPC+ and PPC++ will be subject to constant variability, even though PPC consistently reaches 100%, as shown in Figure 3. Additionally, defects will later lead to informal rework packages (Fireman et al., 2013), and the impact of defects is unveiled by PPC++.

RPA AND RW

Taken into account Figure 3, it can be seen that the number of possible combinations of PPC+ for a given PPC at 100% is equal to 5^5, meaning 3,125 outcomes. Then, it is possible to obtain the different values for PPC+ and define the most frequent as PPC+r. The relation between the PPC+ site obtained and the PPC+ randomly obtained (PPC+r) defines the Rpa (Ratio of Planning Assessment) as follows:

$$R_{pa} = \frac{PPC +}{PPC +_r}$$

In regards to resource usage, in the model, it can be seen that since there are days where *two* columns are concrete casted by *one labor* (e.g., Tuesday), then the previous well estimated one column per *two labor* day proves to be wrong, meaning that there is one labor in excess; so, there is room for improving labor efficiency. These unnoticed added resources (two labor instead of one labor) are the way schedulers face uncertainty and variability. This is a kind of capacity buffer to reduce the impact of variability on a system's operation at different locations along the chain (Hamzeh, 2009). As the PPC+ only considers the activities done when actually scheduled, it will be equal to PPC only when full labor resources are used when scheduled. Thus, the following relation defines the ratio of wasted resources (Rw):

$$R_w = \frac{PPC+}{PPC}$$

Thus said, in given e.g. ten weeks where ordinarily applied PPC could consistently reach 100%, there is, apparently, an optimal case not only due to PPC value but also due to zero variation. However, any of these weeks could have a huge range of PPC+ and/or PPC++ values, as per the example above.

SIMULATION AND THEORETICAL RESULTS

In this section, the study utilizes the theoretical case described in Figure 3, where three possible outcomes demonstrate variability in PPC+ and PPC++ for a constant 100% PPC value. The simulation will consider all possible outcomes from randomness and define the most probable value for PPC+. Thus, by defining the Rpa, this paper links PPC+ with PPC+r, which represents PPC+ estimated from a random scheme.

SIMULATION FOR PPC+

The author organized the data in a spreadsheet for the case under study (see Table 2). In this arrangement, ‘0’ indicates that the activity was completed as scheduled, ‘-1’ signifies that the activity was finalized one day earlier, and ‘+1’ indicates a one-day delay. This is what is called back and forth leaps. There are 3,125 combinations, as aforementioned. One section of the combination record is shown in Table 2. In Table 3 and Figure 6, It can be observed that the most common random PPC+ for this case is equal to 20%. Therefore, any PPC+ result site-obtained close to 20% indicates poor plan execution, as it aligns with the most probable random outcomes. Conversely, a PPC+ close to 80% is highly uncommon, signifying a deviation from randomness and alignment with planned results, indicating good planning and execution.

Table 2. Sample showing rescheduled activities combination with related PPC+ values

ID	M	T	W	T	F	PPC+
1	0	-1	-2	-3	-4	20.0%
2	0	-1	-2	-3	-3	20.0%
…	…	…	…	…	…	…
3124	4	3	2	1	-1	0%
3125	4	3	2	1	0	20.00%

Table 3. Frequency of PPC+r

$PPC+_r$	Occurrences	Frequency (F)
0.0%	1024	32.8%
20.0%	1280	41.0%
40.0%	640	20.5%
60.0%	160	5.1%
80.0%	20	0.6%
100.0%	1	0.0%
Grand Total	**3125**	

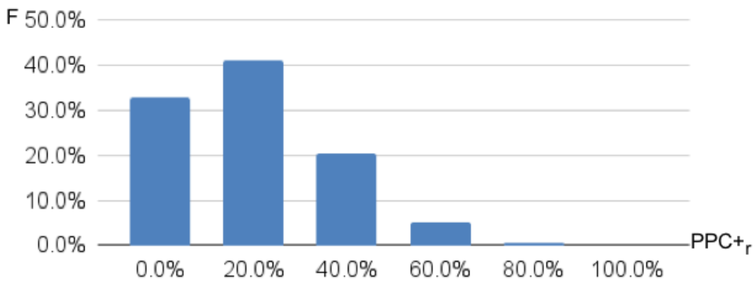

Figure 6. Frequency distribution for PPC+$_r$

Also, Table 4 presents the rescheduling frequency in a random scheme; here, the most frequent value pertains to the not rescheduled activity represented by the '0' value. This symmetrical distribution is expected given the conditions for this scheme explained before.

Table 4. Number of activities rescheduled (back and forth leaps)

Leaps (L)	-4	-3	-2	-1	0	1	2	3	4
Leaps Number (LN)	625	1250	1875	2500	3125	2500	1875	1250	625
Leaps Freq. (LQ)	4.0%	8.0%	12.0 %	16.0 %	20.0 %	16.0 %	12.0 %	8.0%	4.0%

It is worth noting that in a regular project, a trend of delays is the norm. This is addressed to ensure compliance with the weekly schedule, as illustrated by one hypothetical weekly progress recovery curve (dotted curve) in Figure 7. The preventive weekly acceleration curve (continuous curve) depicts the opposite hypothetical pattern in order to keep progress on track, reflecting an intentional early acceleration trend to achieve the weekly schedule. In both cases, this is only possible if labor resources are in excess, and their usage efficiency can be unveiled by Rw. Both hypothetical curves show a schedule compression, this can also biases workers towards getting their tasks done, even when that means spending less time on validation and quality assurance (Ford et al., 2003). Analyzing this, along with trends in site-obtained Rw, can illuminate how excess capacity can be optimally utilized, resulting in cost savings for the project. On the other hand, Table 5 and Figure 8 present the Rpa behavior for different values of a given PPC+r. As the most probable PPC+r value is 0.2, a higher Rpa approaching 5 indicates that the results deviate significantly from randomness, attributed to PPC+ equaling 1.

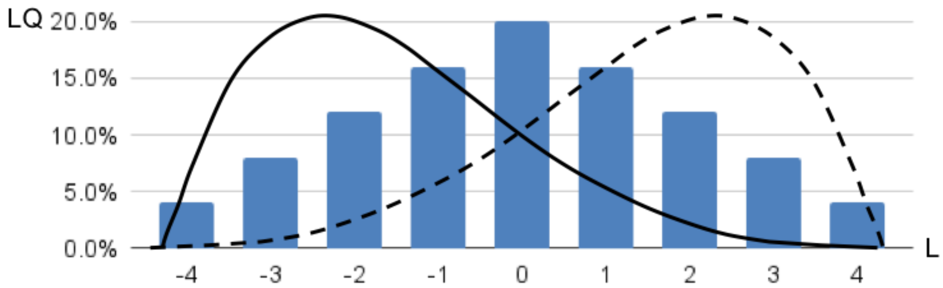

Figure 7. Symmetrical rescheduled activities (back and forth leaps)

Table 5. Rpa value per different PPC+r values

PPC+	PPC+r	Rpa
1	0.0%	---
1	20.0%	5
1	40.0%	2.5
1	60.0%	1.67
1	80.0%	1.25
1	100.0%	1

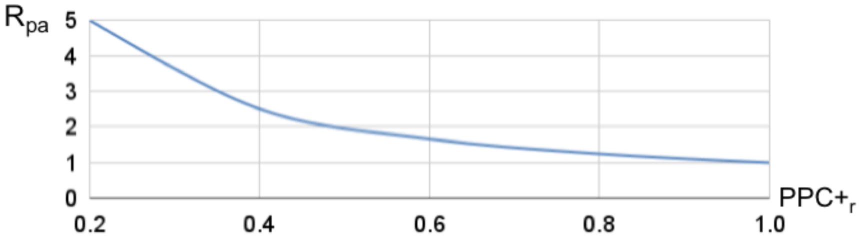

Figure 8. R_{pa} curve per $PPC+_r$ value

SITE RESEARCH PROJECT

The points of departure of this study are based on observations described in this paper, which pertains to misconceptions among LPS practitioners in Peru on completion and PPC. An extended research can be done to strength these observations by: (1) Conducting extended polls about concepts exhibited in this paper among LPS practitioners; (2) Running focus groups among both senior and junior LPS practitioners; (3) Reviewing PPC estimates in active projects. In respect to the new metrics, site validation experiments should consider the following: (1) Conducting experiments in five building projects (towers); (2) Senior LPS practitioners works in the aforementioned projects; (3) The selected project portion shall contain activities independent of one another, without any constraint to move them back of forth (to replicate the conditions of the presented simulation); 4) Daily recording of new indicators and researcher's immersion in the project for a period of one month and applied to selected trade(s).

CONCLUSIONS

This study provided an overview of key LPS metrics developed thus far, with PPC being the most frequently used metric in the industry. While LPS has been proven to enhance planning reliability and reduce workflow variability, there is still room for improvement by identifying hidden variability not yet addressed by LPS deterministic metrics. Additional metrics, PPC+, PPC++, PPC+r, Rw, and Rpa, are presented to address hidden variability and reveal hidden resource waste. Among all of them, Rpa stands out as a pioneering stochastic indicator for the LPS framework.

The study presents a new focus on deliverable completion, which differs from the common focus on activity completion. The consistent results of the polls, though small, provide insights for future studies on PPC estimates and decision-making processes related to completion achievement. In light of this, a research project is proposed to strengthen the findings on LPS Peruvian practitioners' completion understanding. To address related misconceptions, the study provides PPC++, which, in addition to measuring what PPC+ does, adds the criterion of physical deliverable completion. Thus, PPC++ assess if there are zero non-compliances with technical requirements related to properties and characteristics of the deliverable; in other words, PPC++ also serves as a brand new LPS quality metric for deliverables. As planned results are the opposite of random results, and the closer the results are to randomness, the poorer the planning was, a stochastic indicator (Rpa) was developed to provide a random value against which performance results can be compared. In this development, a simulation was conducted on a delimited process model, based on the number of possible combinations of activity leaps, resulting in the most probable value for PPC+ in a random situation (PPC+r). Thus said, should site obtained PPC+ closes to PPC+r, the poorer plan execution was, as this relation is shown by Rpa. Additionally, as the study shows that in order for the activities leaps to exist, there is a need for sunk additional resources, this study proposes Rw (which relates PPC to PPC+), shedding light on hidden resource excess to address variability expressed in activities' back and forth leaps. Finally, the study provides a foundation and directions for further research and on-site validation to refine and expand the application of these novel metrics.

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THE RELATIONSHIP BETWEEN MAKING-DO WASTE AND GOOD MANAGEMENT PRACTICES IN THE CONSTRUCTION INDUSTRY: A SYSTEMATIC LITERATURE REVIEW

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ABSTRACT

The need within the construction market to increase control, performance, reduce waste and impacts on the environment is of utmost importance. In order to fully understand and contextualize the construction management process and help managers make decisions, this study aims to investigate studies through a systematic literature review which address the relationship between good management practices and losses from making-do within good construction practices. The search for articles was conducted in the Scopus, Science Direct and Web of Science databases. This diagnosis revealed the good management practices presented in the literature, which can be facilitating activities or good practices that reduce losses from making-do, guarantee compliance with the minimum requirements of the complete kit or the resilience of the process. The categories of knowledge gaps were structured into: Industry 4.0 and 5.0, Big Data, Multi-criteria decision making, Discrete event simulation, Resilience and Literature review.

KEYWORDS

Making-do. Wastes. Lean construction. Reworking. Planning.

INTRODUCTION

The construction sector becomes competitive when the market and segmentation impose such a perspective, demanding quality and performance from construction companies. As a result, it is necessary to increase control and performance, reduce waste and impacts on the environment (Adewuyi et al. 2014; Ansah et al., 2016). This environment is conducive to applying methodologies, principles and concepts such as lean construction with the aim of reducing costs, waste, improving predictability, and increasing transparency, among other aspects related to production performance.

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The use of lean construction concepts within the planning, execution and control of operational flows and their processes in civil construction ensures that the cost of productivity is achieved with the minimum of available resources. Thus, the high production cost within the civil construction process is related to the waste that exists throughout the construction processes and should be understood as any inefficiency in the use of equipment, materials, labor and capital (Formoso et al., 1997; Viana et al., 2012).

Proponents of lean thinking argue that reducing and eliminating waste leads to improved conversions (Womack and Jones, 1996). Waste measurement has been widely used in the manufacturing industry to evaluate the performance of production systems, as it generally allows areas for potential improvement and the main causes of inefficiencies to be identified (Ohno, 1988; Dinis-Carvalho et al., 2015).

An analysis of areas for potential improvements and identifying the main causes of inefficiency guarantee the existence of a complete kit of activities. The complete kit concept was presented by Ronen (1992), which is the set of components, drawings, documents and information necessary to complete a specific assembly, subassembly or process, highlighting the importance of starting activities only when all the resources necessary for its execution are met.

An important increase in lean construction was the designation by Koskela (2004) of a new category of losses, losses from making-do, supported by the concept of a complete kit proposed by Ronen and added to the widely known and applied list of Ohno (1997) and Shingo (1989).

Since then, research related to ways of using the concept of loss from making-do to minimize or eliminate activities which do not add value to the process has been developed at various stages of the life cycle (from project conception to maintenance), such as in project preparation, in construction site logistics (Ghanem et al., 2018); in the supply chain and its relationships (Taggart, Koskela and Rooke, 2014); in production slack (Fireman, Saurin and Formoso, 2018); in the development or increase of methods or tools, virtual or not, to facilitate the identification of these losses (Sommer, 2010; Fireman, 2012; Leão; Formoso; Isatto, 2016); or identifying other losses in a discussion of cause and consequence in relation to the loss from making-do (Formoso et al., 2011; Fireman, Formoso and Isatto, 2013; Santos and Santos, 2017; Pérez, Costa and Gonçalves, 2016; Pérez; Costa, 2018; Amaral, 2023).

The management process is the logical sequencing of four steps: planning, organizing, directing and controlling to achieve a certain objective. In this sense, Almeida (2002) emphasizes that process management involves evaluating each phase of the process and seeking the best way to execute it with excellence. Thus, the importance of the manager and the concept of resilience is highlighted, which for Hollnagel and Woods (2005) is the ability to recognize, adapt and absorb variations, changes, disturbances, ruptures and surprises, especially those which the system was not designed for, as it is from them that the management process takes place.

In view of the above, this study proposes to investigate the development of work on the relationships between good management practices and losses from making-do within civil construction through a systematic literature review (SLR) in order to understand and contextualize the management process of civil construction and aid managers in decision-making.

Work found in the bibliometric research phase indicates that incorporating good practices can reduce losses (Grosskopf, 2013). They also confirm that activities which do not add value account for more than half of all activities in a project (Daniel et al., 2019; Nassri et al., 2023).

Good practices in the construction field can be understood as solutions used to suppress interruptions in some activity on the construction site (Mesquita, 2014), but it can also be seen as the best way identified by a professional to satisfactorily complete a task (Cleto et al., 2011); in addition, according to the perspective of Sáez et al. (2014), practices which enable better management of processes in order to favor reduced material waste. This means that good practices do not have a unanimous definition in the literature and can be applied to different knowledge areas. Herein, we highlight those good practices used on construction sites and which are based on the philosophy of lean construction, which can be called good lean practices or just lean practices (Liker; Meier, 2008).

Adopting good practices on construction sites leads to improvement in aspects which encompass this environment (Grosskopf, 2013). According to the author, there is a reduction in the executive schedule of projects, reducing delays, as well as an improvement in quality, lower costs, in addition to cooperating with the reduction of environmental impacts all being considered among the benefits caused by adopting these practices.

A SLR aims to identify a set of completed studies which address a given research question and evaluate their results to highlight conclusions on a given subject through a protocol. The SLR protocol used in this work is detailed in the materials and methods section.

Thus, the good management practices raised can be techniques, concepts, facilitating activities or good practices as long as they reduce losses from making-do, guarantee compliance with the minimum requirements of the complete kit or the resilience of the process. These good practices were arranged at each stage of the construction life cycle according to their history or potential application. The phases of the construction life cycle will be defined based on the concepts proposed by Gobin (1993).

METHOD

MATERIALS AND METHODS

A Systematic Literature Review (RSL) is a review planned to answer a specific problem using explicit and systematic methods to identify, select and evaluate studies, and then critically analyze the data present in them that relate to the research questions (Rother, 2007). The guidelines proposed by Kitchenham (2004) were used in order to define the method for preparing the systematic mapping of literature, dividing the study into three stages as described in Figure 1.

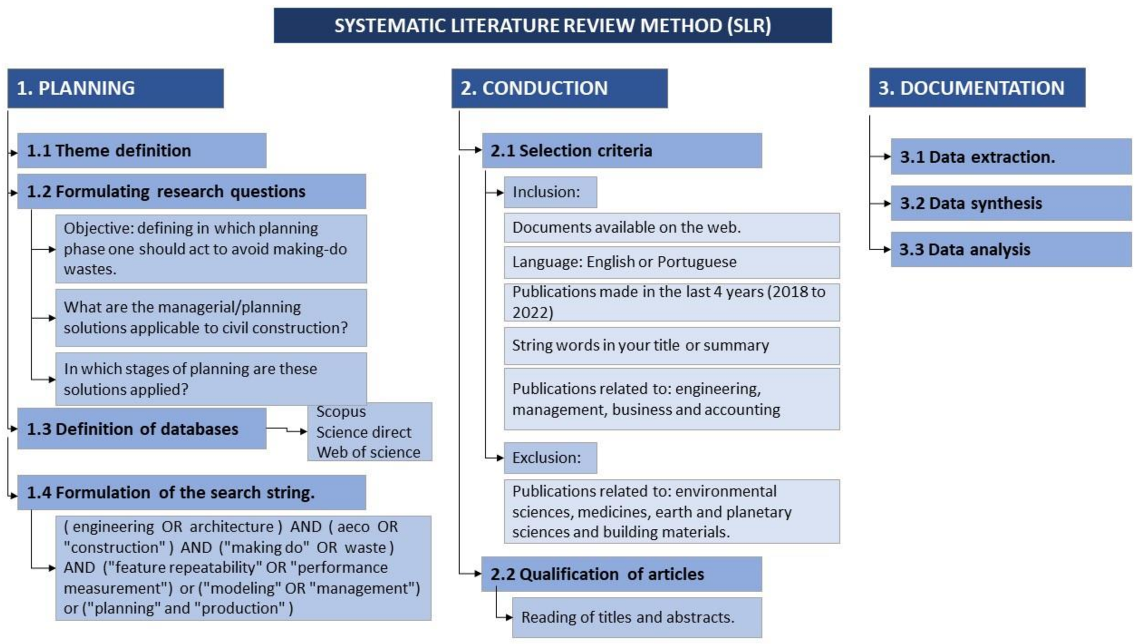

Figure 1: Systematic literature review (SLR) method (source: the authors)

RESEARCH STAGES

Planning

The possible good management practices which are used in different types of industries and can be used within the life cycle phases of the construction industry can be outlined during the planning stage. Thus, the following research questions were formulated: "What are the good management/planning practices applicable to civil construction?" and "In which planning phases are these good practices applied?"

Next, data from articles published in the following databases were collected to conduct the SLR: Scopus (access at: https://www.scopus.com/), Science Direct (access at https://www.sciencedirect.com/) and Web of Science - SciELO Citation Index (access at: https://www.webofscience.com/). The choice of these databases is justified by the greater number of articles related to the research areas of engineering and management. These databases have summaries and citations of articles covering national and international titles in the scientific and technical fields. These databases have tools which enable analyzing the impact of an article, as well as ranking of journals, author profiles, number of articles published by a journal and frequency of use of scientific terms, enabling an analysis of publication trends.

An advanced search was used on all platforms using the following string: (engineering OR architecture) AND (AECO OR "construction") AND ("making do" OR waste) AND ("feature repeatability" OR "performance measurement") or ("modeling" OR "management") or ("planning" and "production").

SLR Conduct

Figure 2 describes the methodology for selecting and extracting articles from the researched databases.

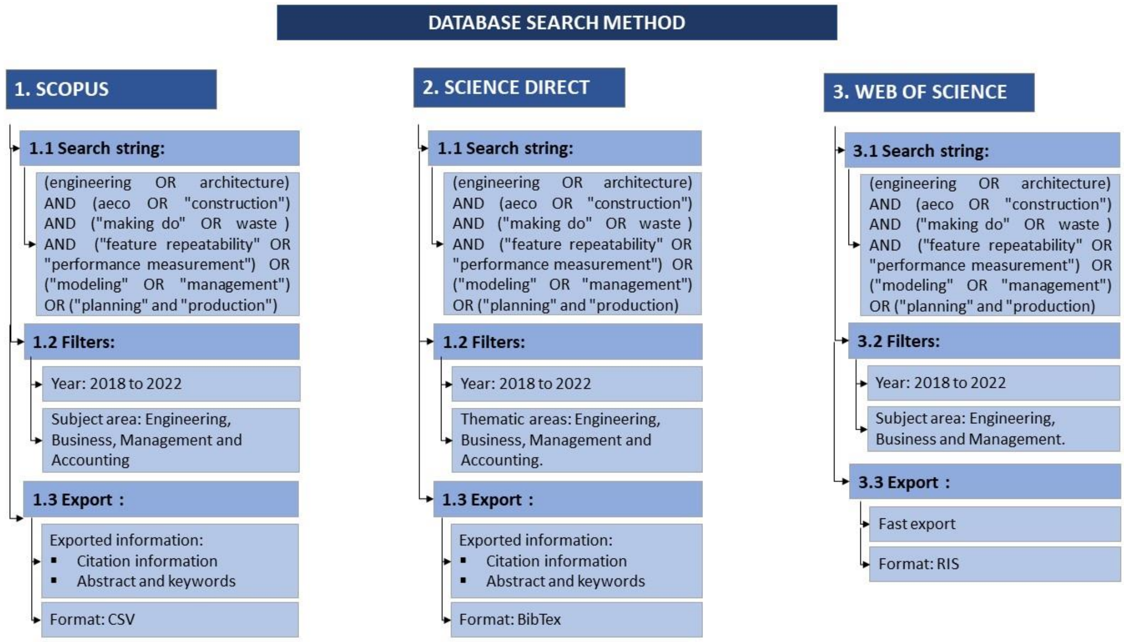

Figure 2: Database search method (source: the authors)

After data collection, all documents obtained at this stage were imported to the Rayann website (accessed at https://rayyan.ai/) and the studies were managed there. The choice of documents began following the protocol:

- Removal of duplicate files;
- Selection and exclusion based on reading the title and then the abstracts, following the following criteria.

Definition of inclusion criteria:

- Work related to: engineering, management, business and accounting.
- Documents available on the web;
- Language: English or Portuguese;
- Publications in the last 4 years (2018 to 2022);
- String words in the title or summary.

Definition of exclusion criteria:

- Work related to: environmental sciences, medicines, earth and planetary sciences and construction materials.
- Works that do not meet the inclusion criteria.

Documentation

We attempted to perform a bibliographic analysis during the documentation stage. This analysis considered the following parameters: selected articles, authors, number of annual publications, place and institution of publication and main keywords. Complementing the documentation stage, the selected articles were divided according to the application of the concepts presented and how they can be used within the phases of the construction industry's life cycle. The construction life cycle phases were divided following the three categories proposed by Gobin (1993) as detailed in image 4.

Microsoft Excel® was used to analyze the data from the selected articles, which had the function of standardizing relevant data such as title, authors, year, publication annals and references for use in the Microsoft Power BI® program.

RESULTS AND DISCUSSION

Searches in the databases according to the method represented in Figure 2 returned a total of 1,411 works, of which 36 were discarded because they were repeated in different databases. Thus, 1,375 publications were analyzed, distributed according to graph 1. The database that presented the highest number of results was Web of Science with 40.87%, followed by Scopus with 29.74% and Science Direct with 29.38% of the works.

After selection and exclusion of repeated publications, the article selection stage began. The results of this stage are presented in Table 1. After reading the title, 173 articles (12% of the total) were selected, and then the number was reduced to 114 (8% of the total) after reading the abstracts. No articles were obtained through snowball sampling. Thus, the number of articles analyzed remained at 114.

Table 1: Quantity of articles in the SLR stages (soruce: the authors)

STAGE	RESULT
Found in all databases	1411
Found in all databases (excluding repeats)	1375
Selected after reading the title	173
Selected after reading the title and abstract	114

The relationship between the total number of publications in the databases and the publications selected after reading the title and abstract following the inclusion and exclusion criteria described in the methodology are represented in Figure 3. The database that presented the largest number of selected articles was Scopus with 40.36%, followed by Web of Science with 38.60% and Science Direct with 21.04%.

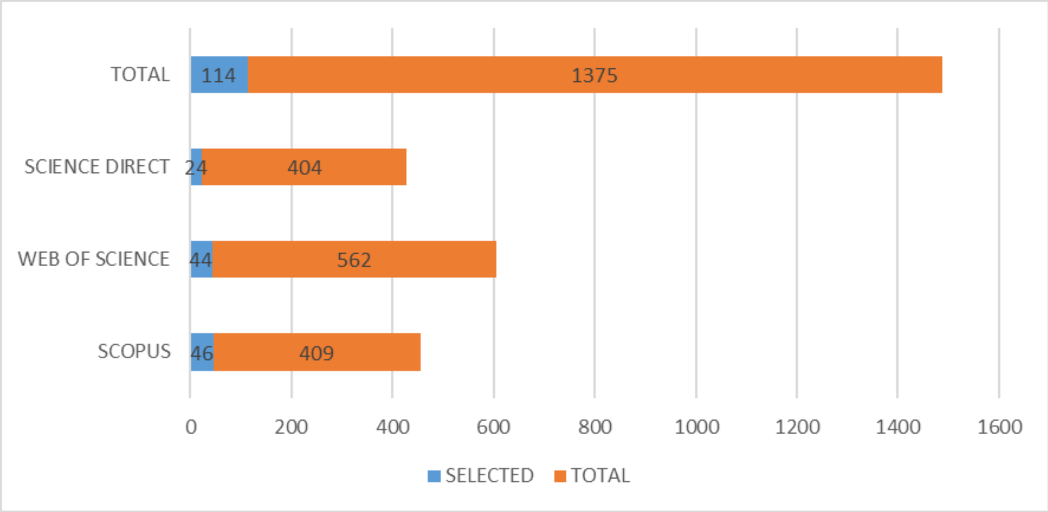

Figure 3: Number of publications selected by database (source: the authors)

Using Power BI, an interactive dashboard was created with a summary of the main results from the analyzes. These started from the analysis of the quantity of publications over the years, shown in Figure 4. The time frame determined in this work was between 2018 and 2022, with the objective of selecting the most recent publications on the proposed topic. Thus, a small variation was observed in the number of works published between the given period, highlighting the years 2020 and 2022 as those with the highest number of publications with 25 and 28 works published, respectively.

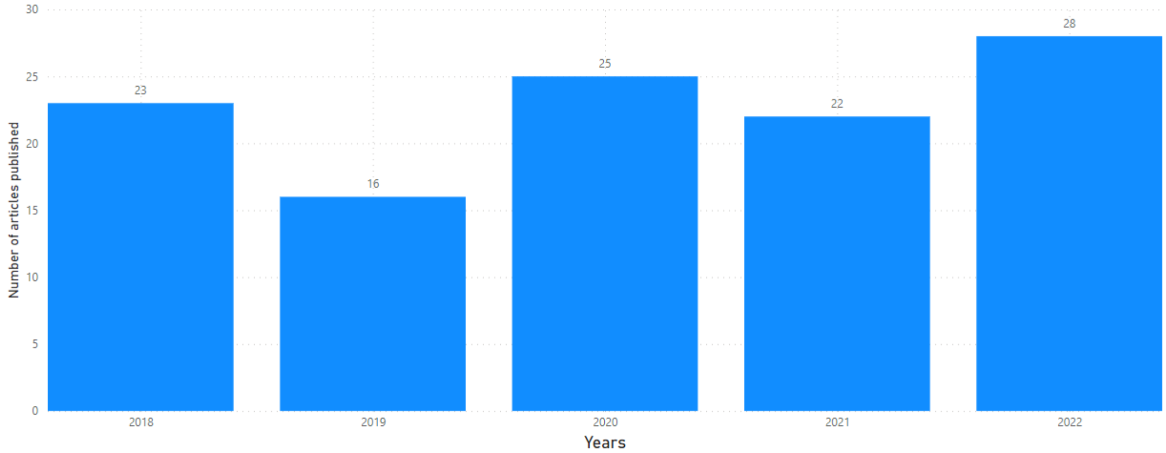

Figure 4: Number of articles published over the years. (source: the authors)

The analyzes continue with the place of publication of the articles. The number of journals which published more than one article from the selected sample was low. Those that had more than 3 publications are shown in graph 3. The Ambiente Construído Journal can be highlighted, which presented 23 publications, corresponding to 20.17% of the total sample. Table 2 describes the importance of the International Group for Lean Construction (IGLC) for the topic by relating the number of publications per journal and the number of publications at the congress in the same time frame as the study (last 4 years), applying the same inclusion and exclusion criteria as the SLR protocol.

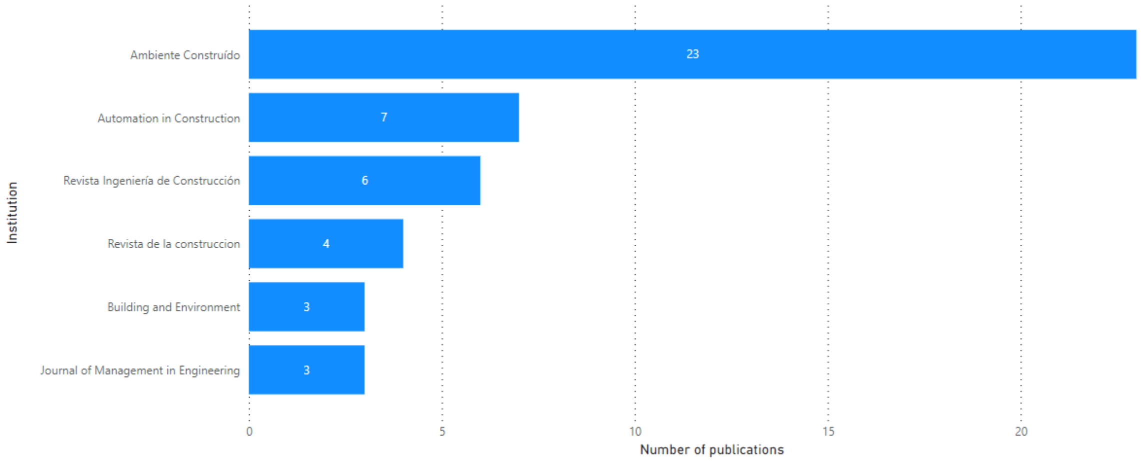

Figure 35: Number of publications by institution (source: the authors)

The recurrence of the main words which appear in the title and summary of the selected articles was analyzed, as represented in the word cloud (Figure 6). It is then possible to identify themes that, despite not being addressed in the string, are present in studies, for example: the centrality is formed by the terms "waste" and "industry", showing that a large part of the publications are related to losses in industries. Relevantly, we have the terms "construction" and "building" highlighting the study topic of this review. Another interesting fact is that even though the terms "BIM" and "Lean" are not present in the string, they were terms of great occurrence in the selected works. This presence demonstrates an integration between the subjects present in the terms of the string, mainly when relating the concepts of these terms with the terms of the string: "feature repeatability" and "performance measurement") since the concepts of the BIM and Lean methodology are directly linked to procedural methodologies with the aim of standardizing processes and increasing performance within the production chain. Thus, these terms can be considered as guiding research when questioning how losses due to making-do are related to BIM and lean methodologies, and how and what is the advantage of integrating these concepts for the decision maker within the construction site.

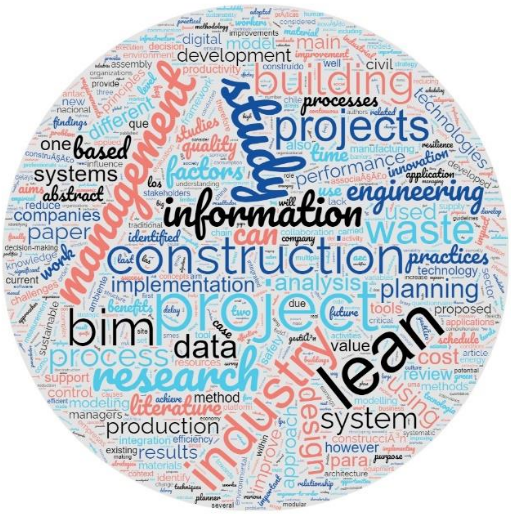

Figure 6: Word cloud. (source: the authors)

Finally, a complete reading of the articles published in 2022 was done in order to identify and understand the most current good management and planning practices and in which phases of the construction life cycle these could be applied. Figure 7 summarizes the life cycle phases of the development of traditional civil construction projects and was adapted from the illustration proposed by Gobin (1993).

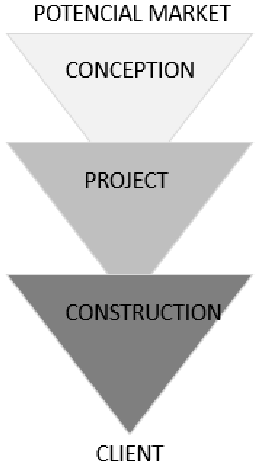

Figure 7: Phases of the traditional life cycle of civil construction projects. (source: Adapted from Gobin (1993)).

The construction life cycle phases for this analysis were divided following the three categories proposed by Gobin (1993), as detailed in Figure 8. However, the programming stage is replaced by "Conception and feasibility" in order to better characterize it. Thus, the results were divided and analyzed following the construction life cycle stages: "Conception and feasibility", "Project" and "Construction". A fourth category was created called "N.A." (not applicable) for articles which analyzed the topic in an industry other than the construction industry.

From a complete reading of the articles, it was possible to identify good management and planning practices used in different types of industries and which can be used within the phases of the construction industry's life cycle. Table 3 and Figure 8 illustrate the distribution of good practices highlighted in the articles in each phase of the construction life cycle, as well as those that were not applied in the construction industry but presented applicability and satisfactory results in other industries.

Figure 8: Distribution of articles selected in the databases in the year 2022 by the life cycle phase of construction management solutions (source: the authors)

Table 3: Distribution of good practices throughout the construction life cycle. (source: the authors)

	CONCEPTION	CONSTRUCTION	PROJECT	NA	TOTAL
BIM	1		4		5
Lean			2	3	5
Supply Chain Management	1	2			3
Agile Project Management		1	1		2
Big Data			1	1	2
Disruptive Technologies (Digital)		1	1		2
Industry 4.0				2	2
Industry 5.0				2	2
Lean Production	1	1	1		3
Material Management		1			1
Techniques Related to Work Safety				1	1
Discrete Event Simulation			1		1
Industry 5.0 - Collaboration Between Human	1			1	2
Linear Regression Techniques					0
Multiobjective Decision Making				1	1
Multiskilling of the Workforce		1			1
Project Management			1		1
Resilience				1	1
Standardization Of Services		1			1
TOTAL	4	8	12	12	36

Knowledge gaps related to good management practices within the context of the construction industry were identified (Table 4). These were divided and analyzed into categories, and the works that use literature review as a method were separated into the "Systematic Review" category, since they present several gaps on the topic covered.

The knowledge gaps presented in Table 4 highlight the lack of studies focused on tools which could be instrumental in planning and decision-making in civil construction. The lack of research on the topic of resilience and the industrial revolutions 4.0 and 5.0 is very evident. These themes involve tools which are dedicated to promoting collaboration between humans, resilience, social value, and customer experience, and should be considered as a suggestion for future work. These themes are related to the also absent concepts of big data, multi-criteria decision making and simulation of discrete events, since these are focused on the knowledge area which studies how to treat, analyze and obtain information from a large set of data. Data analysis is very important for defining tools that enable the civil construction industry to evolve to the level of industry 4.0 and 5.0.

Table 4: Category of knowledge gaps and their selection criteria. (Chart 1 source: the authors)

CATEGORY OF KNOWLEDGE GAPS	SELECTION CRITERIA
Industry 4.0 and 5.0	Articles that address tools dedicated to collaboration between humans, resilience and social value. Research on the concepts of industry 4.0 and 5.0 in civil construction.
Big Data	Articles covering Big Data research in construction safety, site management, heritage conservation and project waste minimization and quality improvements.
Multiobjective decision-making	Articles that address decision-making research on the post-disaster topic using hard data.
Discrete event simulation	Articles that evaluate the simultaneous integration of DES, ABM and SD modeling solutions.
Resilience	Research related to the importance of resilience in the organizational structure of companies.
Literature review	Articles which are SLR and present several knowledge gaps on the topics: Lean; BIM; Solutions related to work safety; Multiobjective decision-making; Supply chain management; Materials management; Disruptive technologies (digital).

These tools are linked to the knowledge area that deals with processing, analyzing and obtaining information from sets of presented data sets, and can be applied to BIM and Lean philosophies. These approaches not only extend the principles of lean construction, but also add assertiveness to decision making.

Despite not being explicitly mentioned in the knowledge gap categories, the concept of making-do can be considered a relevant gap. The lack of management techniques in construction can result in tasks being started or continued even in the complete absence of inputs, leading to a reduction in performance and characterizing losses due to making-do. Highlighting this gap is crucial to improving practices and efficiency in the construction sector.

CONCLUSION

From the systematic literature review it was possible to meet the proposed general objective of identifying and understanding the most current good management and planning practices and in which phases of the construction life cycle these could be applied. The search for understanding losses from making-do at construction sites led to the perception that the use of certain good practices imply actions which can be considered beneficial to the process, but that there are still no studies that correlate such good management practices to the concept of losses from making-do, since no works were returned after applying the SLR research protocol in which the term “making-do” was present in their title or abstract. Good management practices lead to the understanding that those which bring benefits to the process must be studied and their applications correlated with the occurrences of losses from making-do in the different development stages of civil construction projects, and so this question requires new research to be conducted.

The number of articles published over the years shows a growing interest in the topic of management solutions for the phases of the civil construction life cycle, reinforcing the current extremely competitive context of civil construction.

The result of distributing the solutions highlighted in the articles in each phase of the construction life cycle made it possible to evaluate in which phase action should be taken to avoid wastes due to making-do. The design phase was the one that presented the greatest number of management solutions, highlighting the importance of this stage for the positive results of construction projects. Among the solutions we can highlight for the project stage: BIM, Lean, Agile project management, Big Data, discrete event simulation and disruptive digital technologies.

However, it was possible to observe concepts that are not explored in the construction industry, such as: industry 4.0 and 5.0 concepts such as resilience and social value, multi-criteria decision making and techniques related to occupational safety, so it is not possible to prove empirically the real effectiveness of the application of these concepts within the development of construction projects.

Many articles entered the "literature review" category highlight a predominant trend of theoretical analyzes and conceptual reviews related to civil construction. In the context of the Brazilian construction industry, it is necessary to advance further with work that relates the concepts of: Lean, BIM, solutions related to workplace safety, multi-criteria decision making, supply chain management, materials management and disruptive (digital) technologies. in practice, demonstrating the effective application of concepts in the construction industry.

In the field of Lean and BIM, it is important to carry out empirical research, with Brazilian case studies, that highlight how these philosophies are implemented in real projects in Brazil, highlighting cases of success and challenges faced, providing relevant data on the effectiveness of these approaches and relating with concepts such as productivity, formal and informal service packages and the occurrence of improvisations and process resilience.

About solutions related to occupational safety, supply chain management, materials management. Collecting this data and analyzing it using methods to support multi-criteria decision-making is crucial, integrating these concepts into everyday practices within the construction site. This would contribute to the consolidation of these methodologies and good practices and would provide data that guided the manager in decision-making and continuous improvement practices.

Considering disruptive technologies, which are those that significantly revolutionize and improve tools, as well as new services and products, it is essential to study them for application within the construction site. Studies that present new technologies such as BIM, internet of things, efficient data management and augmented reality can provide interesting perspectives on the real scenario of technology application within Brazilian construction companies.

Therefore, influencing research applied to case studies is essential to fill the gap between theory and practice in civil construction, therefore, studies that relate wastes due to making-do in civil construction with the concepts of industry 4.0 can be suggested as future work. and 5.0, Big Data, multi-criteria decision-making methods, discrete event simulation and resilience.

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METHODOLOGY TO AVOID THE OCCURRENCE OF MAKING-DO WASTE IN CIVIL CONSTRUCTION

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ABSTRACT

The scenario of the Civil Construction industry is highlighted by the very high level of production waste, waste generation, and non-value-added activities. Among the array of existing waste types, one significant category is making-do waste, which gives rise to the following consequences: reduced productivity, reduced worker safety and motivation, reduced quality, and rework. The proposed model aims to contribute to efficiency and competitiveness in civil construction by filling gaps in loss management through making-do. Therefore, this study proposes a methodology based on establishing guidelines aimed at avoiding waste due to improvisation by addressing their root causes. To this end, we aimed to analyze a database containing a survey specifically focused on making-do waste at construction sites. A sample of 420 different kinds of waste was obtained, and 47 different guidelines applied to different work stages were created. The guideline with the highest number of occurrences was "Perform verification and inspection from the FVS before, during and after the execution of the service," while the most substantial number of propositions referred to waste whose missing prerequisites were "Information" and "Labor." When applied to the proposed methodology, these guidelines can become a strategic tool combined with production management that is aimed at minimizing waste.

KEYWORDS

Making-do waste; Guidelines; Production management; Civil Construction.

INTRODUCTION

The construction industry has always faced problems regarding deadlines, cost overruns, and waste generation, imposing negative impacts on the environment and excessive consumption of resources (Hussin et al., 2013). In general, it is assumed that there is a very high level of

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waste/non-value-added activities in construction. Moreover, several studies have confirmed that waste in the construction industry represents a relatively large percentage of the production cost (Aziz; Hafez, 2013).

However, waste in civil construction extends beyond the waste generated and can be understood as any inefficiency reflected in the use of materials, labor, and equipment in quantities surpassing what is necessary for building production (Santos et al., 1996).

A possible application to improve performance in construction processes while minimizing costs is applying the lean production system (Yücenur; Kaan, 2021). The principles of the Toyota Production System, developed by Ohno (1988), can be considered a major precursor of Lean Manufacturing. Koskela (1992) proposed the application of a new philosophy called Lean Construction in the construction sector.

The philosophy of Lean Construction proposes reducing waste and improvisations in production in search of a product of higher quality and lower cost (Santos; Santos, 2017). As a result, lean construction incorporates many dimensions and techniques that have become synonymous with lean production, such as just-in-time delivery, value stream mapping, and continuous process improvement (Small; Al Hamouri; Al Hamouri, 2017).

Ohno (1988) further expanded this work by identifying and categorizing the types of waste in production, divided into the following categories: waste of overproduction, waste of time on hand (waiting), waste in transportation, waste of processing itself, waste of stock on hand (inventory), waste of movement and waste of making defective products. In the context of civil construction, Koskela (2004) presents a new type of waste called making-do.

The term making-do is defined as the act of starting a task without ensuring that all necessary inputs (materials, tools, machines, people, external conditions, and information) are accessible or when the task continues to be executed despite one of the inputs being missing causing improvisations to occur in the execution of the service (Koskela, 2004).

According to Koskela (2004), among the consequences of making-do waste, the main highlights are reduced productivity, reduced worker safety and motivation, reduced quality, and rework. The investigation of different types of waste and their impact on the cycle time of construction processes has also been studied by other authors, for example, Sommer (2010) and Fireman (2012).

Despite lean philosophies being an emerging phenomenon in manufacturing and construction project management, the construction industry still needs to work on utilizing its full benefits, whether due to a lack of awareness or lack of application of clear strategies (Aslam et al., 2020). Measures to prevent or mitigate making-do waste processes have not yet been identified in the literature.

Previous works by Braga (2018) and Maciel (2020) addressed the identification and analysis of making-do waste. Amaral (2019, 2021, 2022) carried out studies on making-do waste together with a research group; in 2022, the author conducted research on a significant waste database to analyze the relationship between prerequisites, categories, and impacts.

Amaral et al. (2023) pointed out that only surveying losses due to making-do does not provide enough information for managers to completely prevent these losses from occurring in their next undertaking or task. According to the authors, a mere evaluation of impacts caused by 'making-do' waste is insufficient for a manager to prevent such issues in future ventures or tasks. However, it enables a more comprehensive and interactive information analysis to mitigate these different types of waste. The conclusion is that instead of directing efforts towards rectifying all incidents identified onsite, managers could optimize resources by focusing on stages, teams, and processes with the most significant impact, cost, or project delays. These efforts should include workforce retraining, investing in design and selecting materials and components to align with project specifications, adopting medium-planning methods to eliminate constraints, and ensuring continuous flow between interdependent tasks. Furthermore, it is crucial to evaluate risks related to the consequences of rework, which are directly associated with reduced productivity, material waste, unfinished work, and a decline in quality.

By continuing this area of research, the present work aims to fill a significant gap: namely, establishing guidelines to avoid the occurrence of making-do waste associated with a methodology for its application, that is, to define direct strategies to prevent the occurrence of making-do in the Civil Construction cycle. Such a strategy can help decision-making and assist in the production process at construction sites.

METHOD

This research was classified according to its approach, nature, objectives, and procedures.

Regarding the approach, the research is classified as qualitative, as the data will be analyzed and processed initially in a standardized spreadsheet, and subsequently, classifications and guidelines will be suggested.

Regarding the nature of the work, the research is applied because it is aimed at applicability in the construction industry, suggesting improvements in the analysis processes and waste reduction in construction sites.

Regarding the objectives and procedures, the research is classified as exploratory, as it aims to address the phenomenon under study and provide data and analysis to expand on previous and subsequent research.

The data was extracted by a research group comprising experts in production management, working in the construction market as Civil and Production Engineers responsible for on site decisions, as well as master's students from the Production Engineering Postgraduate Program at the Faculty of Science and Technology, and undergraduate students in Civil Engineering from the School of Civil and Environmental Engineering.

RESEARCH DESIGN

The study methodology for developing the work was designed in 5 stages presented in the flowchart in Figure 1.

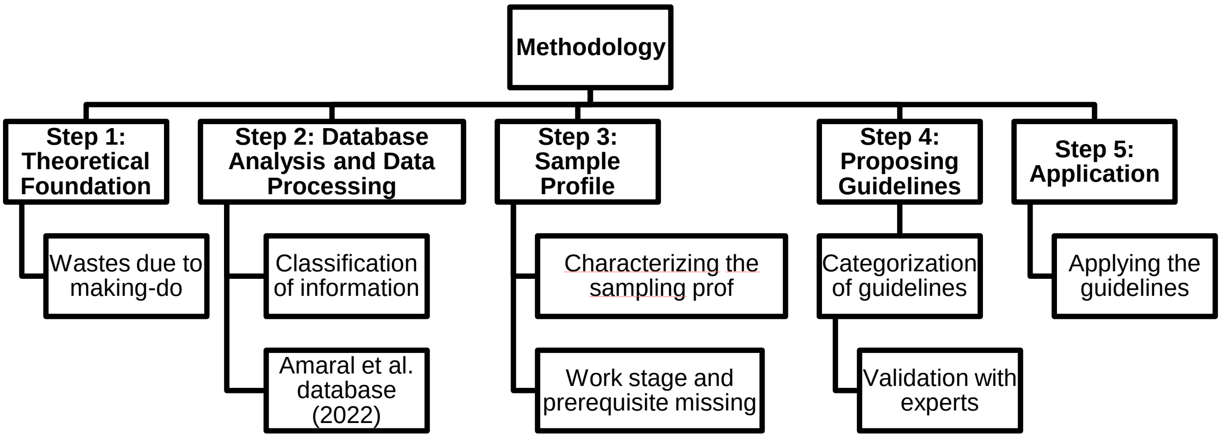

Figure 1: Research execution stages (Figure 1 source: the authors)

In Stage 1, the theoretical basis of the work was addressed, starting by studying the classification of different types of waste in the construction industry, their definitions due to making-do, and the reading of works developed to propose guidelines to minimize waste.

In Stage 2, we sought to process the database to identify the different kinds of making-do waste in 27 projects. The information refers to the database analyzed by Amaral (2022) and the survey carried out by the same research group in 2022.

The different types of waste identified in the projects by the research group encompass several processes, teams, and stages, which involved some research instruments such as questionnaires to characterize the companies, construction sites, and projects; questionnaires to investigate the planning process, semi-structured interviews carried out with production managers, members, directors; as well as document analysis (photos, drawings, drafts, notes, and documents) and web and mobile inspection tools (Amaral et al., 2019, 2022, 2023).

The study database surveyed 7,448 different types of making-do waste, already classified according to the work team involved, prerequisite, category, and impact, in addition to the problem description. To process the information, data lacking clear and complete descriptions of the loss were discarded. This was essential to ensure that the proposed guidelines could effectively manage the causes and impacts generated.

By considering the stage, sub-stage, and category associated with the loss, we were able to identify recurring instances of the same problems in the different studies. Thus, this approach allowed us to focus on analyzing the activities and identifying the missing prerequisites for the loss. As a result, we compiled a sample of 420 instances of waste, each occurring under different stages, sub-stages, and prerequisite conditions, drawn from 19 projects involving 15 companies.

Table 1 presents the characterization of the participating companies, designated by letters “A” to “O.” Information about companies and works from “A” to “K” refers to the database analyzed by Amaral (2022), while the other companies are part of the survey carried out by the research group in 2022.

Table 1: Characterization of companies (Table 1 source: the authors)

Company	City	Time in the market	Certifications	Company size
A	Goiânia -GO	15 years	-	Midsize
B	Goiânia -GO	40 years	PBQPH-level A	Large
W	Goiânia -GO	29 years old	ISO 9001:2015	Large
D	Goiânia -GO	24 years	ISO 9001:2008 and PBQPH- level A	Large
AND	Fortaleza-CE	39 years old	ISO 9001:2015 and PBQPH- level A	Large
F	Fortaleza-CE	40 years	-	Large
G	Goiânia -GO	24 years	ISO 9001:2008, ISO 14001:2004, OHSAS 18001:2007 and PBQPH- level A	Large
H	Goiânia -GO	22 years	ISO 9001:2008 and PBQPH- level A	Large
I	Goiânia -GO	35 years	ISO 9001:2015	Large
J	Tournefeuille - France	20 years	French Standardization Association AFNOR ABNT ISO 9001: 2015 and AFNOR ISO:14001	Midsize
K	Goiânia -GO	19 years old	PBQPH- level A	Large
L	Fortaleza-CE	14 years	-	Large
M	Fortaleza-CE	54 years	-	Large
N	Fortaleza-CE	15 years	PBQPH- level A	Large
O	Fortaleza-CE	-	-	Large

In Stage 3, the sample profile was characterized, observing the construction stage and the missing prerequisite of loss due to making-do. To help identify guidelines at different stages of the development of the work, Table 2 lists the steps considered in the database used with their sub-steps to better understand the scope of each activity analyzed.

Table 2: Steps listed in the database used and their respective sub-steps (source: the authors)

STAGE	SUB-STEPa
Coverings and Linings	Plasterboard Linings and Wooden Structure for Covering.
Hardware and Glass Frames	Smooth Transparent Glass, Wooden Frames, and others.
Structure	Superstructure, Infrastructure, and complementary works.
Facade	Facade Plastering, Ceramic Facade Coating, Facade Plastering, Facade Scaffolding, and Suspended Life-Saving Trays.
Waterproofing and Treatments	Kitchen waterproofing Drain waterproofing.
Infrastructure and Complementary Works	Reinforcements and Consolidations of Foundations, Deep Foundations, and Preparation of Foundations
Fire Fighting Installations	Fire extinguishers.
Installations and appliances	Electrical installations, Additional installations, Appliances and metals, Records, Countertops.
Electrical Installations	Boxes and Control Panels Wires and Cables Conduits Sockets and Switches Piping.
Sanitary, Hydraulic and Gas Installations	Sanitary Sewer Pipes and Connections, Cold Water Pipes and Connections, Piping
Temporary Installations and Machinery	Life Trays, Elevator with Tower/Cabin/Winch, Lifeline, Guardrails Deposits/Office, Temporary Water Installation Facade and Suspended Scaffolding, Work Location, Temporary Power Entry, Rack.
Cleaning and Transport	Permanent Cleaning and Cleaning of the Work.
Carpentry and locksmithing	Closing of Shafts, Fire Doors, Forms, Hood.
Other Facilities	Air Conditioning Installation, Elevator Installation, and Others.
Walls and panels	Masonry and panels, Frames and hardware Block Masonry, Solid Bricks, Plaster Plaster, Mortar Coatings, Contramarco, Internal Plaster Partition, Cobogó.
Skirting and Sill Flooring	Steps and Landings Straightened Concrete Subfloor Ceramic Skirting, Carpets and Rugs Ceramic Coverings/Tile Sills.
Coatings and finishes	Joinery and metalwork, Flooring, Coatings, Linings, and decorative elements.
Coatings and Paintings	Mortar Coatings, Ceramic/Tile Coatings, PVA Painting and Grouting.
Initial Services	Technical services, Machines, and tools.
Preliminary Services	Demolitions Licenses/Fees/Registrations.
Technical services	Architectural Project, Hydrosanitary Project, Structural Project, Electrical/Telephone Project.
Superstructure	Reinforced Concrete and Forms.
Land work	Manual Excavations.

In Stage 4, the guidelines were proposed, in which we sought to consolidate all the results found and define the guidelines. These classifications will support systematic analyses of the guidelines to minimize the causes of wastes.

The guidelines underwent a validation process involving a production management specialist, who addressed queries and suggested improvements. Once the adjustments had been made, the guidelines were taken to a second validation stage, in which the research group was responsible for collecting and organizing the losses that comprise the database used. Four group members took part in a formal validation meeting and suggested adjustments and improvements, which were accepted and, finally, the guidelines were validated. Table 3 below shows the guidelines drawn up for each project stage.

Stage 5 involves applying the guidelines proposed in the construction industry cycle based on a workflow suggestion applied to production management on the construction site

Table 3: Table with examples of guidelines drawn up for each stage of work (source: the authors)

PHASES	SOME SUGGESTED GUIDELINES
Walls and Panels	Training of labor on square, plumb and levels and trims, their checks, tolerances, and limits
Structure	Provide feedback on decision-making regarding the execution of the work. This information must be passed on to the responsible designers and registered as As Built.
Installations and appliances	Carry out training with employees on the use of materials within the quality standards of the service execution procedure, as well as verification by a responsible professional during the execution of the activity.
Coatings and finishes	Perform effective protection of definitive items and finished services
Temporary installations and machinery	The equipment maintenance plan, a daily safety checklist, and operation criteria must be implemented.
Coatings and Paintings	Application of FVM by sampling in all deliveries;
Superstructure	Make sure to carry out not the minimum number but the necessary number of geotechnical tests to obtain the best possible knowledge of the soil.
Flooring, Skirting, and Sills	Monitor FVS, concreting maps, and technological control tests
Electrical installations	Implementation of EPCs and PPE
Initial Services	Create a checklist or use software to list all the official documents required for the work and relate them to their expiration date, renewal period, and revisions.
Facade	Material request planning
Complementation of the Work	Inspect the workplace to allow activities to begin when the impacts of the activity on the work area must be assessed.
Infrastructure and Complementary Works	Carry out verification and inspection from FVS before, during, and after performing the service.
Hydraulic, Sanitary, and Gas Installations	Predict the positioning of all pipes before concreting components

Table 3 (continued): Table with examples of guidelines drawn up for each stage of work (source: the authors)

PHASES	SOME SUGGESTED GUIDELINES
Technical services	Carry out alternative planning for critical cases in which the execution of services is prevented due to unforeseen conditions, listing alternative companies and machinery that could meet the new needs of the work.
Device Installation	Plan an executive service procedure that optimizes the tasks and executive sequence requested in the project.
Cleaning and Transport	Conduct training with employees and implement procedures for ending work, cleaning, and organizing the workplace.
Carpentry and locksmithing	Develop procedures for operating equipment and verify project information and guidelines in accordance with NR18.
Other Facilities	Make sure there is compatibility and clash detection of all subjects
Preliminary Services	Carry out periodic training of the workforce (monthly or bimonthly) according to the greatest needs and execution flaws, promoting qualification and also generating social value for the enterprises.
Frames, Hardware, and Glass	Make sure that the most updated and corrected version of the project is on-site and that it has all the information necessary to carry out the service, site on-site, and that it has all the information necessary to carry out the service before releasing the start of its execution.
Coverings and Linings	Carry out training with employees on the use of materials within the quality standards of the service execution procedure, as well as verification by a responsible professional during the execution of the activity.
Waterproofing and Treatments	Carry out verification and inspection from FVS before, during, and after performing the service.
Fire Fighting Installations	Carry out an inspection before starting activities, check the comfort and safety of the workplace, as well as training to issue the work permit.
Land works	Make sure that the most updated and corrected version of the project is on-site, and that it has all the information necessary to carry out the service before releasing the start of its execution.
Technical services	Carry out alternative planning for critical cases in which the execution of services is prevented due to unforeseen conditions, listing alternative companies and machinery that could meet the new needs of the work.
Device Installation	Plan executive service procedure that optimizes the tasks and executive sequence requested in the project.
Cleaning and Transport	Conduct training with employees and implement procedures for ending work, cleaning, and organizing the workplace.

RESULTS AND DISCUSSIONS

Based on the analysis of 420 different types of making-do waste, it became feasible to verify the work stages with the highest occurrences. Figure 2 shows the steps and number of different types of waste identified.

Based on the approach proposed in characterizing the sampling profile, the missing prerequisite responsible for the occurrence of each loss was verified. Figure 3 presents the prerequisites of the data studied for proposing the guidelines.

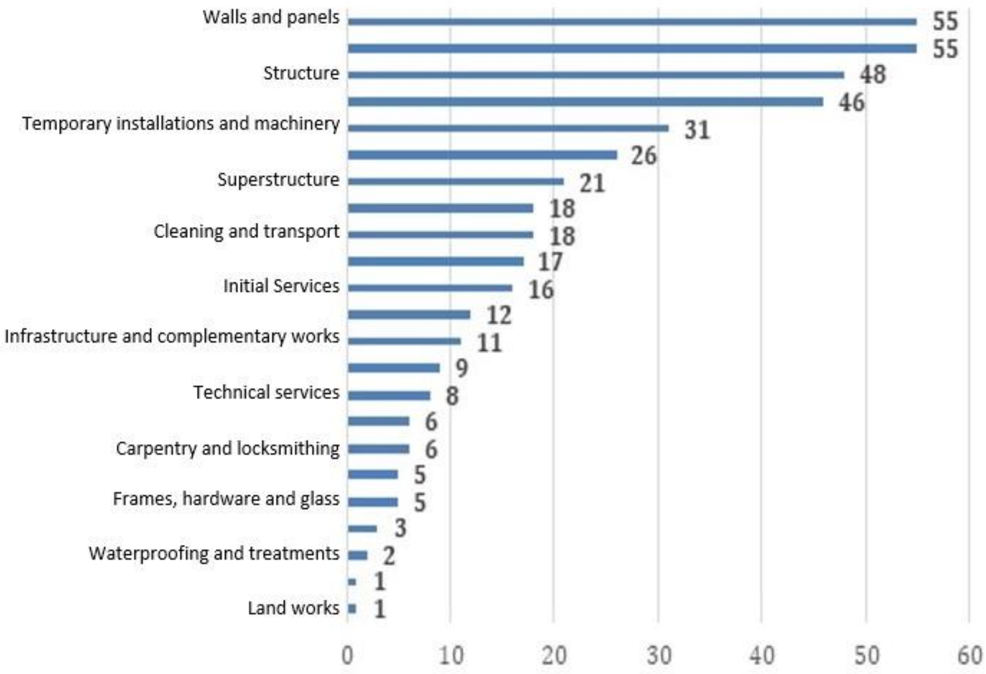

Figure 2: Different types of making-do waste analyzed by the activity stage (Figure 2 source: the authors)

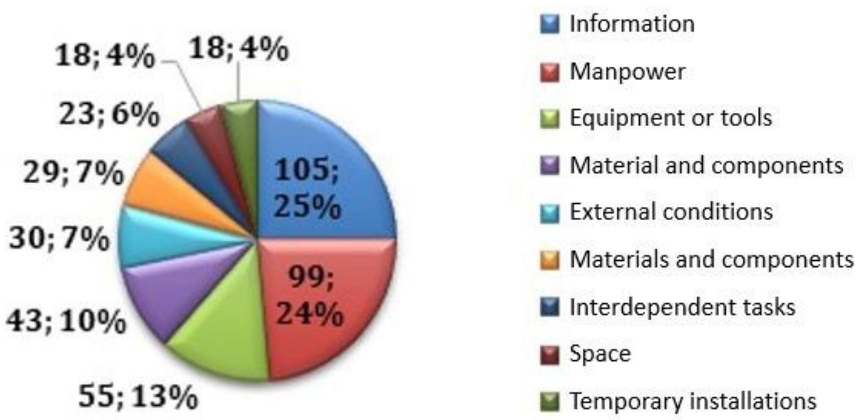

Figure 3: Occurrence of missing prerequisites for different kinds of making-do waste (Figure 3 source: the authors)

In the proposing guidelines stage, the aim was to evaluate all the information provided on the loss occurrence and consolidate all the results found to define the guidelines. These classifications supported the systematic analysis of the guidelines to act on the causes of the loss occurrences. After they were drawn up, the guidelines went through a validation process with a specialist in production management, who suggested improvements and clarified doubts by consulting the guidelines. Once the adjustments suggested by the specialist had been made, the guidelines were taken to a second validation stage, this time with the research group responsible for collecting and classifying the losses that make up the database used in this work. Four group members took part in a focal meeting for discussions and validation and suggested adjustments and improvements, which were carried out, and finally, the guidelines were validated. Thus, one or more guidelines capable of preventing the loss from occurring were proposed. In total, 47 guidelines were created, applied to 420 different types of waste, resulting in 916 propositions in the database. Table 4 presents five guidelines with the highest number of occurrences.

Table 4: Guidelines with the highest number of occurrences in the different types of waste analyzed (Table 4 source: the authors)

PROPOSED GUIDELINE	NUMBER OF OCCURRENCES	PERCENTAGE OF APPLICATIONS AMONG THE PROPOSITIONS
Carry out verification and inspection from FVS before, during, and after performing the service.	203	22.16%
Carry out periodic training of the workforce (monthly or bimonthly) according to the greatest needs and execution flaws, promoting qualification and generating social value for the enterprises.	124	13.54%
Make sure that the most updated and corrected version of the project is on-site, and that it has all the information necessary to carry out the service before starting its execution.	82	8.95%
Perform adequate protection of definitive items and finished services.	44	4.80%

It was observed that the same guideline could be applied to different stages of work to avoid a given loss due to making-do. Given the stages of work with the most significant occurrence of waste, Annex 1 shows an example of a guideline ready for each stage.

As a suggestion to implement the proposed guidelines, Figure 4 presents the application of the developed guidelines in the form of a workflow, that is, a flow of actions that will allow the use of these guidelines. This methodology involves its application from professionals on the service fronts to the management team, which can, in addition to constituting a mechanism for "attacking" the causes of making-do, contribute to forming a preventive and rationalized mentality that will permeate all hierarchical levels of companies.

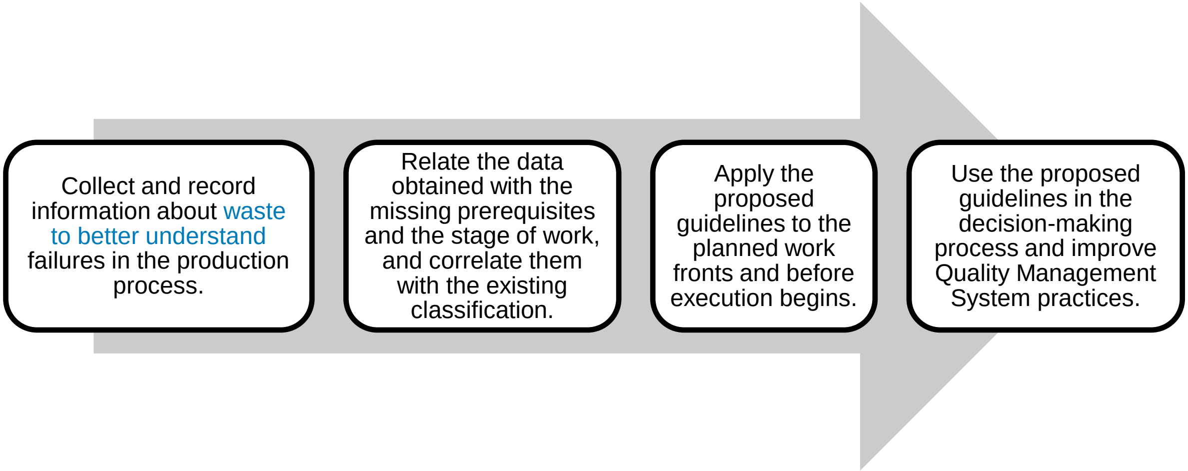

Figure 4: Workflow with a proposed methodology for applying the guidelines developed in this work (Figure 4 source: the authors)

The first step in implementing the proposed methodology involves collecting and recording detailed information about the waste identified during production. This data is essential for an in-depth understanding of the faults that can occur in the process itself. Next, it is necessary to relate the data obtained from the missing prerequisites and identify the specific stage of the construction where these occurred, correlating this information with the existing classification of the identified problems. Next, the obtained data needs to be correlated from the missing prerequisites and the specific stage of the work in which they occurred should be identified. This information is then correlated with the existing classification of the identified problems.

Once the data and correlations have been established, the proposed guidelines must be applied proactively on the planned work fronts before execution begins. This ensures that the recommendations are integrated into the process from the outset, facilitating identifying and preventing potential problems. In addition, the guidelines should be used as part of the decision-making process to improve Quality Management System practices.

CONCLUSION

The present work proposed to outline a methodology capable of preventing the occurrence of making-do waste . Based on data collected at various construction sites, guidelines were drawn up that, when applied, can become a strategic tool combined with production management increasingly free from waste and waste.

Guidelines were developed for 420 types of waste that occurred at the most diverse stages of the work and classified with the most varied missing prerequisites, categories, and impacts. As can be seen in Figure 3, 105 (25%) of the different types of waste with developed guidelines refer to those whose missing prerequisite was Information. The interpretation of this data shows the importance of not only the management team and the construction team having access to all necessary information to carry out each task. This access helps avoid rework, productivity reduction, incomplete tasks, as well as demotivation and other negative impacts (Sommer, 2010; Fireman, 2012).

The guideline with the highest number of occurrences was “Perform verification and inspection from the FVS before, during and after the execution of the service”. This shows the scope that this action can have as the existence of a Management System Effective Quality Management, which includes the assertive application of Service Verification Sheets, permeates all stages of the work, and can eliminate a large amount of waste.

It can also be seen from Figure 2 that 55 (13%) of the types of waste for which guidelines were developed refer to waste that occurred in the Walls and Panels stage, which also highlights the importance of evaluating and applying guidelines in this stage of work. This can contribute to the reduction of inefficiencies or waste during this stage.

Finally, we proposed a methodology tailored to the everyday operations of Civil Construction, drawing from the established guidelines, which were initially validated by a specialist and subsequently by members of the research group responsible for compiling the database used in the present work. This proposed methodology is based on four steps: collecting and recording information about waste during the production process to better understand the failures; then relating this data to missing prerequisites and identifying the stage of the work where they occurred, correlating with the classification of problems; then applying the proposed guidelines before carrying out the work to prevent any type of waste. Finally, the guidelines should be used in the decision-making process to minimize the occurrence of production losses. All this sequencing should be used in the documentary systems of the Quality Management System.

However, it is essential to stress that the management team must also comprehensively analyze the limitations and advantages of the proposed guidelines within their company, recognizing the variation in levels of education, standardized practices and executive processes applied to the context involved. It is also crucial for managers to ensure that the guidelines' viability and effectiveness can be questioned in environments where building systems and procedures differ significantly. For example, adopting certain practices may face obstacles in places where the workforce is less specialized or where procedures are less comprehensive. Therefore, the management team must assess the need to adapt their proposals to local conditions and carefully consider the various factors that influence success.

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THE INFLUENCE OF PRECONSTRUCTION PHASE AND LEAN CONSTRUCTION IMPLEMENTATION ON PROJECT PERFORMANCE

Munther Hamaidi [1], Nour Ghandour [2], Mohammad Abdel Hadi [3] and Ayman Naser[4]

ABSTRACT

Effective design management during the preconstruction phase has significant effects on project performance within the Architecture, Engineering, and Construction (AEC) sector. This research examines critical factors that impact the design outcomes at the preconstruction phase in the construction of infrastructure projects which affect the overall project performance. Using a sequential hybrid research approach that combines qualitative interviews and quantitative surveys, this study identifies ten crucial factors that influence project performance during the preconstruction phase. The relative importance index (RII) method is used to prioritise these factors, emphasising the most influential areas for enhancement. This study investigates the use of lean construction (LC) principles and tools to minimize the impact of these factors. These tools include integrated project delivery (IPD), building information modelling (BIM), last planner system (LPS), value stream mapping (VSM), target value design (TVD), set-based design (SBD), and choosing by advantage (CBA). Authors propose a comprehensive Lean Construction-based Risk Mitigation (LC-RM) framework to integrate these methodologies and enhance the design process during the preconstruction phase, thereby improving overall project performance. This research makes a valuable contribution to the field of construction management by providing practical recommendations for effective decision-making and lean practices during the preconstruction phase. It serves as a preliminary step towards improving construction management processes and has the potential to be further explored in future studies.

KEYWORDS

Lean construction, Design management, Preconstruction, Risk mitigation, Critical factors, Infrastructure construction project

INTRODUCTION

Poor design management (DM) in construction projects can have significant negative impacts on various aspects of the project, including cost, schedule, quality, and overall project success (Pikas et al., 2019). The most effective and efficient method for managing the design during the preconstruction phase is still unclear (Niranjan et al., 2022). The architecture, engineering, and construction (AEC) industry is well-known for its dynamic and unpredictable nature, which presents challenges in achieving effectiveness. Effectiveness, as conceptualised by scholars,

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pertains to the efficient allocation of resources necessary for the successful execution of a given task (Gholinezhad Dazmiri & Hamzeh, 2023). According to Koskela (2000), the main objective of improving productivity within the context of LC is to reduce waste and enhance value. The AEC sector generates a substantial quantity of waste. In recent years, the organisation has been utilising lean tools such as the LPS in order to reduce waste (Skaar et al., 2023). Within the framework of lean principles, waste is operationally defined as the suboptimal utilisation of machinery, supplies, personnel, or other valuable resources, leading to the inappropriate allocation of time, financial resources, or other valuable assets (Skaar et al., 2023). As per Koskela (2000), it denotes any task or asset that does not add value to the final product. According to Aslam et al. (2020a), waste in design can be defined as any activity that results in the depletion of resources without providing any value. Time measurement is a crucial metric for assessing waste, particularly when determining the proportion of tasks that do not add value. According to Aslam et al. (2020b), waste during the design phase can arise due to various factors such as delays, waiting times, design flaws, excessive processing, and negative iteration or rework. The presence of these waste materials can significantly affect construction projects, as design errors are the primary factor contributing to the decrease in both cost and value (Tzortzopoulos et al., 2020). Tzortzopoulos et al. (2020) posit that the incorporation of rework and non-value-adding activities within the design process has the potential to prolong the duration of the design phase and give rise to delays. The delays mentioned above can be attributed to various factors, such as the delayed acquisition of design information, frequent modifications to the design, alterations in the timing and order of the implementation, fluctuations in demand, and insufficient design efforts (Naji et al., 2022a; Salam et al., 2023). As a result, it is critical to engage in thorough design management (DM) planning during the preconstruction stage of the infrastructure project in order to ensure its long-term success. This is because DM planning has a significant influence on multiple factors, including client satisfaction and operational and maintenance expenses (Chaize et al., 2022). Hasty designs, design processes, and DM practices are the root causes of many persistent production and construction challenges (Naji et al., 2022b&c). Naji et al. (2022b) identified design errors as the primary cause of structural failures, time and cost overruns, and catastrophic accidents in building construction and maintenance. Inadequate designs may give rise to the need for rework, change orders, and preliminary estimates, thereby potentially resulting in excessive expenditure or project delays. The AEC sector widely acknowledges the aforementioned concerns as prominent contributors to waste (Naji et al., 2022a, b, c)

Previous studies seek to improve the design process during the preconstruction phase in the AEC industry, with particular emphasis on integrating design with advanced technology like BIM to enhance efficiency (Gholinezhad Dazmiri & Hamzeh, 2023; Gunduz et al., 2023), focusing on developing a framework to facilitate early supplier involvement as an approach for reducing construction waste generated during the design process (Othman & El-Saeidy, 2024), investigating only the activities related to early contractor involvement (Memić et al., 2023), targeting preconstruction phase management practices (PCMPs) that can improve labor productivity in multistory building projects (Tarekegn Gurmu, 2023), focusing on the financial aspect of collaboration but undervalued the social dimension which reflects behavioral actions that can lead to goal misalignment (Salam et al., 2023), supporting a visual model with design parameters that are specific to manufacturing to reduce waste in the design stage of a construction project (Cardenas Castaneda et al., 2022), focusing on collaborative decision-making process in the design phase (Schöttle et al., 2018), and developing an initial framing for design process support systems to facilitate the error and knowledge management (Pikas et al., 2019).

According to Lin and Golparvar-Fard (2021), lean is a management methodology that adopts a proactive approach to planning. This approach entails the early identification of constraints to prevent their occurrence during the execution phase. The transformation of the aforementioned limitations into potential risks and inefficiencies significantly impacts the entire lifespan of the construction project (Bajjou & Chafi, 2020). Therefore, various scholarly sources in the field of construction management (Naji et al., 2022b&c) provide a comprehensive analysis of the quantification of performance factors in project management. Construction companies are prioritizing efficient DM and implementing more stringent strategies to evaluate it in order to create preventive measures and improve performance during the preconstruction phase (Naji et al., 2022a). The prompt identification of outcome measures and risk factors linked to DM can aid in mitigating these effects and diminishing the probability of a construction project encountering cost and schedule repercussions.

KNOWLEDGE GAP AND POINT OF DEPARTURE

The literature review reveals that inadequate design management during the preconstruction phase has a significant impact on the overall performance of a project. The authors contend that the current frameworks pertaining to enhancing DM during the preconstruction phase of infrastructure exhibit various limitations. Furthermore, the main reason for these limitations is the absence of a comprehensive lean construction-based risk mitigation framework (LC-RM) that encompasses the global perspective of design management activities during the preconstruction phase (Naji et al., 2022b) (Salam et al., 2023). This framework should encompass the most effective practices, factors contributing to success, and operational procedures that can be implemented in infrastructure projects. Therefore, the primary objective of this study is to investigate the monitoring of performance factors related to design management in order to mitigate the impact of design management during the preconstruction phase and enhance the overall performance of infrastructure projects. Additionally, it aims to explore the potential applications of the study's findings for construction management practitioners, with the goal of proactively addressing and minimising adverse design modifications during the preconstruction phase of infrastructure projects. Hence, the primary aims of this research endeavour encompass the identification of pivotal factors that contribute to suboptimal design outcomes, the evaluation of their significance in impacting project performance, and the proposition of a LC-RM framework to address the existing research gap.

METHODOLOGY

The chosen research methodology is derived from the sequential hybrid approach proposed by Naji et al. (2022c), which involves the collection, interpretation, and modelling of both qualitative and quantitative data. Figure 1 visually represents this approach. The research methodology consists of four phases, namely: (1) identification of the critical factors resulting in poor design outcomes; (2) questionnaire and data collection; (3) data analysis and discussion; and (4) conclusion. Phase one deals with identifying the key factors that contribute to subpar project performance and are associated with unsatisfactory design outcomes; a set of semi-structured interviews with eight construction experts as a pilot-based study (Naji et al., 2022b) to validate the identified factors; and the development of the initial questionnaire of the study. Literature research was undertaken to discover the critical factors, which consisted of three phases: journal selection, article selection, and paper analysis. Using databases such as Scopus, The International Group for Lean Construction (IGLC), the American Society of Civil Engineers (ASCE), Taylor & Francis Online, the International Journal of Project Management (IJPM), IEEE Xplore library, Elsevier, and Emerald, the first stage involved a thorough selection of highly ranked publications in construction engineering and management research.

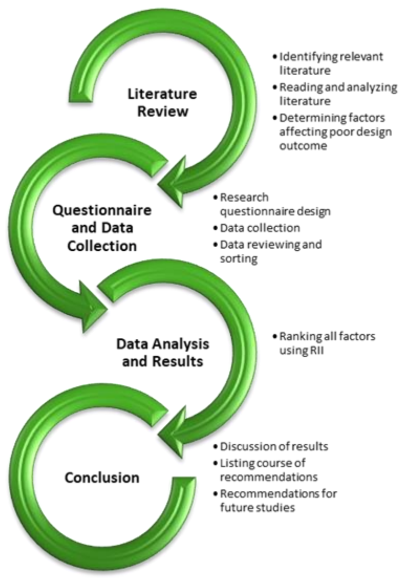

Figure 1: Research Methodology Stages

The second stage involved identifying relevant papers published between 2014 and 2024, based on their titles, abstracts, and keywords. “lean construction”, “design phase”, “infrastructure project”, “lean in design stage”, “successful factors in design stage,” and “design management” were among the terms used in the study. Papers were chosen based on the following criteria: (1) the paper should be specifically related to DM with the goal of mitigating the impact of poor DM; (2) the paper should discuss techniques and tools for controlling and managing DM with an emphasis on application in the field of construction management; and (3) the paper should use a unique assessment technique. Consequently, the review has identified 10 key factors that significantly contribute to the subpar performance of projects. Table 1 displays a comprehensive list of these factors, accompanied by their corresponding references.

The second phase involved the developing the questionnaire and the collecting data. The questionnaire was developed to gather data on the relative significance of the predetermined factors. After finalising the questionnaire design, the sample size was determined, and the data was gathered and organised. The questionnaire was divided into three parts, namely general information, the importance of lean implementation at the preconstruction phase, mainly the design phase and its influence on the project performance, and the level of importance of design management factors influencing the project performance.

Naji et al. (2022b) recommend aiming for a sample size of at least 100, preferably exceeding 200. As per Naji et al. (2022b) findings, the sample size should be sufficiently large to maintain a ratio of observations to estimated parameters of 1:5. In the context of this study, this implies that a minimum sample size of 50 is required. The sample size of the population is determined to be 96, using a confidence interval of 95% and a margin of error of 10%, according to the equation provided below.

$$Sample\ Size = \frac{\frac{z^2 * p\ (1-p)}{e^2}}{1 + (\frac{z^2 * p(1-p)}{e^2 * N})} \qquad (1)$$

Table 1: 10 critical factors that contribute to both poor project performance and a subpar design outcome

Code	Factor	References
DES1	Improper defining of client value/ need	(Aslam et al., 2020b) (Mahamid, 2021) (Osamudiamen et al., 2022)
DES2	Insufficient and unrealistic constraints on project cost	(Schöttle et al., 2018) (Aslam et al., 2020b) (Osamudiamen et al., 2022)
DES3	Insufficient and unrealistic constraints on project time	(Schöttle et al., 2018) (Aslam et al., 2020b) (Naji et al.,2022c)
DES4	Lack of information for project full scope	(Naji et al.,2022c) (Aslam et al., 2020b) (Mahamid, 2021) (Salam et al., 2023)
DES5	Lack of awareness of local market	(Naji et al.,2022c) (Mahamid, 2021) (Schöttle et al., 2018) (Salam et al., 2023)
DES6	Individual decision making of design conflicts	(Pikas et al., 2019) (Osamudiamen et al., 2022) (Pikas et al., 2020)
DES7	Making design decision based on cost rather than the value of work	(Pikas et al., 2019) (Pikas et al., 2020) (Naji et al., 2022c)
DES8	Inadequate coordination meeting with other stakeholders	(Aslam et al., 2020b) (Naji et al., 2022c) (Mahamid, 2021) (Salam et al., 2023)
DES9	Lack of constructability review of design	(Pikas et al., 2019) (Naji et al., 2022c) (Assaf et al., 2023) (Gunduz et al., 2023)
DES10	Inadequate involvement of construction experts during design	(Naji et al., 2022c) (Salam et al., 2023) (Gholinezhad Dazmiri & Hamzeh et al., 2023)

Where z is the number of standard deviation a given proportion is away from the mean which is related to the level of confidence, p the population proportion, e the margin of error and N the population size.
The study includes a total of 111 participants, surpassing the minimum requirement in all instances. The questionnaire was disseminated as an online survey in response to limitations on conducting in-person interviews imposed by various organisations. The third stage involved conducting data analysis using the Relative Importance Index method (RII) to identify the primary factors causing poor project performance.

The final phase involved formulating recommendations that could enhance productivity and project delivery, as well as address the triple constraints (i.e., time, cost, and scope) in infrastructure projects. These recommendations pertain to all individuals and groups who are accountable for subpar performance and design results.

DATA COLLECTION AND ANALYSIS

The data was collected through an online questionnaire survey that was distributed using the SurveyMonkey platform. The researchers employed the nonprobability sampling technique to select potential participants, which involves using non-random methods to gather the sample (Naji et al., 2022a). The study employs purposive sampling, a method that involves selecting participants based on specific criteria or their knowledge of particular phenomena. The questionnaire survey was disseminated to over 200 participants in the State of Qatar who possess expertise and familiarity in lean construction, design, engineering, and construction projects through the assistance of industry experts, personal connections, and social media platforms. 116 individuals have participated in the survey, with 5 responses being excluded due to incompleteness. This leaves us with a total of 111 complete responses. The questionnaire was disseminated among various categories of organizations, including clients, designers, consultants, and contractors, to mitigate any potential bias in data collection. In part 1, the respondents were asked to provide information about their backgrounds. In part 2, rate the influence of the lean approach at the design phase on the project performance using a five-point Likert scale with the following numbers and corresponding answers: 1 = not at all important; 2 = slightly important; 3 = moderately important; 4=very important; and 5=extremely important. In the last part of the questionnaire, the respondents were asked to rate the level of importance of design management factors that influence the project performance using the same Likert scale. The ratings were analyzed utilizing a systematic approach employing quantitative statistical results to guide the next step in data collection.

RESULTS

RESPONDENT DEMOGRAPHICS

The responses include executive managers, department managers, project managers, infrastructure facility managers, senior design engineers, construction engineers, and quantity surveyors in the private and public sectors using a variety of parameters, including years of experience, working division, organization type, and position. Most of the respondents were international experts and practitioners from the public and private sectors, representing a wide range of experience and backgrounds in infrastructure projects. For example, the distribution of respondents based on years of experience was nearly equal, except for those with 11 or more years of experience who constituted the majority, accounting for approximately 65%. Figure 2 depicts a summary of the respondents' years of experience. Figure 3 demonstrates that approximately 56% of the respondents were highly or exceedingly knowledgeable about LC, while roughly 33% had a moderate level of familiarity. This demonstrates that the survey respondents were knowledgeable about the subject and were able to understand and respond accurately to the survey questions. As a result, the gathered data are deemed to be sufficient for experienced respondents in this sort of perception study to reach a sound judgment.

DATA ANALYSIS

Using the Relative Importance Index (RII) method, which ranks the influence of various factors on poor project performance, the data were analysed. Afterwards, the five most important factors are selected as the main areas for improvement using the lean approach during the design phase. In their study, Naji et al. (2022a) demonstrated that the RII is a highly efficient approach for analysing questionnaire data and precisely prioritising factors or variables. The RII value, which ranges from 0 to 1, represents the extent of influence on the dependent variable, with higher values indicating a stronger impact. Equation 2 calculates the RII.

$$RII = \frac{\sum W}{A * N} = \frac{5n_5 + 4n_4 + 3n_3 + 2n_2 + 1n_1}{5 * N} \quad (2)$$

Where W is the weight value (ranging from 1 to 5) given by respondents to each factor, in where 1 represents “Not at all Important” and 5 represents “Extremely Important”. A is the highest weight value which is 5 in this case, and N is the total number of responses. However, n is the number of responses to each weight value.

Table 2 presents a summary of the RII value and ranking outcome for the level of significance of the ten identified factors. It has been observed that factors DES9 and DES10 have identical RII values. Further examination revealed that the descriptions of these two factors essentially convey the same point: the insufficient involvement of construction experts during the design phase.

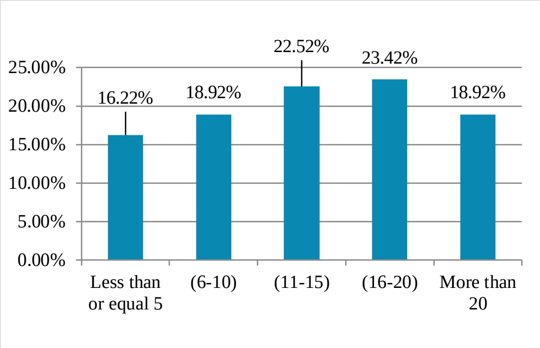

Figure 2: Respondents' years of experience

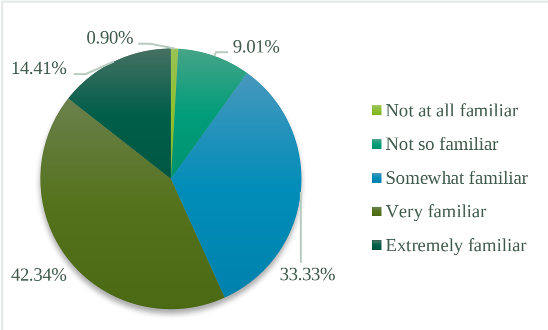

Figure 3: Participant's self-reported level of awareness regarding lean construction

Table 2: RII Value and Ranking Results for DM factors

Code	Factor	RII	Ranking
DES4	Lack of information for project full scope	0.838	1
DES1	Improper defining of client value/ need	0.818	2
DES3	Insufficient and unrealistic constraints on project time	0.811	3
DES9	Lack of constructability review of design	0.810	4
DES10	Inadequate involvement of construction experts during design	0.809	5
DES2	Insufficient and unrealistic constraints on project cost	0.806	6
DES8	Inadequate coordination meeting with other stakeholders	0.798	7
DES6	Individual decision making of design conflicts	0.785	8
DES7	Making design decision based on cost rather than the value of work	0.766	9
DES5	Lack of awareness of local market	0.742	10

DISCUSSION

The result of questionnaire shows the implementing lean practices has a greater impact on project performance during the preconstruction phase, in design phase. Table 3 illustrates the influence degree categorized by various types of organizations. The feedback from the client, consultant, and contractor revealed that the influence of lean principles in design varied from moderate to high. In contrast, the responses from the designers indicated a range of impact from slight to moderate. However, a substantial 76% of all participants hold the belief that integrating lean practices during the design phase has considerable significance, ranging from moderate to extremely crucial. Lack of information for the full scope of the project is the highest RII, which is considered a critical factor to be considered during the development the design in the preconstruction phase to avoid change orders during construction. The outcome is in-line with the outcome of Naji et al. (2022c) study to manage the change-orders. Improper defining of client value is the second RII has been highlighted in Cardenas Castaneda et al. (2022) paper, as one of the wastes during the design phase has to be mitigated. The third RII factor concerns about the inadequate and unrealistic constraints on project time that have been assigned for some activities, which may affect the project duration. The same has been considered a significant and top ranked delay factor in Mahamid (2021) study.

Table 3: The influence of implementing lean principles during the design phase on project performance, with respect to the type of organization

	Level of Impact (%)				
Organization Type	**Extreme Impact**	**Highly Impact**	**Moderate Impact**	**Slightly Impact**	**No Impact at all**
Client	8.33	41.7	41.67	0.00	8.33
Consultant	11.36	40.9	31.82	13.64	2.27
Contractor	5.13	51.3	28.21	12.82	2.56
Designer	0.00	25.0	37.50	37.50	0.00

Moreover, inadequate involvement of construction experts during design phase plays a vital role in minimizing the design error and installation priority. This waste can be avoided and considered during the design phase as highlighted in Gholinezhad Dazmiri & Hamzeh et al. (2023), and Aslam et al. (2020a) as the main lean successful factors to avoid time and cost wastes during the project design. Besides, insufficient and unrealistic constraints on project cost as a sixth RII has a bad impact during the construction that has to be controlled during the design phase as mentioned in Osamudiamen et al. (2022) study.

DEVELOPING A MITIGATION MODEL USING LEAN TOOLS

The processes of the initial two stages, namely initiation and design, have been dissected to fulfil the objective of this research. Figure 4 illustrates the use of process mapping to depict the sequential stages involved in any new construction project. The visual lean tool facilitates the identification of problematic processes that require improvement. Hence, the Kaizen burst icon is utilized to indicate the processes where the six most influential factors affecting project performance are present (highest RII). These processes include identifying the client's needs, developing a comprehensive project cost, creating a detailed project schedule, defining the scope of work for the project, and selecting the project delivery method. This paper aims to identify various lean construction tools and analyze their application to improve the processes. Table 4 provides a summary of various lean construction tools and methods that can effectively mitigate the influence of the six factors.

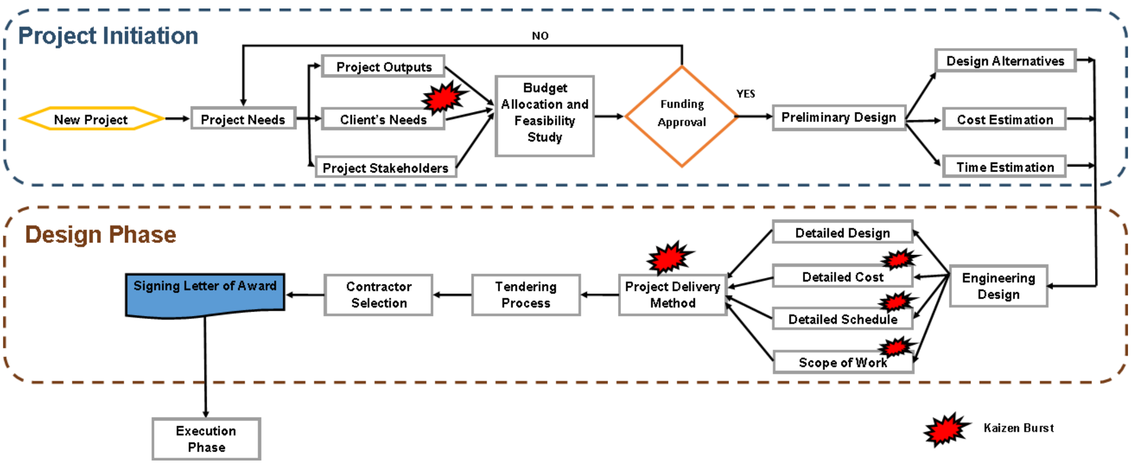

Figure 4: Process map of construction project phases and processes

Each lean tool is utilized and assigned to eliminate the impact factors in Table 4 has the potential to significantly improve the performance of construction projects, during the design phase. That can contribute to mitigating the critical impact factors during the design phase in the following approach:

Table 4: Summary of LC tools for mitigating critical factors affecting the design phase

Lean Tool	Definition	Factors
Integrated Project Delivery (IPD)	A tool that creates a better system of collaboration and communication between the various parties involved in a construction project, from the owner to the designer to the builder and any suppliers involved.	DES 2, DES 3, DES 9 and DES10
Building Information Models (BIM)	A modelling technology and associated set of processes for producing, communicating, and analysing project models.	DES 2, DES 3 and DES 4
Last Planner® System (LPS)	System for project production planning and control, aimed at creating a workflow that achieves reliable execution.	DES 6, DES 8, DES 9 and DES 10
Value Stream Mapping (VSM)	A tool to analyse and identify any weaknesses or waste sources within a complete process.	DES1
Target Value Design (TVD)	A complex system that includes the project definition, design, and construction stages. (Architecture, Engineering, and Construction)	DES1
Choosing by Advantages (CBA)	A tested and effective sound decision-making system to determine the best decision by looking at all the advantages of each option.	DES 6 and DES 7
Set-Based Design (SBD)	A method that keeps requirements and options flexible for as long as possible in design.	DES 5
Lessons Learnt for Continuous Improvement Cycle	Valuable knowledge and experiences gained leveraged for the benefit of future projects.	DES 9 and DES 10

- **Integrated Project Delivery (IPD):** fosters collaboration among key stakeholders (owner, architect, contractor, etc.) from the early stages of a project. It encourages shared risk and rewards, aligning everyone's goals towards project success. By integrating various perspectives and expertise, IPD can lead to more efficient decision-making and problem-solving during the design phase (Assaf et al., 2023).
- **Last Planner System (LPS):** focuses on detailed planning and coordination of tasks, particularly in the construction phase. However, it can also be applied during the design phase to identify dependencies, constraints, and milestones. By breaking down design tasks into manageable chunks and establishing reliable workflows, LPS can improve the efficiency and reliability of the design process (Tzortzopoulos et al., 2020).
- **Building Information Modeling (BIM):** enables the creation of digital representations of a building's physical and functional characteristics. During the design phase, BIM facilitates collaborative design, visualization, and simulation, helping stakeholders better understand the project's scope and requirements. By providing a centralized platform for information exchange, BIM reduces errors, conflicts, and rework, thus improving project performance (Gunduz et al., 2023).
- **Value Stream Mapping (VSM):** is a lean management tool used to analyze and improve processes by identifying value-added and non-value-added activities. Applied

to the design phase, VSM can help identify inefficiencies, bottlenecks, and opportunities for optimization. By streamlining design workflows and eliminating waste, VSM can enhance the overall efficiency and effectiveness of the design process (Gunduz & Fahmi Naser 2017).

- **Target Value Design (TVD):** is a collaborative approach that aims to achieve project goals within a predefined budget. During the design phase, TVD involves setting clear cost targets and continuously evaluating design decisions against these targets. By aligning design decisions with budgetary constraints, TVD helps prevent cost overruns and ensures that the project delivers value to the owner (Kim et al., 2023).
- **Set-Based Design (SBD):** involves exploring multiple design alternatives simultaneously before converging on a final solution. During the design phase, SBD encourages creativity, innovation, and risk management by considering a range of possibilities. By promoting flexibility and adaptability, SBD increases the likelihood of finding optimal design solutions that meet project objectives (Lee et al., 2012).
- **Choosing by Advantage (CBA):** is a decision-making framework that helps prioritize design alternatives based on their advantages and disadvantages. During the design phase, CBA enables stakeholders to evaluate design options systematically, considering factors such as cost, performance, and sustainability. By facilitating informed decision-making, CBA ensures that design choices align with project goals and contribute to overall performance improvement (Dahmani et al., 2023).

Integrating these methodologies throughout the design phase, a lean construction-based risk mitigation model is developed and will enhance the performance of construction projects by fostering collaboration, efficiency, cost-effectiveness, and innovation.

CONCLUSIONS

DM plays a vital role in the AEC industry, particularly during the preconstruction phase, because it has a significant impact on project performance. Preconstruction design management enhances the chances of success in construction projects. A thorough review of the existing literature and an empirical investigation have identified ten critical factors that contribute to poor project performance. The research methodology used a sequential hybrid approach to collect and analyse qualitative and quantitative data. Semi-structured interviews with construction industry experts and practitioners were conducted, as well as an online survey, yielding a comprehensive dataset for analysis. The use of the RII method enabled the identification and prioritization of critical project performance factors, resulting in practical and operational recommendations for improving performance. The study uses LC principles to demonstrate how lean tools and methods can mitigate the identified factors while improving project performance. The proposed framework is a comprehensive approach based on LC principles for risk mitigation during the pre-construction phase, combines lean principles such as VSM, TVD, and SBD with collaborative approaches such as IPD, BIM, and CBA to simplify design processes, maximize resource utilization, and foster innovation. The study enhances construction management by presenting a practical framework for improving project performance through effective decision-making and lean practices during the preconstruction phase, which can be expanded on in future research.

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AN AI COPILOT FOR MAKE-READY PLANNING IN THE LAST PLANNER SYSTEM

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ABSTRACT

Many challenges in partial Last Planner System implementations can be attributed to the underutilization of Make-Ready Planning, although other factors also play a role. Failing to identify constraints in time to prevent Reasons for Noncompliance (RNCs) decreases short and long-term performance. Reducing the complexity of identifying, registering, and managing constraints systematically was found as a critical improvement opportunity. This research proposes the use of an artificial intelligence (AI) recommender system to facilitate constraint identification and RNC prevention. The system employs Large Language Model (LLM) embeddings to represent new task descriptions and find the most similar previously seen tasks. Subsequently, it fetches the set of constraints and RNCs belonging to these past tasks, represented in the embedded system, and uses it to produce three prioritized recommendations. Finally, the selected recommendations are categorized using Machine Learning Classification. The model was able to provide three sound recommendations for 69% of tasks and yielded a 60% relative improvement compared to a rule-based frequent pattern probabilistic system. The results pose three benefits for LPS practitioners: Reducing the effort needed to identify and register constraints, alerting probable RNCs needing to be prevented, and enriching data registration, allowing it to be used in future knowledge management.

KEYWORDS

Last Planner System, artificial intelligence, large language models, constraints, reasons for noncompliance.

INTRODUCTION

The Last Planner System (LPS) systematizes the transition from long-term Master Planning to mid-term Lookahead Planning and subsequent Short-term Planning through the Make-Ready Process (Kim, 2019). This process, known as the Make-Ready Process, involves breaking down upcoming activities into manageable work packages typically planned over a variable period that can extend beyond the often-cited four-to-six weeks, especially when dealing with complex materials or detailed design information from engineers, then screened to identify and remove constraints, before selecting constraint-free tasks to commit in the short-term plan and controlling the short-term compliance in search of Reasons for Noncompliance (RNCs)(Ballard & Tommelein, 2016). The process of identifying, managing, and removing constraints to

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produce a workable inventory of constraint-free tasks is called make-ready planning (MRP)(Jang & Kim, 2007) (Ballard & Howell, 2003).

Systematic MRP allows to effectively select constraint-free tasks for the short-term plan and carry out short-term commitments efficiently (Javanmardi et al., 2020). Effective constraint removal, captured by the Percent of Constraints Removed (PCR), has a direct positive correlation with sustained short-term compliance, measured by the mean and standard deviation of the Percent Plan Complete (PPC) (Lagos & Alarcón, 2021a). Nevertheless, MRP is one of the least mature components in LPS implementations (Samad et al., 2017) and transversal studies have found that over 70% of constraints are identified less than two weeks before task execution (Pérez et al., 2022) and 55% of constraints are removed later than required (Bellaver et al., 2022). Despite the growing interest in applying AI to project management, there remains a significant gap in its integration with established methodologies like the Last Planner System. Particularly, there is a lack of research on how AI can be effectively implemented to predict and manage task constraints in real time, a gap our study seeks to fill by developing an AI copilot designed for Make-Ready Planning. The primary objective of this study is to develop and validate an AI-based recommender system designed to enhance the Make-Ready Planning process within the Last Planner System by systematically identifying potential constraints and preventing Reasons for Noncompliance (RNCs). The use of past knowledge is powered by an Artificial Intelligence algorithm fitted to a dataset of 1,000 tasks retrieved from 30 projects, the 3,300 constraints identified during MRP, and 4,100 RNCs impacting execution. The algorithm uses the relationships found between the tasks, constraints, and RNC categories and descriptions to find common patterns. These associations allow to predict potential constraints when prompted. Its implementation in LPS support systems can facilitate practitioners to identify and register constraints systematically and more efficiently.

LITERATURE RESEARCH

FACTORS LIMITING MRP AND THEIR IMPACTS

While MRP is key in securing a stable flow of tasks into the short-term plan, thus, increasing short-term plan reliability (Kim, 2019), is often one of the least systematized components of LPS (Lagos et al., 2022). Effective MRP requires allocating time and effort from all last planners to identify constraints with subsequent time in advance, registering in a standardized manner, committing their removal to habilitate task execution, and monitoring their status regularly so that the workable inventory can be updated (Bellaver et al., 2022). Prior transversal LPS adoption studies have found that partial LPS implementations fail to systematize the MRP (Hunt & Gonzalez, 2018). These surveys have found that while short-term planning and control is a widely adopted practice, the selection of short-term tasks is carried out without proper use of a workable-task inventory, active monitoring of constraint status, registering constraint identification and removal, or late constraint identification (Salling et al., 2023).

A Danish survey with over 1,600 responses (Salling et al., 2023) showed that 45% of teams did not know "how the project plan looks 1 month from now" and 44% did not know their upcoming tasks one month in advance. A similar study addressed subsequent increments of IT support for MRP in 162 Brazilian projects (Bellaver et al., 2022). The first iteration, using a cloud-based constraint status table in 38 sites, found that most teams failed to identify and manage constraints using the tools provided, despite it automating constraint management indicators. The second added constraint identification surveys and alerts in 92 sites. These were adopted by only half of the projects and only one-third of the constraints included removal commitment dates. The third iteration added automated guides and a standardized flow, tested in 32 projects. The guiding checklists and the requirement to fulfill them before continuing with the Lookahead Plan improved collection significantly ensuring all constraints were committed and reported. While the study observed an average increase of 50% in identification, 55% were identified late and failed to be removed when required for task execution.

On the other hand, a study covering a sample of 71 high-rise building projects employing IT support for LPS across their entire execution (Pérez et al., 2022) found that the constraint removal time of successful projects was 48% lower than in projects that failed to accomplish the scheduled completion. The same study found statistically significant correlations between constraint identification and removal times, the number of constraints identified, the PCR, and PPC. Finally, another study capturing over 24,000 constraints across 3,700 weeks from 69 projects (Lagos & Alarcón, 2021a) found that teams identify them on average 10 running days before execution and take an average of 16 days to remove them. The same study, which clustered the projects into 37 successful and 32 failed ones according to their schedule accomplishment outcome, observed a 47% difference in constraint removal efficiency and 42% in constraint planning efficiency among the clusters. The differences increased by over 150% when excluding projects with mid-schedule-accomplishment outcomes.

IT-SUPPORT SYSTEMS FOR LPS

The support functions of project management software can be categorized into: Assigning overhead rates to tasks; Job sizing adjustments of overheads; Predictive tender modeling; Work structuring and scheduling; Forecasting resources demand; Unit-based reporting; Load balancing; Task completion monitoring and measuring; and Material laydown planning and logistics (Costa et al., 2023). In addition, the key value propositions of software support have been characterized as Providing systems integrations; registering and consolidating information; standardizing workflows; facilitating analysis; automating updates and notifications; and improving communication and information sharing (Stevens & Olayiwola, 2023). LPS software focuses mainly on the support functions comprised of work structuring and scheduling, and task completion and monitoring (Lagos et al., 2019). Based on the literature findings, LPS support software can be characterized as encompassing a workflow of the master, Lookahead, and short-term planning, is immediately available to other users, consolidated over time, and summarized into reports or indicators captured through short-term control (Daniel et al., 2019; Dave et al., 2016; Faloughi et al., 2014). Therefore, forecasting upcoming Master Plan activities through Lookahead Planning and facilitating resource planning and allocation to bring them into the short-term plan (Heigermoser et al., 2019), as well as allowing short-term control cycles to report the accomplishment of the plan and RNCs are fundamental requirements of LPS-supporting software (Sbiti et al., 2021).

A key distinction is the extent to which they integrate constraints into the workflow. While some systems offer detailed means to register constraint identification, categorize, plan, commit, and report their removal (Lagos et al., 2019), others limit the registration of constraints to representing a blocker status in a task (Faloughi et al., 2014). There are also similar differences in the way in which constraints impact the collaboration workflow. More thorough systems incorporate logic to restrict the movement of tasks from the Lookahead Plan to short-term commitment, while others are limited to the collection of constraints and their status almost independently from task planning, commitment, and execution (Warren, 2019). The minimum viable information found across the systems corresponds to the link between a task belonging to a hierarchical and sequential structure in the WBS, its constraints, and the RNCs experienced by it during its execution (Pérez et al., 2022; Warren, 2019). Tasks can be better characterized considering their dependencies to mother-level activities in the WBS, as sequential pre-requisites, while most RNCs could be considered unforeseen constraints, and system categorization functionalities allow the identification of common types of constraints and RNCs associated with those tasks. Finally, depending on the connections captured by the different database architectures employed, the impact of constraints and RNCs on a given task can be estimated using the schedule differences between the planned and actual start and completion of the task (Lagos & Alarcón, 2021b).

VALUE OF PAST PROJECT INFORMATION FOR PROACTIVE PLANNING

Standardization, knowledge management, data-driven decision-making, benchmarking, and continuous learning are key Lean Construction practices (Castillo, 2015; Kifokeris, 2021). The inherent characteristics of LPS help promote standardization of workflows, data-driven decision-making, and continuous learning and are enriched with the use of IT support to systematize data collection and automate reports (Lagos et al., 2019). Various scientific contributions have shown the value of benchmarking significant LPS project samples to generate and consolidate knowledge (Kim, 2019; Lagos et al., 2019, 2022; Pérez et al., 2022), but its practical use in the industry remains lacking due to the lack of system integrations with data science and Machine Learning(Gondia et al., 2020; Shehab et al., 2022). Such IT contributions would provide value to practitioners in four ways: Information indexing; alerts and forecasting; prescriptive recommendation; and process automation (Cisterna, Lauble, et al., 2022; Cisterna, Seibel, et al., 2022; Kecman, 2001).

Indexing deals with using patterns and similarities found across data to provide structure. For example, unsupervised clustering algorithms can help differentiate groups of projects with different performances and identify quantitative thresholds to divide or benchmark them (Lagos & Alarcón, 2021a). Also, supervised classification algorithms can be trained to automatically sort information based on patterns learned from past data (Y. R. Wang et al., 2012). Among other uses, they can automatically categorize and/or prioritize constraints and RNCs (Lagos & Alarcón, 2021b). Providing alerts and forecasting is another use of the patterns learned through past data observation. For example, fitting a function to explain the behavior of a repetitively measured variable can help forecast the trends of metrics such as the Schedule Performance Index (SPI). A regression prediction model can allow to estimate of the future SPI employing an array of performance variables already captured by LPS such as the PPC, PCR, and RNCs (Jang & Kim, 2007).

Prescriptive recommendation can also employ predictive regression and classification systems to determine or maximize a future state (Wong, 2004). For example, Machine Learning prescription could recommend the most likely constraints or RNCs to be experienced by a task, given its characteristics, recommend corrective actions given a task and RNC tuple or help identify the tasks from the workable inventory with the highest chance of completion in the short-term plan (Shehab et al., 2022). Finally, process automation is simply the use of indexation, forecasting, and prescription to streamline repetitive processes based on previous patterns, predicting the next step, and providing a recommendation accordingly (Cisterna, Seibel, et al., 2022). Since ML systems can employ advanced algorithms and high computing power, they are more likely to identify underlying patterns invisible to a human practitioner and employ them in their predictions (Cisterna, Lauble, et al., 2022).

APPROACHES TO AID CONSTRAINT IDENTIFICATION AND RNC PREVENTION

The literature research yielded three alternative ML approaches to aid in predicting the most likely constraints and RNCs faced by a project task: Fixed rule-based systems; extrapolation models, and generative models (Cisterna, Seibel, et al., 2022; Hatoum & Nassereddine, 2023; Oprach et al., 2019). Fixed rule-based models employ logical conditions and weights to generate predictions, which remain fixed after the model creation. Consequently, these algorithms cannot extrapolate to unseen dimensions or variables (Feng et al., 2019; Wong, 2004). For example, an expert system trained to classify text based on a predetermined set of keywords cannot adapt to new keywords for making predictions.

Extrapolating and reasoning models introduce a degree of flexibility by extrapolating the "meaning" of a token. In NLP, words and statements are the tokens, represented as vectors elucidating their context in an extensive corpus of keywords (Nie et al., 2020). If an unknown word is encountered, the system leverages other embedded tokens to find similar statements. "Synonyms" of the unknown component allow to extrapolate meaning. The extrapolations can range from embedding exact words to high levels of abstraction through stemming, combining, and transforming (Grohe, 2020; Nie et al., 2020). Their robustness depends directly on the size of the corpus and the number of examples used for training, as the embeddings essentially consist of a set of expert rules and transformations applied to the text.

Generative models enhance prediction flexibility by enabling the "creative" use of embedded similarities to generate new text. Systems like Chat GPT employ transformers, which, in turn, utilize embeddings (Hatoum & Nassereddine, 2023). A transformer functions as an encoder-decoder system, to produce and fetch tokens. A large embedding system transforms these tokens into vector representations, preserving their core "meaning" and use. The decoder, trained on a substantial number of input-output statements, utilizes the embedded representations of tokens to select the best set of output tokens for an appropriate response (N. Wang & Issa, 2023). Finally, the degrees of flexibility gained by moving to more advanced systems pose a trade-off between robustness and precision. Robustness depends, among other factors, on the size of the corpus employed, or in other words, the amount and variety of texts employed to train them. As the amount of the corpus increases, so does the embedded space, and, hence, there is a higher chance of finding similarities with words or statements outside the realm of the problem at hand (Nie et al., 2020). Hence, the precision decreases as the predictions obtained might not correspond to constraints and RNCs commonly experienced by LPS projects.

METHODOLOGY

This research employed the Design Science Research Methodology (DSRM) (Venable et al., 2017). DSRM empirically evaluates a solution artifact to validate it and identify key benefits. The artifact resides in the intersection between the Problem Space and the Solution Space, which contrasts the state-of-the-art in the body of knowledge to the state of practice. The body of knowledge captured by the literature research can be summarized as follows:

- Problem Space: Constraint identifying complexity causes late identification and misses. Registering and managing efforts then decreases MRP effectiveness. IT support systems facilitate capture and future use to a limited extent.
- Solution Space: Tasks constraints and RNCs can be retrieved from IT support. ML can detect underlying relations and use them in similarity analyses. LLM embeddings allow similar tasks, and their constraints, and RNCs can retrieved, embedded, and used to produce a new set of recommended constraints for this new task.

The following constructs were produced employing DSRM:

- Solution concept: An input-output predictor producing a prioritized set of recommended constraints, categorized based on their similarities with previously existing ones.
- Proof of Concept (POC): Using embeddings to represent tasks, constraints, and RNCs; K-Nearest-Neighbours to find similar tasks and fetch their constraints and RNCs. Then, employing their embeddings to provide three prioritized and categorized constraints.
- POC validation scope: AI predictions against a deterministic expert prediction model.

DATA COLLECTION

30 projects were randomly selected from a universe of 110 Chilean high-rise building projects that used the same IT support during their complete execution scope. The sample represented almost 30,000 unique construction tasks, filtered to obtain a rich sample of task-constraint and task-RNC (input-output) tuples, based on the following conditions:

- Tasks are limited to a set of 12 superstructure framing categories.

- Exclude tasks without at least one RNC belonging to an MRP-preventable category.
- Exclude tasks that did not contain at least six constraints and/or preventable RNCs.
- Exclude tuples with inputs or outputs with less than five unique stemmed keywords.

Limiting task selection to those with at least six constraints and/or preventable RNCs, as well as five stemmed keywords was required to ensure sufficient data to train, test, and compare the AI and expert systems. A lower threshold could result in failing to predict at least three new constraints. The criteria produced almost 3,000 tasks and 21,000 tuples. The inputs were represented by the name of the task and its mother activities, up to two levels above and excluding the mother activities representing the building's floor levels. The outputs were represented by the category and the description of the constraint or RNC. To ensure clarity, we define 'Mother activities' as tasks that are hierarchically superior or precede the current task in the project schedule. These are activities that need to be completed or significantly progressed before the current task can commence. For example, in the case of constructing a building, if the current task is 'Pouring concrete for the second-floor slab,' its mother activities might include 'Completion of all first-floor structural worksA random sample of 1,000 unique tasks, linked to 3,300 constraints and 4,100 preventable RNCs was retrieved. The input (task categories) and output (constraints or RNCs) taxonomy are presented in Figure 1.

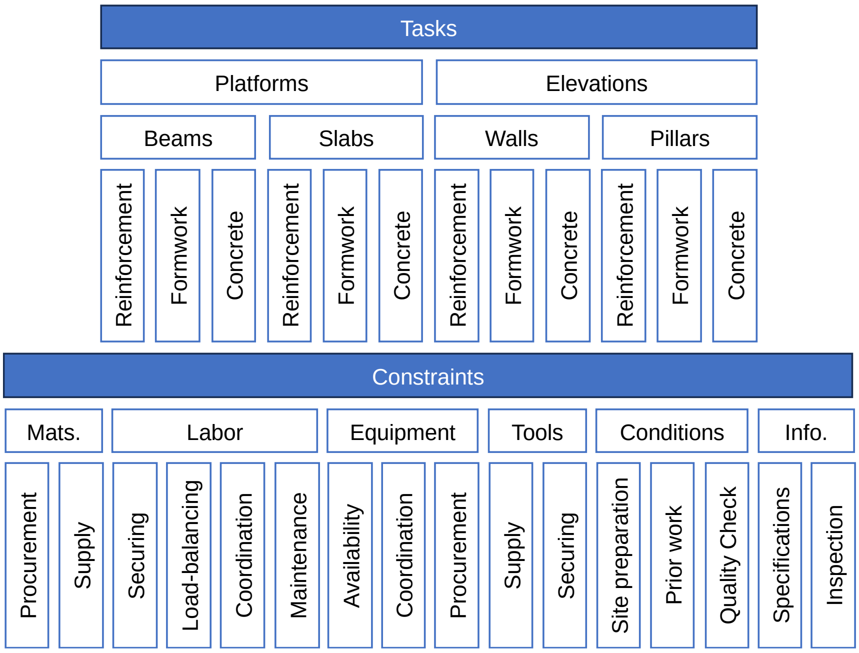

Figure 1. Task and constraint recommendation taxonomy (categories)

AI MODEL

Figure 2 describes the system. The original texts are embedded using the Word2Vec model available in the Python Gensim Library, with default parameters and excluding the use of multiword Ngram embeddings. The vector size was limited to 100 dimensions to avoid overfitting and improve performance. The embedded texts are categorized into input and output statements. A Euclidian distance algorithm computing the sum of squared differences between NumPy arrays is used to measure embedded text similarities for inputs and outputs respectively. A Naive-Bayes text classification algorithm predicts the lowest-level category of any given new task, and the classification results are used to slice the 1,000 task descriptions in the embedded space by removing all who do not belong to the same L2 group as the predicted category. This slicing helps improve performance and avoid unrepresentative similarities in future steps.

Afterward, the new task description enters the embedded space containing only the filtered tasks according to its predicted category. Subsequently, a K-Nearest-Neighbors algorithm fetches the 50 tasks with the minimum Euclidian distance. The ground truth data is then used to describe the constraint descriptions present in all tuples containing the 50 most similar tasks. The embedded representations of these past constraint descriptions are used to predict the three most likely new constraint recommendations. The recommendations are limited to constructing text descriptions using a maximum of five tokens. Since the constraint categories were included in the descriptions when inputting them into the embedding system, the produced outputs are most likely to contain one of the first-level constraint categories (materials, labor, equipment, tools, conditions, and information), and one of the second level categories (16). The remaining tokens are used to construct the specific description, most likely, providing a verb, noun, and adjective to construct the recommended constraint.

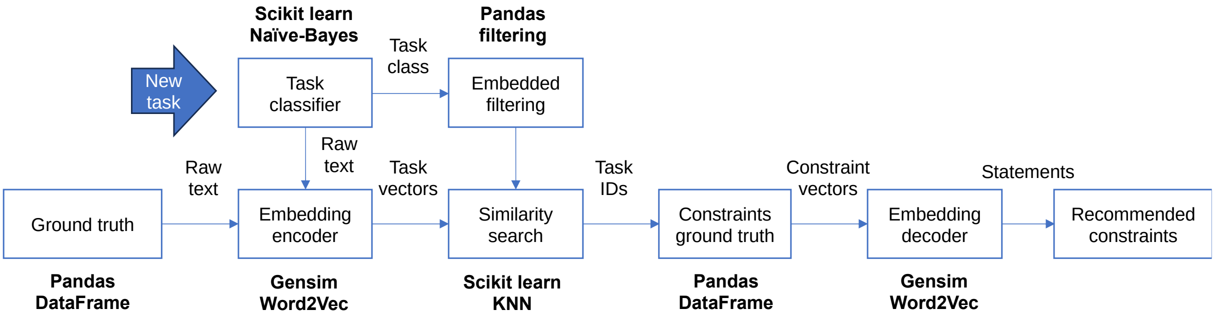

Figure 2. AI model pipeline

MODEL COMPARISON

A rule-based model was employed to benchmark the performance of the recommender system. Since fixed rules cannot be applied to natural language descriptions, the system uses the task-category prediction given by Naive-Bayes as an input to predict constraint categories. The model employs frequent pattern recognition to derive the most-likely class to enter a known set and turns these probabilities into rule-propagation tree using the FP-Growth algorithm. The FP-Growth algorithm, like A-Priori, is an pattern mining algorithm fitted to cases referred to as the supermarket cart problem (Feng et al., 2019). It predicts the most likely N+1 element to be added to a known bundle. The bundle of unique task categories and their linked constraint and RNC categories (ground truth) are passed as association rules. Since tasks contain at least six unique constraints and/or RNCs, the association rules can rank up to six predictions for each task category, the latest being the most frequently observed full set. In this implementation, the FP-Growth predictions were not limited to bundles composed of unique predicted categories, since a task can contain two or more constraints belonging to the same category. Also, the order of the factors in the ground truth bundles did not alter the resulting rules, since the predictions were based on the conditional probability of a new constraint appearing given the frequency of the set's unique components (i.e. constraints and RNCs), structured into a probabilistic frequent patterns tree. As a result, all tasks in the same category received the same ranked sets.

The expert system was implemented employing the FP-Growth model available in the Python MLX tend Library. Both the AI and rule-based systems were trained and tested employing the same 80%-20% sample split. Also, both used the same task category prediction obtained from the Naïve-Bayes algorithm as an input. The cases where the task classification was incorrect were excluded from the subsequent model performance comparison. The outputs produced by both models were contrasted against the ground truth categories of each of the constraints associated with the test tasks to measure the performance. Each model was assigned one point for each predicted constraint present in the ground truth and deducted one point for each prediction that was not present in it.

RESULTS

First, the Naïve-Bayes classification algorithm produced 182 correct task classifications out of the 200-task category ground truth samples employed in the testing set, yielding a recall of 89%. The recall is calculated as the number of correct predictions divided by the test set size. Table 1 presents the prediction recall results. Subsequently, the model comparisons employed a testing subset comprised exclusively of the 178 correctly predicted task categories. It must be noted that FP-Growth results can be directly compared at the category level, but lack a more detailed natural language description, while the AI results give a natural language description but can also not allow the direct identification of a category. In total, 34 out of 600 NLP predictions did not allow for clearly detecting one of the 16 possible constraint categories, 29 of which occurred in the correctly classified tasks. Hence, the maximum theoretical points to achieve with the AI model and FP growth were 505 and 534, respectively.

Table 1. Task categorization results.

	Platforms: Beams			Platforms: Slabs			Elevations: Walls			Elevations: Pillars		
	R	**F**	**C**	**R**	**F**	**C**	**R**	**F**	**C**	**R**	**F**	**C**
G.T.	11	9	10	22	28	23	20	24	25	11	9	8
Pred.	8	8	7	20	26	21	20	23	21	10	8	6
Rec.		77%			92%			93%			86%	

FP growth provided 395 correct recommendations and predicted 139 constraints that were not present in the ground truth data, yielding a net performance of 256 points or 43% predictive capability. On the other hand, the AI model achieved a score of 415 points, with 460 correct predictions, 45 incorrect predictions, and 29 predictions that could not be categorized. Overall, considering that 89% of the task descriptions were misclassified, the AI model showed a consolidated capability to foresee and recommend effective real constraints in 69% of cases when prompted only with the task description and 78% if aided with a human-verified category. Table 2 summarizes this analysis. Furthermore, part of the AI predictions that were not present in the ground truth data could also be explained by the lack of proper registration by the users of the IT support system employed for the data collection.

DISCUSSION

POC LIMITATIONS

This POC was carried out employing 7.400 tuples from 1,000 unique tasks. The data corresponded exclusively to superstructure framing activities and a taxonomy of 16 constraints captured by the single IT-support system in Chilean high-rise building projects, employing Chilean-Spanish dialect and construction terminology when registering information. A hybrid ML architecture was employed instead of state-of-the-art LLMs. Also, the models employed in the POC architecture were not finetuned to further optimize prediction performance, since the results already signaled its benefits over traditional fixed-rule systems and manual identification. Finally, the model was fitted and evaluated using an artificially enriched sample produced by the selection of tasks linked to at least six constraints or preventable RNCs. Enriching the sample was deemed necessary to facilitate prediction outcomes and the existence of constraint-free tasks could be caused simply by the lack of proper registration in the IT support systems. Nevertheless, the POC model should be expanded with a larger corpus to include variance in the tuples and trim unnecessary predictions when a task exhibits a low constraint probability or a reduced set of potential constraints and preventable RNCs.

Table 2. Model performance results.

	Cat. tasks	Constraint preds.	Cat. predictions	Correct predictions	Incorrect predictions	Score
Ground truth	200	1320	1320	600 (aim)	0	600
Expert System	178	534	534	395	139	256 (43%)
AI Model	178	534	505	460	45	415 (69%)

CONTRIBUTIONS

This research shows that even a basic AI pipeline can provide domain-accurate constraint recommendations on 70% of cases based on past project information. This means that 70% of constraints that should be identified during the MRP could now be automatically registered as soon as a task enters the Lookahead Plan. Also, an LPS practitioner employing the IT support systems could quickly validate or modify the predicted task categories and recommended constraints, improving the percentage of use cases covered. Hence, it is estimated that up to 90% of the constraint identification workflow could be streamlined, significantly decreasing the time and effort needed to kickstart the MRP and giving Last Planners a wider time scope to then commit and remove those constraints. Having access to better-registered information facilitates the use of knowledge management for other data-driven decision tasks (Franz et al., 2022), such as improving MRP performance and reducing constraint removal times. Finally, the same concept can be applied to repetitive decisions such as corrective action implementation, RNC registration, and selection of tasks from the workable inventory. The study significantly contributes to the integration of AI in the Last Planner System by providing a validated AI-driven approach to Make-Ready Planning. This contribution not only enhances theoretical understanding but also offers practical tools that can improve efficiency and predictability in construction projects. The implications of these contributions are profound, potentially enabling project managers to reduce delays and better manage resources. While we acknowledge certain limitations in our current model, these should be viewed as starting points for further refinement. The opportunities for future research, such as integrating more advanced algorithms, ultimately aim to build upon the solid foundation this work provides.

OPPORTUNITIES

This POC was carried out employing only 7.400 tuples from 1,000 unique tasks, while the data captured by the single IT support system employed in this study comprises over 290 projects, with over 100,000 unique tasks, 220,000 reasons for noncompliance, and 130,000 constraints. Also, several other LPS support systems have collected similarly sized structured datasets. The results can be further improved by finetuning the existing architecture. Particular examples of finetuning opportunities include (1) the number of neighbors employed by KNN, which was fixed to 50 tasks, (2) the dimension of the embedding vectors, which was limited to 100, (3) the number of tokens employed to produce the outputs, currently fixed to five, (4) adding additional relative value to the tokens describing the constraint category predictions, and (5) employing alternative task classification algorithms instead of NB. State-of-the-art models allow for better embeddings fitted to significantly larger LLM corpora. Open-source LLMs like Large Language Model Meta AI (LLaMA) also offer finetuning and retraining opportunities to better capture the specific LPS task management corpus. Equivalent models like Google's BARD and Bidirectional Encoder Representations from Transformers (BERT) offer end-to-end question-and-answering pipelines, which already incorporate reasoning and generative technologies. State-of-the-art AI research is constantly producing new open-source models and architectures for a wide array of domain-specific challenges, contexts, and corpora.

CONCLUSIONS

This research assessed the use of AI to identify and register constraints early during Lookahead Planning and facilitate Make-Ready Planning. LPS adoption studies found that inefficient MRP impacts short- and long-term performance. Practitioners often fail to identify constraints in time, and they take longer than planned to be removed, 55% of times past planned execution. The hypothesis that task-constraint relationships found on past projects can be used to recommend new ones for a task entering the Lookahead Plan was validated via the Design Science Research Methodology. A Proof-of-Concept AI model was developed using 1,000 tasks connected to 7,400 constraints and preventable RNCs. LLM embeddings helped find similarities among them and use tokens to produce three ranked recommendations. Its performance was compared against an expert recommender based on the FP-Growth algorithm. While FP growth showed a 43% net rate of correct recommendations, the AI model achieved 69%. This rate increases to 78% if the input task is classified beforehand. The model can be finetuned to improve results using a larger sample and the POC can be replaced by state-of-the-art end-to-end question and answering LLM models. The resulting system acts as a copilot for LPS practitioners, helping them kickstart MRP early and more effectively. The same approach can be employed to recommend corrective actions, select tasks to enter short-term plans, or register RNCs. Further research could explore the integration of more advanced machine learning algorithms to improve predictive accuracy and user interaction. Additionally, extending this research to other phases of project management or different industries could provide insights into the broader applicability of AI tools. Long-term studies focusing on the sustained impacts of AI integration in actual project environments would also be invaluable to assess its long-term benefits and challenges.

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TAKT AND PULL ZONES IN THE CONSTRUCTION OF LOGISTICS WAREHOUSES

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ABSTRACT

This article will describe how the application of lean philosophy tools in the construction of logistics warehouses can offer new perspectives on project planning, promoting clearer and more visual communication, collaboration, and decision-making processes. this article investigated the use of takt and pull planning methods for the development of an integrated management system for logistics warehouses located in different Brazilian cities. Takt planning of scheduled activities decreased waiting times, leading to a reduction of approximately 8% in the execution time of construction works. Other benefits included greater team engagement and participation in activity planning and sequencing. Two takt zones (repetitive elements) and one pull zone (non-repetitive elements) were demarcated at each construction site, which were planned using line balancing as a unifying element. This strategy facilitated visual management by the field team, ensuring that the entire planning process flowed through the actors actively involved in carrying out the work. In a questionnaire-based survey, construction teams reported great improvements in planning, work comprehension, and coordination between work fronts, as well as improvements in visual management and collaboration. The responses indicated a notable shift in how the field team approached planning and conceptualized their work and demonstrated that the incorporation of takt and pull planning concepts was essential for achieving these results.

KEYWORDS

Last Planner System, Lean construction, Logistics warehouses, Pull planning, Survey, Takt planning

INTRODUCTION

The desire to increase construction productivity is driven by the sector's known inefficiency in transforming raw resources into commodities and the importance of building or infrastructure development for economic growth (Hussain & Al-Turjman, 2021), so more than More than ever, strategies to redesign the production chain, analyze internal and operational processes and seek alternatives and opportunities to produce increasingly more efficiently are objectives of organizations seeking to sustain themselves and grow in the market (Sage et al., 2012).

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In this context, more recent studies present a wide range of Lean Construction tools to reduce waste and improve production efficiency, which can be used depending on the type of construction or integrated. Zhang and Chen (2016) bring lean techniques and practices that were brought from lean manufacturing, such as daily meetings, Kanban and value stream mapping, in addition to the Pull Planning methodology of the Last Planning System (LPS) concept presented by Silva, Etges and Pereira (2022), which the application in construction brought considerable benefits in meeting deadlines in the construction of buildings.

Takt Planning, Haghsheno et al. (2016) defines it as a methodology that can also result in increasing the stability of the production system in activities with repetitions. It is widely used in various production processes, such as bridge construction, underground construction, tunnel construction and excavations, due to its repetitive work package characteristics, which is why the use of a Takt becomes highly relevant (Haghsheno et al., 2016). Also according to the authors, there are restrictions on the use of this tool in buildings, since often not all floors and the layout of environments are designed identically, and these conditions make greater preparation and planning necessary to integrate the different areas into one. Common takt. In this sense, Formoso et al. (2011) states that the focus should be on the causes of losses, rather than trying to monitor or control the consequences of losses in production, using techniques and tools that have greater adherence to the construction typology and the objectives sought.

Bringing this scenario to the construction of warehouses, Mora (2016) highlights that it is an area that maintains the same concern in the real estate segment, seeking to offer design and construction solutions with appropriate attributes in terms of quality, deadlines and agreement. with the needs of potential customers. Kamaruddeen et al. (2020) presents in their study research results on several modular warehouse construction projects around the world, only 30% of projects can be completed on time, while the rest have experienced delays. In addition to having an impact on excess costs, delays also cause other impacts, such as customer dissatisfaction.

Therefore, this article aims to study the applicability of the Pull and Takt Planning tools in the construction of logistics warehouses as they have previously been identified as the most suitable methods for this type of construction and as the most appropriate alternative to resolve the problem of difficulty in complying with the construction schedule identified, in addition to the perception of a gap that currently exists due to the lack of studies on lean thinking practices in this construction model.

To achieve the research objectives, the work was divided into three main stages, the first being a literature review on the warehouse market in Brazil in order to understand its relevance, and the Takt and Pull planning methodologies. The second stage consisted of structuring the methodology, with the elaboration of strategies for applicability to the phases of building a warehouse, and the third stage, the application of practices in the field in a unified way in works in progress, in order to obtain and evaluate the performance of the work, in addition to the perception of engagement of those involved. The results could be compared to other constructions that do not use the methodology, and, finally, it was possible to conclude that adoption of the practices provided an 8.3% reduction in the total construction time, in addition to contributing to better management, visibility the direction and stability of production.

THE LOGISTICS WAREHOUSE MARKET IN BRAZIL

Poletto (2011) defines that logistics warehouses are enterprises developed in a large area already subdivided, in which these industrial or logistics lots are organized and sold for this purpose, containing infrastructure of paved roads suitable for supporting heavy loads and vehicle traffic, guides , gutters and sidewalks, rainwater galleries, sewage collection and treatment system, drinking water network, electricity and public lighting, signage, and even preserved green areas, where each company or investor is responsible for the construction of their own shed. According to the author, within this type of enterprise, warehouses are commonly built by investors who seek to rent them to an end user.

Mora (2016) observes that currently the development of the Brazilian market for logistics condominiums has adjusted to the new demands and needs of the logistics market, due to the demand for competitiveness and efficiency present in the operation of companies and business segments that rely on large logistics infrastructures, including large storage centers.

Recent data from a survey by specialized consultancy Colliers (2024), concluded that the 51 projects delivered throughout the year added 2.3 million m² to the country's existing inventory, surpassing the mark of 25 million m² of high-end logistics condominiums throughout the national territory, an increase of 10% in the São Paulo region. With the expectation of a fall in interest rates in Brazil throughout 2024, the market is expected to register new acquisitions of logistics assets, making clear the importance of implementing production strategies in this area of construction to monitor the viability of these projects.

TAKT PLANNING

The influence of assembly line principles on building construction was first observed during the construction of the Empire State Building in New York City in 1930. The project emphasized the need to achieve continuous production, accomplishing construction cycles of one pavement per day. This systematic approach not only marked a significant transformation in the construction practices of the time but also established a paradigm for efficiency and productivity in the construction industry. The cost, execution time, and safety indicators of the project were markedly better than those of any comparable enterprise. Thus, the project stood out for its technical innovation and brought significant benefits to civil construction (Kenley and Seppänen, 2010).

As argued by Haghsheno et al. (2016), takt implementation provides increased stability for production systems, contributing to reducing inventories and waiting times between activities, while optimizing transportation through continuous flows. Takt planning is of utmost importance for effective synchronization between different areas, ensuring that individuals operate at an agreed-upon pace. According to Hopp and Spearman (2008), takt time planning provides a standardized time for the execution of each activity in the production line, leading to synchronization of individual deliveries. Adequate definition of the daily production quota provides greater predictability and stability for supporting sectors, while mitigating the influence of variability in customer demands. Frandson, Berghede, and Tommelein (2013) defined takt time as the unit of time within which a product must be produced in order to match the demand rate. Haghsheno et al. (2016) emphasized the importance of understanding the production process and its delivery milestones for defining work packages, including the scope of each action area and the sequencing of activities.

It is possible to determine the takt time of a logistics warehouse project using the equation proposed by Reck and Fireman (2023) (Equation 1). The takt time is mainly influenced by the following three variables: the time available for project execution, the number of slots, and the number of service packages. Additionally, the equation includes a practicability coefficient referring to project-specific uncertainties and characteristics, such as climatic uncertainties. As pointed out by Binninger, Dlouhy, and Haghsheno (2017), the takt time should not be understood as a fixed number applicable to all projects; rather, the takt time should be specific to each project, accounting for its particular characteristics and boundary conditions.

$$\text{Takt time} = \frac{\text{Available time} \times 80\% \text{ Practicability}}{(\text{Repetitions} + \text{Number of activities} - 1)} \qquad \text{Equation 1}$$

A work package, as described by Haghsheno et al. (2016), represents the subdivision of a construction project into smaller areas, which helps to structure and quantify the activities that need to be carried out at each location. The duration of each work package and batch should be similar, thereby providing a stable rhythm to the construction process, with fewer restrictions. Binninger, Dlouhym, and Haghsheno (2017) stated that one of the goals of lean is to reduce batch sizes and individual production times. However, the definition of takt time also depends on the variability and stability of the construction system. Thus, because of the high level of instability of construction processes, a weekly takt is typically adopted. The more refined the takt time, the higher the level of uniformity and control required in the enterprise.

The purpose of lean construction, takt planning, and takt control is to achieve continuous and uniform processes, creating value-generating activities with equal durations throughout the entire process chain (Binninger, Dlouhy, and Haghsheno, 2017). As observed by Haghsheno et al. (2016), takt implementation is particularly relevant for processes that occur frequently and exhibit significant similarity throughout the project. Haghsheno et al. (2016) also underscored that, for the implementation of the takt system to produce positive results, it is essential to ensure that all activities have been completed as planned at the end of each cycle. This enables the uninterrupted execution of subsequent activities, promoting gains in productivity through workflow simplification and transparency.

PULL PLANNING

Pull planning is an LPS tool initially designed to improve productivity. Its conceptual framework was later redirected to creating predictable workflows and fostering rapid learning in various fields associated with civil construction, such as programming, design, construction, documentation, and project delivery (Kalsaas, Grindheim, and Læknes, 2014). Tvedt (2020) described pulled planning as one of the latest additions of the lean thinking toolkit whose function is to create a reliable flow of work across a team of experts.

As noted by Kalsaas, Grindheim, and Læknes (2014), pull planning originates from the master plan, which contains the project's delivery milestones. Similar to takt planning, the project is subdivided into slots, serving as control areas and providing rhythm to work fronts. This approach enables a more efficient and synchronized management of activities throughout the entire project.

As outlined by Tiwari and Sarathy (2012), reverse planning is the subsequent step following the identification of the main project milestones. The method starts from the final delivery and retraces all steps back to the present moment, mapping out the work required for project completion. This approach supports a more detailed understanding of critical steps and activities involved in project development. Kalsaas, Grindheim, and Læknes (2014) complemented the description of the pull planning approach, highlighting the importance of using visual elements in routine management, such as planned start and end dates. These elements generate a clear and accessible representation of the project schedule, making it easier to understand and track planned milestones.

Tsao, Draper, and Howell (2014) described pull planning as a tool that promotes collaborative planning, in which solutions for project execution are reached jointly. Tvedt (2020) underscored that the critical point for success is the collaborative participation of experts, enabling interaction with different perspectives, reducing waste, and anticipating difficulties. Tiwari and Sarathy (2012) argued that pull planning allows building a transparent environment that is empathetic to the difficulties of other team members. This facilitates communication and generates a sense of trust and belonging.

As noted by Silva, Etges, and Pereira (2022), with the development of a transparent environment in which people participate in decision-making and are aware of the team's problems, activities are carried out with greater agility. In this environment, an action plan encompassing the restrictions and potential risks that may impact production is developed. This plan defines deadlines and responsibilities for the solution of the identified points, contributing to efficient management of issues that may arise throughout the project.

Kalsaas, Grindheim, and Læknes (2014) underscored that traditional planning is often long and complex, requiring a large volume of pages and graphics, making it difficult to identify the status of the enterprise with regard to its schedule. Tiwari and Sarathy (2012) reported that pull planning helps the team to build a comprehensive, transparent, flexible, and collaborative planning process in a simplified way. This agile and transparent approach to planning allows for a clearer and more accessible understanding of project progress.

METHODS

Action research was the methodological approach adopted in this paper. Action research focuses on solving real problems (O'Brien 1998) and contributing to the organization's development, being based on simultaneous and collaborative action and research (Coghlan and Brannick 2001). The model was defined on a construction site and replicated in four other warehouse construction sites in Brazil. In each project, the model was adapted to the specific needs of the work site. All figures shown in this work are from the same warehouse, where the pilot was done. Considering the action research, the current paper aims to bring insights from a real case study connecting pull and takt zones for planning of non-repetitive and repetitive activities and the benefits perceived by its participants. After the planning intervention was applied in five work sites, a survey was sent to the involved team members such as managers, engineers, analysts and assistants (n = 43), and 39 individuals completed the questionnaire, representing a 90.7% response rate.

The studied company, herein referred to as Company A, has existed for more than 15 years as one of the largest developers of logistics assets and warehouse rental companies in Brazil. Currently, it has more than 1 million m² of built logistics warehouses in 16 states and 34 cities in the country. The company has eight ongoing developments, corresponding to 365 thousand m2, and delivered 600 thousand m2 of gross leasable area in the last two years. Company A constantly invests in improving product quality, using the best market practices to offer an integrated operation to its customers. Several solutions based on technology and innovation are provided. Nevertheless, up to the beginning of this study, the company had not had contact with lean philosophy or LPS tools. Project planning was carried out in the central office using Gantt charts and sent to worksites.

RESULTS AND DISCUSSION

A typical logistics warehouse facility includes the warehouse itself, which can be modularized to meet specific customer needs, auxiliary facilities for warehouse operation, such as cafeteria, changing room, and guardhouse, and infrastructure networks (INs) for the warehouse and auxiliary facilities. Thus, aiming to promote integrated management based on lean and LPS principles, we defined a model for the planning and management of tasks carried out in the warehouse, outdoor environments, and auxiliary facilities.

The first stage in the development and implementation of the lean management model was defining the macroflow of activities in the three lines (warehouse, INs, and auxiliary facilities). For this, a construction team comprising engineers, analysts, master builder, and construction coordinator was formed for the sequencing of activities and definition of work packages. This step was carried out collaboratively, using sticky notes to promote team engagement and facilitate visual management of the activity. After work package sequences were defined, the tasks included in each work package were described in detail to enhance the understanding of the process and sequencing. Each work package became a line in a line of balance (LOB) and the sequence of those packages served as the sequence of lines in the LOB in the activity planning stage.

Having analyzed in depth the projects of the different ventures of the company, it was understood that takt time was applicable to logistics warehouse and IN activities, which have repetitive elements in their design. Previous works using takt planning in non-repetititve labour have shown a high risk of losing effectiveness in field due to a lack of knowledge of information about productivities, means and methods, defining identical labor content for the trades (Linnik, Berghede and Ballard, 2013; Tommelein, 2017). Therefore, for auxiliary facilities, the focus would be to apply pull planning strategies, given that activities were slightly repetitive and slots differed greatly in workload, for that reason, we could treat them as non-repetitive elements in a pull planning section.

The company had a very large focus on the warehouse and had good control over its activities; however, the other areas received less attention and planning. With the advancement of planning, an integrated vision of all areas was developed, aiming toward work assertiveness. Table 1 depicts the factors evaluated in this study.

Table 1: Evaluation of work zones

Criterion	Takt zone: warehouse	Takt zone: IN	Pull zone: auxiliary facilities
Repetitive unit	Yes	Yes	No
Clear constructive sequence	Yes	Yes	Yes
Possible to determine the rhythm of each slot	Yes	Yes	No
Integrated view of the project (before/after)	Yes / Yes	No / Yes	No / Yes

TAKT ZONE

Takt was applied to enhance production stability, maintain the rhythm of activities, reduce waste, and reduce the total time of project execution. This section explains the repetitive elements aspects in constructing a logistics warehouse.

Takt Zone: Warehouse

The first line to be planned was the warehouse, as it is the core of the project and must be delivered as soon as possible for customers to adapt the facility to their needs to being operation. Logistics warehouses are designed for modularization, so that they can be rented to more than one customer. According to the project designs, warehouses are created as repetitive modules (for rental purposes) that can be compartmentalized in the future if needed. Each module consists of a leasable storage area, reception, and loading docks. It was clear to the project team that the leasable lots would be takted. However, the lots were too small for some activities (e.g., subbase and base execution); therefore, two leasable lots were used for the planning of one slot. When estimating the takt time for the activities (Equation 1), it was observed that dividing by two lots was relevant for several ventures in the company. With this method, the takt time was close to one working week, representing an easy time measure for everyone on the project. The standard slot was defined as 4 lots and 2 sublots for leasing, two receptions, and part of a mezzanine.

The first stage of the process was to prepare the list of quantities for each slot. The list of quantities was not detailed in this step, corresponding to large volumes of work. This was made so as to identify the workload of each work package within slots in the established takt time. This method allowed obtaining the metrics to be controlled on a day-to-day basis. Subsequently, a scheme was drawn on the warehouse layout containing all lots and the quantities of all work packages to be managed (Figure 1).

Takt Zone: INs

The environment surrounding the warehouse, comprising underground and aboveground networks, pavement, and landscaping, posed challenges, primarily contributing to the failure to meet the delivery deadline. IN always differs across worksites because of differences in land type, land size, neighborhood, number of auxiliary facilities, state legislation, and many other factors that influence the project. To identify the rhythm required to meet the client's deadline, it was first necessary to determine the division of areas for takt.

The team decided that areas should be divided so as to meet an attack plan focused on a single work front (designing a train of activities passing through the lots). Lots were designed with area divisions as similar as possible. The aim was to create the most homogenous possible quantity of work for activities passing through lots within a week. Activities would pass to the following lot only after being completed to guarantee adequate starting conditions for the following team. This division ensured a very effective allotment of activities from construction of the subbase onward, given that work quantities were divided by area. Another positive outcome was the good division of lots in underground networks, as many networks run parallel to the warehouse, generating a similar workload to be managed under a takt approach. Therefore, the repetitiveness aspect of the project was satisfied again and takt time would be the methodology to go for. The lot division is shown in Figure 2. The lot layout was drawn and the list of quantities was prepared to obtain monitoring metrics and allow the sizing of teams and equipment.

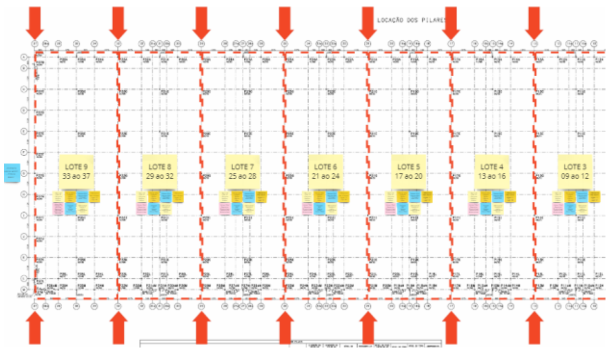

Figure 1: Warehouse layout and lists of quantities for takt time implementation

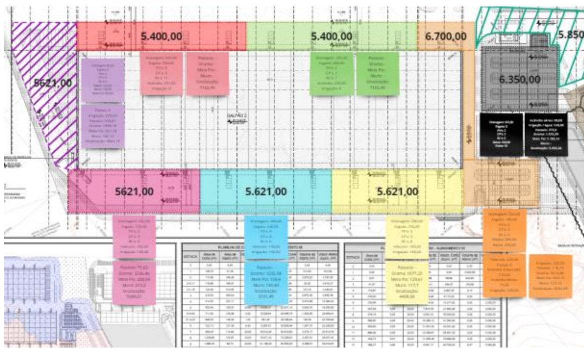

Figure 2: IN Layout and list of quantities of external areas for takt time implementation

PULL ZONE: AUXILIARY FACILITIES

The design of auxiliary facilities (comprising cafeteria/leisure area, changing rooms, reception, truck driver support, water tower, pumping station, measuring booth, and reuse water station) was approached differently. The first step was to prepare all lists of quantities for tasks defined in the macroflow of auxiliary facilities, per building. Not all work tasks were carried out in all buildings (e.g., installing ceramic flooring in the water tower); therefore, takt implementation would be difficult because of the non-repetitive aspect of this activities. As a result, it was decided to apply pull planning for auxiliary facilities, in a collaborative way with the team.

The sequences of work packages were defined by the team. Milestones for the delivery of materials with long lead time and the final work deadline were defined. With this information, the pull planning session began. On the basis of estimated team productivity rates, the necessary deadlines for each work package were determined, defining the work plans of the facilities.

INTEGRATED MANAGEMENT MODEL

Given that two different methodologies were used for planning, it was essential to unify them into a single model for integrated management of the entire project. Visual management is crucial to increase team engagement, communication, understanding of goals, and general alignment of teams to meet deadlines and customer demands. Thus, a LOB was used for unification of plans and visual management of lines.

The union of these methodologies and the definition of visual tools, increasing the transparency of the process, considering the takt phase and the pull phase, proved to be a great gain for the project and a new methodology that can provide a new way of visualizing planning. Not following just one methodology, but using the best of both and generating concise information that adds value to the construction team.

For this, a grid panel was mounted on the wall, and sticky notes were used to construct the lines of balance, being visible to everyone in the room. The columns represented weekly time horizons. The vertical axis was divided into three lines: warehouse (green notes), IN (red notes), and auxiliary facilities (yellow notes). Slots were distinguished by an additional axis used for writing dates. Thus, takt planning was unified with pull planning (Figure 3). The lower part of the panel shows activities differing in the degree of sequencing.

Figure 3: Lines of balance contemplating takt and pull planning zones

SATISFACTION SURVEY WITH THE CONSTRUCTION TEAM

At three months after the beginning of the last project, the construction team was asked to answer a questionnaire to evaluate their perception of value of planning based on lean, takt, and pull methods. The survey contained seven questions rated on a 5-point Likert (1 = lowest level; 5 = highest level). Table 2 presents the questions, their score frequency, and their mean score. An additional item (multiple choice) was used to evaluate whether participants believed the proposed planning tool, together with its philosophy and methodology, to have contributed to other areas of their day-to-day work. The answers are shown in Figure 4.

Table 2: Questions and answers about the process of implementing collaborative planning with takt and pull zones in logistics warehouse construction

Question	Score frequency (%)					Mean
	1	2	3	4	5	
Rate your participation and use of the proposed tools	0%	0%	10.3%	33.3%	56.4%	4.46
Rate your level of understanding of lean construction	0%	2.6%	7.7%	43.6%	46.2%	4.33
Rate the improvement in your understanding of project planning	0%	0%	2.6%	33.3%	64.1%	4.62
Rate the improvement in your understanding of possible interferences between different work packages	0%	2.6%	5.1%	35.9%	56.4%	4.46
Rate the importance of takt planning for collaborative planning	0%	0%	20.5%	28.2%	51.3%	4.31
Rate the importance of pull planning for collaborative planning	0%	0%	17.9%	38.5%	43.6%	4.26
Rate the benefit of viewing warehouse, infrastructure network, and support facility plans in the same tool	0%	0%	2.6%	25.6%	71.8%	4.69

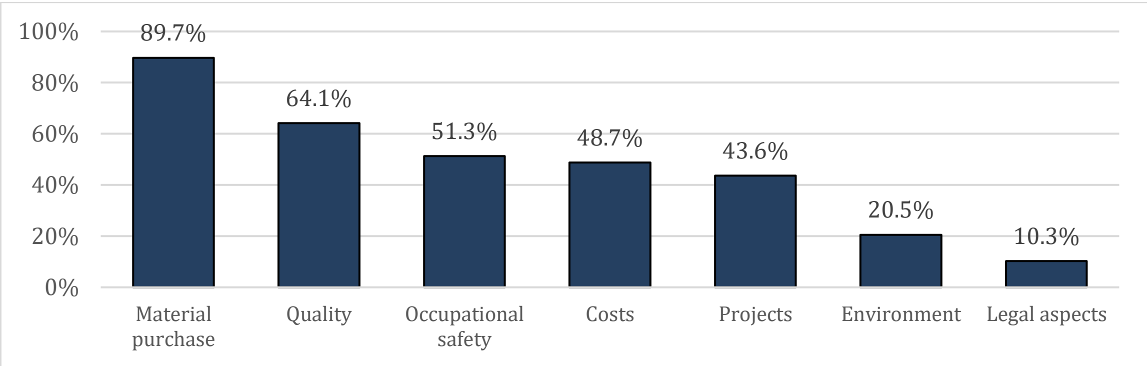

Figure 4: Areas that benefited from integrated planning, as identified by participants

The results showed that the construction team valued the planning strategy. The highest score (5) was attributed to all questions by many participants. The team reported a significant improvement in the planning and understanding of the construction project, as evidenced by question 3: 97% of participants rated the item with a score of 4 or 5. In question 4, concerning the improvement in participants' understanding of interference between work packages, 91% of respondents attributed a score of 4 or 5. The concepts of takt and pull planning were essential for the development of lean, collaborative, easy-to-understand plans. Takt and pull planning concepts were deemed very important (score of 4 or 5) by 80% and 82% of respondents, respectively. Finally, 97% of the team gave high importance (score of 4 or 5) to being able to visualize the different plans in the same visual management tool.

The majority of respondents (35 out of 39) reported improvements in material purchase with the use of integrated management plans. This assertive, visual, collaborative planning method allowed anticipating purchases and visually identifying needs when working together with other routines implemented in the project. The planning technique was also reported to improve quality and occupational safety. The importance of knowing how to identify what is needed to perform a given activity in its fullness, coupled with routines of activity monitoring, was valued by the team. Benefits to cost control were also perceived by participants. Knowing what was happening, what would happen, when, and why improved the understanding of the current situation and the possibility of obtaining better results. Regarding projects, identification of deadline dates well beforehand and their discussion with the multidisciplinary team were valued by participants. The other possible benefits were given minor importance. Therefore, it can be said that lean, takt, and pull concepts not only contributed to project management but also added value to several other areas of the construction project.

The mean scores for planning improvement criteria, represented by items 3, 4, and 7, were 4.62, 4.46, and 4.69, respectively. The overall score of the three items was 4.59, demonstrating that the team had a completely different perception about the way of thinking and executing the work. Questions regarding takt and pull planning concepts had mean scores of 4.31 and 4.26, respectively, demonstrating the importance of these concepts to the team, greatly changing the way of planning and thinking about the project. The findings confirm the importance of these planning tools for construction management.

CONCLUSIONS

Before the implementation of the integrated planning and management system based on takt and pull planning, the team used the Gantt chart as the sole planning tool. All efforts were concentrated on the warehouse, in detriment of external areas and auxiliary facilities. As a result, the company faced average delays of 3.8 months in the delivery of these additional areas after warehouse delivery. With the application of the proposed techniques, the team had a greater engagement with planning goals and metrics and there was a greater involvement of front-line actors. Participants gained understanding of the steps to be executed and greater commitment to the plan because they felt included in its development, not perceiving it as something imposed by another sector or board. The use of the LOB as a centralizing tool of information and guidance for the field team was of great value and increased the clarity of goals, constructive sequences, and future steps. Furthermore, the LOB served as a basis for the planning of medium- and short-term routines in LPS, which were developed on site for better production management and stability.

As a result of the proposed planning, the first executed project had a 4-week shorter delivery date than the previous project (12 months). This is equivalent to a reduction of 8.3% in the total project schedule. For this type of enterprise, there are three major projects occurring in parallel that need to be executed to meet the client's short deadlines. Their visualization helped improve the team's understanding of what is and should be happening on site. The concepts have been applied in other projects. Takt planning proved to be very effective for lots with similar workloads, facilitating the understanding of what was expected by teams on a daily and weekly basis. In activities that varied greatly in quantities between lots, the method did not provide good results, because their planning was not feasible. In these cases, pull planning was a good strategy to ensure compliance with the deadline, engage teams, and plan collaboratively and assertively.

The questionnaire aimed to provide insight into the perceived value and comprehension of the proposed concepts by the construction team. The results indicated an enhancement in the team's understanding of project planning. The method made it easy to understand the influence of a work front on other fronts. It improved visual management, collaboration, and understanding of subsequent steps, goals, and the required rhythm of each work front to meet the client's deadline. In addition to planning, the proposed method brought benefits to material purchase, work quality, occupational safety, cost control, and adherence to time schedules.

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EXPLORING THE LIMITATIONS AND OPPORTUNITIES OF INDUSTRIALIZED CONSTRUCTION IN COLOMBIA FROM A LEAN PERSPECTIVE

William León[1], Jose Guevara[2] and Nelly García-López[3]

ABSTRACT

Despite the significant impact that industrialized construction (IC) has on the project production chain and its clear influence on productivity levels across the industry, multiple limitations hinder its suitable implementation worldwide. Existing research has identified synergies between the implementation of Lean Principles (LP) and the adequate implementation of IC processes. However, most of these studies have been carried out in markets with a high maturity and implementation levels of both IC and LP. This paper aims to explore the synergies between the implementation of LP and opportunities for improvement for the effective implementation of IC in Colombia. This article presents a qualitative analysis of twenty semi-structured interviews with construction professionals from some of the largest construction companies in Colombia. The analysis revealed that despite growing interest in applying IC by leading companies in Colombia, the current implementation of IC principles is still low. Additionally, the application of LP such as continuous improvement, variability reduction, value generation, and waste reduction are identified as key enablers for IC.

KEYWORDS

Industrialized Construction, Lean Principles, Productivity, Developing Countries, Semi-structured Interviews, and Literature Review.

INTRODUCTION

The implementation of industrialized construction (IC) has been recognized as a viable approach to enhance project performance (Andersson & Lessing, 2017). IC implementation implies a significant shift in the construction paradigm, indicating a fundamental restructuring of organizational frameworks and methods (Smith et al., 2018). Despite its benefits, the implementation and adoption of IC are still in their early stages, as the market and industry continue to pose substantial challenges (Lessing et al., 2005). In developing countries, these challenges include skilled labor shortages, rising labor costs, low productivity, and a lack of standardization. Interestingly, these issues can be mitigated through the implementation of industrialization processes (Vásquez-Hernández et al., 2022).

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On the other hand, construction management literature shows that Lean Principles (LPs) allow for improved integration by fostering long-term relationships among stakeholders. This is beneficial for implementing IC, as LPs facilitate sophisticated supply chain management, simplify design for manufacturing and installation, and enable experience capture and knowledge management for continuous improvement. Consequently, an increasing body of literature recognizes that LPs offer tools that strengthen and support the implementation of IC practices (Zhou et al., 2023).

This paper aims to gain insight into the dynamics between the concepts of IC and LP in Colombia, serving as an initial reference for the maturity level in developing countries (Smith et al., 2018). The goal is to provide a preliminary diagnosis of the status of IC implementation and identify strategies that can facilitate and enhance its implementation(Vásquez-Hernández et al., 2023).

POINTS OF DEPARTURE

INDUSTRIALIZED CONSTRUCTION

Standardization of processes, mass manufacturing, and reduced unpredictability are the main goals of industrialized construction (Dave et al., 2016). This approach differs from conventional construction methods, which frequently exhibit considerable variability and depend heavily on the subjective judgment and experience of the contractor (Hairstans & Smith, 2018). Industrialized construction seeks to create a consistent production model that guarantees punctual delivery, resource stability, and quality assurance. Its objective is to integrate repeatable production cycles and transparent processes, thereby enhancing predictability and reliability in construction project planning (Ji et al., 2017).

In the construction sector, there is no universally agreed-upon definition for the term “industrialization” (Liu et al., 2019). Depending on the specific guidelines and features of construction processes, it encompasses various developmental phases and maturity levels, ranging from in-situ production systems to fully prefabricated systems (Andersson & Lessing, 2017). In the context of this research, we based our interviews on the industrialized construction framework developed by Lessing (Lessing, 2015), that views industrialized construction as a system composed of eight IC practices: planning process and control, supply chain management, technical systems development, customer focus, factory-based component manufacturing, information and communication technology utilization, performance measurement and integration of prior experiences.

LEAN PRINCIPLES

According to Koskela (Koskela et al., 2002), Lean Construction is a concept based on production theory that is crucial for the advancement of economical, sustainable, and effective practices in the Architectural Engineering and Construction (AEC) industry. This approach focuses on maximizing the final value of the building product for the client, reducing waste, and continuously improving processes to enhance management of construction projects (Koskela et al., 2002). When this concept is applied, processes become more productive, leading to increased project profitability and a reduction in wasteful practices that result in value loss for the project (Aslam et al., 2021). Consequently, LC is viewed as an essential tool for maximizing value and eliminating waste (Igwe et al., 2020).

This general definition of Lean Construction incorporates some implementation principles, such as identifying the value of the product from the customer's point of view, establishing a value chain for each product, characterizing a value stream, eliminating waste, implementing a pull workflow (Pull System), ensuring continuous process improvement, maintaining transparency, and providing training (Bajjou et al., 2019).

RESEARCH METHODOLOGY

Using a mixed methods approach, this study combines a literature survey with a qualitative analysis based on the perspectives of professionals in Colombia's construction industry. The goal is to cross-validate the interview findings with theoretical foundations of the global state of the art in IC and LP. This specific methodology was chosen because it provides a strong synergy between qualitative data gathered from ongoing project experience in Colombia and the assessment of literature that supports or explains IC behavior. It offers a thorough review of the state of continuous improvement in specific work contexts, examining constraints and obstacles from a Lean perspective. These opposing and reliable points of view make it possible to critically assess the situation and identify areas for further improvement.

Using this data, a cross-analysis of the benefits of industrialization and lean principles is conducted, with a particular emphasis on the relatively new industrialized construction sector and its unique risks and problems. In conclusion, a list of constraints and opportunities for development in the industrialized construction sector in countries with low levels of industrialized construction maturity is established.

FIRST STEP – PAPER SELECTION STRATEGY

This step involved searching the Web of Science database for relevant articles. Key ideas were extracted from the selected articles to establish a reference framework for understanding the concept of global IC and its implications for the construction process (Doerfel & Barnett, 1999). In addition to this general search, a focused investigation was carried out to identify Lean principles in the construction sector, exploring their implications, advantages, restrictions, and consequences on the production chain in construction projects. Concepts such as Lean Construction, Industrialized Construction, Last Planner System, and Productivity served as the foundation for this specific search.

SECOND STEP –INITIAL QUALITATIVE ANALYSIS

The authors adopted a qualitative approach, conducting over 20 hours of expert interviews to analyze the qualitative data. These interviews were recorded, transcribed verbatim using NVivo software, and subsequently synthesized into a coherent narrative that encapsulated the significance of LP within the realm of IC (Biygautane et al., 2019). Before conducting the interviews, interviewers explained key concepts to ensure respondents were aware of proper definitions of IC practices and LP with the aim of reducing the risk of bias or interviewer-induced partiality.

THIRD STEP – MULTICATEGORY UNIT ANALYSIS

This phase involved summarizing the data gathered from the 20 hours of interviews and initiating the process of distilling the key ideas covered (Yin, 2018). To achieve this, it was essential to identify the analytical categories with the greatest influence and generality. These categories were subject to further examination during the results discussion (Yin, 2003). According to Taylor (Taylor et al., 2011), utilizing these categories or units of analysis helps highlight key ideas, facilitating a better understanding of how IC and LP synergize in nations with low IC maturity. Key topics of discussion include efficiency, rework, information flow, productivity, and collaborative work settings. Throughout this discussion, these ideas will be referred to as units of analysis or categories.

FOURTH STEP – COMPARISON, LIMITATIONS AND OPPORTUNITIES ANALYSIS

To validate and assess the findings comparatively, data from qualitative interviews related to LP and IC are juxtaposed with an examination of relevant literature. This process involves aligning qualitative classifications and interview data with conclusions drawn from a global body of research on lean construction. Through a comparative analysis, a precise point of reference can be established to identify constraints, opportunities, and potential areas for continuous improvement in nations with low IC maturity (Yin, 2003). Figure 1 presents the methodological approach.

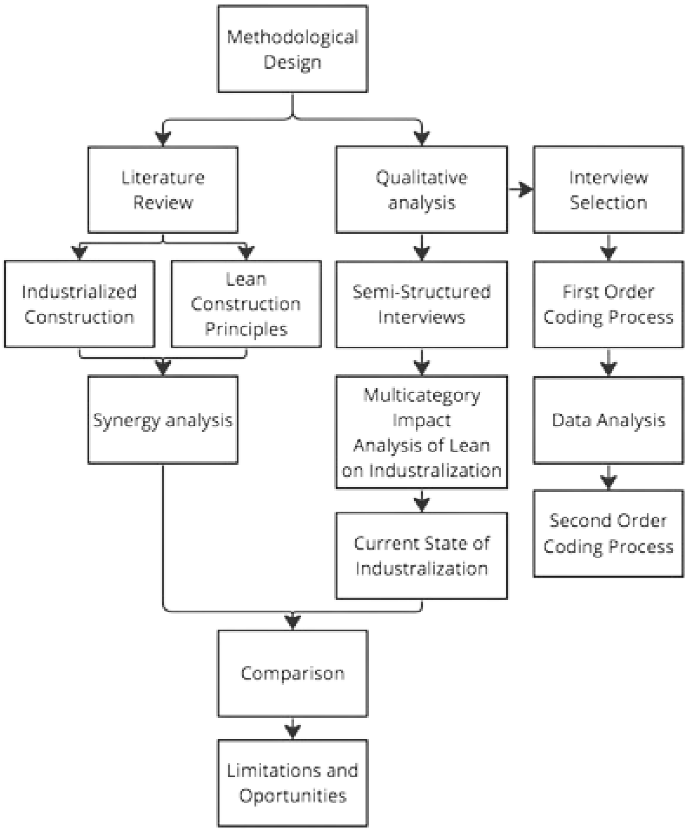

Figure 1: Methodology

RESULTS

A comprehensive profile of the respondents, including their years of experience and area of work in the construction industry, is presented in Table 1. These profiles serve as the basis for conducting semi-structured interviews, information processing, and extracting categories for analysis.

Table *1*: Interviewees

Interview	Sector	Years of experience	Field of experience
1	Design and construction execution	3	Design
2	Design and construction execution	3	Coordination
3	Design and construction execution	7	Construction
4	Design and construction execution	4	Design
5	BIM Manager	7	Model
6	BIM Manager	7	Model
7	BIM Manager	3	Coordination
8	BIM Manager	4	Coordination
9	Construction Manager	3	Construction / Industrialization
10	Construction Manager	3	Construction / Industrialization
11	Construction Manager	3	Construction / Industrialization
12	Construction Manager	4	Construction / Industrialization
13	Lean Manager	5	Productivity
14	Lean Manager	4	Processes
15	Lean Manager	3	Scheduling
16	Lean Manager	7	Scheduling
17	Project Manager	5	Productivity
18	Project Manager	5	Scheduling
19	Project Manager	5	Budget
20	Project Manager	6	Scheduling

Table 2 provides a summary of IC practices derived from the literature review, interviews, international references, and selected quotes illustrating Colombia's current adoption status.

Table *2*: IC practices

IC Practices	Literature-based description	Colombia-based description
Planning and Control	Effective management and organization throughout the design, fabrication, assembly, and other related operations are essential to achieving goals and providing customers with the best value define the concept of planning and control. (Lessing et al., 2005).	"Initiatives focused on process optimization at various stages of the project life cycle are increasingly being observed, including the early implementation stages of systems such as the Last Planner System."
Supply chain management	This concept refers to the optimization of construction activities, from the construction site to the factories where pre-assembly takes place. The aim is to improve logistics and supply management at all stages. (Erik Eriksson, 2010).	"Prefabricated building solutions can only be employed on-site with a specific number of components on specific projects."
Technical systems development	This idea involves integrating technical production systems throughout every stage of the project to enhance the quality of the final product and standardize processes. (Lessing et al., 2005).	"It is considered acceptable at present the development of technological systems focused on continuous improvement of quality and process standardization."
Customer focus	This concept refers to a managerial vision where there is a production focus based on the customer, understanding that it is necessary to ensure that products are delivered to the end consumer with the appropriate cost and quality. (Lessing et al., 2005).	"Strong connections exist between the builder and the client. Items are crafted with the customer and the market in mind."
Factory-based component manufacturing	Building components are manufactured with state-of-the-art equipment in comfortable working environments that promote efficient manufacturing (Abdel-Jaber et al., 2022).	"The construction techniques are by no means entirely prefabricated and preassembled. Most procedures are carried out on-site."
Information and communication technology utilization	This concept refers to a working structure where accurate and reliable data exist to make operations more industrialized. Current Information and Communication Technology should provide tools for effectively managing updates and revisions of digital content, along with solutions for data interchange and storage (Sacks, Koskela, et al., 2010; Sacks, Radosavljevic, et al., 2010; Sami Ur Rehman et al., 2022).	"The implementation of the Common Data Environment is progressing through many of the key stages of the construction process, alongside efficient collaborative processes."
Participant relationships	This concept refers to the development of adequate relationships among participants focused on enhanced performance and the production of effective outcomes that optimize value. Fostering sustained engagement with the processes. (Koskela et al., 2002).	"Discipline coordination is continuously improving and favoring standardization, resulting in fruitful outcomes for process optimization."
Performance measurement	This concept refers to the use and improvement of methods aimed at optimizing construction processes through industrialization strategies. (Ballard, 1993).	"It is observed that strategies for mass construction involve standardized procedures, ensuring consistency across processes, schedules, and resources."

A summary of LP based on interviews, literature review, and selected quotes illustrating Colombia's present potential for improvement is shown in Table 3.

Table *3*: Lean Principles (LP)

LP	Literature-based description	Colombia-based description
Continuous improvement	Organizational guidelines emphasizing continuous process enhancement (Koskela et al., 2019).	"The Last Planner System is being implemented alongside methodical meetings as the fundamental tools to foster an environment of continuous process improvement."
Improving flow and reducing variability	Strategies focus on controlling time deviations in the execution of activities and ensuring a continuous flow of processes (Salhab et al., 2022) (Garcia-Lopez & Fischer, 2024).	"A significant variability is observed in the execution of activities at all stages of the project life cycle."
Value generation	Long-term projects that add value for the client (Koskela et al., 2019; Sacks, Koskela, et al., 2010.	"The creation of value for the client is the foundation of project design, ensuring the production of goods suited to the market."
Waste reduction	A methodical and ongoing approach to waste reduction (Igwe et al., 2020; Womack, 1996).	"Preliminary, experience-based attempts are observed to reduce waste, but with many opportunities for improvement. There is no standardization in waste reduction practices."

In Table 4, the primary LP are listed, along with their direct impact on IC practices. These serve as instruments for continuous improvement and as means of facilitating implementation, particularly in emerging nations.

Table 4: LP and IC practices interaction

2nd-Order Codes (LP)	1st-Order Codes (IC practices)	References	Illustrative Quotes
Continuous improvement	Supply chain management	(Aslam et al., 2020, 2021; Ballard, 1993; Koskela et al., 2002, 2019)	"There is no culture of continuous process improvement or learning from past experiences. The production system and project stages are consistently developed in the same manner. A shift in the learning paradigm would facilitate the implementation of more efficient processes."
	Information and communication technology utilization	(Eastman, 2008; Sacks, Koskela, et al., 2010; Sacks, Radosavljevic, et al., 2010; Sami Ur Rehman et al., 2022; Sharma & Trivedi, 2021; L. Zhang et al., 2017)	"In terms of technology, we remain quite traditional. We don't learn from past mistakes and avoid adopting new tools due to a fear of change."

Table 4 (Continued): LP and IC practices interaction

2nd-Order Codes (LP)	1st-Order Codes (IC practices)	References	Illustrative Quotes
Improving flow and reducing variability	Planning and Control	(Chauhan et al., 2018; Gonzalez et al., 2008; Hamzeh et al., 2016a, 2016b; Kenley, 2004; Laufer et al., 1994) (Garcia-Lopez & Fischer, 2024)	"Project planning and process variability often result from inadequate information management. The absence of effective channels hinders the standardization of processes."
	Technical systems development	(Cândido et al., 2014; Pasquire & Ebbs, 2017; Tatum, 2005; Vásquez-Hernández et al., 2023; F. Zhang et al., 2019)	"There is a lack of standardization in our processes, leading to variations in execution and an inability to control uncertainty. The absence of standardized technical systems hampers productivity. It is crucial to implement standardization and eliminate variability."
	Participant relationships	(Ballesteros-Pérez et al., 2020; Fischer et al., 2021; Gonzalez et al., 2008; Lindhard et al., 2019; Poshdar et al., 2014; Salhab et al., 2022; Thomas et al., 2002; Tommelein, 1997)	"It is common to encounter information silos. Poor integration of disciplines hinders effective communication and decision-making efficiency. The flow of information is consistently disrupted, making process optimization unattainable."
Value added	Customer focus	(Freeman et al., 1991; Gomez & Rameson, 2019; Igwe et al., 2020; Kim & Ballard, 2010a, 2010b)	"I believe the current construction industry recognizes the significance of the end customer. Value creation is intricately tied to establishing a direct relationship with the client and understanding their needs and expectations."
	Factory-based component manufacturing	(Abdel-Jaber et al., 2022; Bajjou et al., 2019)	"In the context of prefabrication, significant information gaps exist. We lack effective implementation of these technologies and an understanding of their added value. There is considerable resistance to change. If viewed from the perspective of value creation, people would likely embrace these new trends more readily."
Waste reduction	Performance measurement	(Igwe et al., 2020; Maraqa et al., 2020; Womack, 1996)	"Undoubtedly, waste poses a challenge for project managers. While we are aware of its presence, finding effective ways to mitigate this problem remains elusive. Implementing active and radical measures against this issue could significantly enhance project performance."
	Planning and Control	(Chauhan et al., 2018; Gonzalez et al., 2008; Hamzeh et al., 2016a, 2016b; Kenley, 2004; Laufer et al., 1994)	"Once again, planning and time control in construction are influenced by nearly all variables. Surprisingly, the matter of waste has not been forcefully addressed as a mitigation measure. It is crucial to acknowledge the necessity of responsibly managing waste as a means to enhance the reliability of planning."

DISCUSSION

EXPLORATION OF IC MATURITY IN COLOMBIA

Based on Table 2, the maturity of IC in Colombia is still incipient in certain enumerated categories. Interview responses show that construction projects in Colombia implement many industrialization practices, but their level of development is still in early stages. The implementation of prefabrication, technology in construction systems, coordination, process standardization, and planning relationships between the developer and contractors present clear improvement opportunities for a comprehensive and efficient implementation of industrialization initiatives according to the parameters obtained from Lessing (Lessing, 2015).

As shown in Table 2 and 3, the areas with the relative highest degree of implementation are not directly related to prefabrication or the development of technical systems, as areas focused on information management, collaborative work environments, and coordination between the developer and the client demonstrate a more advanced level of development. The categories of customer focus, utilization of information and communication technology, and performance measurement reflect a more positive perception of development according to the interviewees.

Results show that the primary focus of industrialization in Colombia is on strategies that facilitate the integration of key industry players and optimize project life cycle processes and management techniques. For instance, value generation from customer integration and waste reduction within the implementation efforts associated with LPs outperforms technological implementation or prefabrication shown in Table 2. Accordingly, it is noteworthy to emphasize that, based on the semi-structured interviews, only two of the eight IC practices have reached an advanced level of maturity. Furthermore, both the literature study and the respondents' perspectives indicate that none of the four LPs discussed in this research currently effectively support the application of real-world IC in Colombia.

LIMITATIONS IN THE INDUSTRIALIZATION PROCESS

The challenges associated with performance metrics primarily involve increased overall project costs, higher early-stage expenses, and elevated technological expenditures. This includes greater economic risk, higher labor expenses, increased transportation costs, and longer timeframes during the planning and design stages. Most of these obstacles are linked to circumstances that would change if LP were implemented—essentially, focusing on value generation and continuous process improvement (Andersson & Lessing, 2017).

Furthermore, the lack of integration and process modifications are typically associated with hurdles in process flow (Qi et al., 2021). The primary causes of integration barriers include disjointed supply chains, inadequate short-term business partnerships, unsuitable project delivery models, and contracts, as well as insufficient cooperation and communication among involved parties (Ekanayake et al., 2021a). Once again, applying LP, centered on creating cooperative work environments that optimize information flow and discipline integration, could help overcome these obstacles (Ekanayake et al., 2021b). The result is that many of the IC practices may potentially benefit from the improvement of flow and reduction of variability.

Additionally, there are noted obstacles related to planning and design. A clear absence of a planning and control framework tailored to the specific market requirements is observed within these barriers (Vásquez-Hernández et al., 2023). Incompatibilities between conventional and industrialized designs are apparent, as are constraints on customization, the failure to specify or decide on the design in a timely manner, the inflexibility of applying changes to the design later, the absence of design standardization, and minimal investment in the design stage (Qi et al., 2020).

Finally, inadequate change management, low motivation, and a lack of experience, training, and knowledge in construction firms are impediments related to knowledge management. This includes a lack of process documentation, low levels of research in the industry, insufficient collaboration between academia and industry, inadequate planning capabilities, a lack of skill techniques, a shortage of skilled labor, an inability to objectively assess the benefits of industrialization, inadequate education and training, an inability to synchronize off-site and on-site activities, and a lack of prior design, on-site management, and on-site experience as some of the barriers related to knowledge, skills, and experience (Kedir & Hall, 2021).

IMPLICATIONS AND OPPORTUNITIES

This study integrates literature review with the collection of empirical information from semi-structured interviews with experts in the Colombian industry. This combined methodology helps identify fundamental LP associated with opportunities for improvement in the construction sector, fostering synergy and facilitating their proper implementation.

Results suggest that the construction industry in Colombia has embarked on a significant transition toward industrialization, but still has ample room for continuous improvement and significant opportunities for development in many IC practices. This presents significant challenges in terms of productivity, efficiency, and value generation. Therefore, the simultaneous application of LP in each of the previously analyzed categories holds great potential to expedite the implementation of industrialization and its seamless integration with construction paradigms in Colombia.

The four main LP identified in the results phase demonstrate substantial potential for improvement across the eight IC practices addressed in this study. This approach can bring about significant changes in the industry, promoting process standardization, enhancing information flow, increasing productivity, integrating multidisciplinary groups, and creating streamlined processes to accelerate the production chain. The combined impact of LP and IC practices facilitates the effective implementation of an acceptable level of maturity of industrialization in the short term in Colombia and offers a valuable pathway to accelerate efficient IC practices in other countries with a low IC maturity.

Finally, this study, structured from construction projects in Colombia, provides valuable information about the current state of industrialization in developing countries, which constitute a significant sector in global construction. This study also enables understanding of improvement opportunities in the development of industrialization in countries with initial stages of maturity. The analysis is useful to other Latin American countries with similar industrialization conditions and Lean implementation efforts.

CONCLUSION

Through semi-structured interviews and a comparison with the literature in the Scopus and Web of Science (WoS) databases, this study conducted an analysis of the influence of LP in IC practices in Colombia. Based on the results of the literature review, four LP were identified. These principles have the potential to mitigate the impact of adoption barriers by modifying critical conditions that are considered to have a high and very high impact on the adoption of IC practices in the Colombian context.

Various criteria were used to assess how much the application of LP contributed to the examples under study. First, it is observed that the identification and reduction of waste contribute to the improvement of performance metrics (cost, time, quality, and productivity), thereby mitigating the negative perception associated with unsuccessful attempts and inconsistent outcomes. Second, the reduction of information silos is associated with enhanced communication and teamwork, increased early integration, and improved phase synchronization—both between design and external production and among production, external installation, and internal processes. Third, knowledge, value creation, continuous improvement, and change management are crucial aspects. Research efforts in LP within the context of project management are particularly focused on the external production phase. A substantial body of research and the consulted experts agree that incorporating LP at an early stage enhances the adoption and implementation of IC practices in the construction industry.

There are limited studies focusing on the application of LP in both construction management and integrated design management in countries with low IC maturity. Practices aimed at reducing project fragmentation are not well-documented. However, integration-based approaches involve collaboration among project stakeholders within a phase and across different project phases. To manage their production system and associated subsystems, oversee current operations, and execute construction projects, construction companies require an integrated vision of work across disciplines. This strategy, which integrates discrete projects with continuous activities, requires different technical systems, organizational structures, procedures, and supply chains compared to traditional construction enterprises.

By examining the utilization of LP and their role in reducing adoption barriers, the current paper offers a practical contribution by identifying specific Lean strategies that can be integrated into various stages of the continuous improvement process and linking them to outcomes that modify circumstances related to adoption obstacles in IC practices implementation. These findings serve as input for transformations based on the LP, which, through process flow, knowledge management, performance enhancement, and value generation, helps reduce the uncertainty surrounding the enhanced utility perception of coordinating fitted work units compared to conventional construction practices, thereby lowering adoption barriers.

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QUANTIFYING AND PLANNING CARBON EMISSIONS IN CONSTRUCTION WITH LOCATION-BASED SCHEDULING

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ABSTRACT

Many countries focus on limiting greenhouse gas (GHG) emissions, such as carbon dioxide, which also impacts the construction industry. The most forward-thinking countries have already enforced regulations on the maximum allowed emission from new buildings. Regarding building lifecycle stages after EN15978, the regulations primarily target product and usage stages, neglecting construction process emissions. This oversight is concerning as material innovations reduce product emissions, shifting the need for optimization to the construction stage.

This study quantifies construction emissions, optimizing GHG during construction using the Location-Based Management System (LBMS) method. It incorporates construction-related emissions and uses a Location-Based Schedule, calculating anticipated kilowatt-hours (kWh) usage per location with data from various sources. Tested on three cases—residential building, office renovation, and medical facility—the method shows varied results based on project size, complexity, and LBMS introduction time.

Findings indicate a potential 42% CO_2 reduction in the scenario with the longest construction time. The study identifies site emission rates surpassing the 2023 limit over 30 years, underscoring the importance of comparing planned and realized schedules. Given climate regulations until 2050, the research deems the quantification method crucial for accurately addressing construction site emissions.

KEYWORDS

Location-based Management System (LBMS), Takt Planning (TP), environment, greenhouse gas emissions (GHG), planning

INTRODUCTION

The Climate Act in Denmark, where the research is conducted, aligns with the Paris Agreement's aim to limit the rise in global temperature. Denmark targets a 50-54% emission reduction by 2025, 70% by 2030, and climate neutrality by 2050. However, the building industry, responsible for approximately 39% of global greenhouse gases (GHG) (UNEIEA, 2017), is often overseen in the green transition, which poses a challenge to achieving the

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ambitious targets. Historically, efforts to reduce GHG from buildings have mainly been focused on the use face, i.e., Operational Energy (OE), as it constitutes the majority of lifecycle energy use. However, in recent years, the emissions due to Embodied Energy (EE), i.e., the energy used for extraction of raw materials, processing into building materials, transportation, and on-site construction, have started to gain focus (Wandahl et al., 2021). Recognizing the slow pace of industry change, strategies and tools must be promptly discussed, tested, and implemented to meet targets concerning EE.

In 2011, the European Committee for Standardization (CEN) released a new standard for measuring the environmental sustainability of buildings. Figure 1 illustrates the diagram used for the LCA method in 'EN15978:2011 Sustainability of construction works' (CEN, 2011).

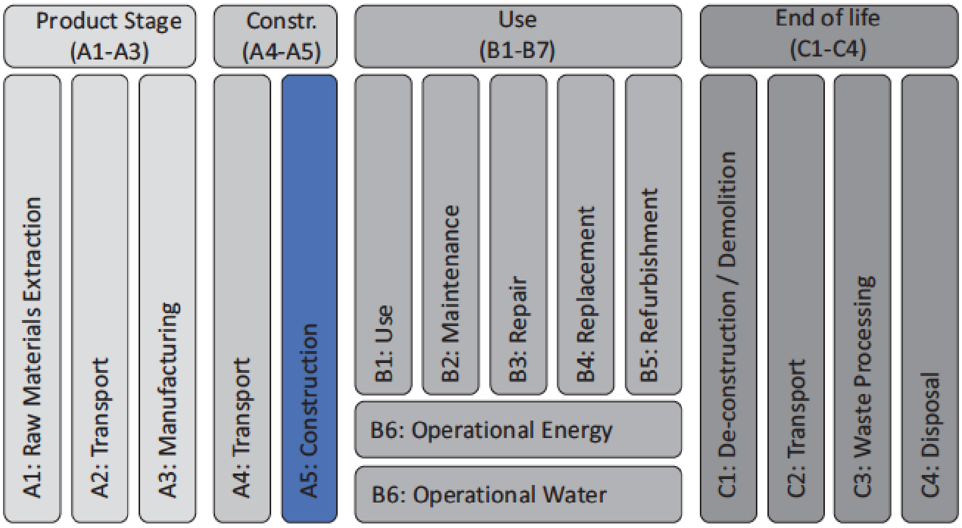

Figure 1: Life Cycle phases according to CEN (2011).

Today, many emissions arise from producing building materials (phases A1-A3), prompting a shift to more sustainable materials with lower life-cycle emissions. Architects and engineers will increasingly be responsible for proving the carbon footprint calculations, aided by tools like EC3 (CLF, 2023). Transportation emissions (phase A4) are challenging to quantify, but it is imperative to acknowledge their significance in the broader context of sustainable construction. Despite its complexities, efforts to address A4 emissions should not be sidelined. Meanwhile, energy consumption for heating, drying, lighting, and processing electricity on construction sites (phase A5) can more easily be monitored and quantified. Construction site-related emissions (phase A5) remain relatively undiscovered, studies on how scheduling can impact emissions are scarce (Lim et al., 2016), and suitable quantification tools are absent, leaving stakeholders in the dark.

This study explores how schedule changes impact energy consumption at construction sites (phase A5), caused by delays or schedule optimization using a Location-Based Management System (LBMS). Initially centered on A5 and leveraging LBMS for measurement, our research will prioritize A4 emissions in continuous sustainability assessments. This shift aims to provide a comprehensive understanding of construction-related emissions, thereby improving decision-making for sustainable practices.

Due to limited empirical data, this study relies on reports, some over five years old, using average values for analysis, making the methodology somewhat experimental.

METHOD

This paper presents a research work classified as an explorative case study (Yin, 2003). This research strategy was chosen because it enabled the present authors to investigate a phenomenon characterized by a lack of detailed preliminary research (Yin, 2003). The study's phenomenon comprises understanding how schedule changes positively or negatively affect construction site energy consumption.

As a starting point, a literature review is conducted to identify A5 energy consumption from actual cases. It is not easy to identify the necessary data, as many studies assume that the energy consumption in A5 is limited and, therefore, negligible (Hendrickson and Horvath, 2000; Lemay, 2011). In general, reported research on EE of construction is limited, and when said, it is often for the accumulated production stage only (A1 to A3) or occasionally as accumulated production and construction (A1 to A5). Very few case studies report designated A5 values, cf. Table. 1. This lack of data for A5 constitutes a critical knowledge gap in reducing lifecycle CO_2 emissions from buildings during the construction phase.

Table 1: Consumption of energy in A5 for different projects (values in kWh/m2)

Project	Heating of building (A5.1)	Drying (A5.2)	Process & lightning (A5.3)	Sum A5
DK1 – commercial (Sommer et al., 2013)	121.96	0.00	34.79	157
DK2 – commercial (Sommer et al., 2013)	12.86	67.50	24.74	105
DK3 – commercial (Sommer et al., 2013)	107.20	0.86	16.91	125
DK4 – residential (Sommer et al., 2013)	34.00	0.00	30.39	64
DK5 – commercial (Sommer et al., 2013)	154.22	17.33	25.85	197
TYR1 – residential (Bozdag & Secer, 2007)	na	na	na	148
TYR1 – residential (Bozdag & Secer, 2007)	na	na	na	159
TYR2 – residential (Bozdag & Secer, 2007)	na	na	na	143
Averages	86	17	27	130

As argued earlier, the focus of this study will be only on point phase A5. A5 can be split further into sub-groups, cf. equation 1, which are the most demanding energy sources during the construction phase - (A5.1) Heating, (A5.2) Drying, (A5.3) Lighting and Process (Sommer et al., 2013).

$$E_{construction} = E_{heating} + E_{drying} + (E_{lighting} + E_{process}) \quad (1)$$

Where:

$E_{construction}$ = Energy consumption in A5 in total [kWh/m2]

$E_{heating}$ = Energy consumption for heating of building [kWh/m2]

E_{drying} = Energy consumption for drying of building [kWh/m2]

$E_{lighting}$ = Energy consumption for lighting of the site [kWh/m2]

$E_{process}$ = Energy consumption for processes on the site [kWh/m2]

Table 1 includes five Danish cases, DK1 to DK5. For these cases, diesel-powered machines are not included, as the data is limited to machinery using on-site electricity, including lighting. Secondly, three Turkish case studies, TYR1 to TYR3, are included. In the Danish studies, the average energy consumption is 129.72 kWh/m2, while theoretical values from the early 90s suggest 150 kWh/m2 for the "Erection" phase (Bozdag & Secer, 2007), indicating a 15%

difference. Technological advancements may explain this gap, with site equipment improvements over the last 20 years. Notably, the Danish report excludes diesel-powered machinery, potentially contributing to lower numbers than the Turkish report. Despite variations, the Danish measurements align with literature expectations, justifying their use as a calculation base.

Although relevant, other aspects that impact the overall CO_2-Emission, such as changes to the project and materials, will be disregarded for this paper's focus.

As a result of exploratory work, the authors suggest 10 important parameters to estimate the base consumption factors called $C_{heating}$, C_{drying}, ($C_{lighting + process}$): The parameters are explained below:

1. **Construction period for the project.** How long does the project run for? It is relevant for calculating the number of workdays requiring lighting and construction process electricity. It is determined with the Start date of the first activity and the End date of the last activity and circled with purple below.
2. **Full construction period per location**. The start and End dates for activities within the location are used to determine operational days in the location. This is relevant to determining the days when lighting and construction process electricity will be required per location and marked with red below.
3. **Winter period definition**. Defining the Start and End date of a winter period. In this research, it is assumed to be from the 1st of October to the 31st of March.
4. **Number of winter periods**. Determining the number of winter periods during ongoing work, impacting heating energy consumption (highlighted in blue in Figure 2).

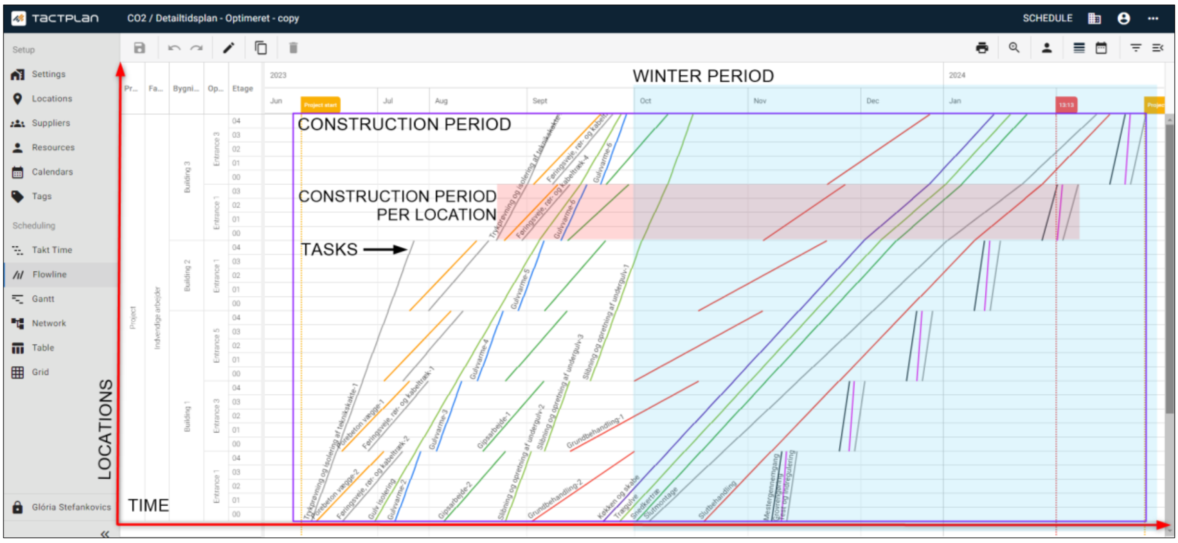

Figure 2: Location-based schedule illustrating full construction period, period per location, and winter period.

5. **Multiple construction periods within a location** – Investigating energy waste during idle periods in a location with starts and stops (marked in green in Figure 3) where no work is executed. The location must be segmented into multiple work periods to facilitate this calculation.

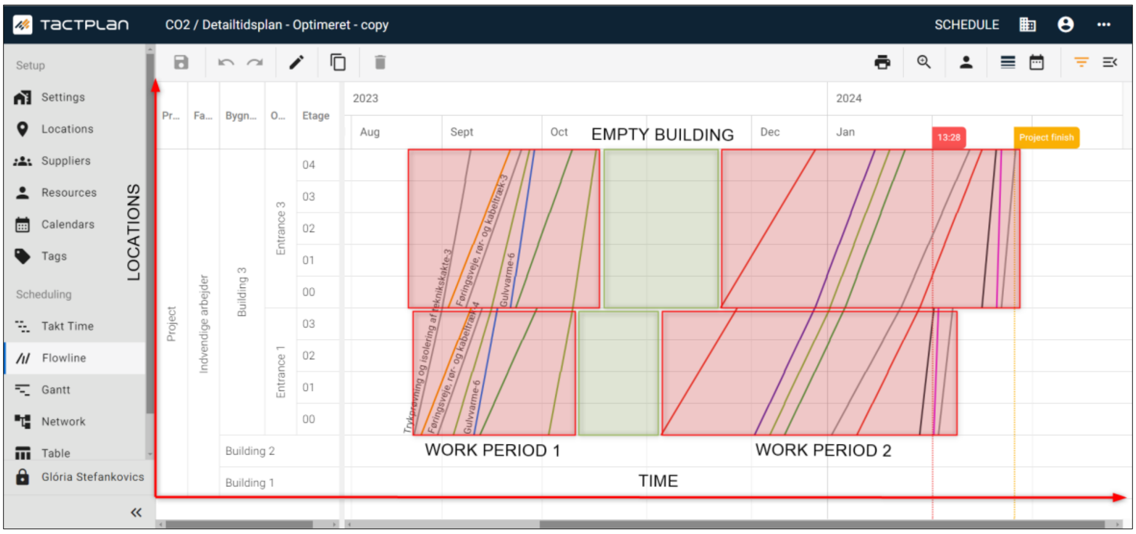

Figure 3: Possible break periods within a location during no work periods.

6. **Number of winter workdays (N_{wdays}).** Only the working days have been taken to calculate the energy consumption.
7. **Area per location (A**). The size of each location. It is essential as the base values described earlier are measured in kWh/m2.
8. **Type of heating**. Identifying the heating method employed (e.g., district heating, calorifiers). This paper and the two referenced reports utilize district heating.
9. **Type of installation**. Determining if the electricity and heating for the construction site has one common installation or if each building has its own installation. This is important because if there is a period when there is an empty building, there needs to be a method to turn off the electricity and heating for that building without stopping it for the other parts of the project. It is understood that having such installation per floor might be very complicated to achieve, so this is limited to per building within a project.
10. **$kgCO_2$/kWh produced (I)**. Based on the production method for energy, this number varies depending on the country for which the calculations are made.

With the base consumption factors (Table 1) and the relevant parameters listed above, plus the use of Tactplan (Tactplan, 2024), a software designed to streamline location-based planning, which provides a seamless workflow, enabling efficient data collection for analysis, it is possible to calculate the consumption per location. The next section will present the results based on equations 2, 3, 4, and 5 below. Other software tools, such as Vico Schedule Planner, could also have been used. However, it is important that the scheduling tool show and utilize both task and location dependencies, which makes traditional CPM/Gantt-based tools unsuitable for this method and analysis.

$$E_{heating} = N_{wdays} * A * C_{heating} \quad (2)$$

$$E_{drying} = N_{wdays} * A * C_{drying} \quad (3)$$

$$(E_{lighting} + E_{process}) = Day * A * C_{lighting +process} \quad (4)$$

$$Q = \sum E * I \quad (5)$$

$E_{heating}$ = Energy consumption for heating of building [kWh]
E_{drying} = Energy consumption for drying of building [kWh]
$E_{lighting}$ = Energy consumption for lighting of the site [kWh]
$E_{process}$ = Energy consumption for processes on the site [kWh]
N_{wdays} = Number of winter days [days]
A =Area per location [m^2]
$C_{heating}$ = Base consumption for heating of building / day =86 kWh/m^2
C_{drying} = Base consumption for drying of building / day = 17 kWh/m^2
$C_{lighting + process}$ = Base consumption for lightning and process / day = 27 kWh/m^2
Day = Construction time [days]
Q = total quantity of CO_2 emissions [$kgCO_2$]
I = CO_2 intensity of the produced electricity [$kgCO_2$/kWh]

The total energy consumption for each scenario within every case study is determined by combining the kWh usage for lighting, process energy, and heating. Heating is calculated by summing up the square meters under construction, multiplied by the number of winter days in the building period, and multiplied by the heating consumption rate in kWh/m2. Similarly, the estimate for lighting and process energy involves multiplying the number of workdays in all work periods by the square meters of the areas under construction and the lightning + process electricity consumption rate in kWh. No additional drying equipment is planned, as temperature-sensitive internal works coincide with internal heating, resulting in an E_{drying} value of 0,2, which can then be disregarded.

CASE STUDIES AND RESULTS

This research examines three real-life cases, each described with preconditions, results, and conclusions. To maintain confidentiality, project names and details are undisclosed. The cases involve different building types, introduction periods for Location-Based Scheduling (LBS), and optimization tasks, aiming to mitigate single random good results and assess outcomes without bias towards single projects with the best results. Location-Based Scheduling is today widely adopted in construction (Lerche et al., 2019) and known for its ability to optimize the schedule (Kenley & Harfield, 2015; Seppänen et al., 2010).

CASE STUDY A – 9,000 M² NEW RESIDENTIAL

The task for this project from the management team was to create a Location-Based Schedule with given constraints for resources and start and end dates.

Preconditions

The project's management team adopted LBS exclusively for internal works, with energy consumption calculations covering the period from June 14, 2023, to February 23, 2024. The case study involves three buildings with varying entrances and five floors.

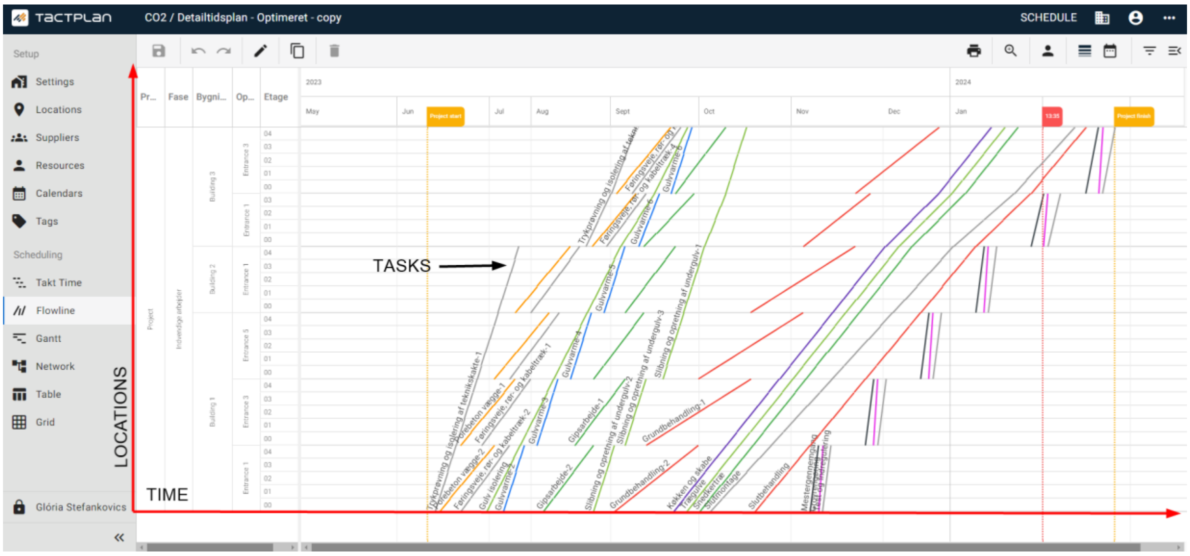

Figure 4: Schedule for Case Study A

- ***Scenario 1*** **-** Common heating and electricity installation for the entire construction site without the option to isolate empty buildings. Traditional practices involve continuous internal lighting and heating during the winter, serving as a benchmark for comparison.
- ***Scenario 2*** **-** Heating and electricity installation with the option to isolate empty buildings. Stricter emission control requires enhanced project management during construction, potentially prompting operational changes. This scenario explores optimizing heating and lighting schedules, proposing their shutdown during pauses of at least two weeks between two finish-to-start activities in the same building, as illustrated in Figure 3 (marked with green). Maintaining a minimum indoor temperature in colder climates is crucial for preventing materials from freezing or deteriorating, which could affect their quality and integrity. Completely turning off the heating could lead to issues, which could cause delays and additional costs to rectify. But continuously running heating systems during periods when no work is taking place can be costly in terms of energy consumption, so even though it is not the current practice, the point of the scenario is to see if the CO_2 emission savings justify further investigation into the feasibility of minimal or no heating strategies.
- ***Scenario 3*** **-** Shifting work to non-winter months. Results from previous cases highlight heating as a significant contributor to energy consumption. To determine potential energy savings, the project start is shifted to the first non-winter day (April 1, 2023) while maintaining other preconditions, resources, and durations, resulting in a project end date of December 5, 2024.

Case A - Conclusions

Table 2: Results for Case Study A.

Scenario 1			**Scenario 2**			**Scenario 3**		
Energy kWh	*CO_2 tons*	*CO_2 kg/m^2*year for 30 years*	*Energy kWh*	*CO_2 tons*	*CO_2 kg/m^2*year for 30 years*	*Energy kWh*	*CO_2 tons*	*CO_2 kg/m^2*year for 30 years*
219,002	36	0.161	178,454	30	0.131	68,445	11	0.050

Transitioning from traditional site operations to a more sustainable process presents an opportunity to reduce emissions. In this case study, a potential improvement of 17% is demonstrated. For shorter projects lasting less than a year, minimizing internal work during winter can result in a 69% improvement in emissions without additional effort.

CASE STUDY B – 8,000 M2 OFFICE RENOVATION

Tasked with minimizing project extension in a delayed project, the management team aimed to address significant delay costs after initial milestones. Despite having a Location Based Schedule, commissioning works at the project's end overlapped, assuming contractors could share locations during that period. However, detailed analysis revealed finish-to-start relations among various activities, hindering simultaneous execution. The initially reserved time was insufficient, leading to a 3-month project extension and a potential one-year delay.

Preconditions

Due to tight deadlines, project complexity, and continuous work, a scenario like turning off heating in inactive locations is not feasible.

- ***Scenario 1* -** Lighting + process energy usage at all times and heating usage during winter periods – 12-month delay
- ***Scenario 2* -** Lighting + process energy usage at all times and heating usage during winter periods - Optimized 3-month delay.

Case B - Conclusions

Table 3: Results for Case Study B.

Scenario 1			Scenario 2		
Energy kWh	*CO_2 tons*	*CO_2 kg/m^2*year for 30 years*	*Energy kWh*	*CO_2 tons*	*CO_2 kg/m^2*year for 30 years*
1,544,112	256	1.187	1,323,216	220	1.017

The results highlight a potential correlation between project duration and energy consumption, a logical inference given the expectation of higher energy usage in longer projects. The transparency and detailed construction process provided by LBMS underscore its importance. As regulations evolve, the need for methods to quantify the energy implications of delays is anticipated.

CASE STUDY C – 50,000 M2 NEW MEDICAL FACILITY

The project's management team initiated LBMS from the project's inception. The available information includes start and end dates for the tender schedule and actual execution, allowing for an investigation into how time impacts energy consumption and emissions in the context of delays.

This case study compares actual project end dates with the industry average delay for medical buildings. A 2022 report by the Ministry of Health in Denmark indicates an average delay of 2.3 years for 16 medical facilities. Since structural works are typically on time while delays often occur during internal works, the 2.3-year delay is proportionally added to the planned duration of interior works.

Preconditions

Due to tight deadlines, project complexity, and continuous activity, creating a similar scenario to turn off heating in inactive locations is not feasible.

- ***Scenario 1*** - Tender Schedule: Lighting + construction process electricity usage at all times and Heating usage during winter periods.
- ***Scenario 2*** – Actual Schedule: Lighting + construction process electricity usage at all times and Heating usage during winter periods. Compared to the tender schedule, there is a delay of approximately 5 months.
- ***Scenario 3*** – Theoretical industry delay (+2.3 years): Lighting + process electricity usage at all times and Heating usage during winter periods.

Case C - Conclusions

Table 4: Results for case study C.

Scenario 1			**Scenario 2**			**Scenario 3**		
Energy kWh	*CO_2 tons*	*CO_2 kg/m²* year for 30 years*	*Energy kWh*	*CO_2 tons*	*CO_2 kg/m²* year for 30 years*	*Energy kWh*	*CO_2 tons*	*CO_2 kg/m²* year for 30 years*
6,552,733	1,088	0.725	8,336,426	1,384	0.923	11,839,282	1,965	1.310

As can be seen, there is a big difference between the actual (scenario 2) and the theoretical industry delay (scenario 3), amounting to 581 tons (42%) of extra CO_2 emissions. The amount has been converted to other equivalents in Table 5 to understand better what that means.

Table 5: Conversion to illustrate the amount of CO_2 emissions.

581 tons of CO_2	274 family homes' electricity for one year
	216,044 liters of diesel consumed
	2,396,992 km driven by an average gasoline-powered car
	70,674,377 smartphones charged

The results indicate that delays significantly impact energy consumption. Complex projects with a history of overrun risk face penalties for excess emissions, further adding to the already exceeded budgets due to delays.

CURRENT LIMITATIONS OF THE METHOD

The method relies on data from reports dating five or more years back, potentially underestimating efficiency gains in energy consumption due to technological advancements. However, the developed method allows quick parameter changes, automatically adjusting results with updated information.

The challenge lies in obtaining updated, reliable data, requiring cooperation from building owners, management teams, equipment vendors, and contractors willing to track and share relevant consumption numbers. Detailed research could be pursued with the involvement of interested parties sharing information.

Such factors are: 1) kWh used for electricity on site, 2) kWh used for heating on site, 3) kWh used for warm water, 4) kWh used for heating the temporary offices, 5) kWh used for heating the changing rooms for workers, and 5) Emissions from diesel-powered heavy machinery.

Another limitation is that the calculations are made with average values from different types of projects. A better approach would be if there were an extensive library of projects where the most similar one could be chosen based on the parameters listed in Section 2. In that way, the correlation between historic projects and new estimates will be stronger. However, such reliable data currently doesn’t exist.

DISCUSSION

Based on the results across the three case studies and examined scenarios, it is evident that the quantification method applies to various situations.

What is the ratio between the emissions from Production and Use compared to Construction process emissions?

Currently, material production (phases A1 to A3) and building operation (phases B1 to B7) contribute the most to emission production (Wandahl et al., 2021).

The construction phase (phase A5) accounts for approximately 10% of GHG emissions from buildings (Klimapartnerskab, 2020). Upcoming Danish regulations targeting 12 $kgCO_2$ per m^2 per year will decrease values for materials and occupancy, the most significant contributors. As these values decrease, the attention will shift to the construction phase as a substantial area for emissions reduction demands. Notably, the 12 $kgCO_2$ per m^2 per year regulations exclude the construction process but results from case study C demonstrates a potential reduction of over 1 $kgCO_2$ per m2 per year, constituting 8% of the threshold value solely from energy consumption. This 8% could increase by including transportation and diesel-powered machinery.

Additionally, the initial threshold of 12 $kgCO_2$ per m2 per year is just a starting point. As regulations become stricter, by 2050, there will be a growing need for a quantification method for emissions produced by construction sites, along with a requirement to document A5 and reduce A5 GHG.

Possibilities for future development

More recent data

Similar to Sommer et al. (2013), new research can validate if technological advancements have reduced overall energy consumption. Comparing calculations from study cases using this quantification method with actual metered consumption on construction sites can yield more accurate conclusions.

Resources – Manning linked to energy consumption

The simplest improvement entails considering heating consumption for temporary offices and worker changing rooms. By utilizing resource counts from a graph, one can determine the necessary work crews and their areas during different project phases. This calculation method, utilizing average numbers from Table 1, becomes applicable.

Resources - Diesel-powered machinery energy consumption

Addressing the limitations, the calculations did not consider energy use and GHG from diesel-powered construction equipment. However, by creating a catalogue of commonly used heavy machinery brands and examining their technical specifications for hourly consumption, it's feasible to multiply the number of resources by their consumption and convert it to CO_2 emissions. Fossil fuels are a significant source of CO_2 emissions, and the LBMS method facilitates efficient planning for heavy machinery use. The European Rental Association's "Equipment CO_2 Calculator" (ERA, 2024) is a potential source of inspiration.

Automated calculation method integrated into software

The calculations in this research are time-consuming, done in spreadsheets, and should be integrated directly into a scheduling tool, automating the process. With an LBMS engine, the software could extract start/end dates, identify winter periods, and apply base values for heating/lighting, requiring only user input for area per location. Resources, including heating and diesel-powered machinery emission factors, should be part of any future construction schedule. Background calculations would enable rapid estimation updates with each schedule change, allowing users to evaluate the environmental impact of strategic moves in seconds.

CONCLUSIONS

Results from all study cases underscore that the primary correlation with CO_2 production is tied to duration and scale. Larger areas require more heating energy, and expansive projects often lead to longer construction periods, increasing winter periods and energy usage for heating. Given that heating is the primary energy consumer, building types prone to delays and cost overruns face a higher risk of surpassing CO_2 limits once regulations are in place.

The core reason for utilizing location-based planning methods such as Location-Based Scheduling or Takt planning (TP) in projects is to minimize the risk of time overruns, leveraging their superior overview and coordination capabilities. As also stated by (Ballard & Tommelein, 2021), when projects can be divided spatially, it is recommended to use a form of location-based planning method. Larger and more complex projects stand to gain significantly from LBMS, reducing risks in the planning phase and ensuring a healthier schedule.

LBMS enables pinpointing schedule problem areas by considering both time and location, a capability lacking in the Critical Path Method (CPM) due to its omission of task placement data. A CPM/Gantt-based schedule lacks the ability to show and optimize non-working zones which have been found critical for reducing CO_2 emissions. By highlighting location, LBMS facilitates analysis of electricity, lighting, drying, and other processes, allowing for consumption calculation based on area and time.

Another location-based method available is Takt planning (TP). This planning form is somewhat similar to LBMS apart from its rigidity, which stems from operating on fixed time intervals and relying heavily on completing preceding tasks within the allocated time frame. That is all to say, that bearing in mind the disadvantage of TP, the method could also be used to help quantify CO_2 emissions on site, as it also entails the necessary data (area and time).

In summary, optimizing schedules for time and resources doesn't necessarily equate to reduced CO_2 emissions. Sometimes, optimizing for time may inadvertently lead to increased energy consumption and emissions, particularly if activities are shifted to winter periods without prior heating plans. However, project management can make informed decisions by quantifying the impacts of schedule changes. They can evaluate the extra emissions and costs, compare them with the initial optimization, and choose between schedules aligned with milestones or delayed schedules.

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SYNERGY BETWEEN LPS AND SLACK: A CASE STUDY IN BRAZILIAN HORIZONTAL HOUSING DEVELOPMENTS

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ABSTRACT

Construction projects are remarkably unique, given the specific nature in which their production processes are organized and the high levels of variability and uncertainty that permeate their entire life cycle. Several initiatives can be implemented to mitigate the effects associated with unpredictability in construction projects. The Last Planner System has emerged as a valuable tool to provide greater confidence in the planning of construction projects. Another practice that has been increasingly adopted in the sector is the use of buffers. Despite the incipient perception that buffers may be associated with waste, studies conducted in airports and logistics centers have suggested their use as a valuable ally in combating uncertainties and protecting the production system. Research also points to the combined use of buffers with pull planning to reduce the effects of variability. In view of the foregoing, this study aimed to investigate the use of slack practices together with the long-, medium-, and short-term plans of the Last Planner System. The investigation used as a reference the following classifications of time off practices mapped in the literature: Redundancy, work-in-progress and margins of manoeuvre. The research was based on a case study of Brazilian horizontal housing developments. The main finding highlights the synergy between the categories of time off practices found and the objectives established by each of the horizons of the Last Planner System. Furthermore, other dimensions of analysis, such as logistics, supplies, security, may arise due to the nature of the project typology, and the need for practices that mitigate the uncertainties inherent in the execution of these projects.

KEYWORDS

Lean Construction, slack, last planner system.

INTRODUCTION

Construction projects have a unique nature, characterized by distinct products, temporary mobilization of production teams, local production conditions, and the need to meet pre-established criteria of cost, execution time, quality, and risk (Ballard and Howell, 1998; Limmer,

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2008). In addition to these factors, construction projects are commonly associated with high variability and high levels of uncertainty (Formoso et al., 2021). However, as noted by Onho (1988), the basis of a well-balanced production system lies in its stability.

In the field of construction projects, the Last Planner System (LPS) has emerged as a valuable tool to ensure that the work that should be done can be done. With LPS, it is possible to manage an inventory of available work, from which teams commit to what they will do, improving workflow and increasing the reliability of construction planning (Samad et al., 2017; Ballard 2000).

In parallel, studies have proposed the use of buffers as protection measures against variability (Fireman et al., 2022). Traditionally, buffers have been viewed as a form of waste because of the lack of a clear recognition of their potential to add value to production processes. Nevertheless, their consistent application has proved to be an important ally in combating uncertainty and increasing predictability (Horman et al., 2003).

Buffers can be defined as a set of resources implemented to protect the production system against unforeseen events, fluctuations, and delays in resource availability (Alves and Tommlein, 2003). Formoso et al. (2021) and Saurin (2017) introduced the concept of slack. Although related to the buffer approach, slack practices, in addition to addressing uncertainty aspects, contribute to meeting demands or actions at a more strategic level. Buffers are mostly recommended for dealing with random variability that can undermine production goals (Büchmann-Slorup, 2014).

Previous studies described slack as a leading element in combating variability. Fireman (2018) assessed the influence of slack on work standardization in the construction environment. Saurin et al. (2021) discussed practical applications, requirements, and consequences of using slack according to strategic orientation and resource availability.

Recent studies have explored the application of slack resources and practices in construction, focusing on large-scale projects such as airport terminals and logistics centers. The investigations aimed to establish an association between slack and LPS-based planning and control methods, particularly in the context of pull planning, to effectively manage variability (Fireman et al., 2022).

Based on the study of Fireman et al. (2022), who proposed the slack practices and resources (SPR) model, this research aims to investigate the use of slack concepts and their consonance with LPS practices for reducing variability and protecting production systems in the context of horizontal housing developments in Central-Western Brazil.

SLACK

Lean construction focuses on minimizing non-transformative steps (waiting, inspection, handling), especially through reduction of variability (Koskela, 2000). As pointed out by Hopp and Spearman (1996), variability is defined as the lack of uniformity of a class of entities, which can be random (equipment downtime) or systematically observed in a given system (product diversity).

The literature contains some discussions on the subject. Ballard (2001) discussed the impacts of slack on cycle times, underscoring gains in reliability and, consequently, reduced variability. Saurin et al. (2013), in studying guidelines for managing complex systems, noted that slack contributes to absorbing the impacts of variability. Slack can take various forms, such as redundant equipment, underutilized space, excess labor, and time margins; however, it may potentially mask problems and obscure system inefficiencies.

The role of slack practices in supporting organizations to deal with variability has been discussed and associated with different managerial processes (Fireman et al., 2022). Saurin and Werle (2017), in a literature review, analyzed slack in sociotechnical systems and proposed a structured framework to better understand slack practices, their uses, and categories (Table 1).

Based on the framework of Saurin and Werle (2017), Fireman et al. (2022) investigated how slack practices and/or resources can be used in production planning, demonstrating their positive effects in mitigating variability at different hierarchical levels (long-, medium-, and short-term planning).

LPS

LPS improves the reliability of activities in the short term, functioning as a shield against variability in planned work and promoting workforce engagement through increased collaboration of the work teams that integrate the decision process (Ballard, 1994). In LPS, planning is structured on three levels. At the lowest level, what will be done is the result of the planning process that best aligns what should be executed (planned) with what is possible to be executed based on constraints imposed by the scenario (Ballard, 1994). The medium-term plan (six-week look-ahead) determines the path to achieve these objectives, identifying and removing constraints and ensuring that resources (materials, information, and equipment) are available for task execution (Ballard, 1994). The master plan focuses on global objectives and constraints, addressing the project as a whole and describing what should be done.

Table 1: Slack practices (Saurin and Werle, 2017)

Practice	Definition	Subcategory	Definition
Redundancy	Resources in addition to the minimum necessary to perform a function (Nonaka, 1990) or more than one resource performing the required function (Azadeh et al., 2016).	Standby	The redundant resource is not immediately involved in the task at hand, and is typically not present in the operator's immediate environment (Clarke, 2005).
		Active resource	The redundant resource is involved in the task at hand (Clarke, 2005).
		Redundant procedures	Redundant checks are made to detect failures, usually involving different professionals and types of inspection (Ong and Coeira, 2010) and alternative procedures to execute an activity (Saurin and Werle, 2017).
Work-in-progress	Resources waiting to be processed in between process steps and stages.	Simultaneous work zones	Number of simultaneous work zones in a construction site. They offer alternative activities to keep the teams busy in case of temporary stoppages in one or more work zones (Bashford et al., 2003; Sacks et al., 2010).
		Stock of materials	Stocks of semi-processed products, raw materials, and finished products (Saurin and Werle, 2017). The latter two types are interpreted here from an expanded view of work-in-progress (i.e., raw materials are waiting to be processed, whereas finished products are waiting to be delivered to customers).
Margins of maneuver	Practices that create or maintain margins that allow the system to function despite unexpected demands (Saurin and Werle, 2017).	Defensive practices	Practices that create or maintain margins that allow the system to function despite unexpected demands (Saurin and Werle, 2017).
		Autonomous practices	Practices restricting other units' actions or borrowing other units' margin (Stephens et al., 2011).
		Coordinated practices	Practices that recognize or create a common-pool resource from which two or more units can draw (Stephens et al., 2011), such as multifunctional workers or general-purpose machines (Fireman et al., 2018).

RESEARCH METHOD

METHOD DESCRIPTION

Certain factors must be considered when selecting the research strategy. These include the type of research question, the extent of control the researcher has over events, and the emphasis on historical or contemporary events (Yin, 2003). According to Yin (2003), a case study approach is recommended for research with exploratory characteristics or descriptive aspects in a real and contemporary context. It should be noted that this research method has some inherent limitations regarding result generalization, as its focus lies on seeking an analytical understanding and interpreting facts within the studied context (Costa, 2010). This study aims to understand how slack practices and resources are applied in the context of horizontal housing developments. Thus, a case study approach aligns well with the research theme.

The data were collected by an auxiliary researcher, who acted as a consultant in the studied project. The company where the study was carried out had no previous experience with LPS. The consultant provided guidance on the development of long-, medium-, and short-term plans, logistics plans, and control routines and offered training and workshops for indirect workers. The consultant's role in the project was not that of a decision-maker; rather, the role focused on ensuring the implementation of core LPS practices and facilitating the identification of waste during planning phases. The consultant remained in the project for approximately 9 months, being 4 months for the development of long-term and logistics plans and 5 months for the formulation of medium- and short-term work routines.

The content of this study is divided into four parts: (i) a brief contextualization of the theme, (ii) a description of the chosen company and its characteristics in the context of lean implementation, (iii) an overview of the data collection process and the researchers' contributions to the project, and (iv) a presentation of the findings from the case study.

THE SELECTED COMPANY AND CONSTRUCTION PROJECT

The research was conducted in a Brazilian construction company founded in 1986. The company specializes in residential civil construction, specifically in medium- and high-end buildings and horizontal developments (residential lots) (Figure 1). The company has launched 37 projects, resulting in the construction of 22 million m^2 over its 35 years of history. Recently, the company has expanded its operations to include house construction projects.

Figure 1: Illustrative image of the horizontal housing project (source: the authors)

The project selected for the case study is a horizontal housing development with 626 units and 37,000 m^2 built. The project has a total duration of 25 months, starting in October 2022 and predicted for completion in December 2024.

DATA COLLECTION

The data used in the research were acquired by the auxiliary researcher during the consulting process of the study project. The data sources included documents generated in the period and participant and non-participant observations. There were no major difficulties in data collection, as the consultant had direct access to project plans, control documents, and work routines.

The **analyzed documents** included long-, medium-, and short-term plans; minutes of meeting with contractors; logistics plans, including site layout and zoning studies of inventory areas and equipment; constraints identified in weekly meetings for medium-term planning; weekly plan spreadsheets and daily monitoring spreadsheets of production leaders' goals.

Participant observations were conducted by the consultant, who integrated the planning team responsible for drafting all stages of long-term and logistics plans for the project. Although actively engaged in discussions, the consultant lacked decision-making authority. The consultant also took part in about 20 medium-term planning meetings addressing issues related to the construction staff and support sectors, and participated in approximately 60 daily meetings for monitoring weekly goals.

Non-participant observations were carried out weekly during visits to the site. These observations involved monitoring practical aspects in progress, such as instances when a supplier truck was used to transport material kits. Observations also included reviewing documents produced during the consultant's absence. Of note, the consultant did not partake in all short-term planning meetings where weekly goals were defined.

From this, the time off practices consolidated by Fireman et al. were used as a reference. (2022) seeking to identify the action, map the practice of time off and classify the variability and resources involved.

RESULTS

LEAN IMPLEMENTATION

The lean implementation process began in April 2022 with the structuring of the long-term strategy and logistics plan for a single project. Lean planning introduced the concept of work packages, whereby it is possible to create work scenarios that take into account pace variations, activity durations, and labor histograms. A total of five scenarios were created, with participation of about 15 professionals from Operations, Planning, Budget, Projects, and Strategy departments. The company's top management ultimately chose the optimum version in terms of time and cost.

Scenarios were generated using the time path tool in zoomed view and the line balance tool in the most detailed version. Each version incorporated variations in productivity based on the rainy periods of the city. The site is situated in a region prone to intense rainy periods lasting up to 5 months per year. This reduction in productivity was subsequently transformed into time spaces between work packages. At this point, the first slack was identified, categorized as redundancy (standby).

After the long-term plan was developed, the next step was to promote the diffusion of lean concepts within the organization and create work planning and monitoring routines. LPS served as the basis for unfolding the masterplan into medium-term, short-term, and daily routines. Medium-term routines involved collaborative planning with the company's support sectors, with goals and restrictions defined over an 8-week horizon. Short-term routines, referring both to weekly schedules and daily hurdles for goal monitoring, were prepared by the production team together with outsourcing labor supervisors.

An important component of the work planning routines was the inclusion of work logistics as an essential part of the production process. Given that the project is a horizontal development, the logistics of supplying work fronts played a key role in ensuring productivity. The horizontal displacement of production leaders was physically demanding, making it challenging to effectively manage materials and staff across all fronts. Therefore, logistics leaders were involved in the formulation of medium-term plans, weekly work planning routines, and daily monitoring routines.

Currently, lean implementation has become a significant pillar within the company's restructuring process. Placed under the coordination of the planning sector, it encompasses all five ongoing projects of the company and is centered on reducing variability, enhancing the stability of the production system, and meeting deadlines.

CASE STUDY

The study included team members who had participated in the project since the development of the long-term plan. The production manager, production engineer, engineer, and planning assistant and logistics coordinator also participated in this study. Therefore, it can be said that the team was highly qualified to identify and evaluate opportunities for slack practices in all planning horizons (long, medium, and short term) and the logistics of the project.

The key element of medium- and short-term planning was work packages. All work fronts were designed to allow observation of package evolution, as well as supply and kitification routines. This view was essential for decision-making by site managers when identifying priorities and points to be strengthened in day-to-day management.

Thus, in this research, the analysis was segmented into LPS horizons, namely long, medium, and short terms. Furthermore, a separate analysis was carried out for on-site logistics, given the importance of its integration with planning.

LONG-TERM PLANNING

Long-term breaks were mainly associated with periods of intense rainfall during project execution (Table 2). In this scenario, protection against time variability was achieved by the insertion of waiting times between work packages to ensure that work fronts would not be interrupted by incomplete predecessor tasks.

Table 2: Description of slack practices in long-term planning (source: the authors)

ID	Instantiations of slack practices	Slack practices	Variability tackled by slack practice	Slack resources	Unintentional consequences
1	Use of a generator to cover power shortages	Redundancy – active	Possibility of receiving more energy from the supplier	Financial	None
2	Insertion of waiting times between work packages in long-term planning	Redundancy – standby	Delays in predecessor tasks negatively affect successor tasks, delaying the schedule	Time	None
3	Worker accommodation camp larger than necessary to meet a potentially greater labor demand than initially planned in the resource histogram	Margins of maneuver – autonomous	Lack of dining area infrastructure could result in last-minute mobilization of labor	Space	Increase in worker camp infrastructure
4	Schedule final deliveries before the customer's deadline	Work-in-progress – stock of materials	Protection against unforeseen events that could influence the delivery date	Time	None
5	Project coordinator acting as the resident engineer for the training of new members	Redundancy – active	The project coordinator worked together with the resident engineer to develop technical tasks for the new team member	People	None
6	Use of productivity estimates lower than the historical average in the masterplan	Margins of maneuver – defensive	Possible low performance of the production team	People	None
7	The purchase of extra production equipment was considered in the budget to replace contractor equipment	Redundancy – active	Ensure that third-party labor does not remain idle due to equipment shortage	Equipment	Extra space for equipment storage

Aiming to protect against time variability, the planning team decided to use productivity indicators below the company's historical series, foreseeing the potential waste that would occur in these periods. In another scenario, early delivery dates were set as a goal for the production team to generate a greater sense of urgency in decision-making.

Two other slack practices were adopted by the company with the aim of (i) ensuring quick actions against time variability (e.g., by designing a worker accommodation camp with a greater capacity than that estimated by the initial labor histogram to ensure quick mobilizations, if necessary) and (ii) preventing or eliminating idleness at work fronts (e.g., by having own inventory of tools to equip third-party labor teams when they, for some reason, had a shortage of equipment).

MEDIUM-TERM PLANNING

For the medium-term horizon, slack practices were mainly characterized by production protection (Table 3). For instance, third-party labor teams were mobilized from other projects to compensate for newly integrated teams during their learning cycle.

Table 3: Description of slack practices in medium-term planning (source: the authors)

ID	Instantiations of slack practices	Slack practices	Variability tackled by slack practice	Slack resources	Unintentional consequences
1	Preemptive kit assembly	Work-in-progress – stock of materials	Delays could impact tasks requiring these resources (kits)	Materials	Increase in the area for kit storage
2	Resident engineer acting as a backup front-line production leader	Redundancy – standby	Engineer acting as production leader to compensate for the lack of front-line supervisors	People	None
3	Spare third-party teams mobilized from other worksites to support the learning curve of new teams	Redundancy – standby	Spare teams to support the possibly low productivity of new teams	People	Temporary increase in logistics demand
4	Company designer developed a formwork plan because the contract designer delayed plan delivery	Redundancy – active	A delay in plan delivery could delay the beginning of the work	People	None
5	Purchase of raw material from secondary supplier to cover delays in delivery from the main supplier	Redundancy – active	Delay in material delivery could lead to idleness on work fronts	Materials	None
6	Integration training carried out together with labor teams from other construction sites to speed up possible future mobilizations	Redundancy – standby	Delays in work tasks that would require team mobilization	People	None
7	Alteration of wooden formwork plans for columns to facilitate assembly at the work front	Margins of maneuver – autonomous	Low productivity of the carpentry team	Projects	Additional demand placed on the design team
8	Alteration of the prestressed beam layout to facilitate the assembly of electrical installations embedded in the slab	Margins of maneuver – autonomous	Low productivity of the electrical team	Projects	Additional demand placed on the design team
9	Intended accumulation of concrete tasks to achieve the minimum volume of the concrete mixer truck	Margins of maneuver – autonomous	Achieve the minimum volume for concrete delivery	Materials	None

In another situation, because of a delay in material supply by the primary supplier, the procurement team purchased materials in duplicate from another supplier to ensure that successor work packages would not be penalized by a shortage of resources. In both cases, resource redundancy was deliberate to maintain the production pace.

As a margin of maneuver and to protect production, the company's project team had unscheduled demands when a layout plan did not have sufficient efficiency in production. As a result, plans had to be revised to increase labor productivity, as was the case when column layout plans were revised to increase the productivity of carpentry teams and when layout plans for prestressed beams were revised to increase the productivity of the slab installation team.

SHORT-TERM PLANNING

Short-term breaks were taken mainly to ensure the uninterrupted flow of teams and the rhythm of work packages scheduled in weekly meetings with production leaders (Table 4). The practices categorized as margins of maneuver had greater prominence. For instance, a team of masons was allocated to a carpentry front to prevent idleness. Also for this purpose, the excavation backhoe originally used for digging infiltration wells was mobilized to the bobcat front, as the latter had to undergo unscheduled maintenance.

Table 4: Description of slack practices in short-term planning (source: the authors)

ID	Instantiations of slack practices	Slack practices	Variability tackled by slack practice	Slack resourc e-es	Un-intentional consequen-ces
1	Implement Saturday work schedules	Margins of maneuver – autonomous	Low productivity during weekdays	Time	Direct and indirect overtime costs
2	Plan alternative activities to prevent teams from idling in the event of delays in the predecessor task	Work-in-progress – simultaneous work sites	Delay in the predecessor task	People	None
3	Carpentry teams from column production fronts redirected to the slab front to offset any delays	Redundancy – standby	Carpentry teams working on columns are used as reinforcement for the slab team to compensate for delays	People	None
4	Backhoe for digging infiltration wells being used to replace work carried out by bobcat on foundations	Margins of maneuver – coordinated	Backhoe being used to replace equipment under maintenance	Equip-ment	None
5	Mobilization of a concrete truck from a third-party supplier to make up for unavailability of the company's concrete plant	Margins of maneuver – autonomous	Third-party supplier providing concrete during maintenance of the local plant	Materials	None
6	Resident engineer inspected the quality of tasks carried out after the production leader verified the service	Redundancy – redundant procedures	Tasks completed without being inspected for quality	People	None
7	Deployment of mason teams to the column carpentry service to offset delays	Margins of maneuver – coordinated	Idle workers	People	None

Slack practices were also carried out to ensure compliance with short-term goals, as noncompliance could lead to delays in medium- and long-term goals. For example, work was scheduled on Saturdays to recover goals not reached during the week. A third-party concrete mixer truck was deployed to compensate for the absence of the construction company's own truck, thereby ensuring the supply of concrete to the work fronts.

LOGISTICS

The adoption of slack practices was observed in processes depending on supply logistics, particularly margins of maneuver involving equipment used to transport materials. For example, a ¾-ton truck supplying kits was used to supply steel column starters. A backhoe digging infiltration wells was used to move earth from other work fronts.

Slack practices related to work in progress (stock of materials) were also identified. A buffer area was planned for the storage of raw materials, and material kits were delivered before the planned deadline. These slack practices were adopted to ensure that labor teams or work fronts would not run out of materials, protecting production against equipment failures and delivery of third-party raw materials (Table 5).

Table 5: Description of slack practices in construction site logistics (source: the authors)

ID	Instantiations of slack practices	Slack practices	Variability tackled by slack practice	Slack resources	Unintentional consequences
1	¾-Ton truck adapted for installation kits being used to supply steel column starter	Margins of maneuver – coordinated	Mobilization of new equipment for unloading at new work sites	Equipment	None
2	Use of supplier's pick-up truck to transport small volume materials	Margins of maneuver – autonomous	Mobilization of new equipment for unloading at new work sites	Equipment	None
3	Storage areas designed with buffer zones for the delivery of raw materials	Work-in-progress – stock of materials	Delays in the delivery of raw materials by suppliers could impact work sites	Space	Increase in the storage space for raw materials
4	Forklift adapted to assist in unloading raw materials delivered by the supplier	Margins of maneuver – autonomous	Equipment can speed up the unloading of materials from suppliers	Equipment	None
5	Workers aiding the Munck truck mobilized to the assembly of steel column starter kits	Margins of maneuver – autonomous	Support labor used in the absence of supplier labor	People	None
6	Backhoe for excavating infiltration wells allocated to moving excavated soil from other work sites	Margins of maneuver– autonomous	Equipment being used in the absence of supplier labor	Equipment	None
7	Preemptive provision of kits to work fronts to safeguard against unforeseen logistics equipment issues	Work-in-progress – stock of materials	Equipment-related unforeseen events can result in shortage of materials at work fronts	Materials	None
8	Deduct one hour when calculating the productivity of supply logistics equipment	Margins of maneuver – defensive	Possible unscheduled downtime of machines and equipment and possible low performance in meeting demands	Equipment	None
9	Construction leader verifies the number of material kits delivered and checked by the warehouse team	Redundancy – redundant procedures	Delivery of kits with missing components	Materials	None

CONCLUSIONS

This research portrayed how slack practices and resources can be used to reduce the impact of variability in the context of horizontal residential developments. On the basis of the classification proposed by Fireman et al. (2022), a case study was conducted for the identification, classification, and analysis of slack practices and resources.

The following chart shows all slack practices mapped in this study for each LPS horizon and logistics (Figure 2). The LPS production planning tool allowed structuring the analysis into three planning horizons. Horizons comprised slack practices of different natures.

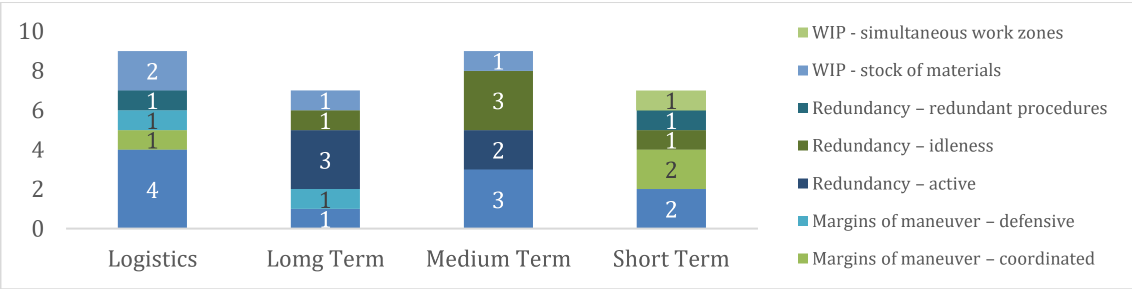

Figure 2: General distribution of slack practices mapped in this study (source: the authors)

In the long term, redundancy slack practices were the most prominent, used to ensure the continuous flow of labor teams. In this horizon, the main slack resources were time and people. The medium-term horizon was characterized by a variety of slack practices. The main practices were redundancy (active and standby) and margins for maneuver. This scenario converges directly with the main objectives of the planning horizon, as its focus is to provide greater reliability to the production system and protect production via resource availability. People and materials were the major slack resources. In the short-term horizon, autonomous and coordinated margins of maneuver were the main slack practices. This finding suggests prior alignment towards safeguarding field teams by taking immediate actions to address daily unforeseen events, avoiding the loss of short-term work packages.

Finally, according to the characteristics of the studied project, logistics was identified as a key element for the effectiveness of long-, medium-, and short-term slack practices adopted to protect production. Therefore, we conducted a more in-depth analysis of this area. There was a greater focus on the acquisition, organization, and distribution of materials and/or equipment, as evidenced by autonomous margins of maneuver and work-in-progress (stock of materials). Another concern of logistics was ensuring availability of equipment in all distribution operations. Such concern was evident by the various actions focused on optimizing equipment use in the supply of materials and inputs.

This study demonstrated how LPS and slack practices and resources interact to protect variability, and how other dimensions of analysis can arise depending on project characteristics, such as logistics, safety, and supply. The uniqueness of this case study is a limitation of the research. The stage of maturity of LPS implementation might have hindered the clarity of horizon objectives by construction teams. Furthermore, because it is an ongoing project, it was not possible to clearly evaluate the results and impacts of slack practices and resources identified in project planning.

Future research should analyze a greater number of developments with similar characteristics to gain a deeper understanding of the use of specific slack practices and resources, leading to more reliable recommendations and improved project outcomes. Furthermore, comparing these results with other similar studies can provide good considerations regarding the use of SPRs for the management of construction projects.

Additionally, there is an opportunity to investigate the infrastructure stage of the project, as our study focused solely on the housing execution phase. A quantitative/qualitative analysis of the impact of slack practices and resources should be carried out to investigate the effectiveness of actions. Finally, given that logistics played a significant role in slack practices and resources, further studies should assess their impacts on LPS horizons.

It was possible to observe that slack practices span across all LPS horizons; depending on the nature and typology of the project, other relevant horizons may arise to protect production against variability. Logistics emerged as a critical element, given the characteristics of the studied construction project and the strong influence of logistics actions on the horizons of the production system as a whole.

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SCRUM'S DISTINCT ROLE DEFINITION COMPLEMENTING LPS & TAKT IMPLEMENTATION

William Power[1], Derek Sinnott[2] and Patrick Lynch[3].

ABSTRACT

LPS and Takt are lauded for their potential to transform construction's approach to planning and execution. However, more explicit specification of the roles and responsibilities of different levels of management would be helpful towards more effective functioning of the methods. Scrum offers distinct role, responsibility, and accountability definition and this paper examines the applicability of such disciplined role clarity to assist LPS and Takt implementations.

This mixed-methods research uses case study design and data from purposeful semi-structured interviews, observation, a literature review, and project documentation review from four projects in three different construction sectors.

Findings posit that the adoption of role definition of Product Owner, Scrum Master, and Developers from Scrum could bring greater clarity and effectiveness to site management team's delivery. Eliminating duplication of effort and crossover of duties allows greater focus on executing work, preparing work, and stakeholder engagement.

KEYWORDS

Lean construction, scrum, agile, last planner system, takt.

INTRODUCTION & LITERATURE REVIEW

Last Planner® System (LPS) has brought distinct change and advantage to construction delivery over the past 30 years and much research is available to showcase this (Hamzeh et al., 2008; Liu et al., 2010). In the past decade, case studies of successful Takt planning implementation have increased (Frandson et al., 2013; Binninger et al., 2017; Dlouhy et al., 2018), as well as growing interest in the application of Scrum and Agile from the software industry to aspects of construction delivery (Poudel et al., 2020; Engineer-Manriquez, 2021; Power et al., 2022).

In the 2020 LPS Benchmark, Ballard and Tommelein (2021, p.55) ask if Agile methods could enhance LPS implementation and suggest a rigorous description and evaluation of methods that fall under the Agile umbrella should be conducted to assess if they should be incorporated into future LPS Benchmarks. This paper examines role definition as espoused in Scrum and how that could address an identified gap in both LPS and Takt implementation.

Again, Ballard and Tommelein (2021, p. 54) ask if more definitive specification of the managerial roles above the crew level Last Planners would assist more effect implementation of LPS. Literature and practice fall short of clearly identifying the roles required by participants

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to ensure effective implementation of both LPS and Takt. Table 1 presents how this 'gap' has been highlighted and suggestions for addressing it.

Table 1 – LPS Facilitator or Champion or Process Manager or Scrum Master or PMO [Adapted from Power et al. (2021)

Publication	Reference to the facilitation / champion / process manager / scrum master / PMO role
Thomassen, et al. (2003, p.65)	Process Manager - An organiser of collaborative planning between the subcontractors. Doesn't hold any formal management responsibilities so can focus on coaching and facilitating effective communication across project teams.
Daniel et al. (2016, p.29)	Internal Facilitator – On two case projects the LPS implementation was internally facilitated. If left to the team themselves it was felt no one would be accountable.
Daniel and Pasquire (2017, p.7)	Lean Champion and Internal Facilitator – Effective facilitation is a prerequisite for effective LPS implementation. Competent Facilitators and Lean Champions, supported with proactive Lean Leadership involvement, increases wider engagement.
Ebbs et al. (2018, p.725, 731)	External Facilitator – Senior management must encourage and support the Project / Site Manager to implement LPS and sustain the effort once the external facilitator departs the project. If the LPS Facilitator has design and / or construction experience it helps build authority and engagement.
Poudel et al. (2020, p.13)	Scrum Master – Having a person like a Scrum Master role in the LPS implementation would assist adherence to the principles and ensure consistent implementation over the duration of the project.
Power et al. (2021, p. 153)	LPS Facilitator – By introducing and ensuring a consistent weekly LPS structure, the LPS Facilitator focuses on implementing all LPS functions which contributes to higher PPC and productivity by stabilising workflow.
Power et al. (2022, p.185)	Scrum Master – The Scrum Masters coordinated the implementation of LPS and Scrum and brought an extra layer of support to site management by coordinating the daily and weekly planning process.
Riekki et al (2023, p.1187)	PMO – The success of the Takt implementation was specifically due to the leadership and enforcement provided by the PMO. If left to the team, Takt would not have contributed as much.

Despite the role definition advanced in Table 1, except for Riekki et al. (2023), it is only a singular leadership role that is being described as opposed to prescribing how a 'Team' should interact and coordinate together. Leaving implementation on the shoulders of a single 'expert' is not going to create or sustain sector wide LPS or Takt embedment. Additionally, the PMO input as described in Riekki et al. (2023) may struggle to achieve requisite voluntary internal collaboration and the implementation may become reliant on full-time PMO oversight. Riekki et al (2023, p.1189) noted the PMO mandated daily contractor attendance at the planning huddles. This emphasised the need for ownership and accountability for daily huddle implementation in Takt planning. A more distinct definition of all roles involved in deployment of LPS and Takt should be considered. Poudel et al. (2020) suggested using Scrum as a benchmark for clearly defining LPS roles and responsibilities. A brief introduction of LPS, Takt, and Scrum follows.

Last Planner System – A word search in IGLC database for 'Last Planner' shows 368 papers, therefore much literature exists to explain LPS. The key concepts of LPS are to assist with construction controlling and planning and has been extended to setting and seeking production targets for project planning and control in the 2020 Current Process Benchmark (Ballard and Tommelein, 2021). Ballard and Tommelein (2016, p.59) state that LPS addresses the high variability which causes low workflow reliability on construction projects. A critical step was to help project participants improve their commitments and to appreciate the need to deliver on what they said they would do.

Takt Planning - A word search on 'Takt' in IGLC database highlights 97 papers, indicating the increasing popularity of Takt as a production planning process in construction projects. Takt time aligns the output rates of various trades by setting a consistent pace to allow continuous workflow through pre-defined zones. It prioritises flow of work dictated by the pace of the labour crews (Frandson et al., 2013) and as well as promoting continuous workflow, Takt also seeks more reliable handoffs, and strives to enhance the design of the production system. According to Frandson et al. (2014) using LPS with Takt offers greater control and stability. Additionally, Takt's continuous planning and system design creates a steadier atmosphere for LPS implementation (Frandson et al., 2014)

Scrum - A search on 'Scrum' on the IGLC database shows only 8 papers up to IGLC 31. Even though Koskela and Howell (2002) and Owen et al. (2006) posited both LPS and Scrum had the potential to improve the coordination of construction operations, practitioner and academic focus has predominantly been on improving LPS. The Scrum Guide (2020) proposes Scrum helps teams generate value by seeking adaptive solutions to complex problems and thus is called a lightweight framework. Scrum relies on autonomous, empowered, and self-sufficient teams which can make their own decisions to progress towards their objectives. Small batches of valuable work are developed within 'sprints' of one to two weeks duration. Daily Huddles and regular demonstrations allow implementation of change if required. This restricts the chance of miscommunication or misunderstanding of where the true value lies (Sutherland, 2014; Layton et al., 2020; Engineer-Manriquez, 2021).

Construction planning - Construction's approach to planning is confined to transformation of inputs to outputs (Sacks, 2016; Daniel et al., 2020); this limits the collaborative environment needed for efficient and orderly task execution (Demir and Theis, 2016; Ballard et al., 2020). Traditional construction management falls short in the 'flow' and 'value' concepts; Daniel et al. (2020) suggests LPS and Scrum addresses these shortfalls by promoting a more collaborative environment for construction planning. A more complete construction production system is offered with LPS (short term planning, execution, and control – Koskela and Howell, 2002, p.6) and Scrum (focusing on Minimum Viable Product through Sprints – Layton et al. 2020, p.438) complementing the 'transformation' of inputs to a continuous workflow of value outcomes.

While LPS and Takt are lauded and widely publicised as having the potential to transform construction execution effectiveness, there are aspects of Agile and Scrum can also bring distinct advantages to production planning and control (Poudel et al., 2020; Power et al., 2022).

This research poses three questions to address the following hypothesis: A clearer definition of construction management team roles and responsibilities, as defined in Scrum, will assist LPS and Takt to enhance construction delivery.

RQ1 – What are the roles and tasks of construction management teams?

RQ2 – How do construction management teams perceive their roles and responsibilities?

RQ3 – How can the role definitions in Scrum benefit construction management?

METHODOLOGY

Mixed methods were adopted with case study design in accordance with Yin (2009). The first author worked as LPS Facilitator across the four projects: two residential, one commercial, and one pharmaceutical. Dissimilar roles and responsibilities were witnessed between different sectors and from project to project. This impacted the effectiveness of the LPS implementation and therefore it became important to examine the disparity in roles and responsibilities. Table 2 presents the research sequence and participants.

Table 2 - Research sequence and participants

Steps	Source	Project and Participants
1	Integrative Literature Review	Construction, Lean, Lean Construction, Agile, Scrum Literature. Scrum Guide 2022.
2	Project Documentation	LPS documentation & data; Lessons Learned; Meeting Minutes; Procurement Logs; Safety & Quality Registers.
3	Direct Observation	Direct Observation / Shadowing of Site Management personnel on 4 projects over 8 months.
4	Purposeful Interviews	Interviews with Site Management teams on four projects (4 X PMs, 4 X Superintendents, 3 X Site Supervisors). N = 11.

A mixed-methods approach was selected as both quantitative and qualitative models can complement and compensate each other's weaknesses (Steckler et al. (1992). The resulting triangulation adds to the validity of the findings (Bogdan and Biklen, 2006). In accordance with Creswell (2009) a sequential explanatory approach was adopted. The quantitative data was gathered over an 8-month observation period and the qualitative data gathering followed. The quantitative data was analysed and influenced the approach to the qualitative data gathering (Creswell et al., 2003).

Four projects across different sectors were deliberately selected to increase validity and to offer a broader perspective, as advocated by Yin (2009) and Stake (1995). The researcher visited the projects weekly over a period of 8 months and accompanied and observed site management executing their daily duties on the projects. The project managers, superintendents, site supervisors, and crew leaders were the focus of the observation. Interviews were conducted with four project managers, four site superintendents, and three supervisors from the four different projects.

FINDINGS & DISCUSSION

Table 3 takes the definition of Scrum roles from the 2020 Scrum Guide and, while maintaining Scrum terminology, proposes how these could align with current construction management roles. It is important to distinguish between a Product Owner (PO) and a Project Manager (PM). Layton et al. (2023) state the Product Owners primary job is to take care of the business side of the product or service and is responsible for maximising the value of the product resulting from the Scrum team's work (p.32). However, in traditional project management, the Project Manager carries huge responsibilities, which are broad, all inclusive, and often too much for one person to deliver effectively (p.173).

Table 3 - Scrum roles applied in construction (adapted from Scrum Guide, 2020).

Scrum title / Construction title	Responsibilities	Accountabilities
Product Owner (PO) / Project Manager (PM)	Ensures overall project progression. Owns the backlog, breaks it down, and prioritises the order and sequence. Owns Sprint Planning and Stakeholder Reviews.	Managing the product backlog. Keeping the product goal to the fore. Creating, ordering, and communicating the product backlog. Ensuring the product backlog is transparent, visible, and understood by all. Being available to the team to resolve escalated impediments.
Scrum Master (SM) / Superintendent	Connects interested parties and ensures backlog items are called into the sprint backlog. Holds daily huddles with team, tracks work progression, highlights blockers and constraints.	Coaching and mentoring team members to become self-managing. Assisting the scrum team focus on progressing highest value items to defined completion. Removal of constraints and any challenges to the scrum team's progress. Adhering to the scrum framework process while developing and improving scrum adoption. Helping the scrum team understand the need for precise product backlog items, facilitating stakeholder collaboration as requested and as needed.
Developers / Supervisor & Crew leaders, Designers, Engineers, Inspectors	Implementing effective and value-creating work methodologies that remove wasteful practices. Decides what work gets done in each sprint. Own getting the planned work completed. Demonstrate the completed work is ready for the next user.	Creating a plan for the Sprint from the Sprint backlog. Instilling quality by ensuring the definition of done is adhered to. Adapting the plan each day towards the Sprint goal. Ensuring any constraints are raised as early as possible. Holding team members accountable for progressing the plan.

RQ1 – What are the roles and tasks of construction management teams?

A Direct Observation (DO) exercise was carried out with the site management team members as they carried out their duties. Table 4 presents a collation of the observations and notes gathered from both the DO and the documentation review. This highlights that the project managers duties involved much liaison and coordination with subcontractors along with involvement in fixing day-to-day problems. A key observation was the impact of the competence and experience of the Superintendents on where the PM could focus their time. Inexperienced and less qualified Superintendents necessitated PMs to become more involved in day-to-day issues which left less bandwidth for higher level lookaheads and client liaison. The middle management role of the Superintendent finds itself pulled towards more face-to-face and day-to-day 'firefighting' and coordination of subcontractor's work. The extent of this depends on the ability of the site supervisor to execute their role and on the personality of the

PM. If the PM tends towards micromanagement and more face-to-face engagement with those executing the work, the function of the Superintendent can become confused and frustrated.

Table 4 – Current site management duties.

Project	What are management doing?		
	Project Manager	Superintendent	Site Supervisor
Project A - Residential	Upward reporting; coordinating external inputs; weekly meetings and reports.	Solving issues; uploading inspections & audits; meetings; safety & quality issues	Ensuring materials are available; ensuring next work zone was available to crews.
Project B - Commercial	Involved in day-to-day problem solving; status meetings; liaising with utility companies and external bodies.	Resolving design issues; ordering materials; responding to subcontractor queries.	Ensuring safety & quality inspections occur and any actions are closed out. Assisting crews with problems.
Project C - Residential	Coordinating subcontractors; scheduling; communicating with cost control; meetings; status reports for clients and senior leadership; Liaise with utility providers, client visits, senior management visits.	Providing inputs for reports; running production, safety, and quality meetings; managing subcontractor's work; coordinating design requests & site raised RFIs; Value Engineering exercises.	Directing crews to locations; resolving daily issues; coordinating plant and managing deliveries.
Project D - Pharmaceutical	Client liaison; reports; meetings; lookaheads; team update meetings.	Attending safety and quality briefings; meetings; liaising with design teams; signoffs.	Day to day safety, quality, and production visits and signoffs; escalating issues for resolution.

From table 4 the Superintendent role duplicates aspects of both the PM and Supervisors roles while its own key duties are unclear. Rather than having defined boundaries the Superintendents role can cross into the PM realm and cross on in some cases completely overlay the role of the Supervisor.

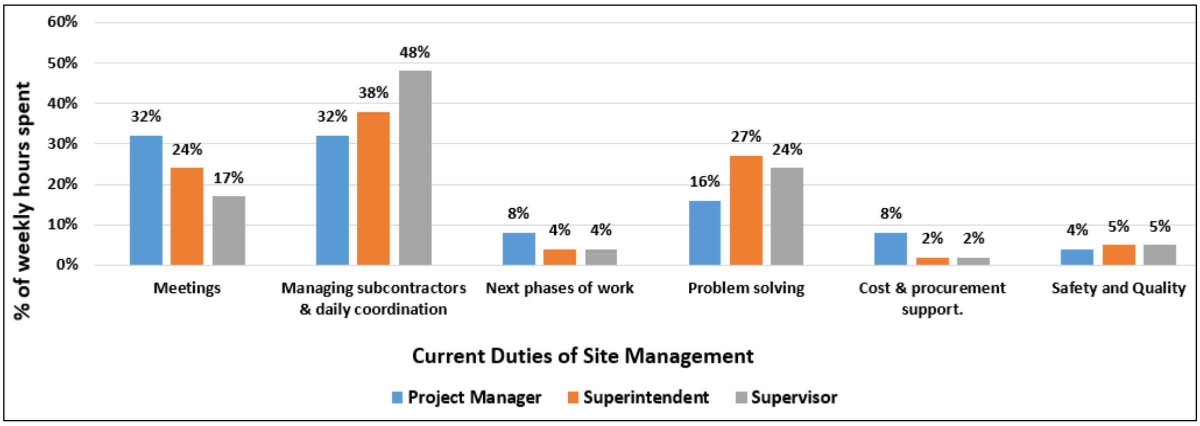

Figure 1 – Current duties of Site Management.

The Supervisor appears to be executing tasks that are helping the crews deliver their work. However, there is inconsistency in the ability of Supervisors – some are competent enough to deliver excellent management, while others are drawn to micromanagement of subcontractors to compensate for both poor contractor management and the Supervisor's own 'comfort' of being close to the work and away from management duties. Key standout points from figure 1 are the amount of time spent in meetings, managing subcontractors and daily coordination, and problem solving. Additionally, it is obvious there is duplication of effort across the PM, Superintendent, and Supervisors as all three expend a similar amount of time attending meetings, managing subcontractors and daily coordination, and problem solving.

In answering RQ 1 the research finds significant crossover of roles and responsibilities and a distinct lack of structure and definition across the levels of construction site management.

RQ2 – How do construction management teams perceive their roles and responsibilities?

After analysis of the quantitative data, semi-structured interviews were conducted with the site management team. These interviews were transcribed and merged with the themes presented in table 5.

Table 5 - Collated interview findings

Theme	Project Managers	Superintendents	Site Supervisors
Meetings	Some days are end-to-end meetings purely because the organisations mandate specific reviews must be held. Preparation and follow up takes a lot of time.	Noted that PMs almost always request Superintendents to attend the same meetings in case a specific answer is required.	Supervisors feel they have nothing to contribute to most meetings they are requested to attend. More effective communication and updates would keep them informed.
Subcontractor coordination	Subcontractors prefer to discuss issues directly with senior site management	Are involved in too much coordination with PMs reaching across them and Supervisors escalating every issue.	Are involved but are fearful of making an error as ultimately the PM or Superintendent will have the last say.
Problem solving	So many issues are escalated to PM level for resolution and verification.	Don't feel adequately empowered to decide as the PM needs to know to be aware of any impacts and may impose an alternative solution.	Will escalate every issue to Superintendent and PM level for decision. They see themselves and 'carriers' of the problems to be solved. Very little decisions are made at their level.

Analysis of table 5 and the interview texts reinforces the crossover of roles and responsibilities and the absence of structure and definition across the levels of construction site management. PMs stated they are constantly 'pulled' towards coordination and problem solving. Some stated they were 'good' at this when they were in Superintendent roles and now find it difficult to delegate responsibility and empower others to develop in the role themselves. Past relationships with subcontractors mean it is easy for subcontractor leadership to bypass other levels of site management and come directly to the PM – this adds to the workload as unforeseen issues that could have been resolved at Supervisor and Superintendent level are now burdened on the PM. This adds to frustrations at Superintendent and Supervisor level and reinforces the siloed mentality when the team should be fostering a collaborative planning environment. The absence of a visual plan of upcoming tasks means that Superintendents keep their own lookahead in their head as two stated in the interviews. None of the Superintendents or Supervisors referred to the master schedule. They noted that was the job of the project scheduler and the PM to manage the schedule. However, only two PMs referred to the schedule with two others attending a weekly meeting with the scheduler to review progress and update the schedule. In answering RQ 2 the research finds an absence of role definition and no hierarchical management structure that would keep resolution of issues at the lowest levels to protect the PMs capacity. An absence of clear responsibilities for Superintendents and Supervisors highlights underutilisation of their talent and capability. Inconsistency could be addressed with specific training to ensure standardisation of the roles.

RQ3 – How can the role definitions in Scrum benefit construction management?

From RQs 1 and 2 the following issues emerged:

- Unclear roles and responsibilities for the levels of construction management.
- No tiered work execution and impediment escalation process to filtered out issues as they rise through levels of management.
- Poor discipline around, and protection of, access to PMs time and calendar.
- Lack of standardisation of competency expectation for roles leads to gaps requiring to be filled by others in the team.
- No specific, short-term, lookahead planning process results in firefighting to resolve impending issues.

LPS and Takt bring order and structure to construction delivery. When used in conjunction with Agile and Scrum approaches there is an opportunity to create a more stable environment to assist construction teams. This stability aligns with Koskela and Howell (2002) and Owen et al. (2006) who identified the advantages Scrum and LPS brough to traditional practices.

Table 6 - Phases of Agile and Scrum, LPS, and Takt planning practices.

Agile & Scrum practices	Last Planner System	Takt
Product Goal – The goal of the initiative and how that supports the company's strategy		
Product Roadmap – Broad list of features that assist achieve the product goal.	High-level Milestone Plan.	Overall Process Analysis
Release Planning – Timescale for release of increments of value	Phase Pull Plan & 6 week lookahead.	Takt Analysis & Takt Planning
Sprint Planning – establish specific iteration goals and tasks.	Make Ready Planning & Commitment Planning	Process Planning
Sprint – fixed-length timeboxes designed so Developers can create a development rhythm.	Execute Weekly Work Plan	Weekly Work Plan
Daily Scrum – Coordinate work for the day.	Daily Huddles	
Sprint Review – demonstration of working product and receiving feedback from stakeholders.	Learning from PPC & RNC report.	
Sprint Retrospective – Team improvement of environment and processes to optimise efficiency.	Implementing improvements.	

Table 6 presents the phases of Agile and Scrum, LPS, and Takt planning practices and how they equate to each other within each method. Takt is precise, fragile, and needs LPS to support its implementation. LPS is a broader, more accommodating framework but the literature has specifically stated that better definition of the roles and responsibilities would assist improving LPS. Scrum is more general, all-encompassing, and being the least structured, can be used to manage any type of work or project. It is flexible and adaptable to almost any scale of problem.

In addressing Ballard and Tommelein's (2021, p. 54) request for clarity regarding the LPS specific or supporting roles and responsibilities of management above the crew-level Last Planners, the research presents the following role descriptions as an antidote to the current issues highlighted in RQs 1 and 2, and in research and practice. The role descriptions contribute to a more supportive management structure for LPS and Takt implementation.

Construction Scrum Master (CSM): This research proposes the Scrum Master role as the key facilitator of production in construction. They are accountable for the team's effectiveness and in construction this can be specifically measured by PPC. The critical roles can be listed as:

- Coaching the supervisors and construction crew leaders in self-management and engaging cross-functionally at crew level.
- Assisting the team define high-value releases of work that progresses the project towards the product goal.
- Facilitating and encouraging the identification of constraints / impediments to the team's progress as early as possible (includes procurement, resource, equipment, design lookaheads). Owning the removal of these constraints / impediments.
- Ensuring all weekly events take place, whether Scrum framework, LPS, or Takt; must have daily huddles, weekly planning sessions to lookahead, identify constraints, make tasks ready, agree weekly work plan, generate PPC and reasons for non-completion of tasks to promote new learning.

The Scrum Guide (2020, p.3) proposes the Scrum Master must create a working atmosphere for success where:

1. A Product Owner organises the proposed work into a Product Backlog.
2. The Scrum Team progresses through a batch of work and turns it into a value deliverable during a Sprint.
3. The Scrum Team and stakeholders review the output and consider and amendments to carry into the next Sprint.
4. Repeat.

If the equivalent role in construction is the Superintendent it therefore infers that this person holds key and pivotal accountabilities for the project's progression. The Superintendent therefore should hold the competencies and soft skills that include a deep knowledge of the construction process plus servant leadership skills to serve both the Product Owner (Project Manager) and the Developers (Supervisors and Crew leaders). The Scrum Guide (2020, p.6) adds the Scrum Master is 'accountable', 'serves', and most importantly are '…true leaders who serve the Scrum Team and the larger organisation'. This would be like the 'facilitator' role as described by Power et al. (2021, p.150) and the 'process manager' as suggested by Thomassen et al. (2003, p.65).

Construction Product Owner (CPO): It is important to remember the distinction between Product Owner and Project Manager. The construction PM role addresses many aspects of management, and we propose it additionally uses aspects of the Scrum Product Owner responsibilities to better 'serve' the Scrum Master and Developers. Critically, we require the CPO to empower the CSM and the Developers to execute their own roles and responsibilities while knowing where and when to distance themselves from the day-to-day running of construction production. Before listing the proposed CPO roles and responsibilities it is important to note that support must be available from higher management levels to ensure the CPO is not overburdened and has the capacity to serve the CSM and the Developers. In aligning with the role as defined in scrum, the CPO should focus on the 'What' and the 'When' – what value needs to be delivered by when? The critical roles are:

- Developing and communicating the Product Goal – value to be delivered, scope, schedule, budget, stakeholder management.
- Creating the Product Roadmap and Product Backlog items – project phases, execution strategy, sequencing.
- Sequencing the backlog before handing off to the CSM and Developers for refinement and execution.
- Ensure clarity around the backlog items so the value required is understood by everyone.

The CPO represents the company and stakeholders, and any scope addition can only be with the CPO's agreement. If capacity allows, the CPO can also work with the CSM and Developers, but roles and responsibilities must be clear, or all will revert to the status quo.

Construction Developer (CD): The Developers consist of the construction supervisor, design team members, quality inspectors, safety auditors, and crew supervisors. These are the Last Planners who are at the point of work planning and execution and deliver the real value on projects. It is therefore critical that those doing the work are working on the correct tasks in the correct order and that all distractions and constraints / impediments are removed to allow smooth flow of inputs. An effective CSM will facilitate this environment and the CD's will be excused from unnecessary meetings and non-value adding 'time-stealing' events – they can focus totally on production, safety, and quality. The CD's will be accountable for:

- Collaborating on building a Sprint Backlog, effectively make-ready planning and commitment planning in LPS and Process Planning as in Takt.
- Ensuring quality completions by agreement on Definition of Done.
- Reviewing and adapting daily at the Huddle to ensure focus on the Sprint Goal.
- Expecting ambitious standards and accountability from others on the Team.

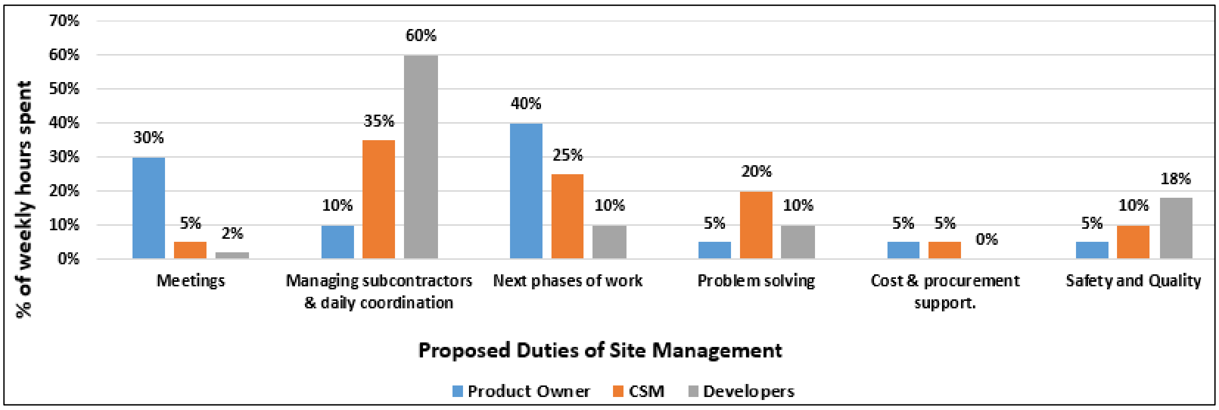

Figure 2 – Proposed duties when aligning to Scrum roles.

Figure 2 proposes how weekly duties should be reordered to allow each role focus on their highest value items. In comparison with figure 1, Project Manager equates to Product Owner, Superintendent equates to Scrum Master, and Supervisor equates to Developer. The CPO focuses on the next phases of work and ordering the backlog while shielding the CSM and Developers from unnecessary meetings. The CSM runs the weekly and monthly operations, coordinating all inputs are in place by ensuring all tasks are constraint free. The Developers execute the daily work in accordance with the weekly work plan and contribute to the look ahead planning sessions. All problem solving is kept closest to the workface if possible.

CONCLUSION & RECOMMENDATIONS

The paper demonstrates the critical role of the CSM in ensuring a flow of ready works is available for weekly execution. This differs from the ad-hoc current state of PM's and team member's planning processes and specifically addresses a gap in current LPS and Takt execution. The value add of the new role brings clarity and definition to all management teams responsibilities relating to site production planning and control. Other benefits accrue from coaching and mentoring supervisors and crew leaders, releasing the CPO / PM to shield the execution team, prioritising highest value tasks to be worked on, and provides oversight of an effective constraint identification and resolution process. Adhering to the proposed roles would bring better order and structure to the construction management team – the CPO / PM could focus on managing the project without distraction; the supervisors and crew leaders could focus on progressing through weekly lists of constraint-free tasks to be executed. Companies should develop and codify the role of the CSM allowing a pathway of career progression towards more effective CPOs. The role takes the ordered backlog from the CPO / PM and supports the Developers in executing each phase of project execution. The CPO / PM shields the CSM and Developers from all unnecessary distractions like meetings and longer-term planning.

Next steps would be the testing of this proposal on a project and to examine what findings can be brought forward to better support current LPS and Takt implementation practices.

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RELATIONSHIP BETWEEN TIME SPENT IN PRODUCTION WORK ACTIVITIES AND PRODUCTION WORKSPACES.

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ABSTRACT

The study presented in this paper is part of an ongoing research project that addresses the absence of established procedures for automatically measuring the distribution of time workers spend on Value-adding (VA) activities. To understand the relationship between workers' time spent on VA activities and VA workspaces, the activities conducted by a carpenter trade were studied during the realization of a Case Study on a renovation building project. The carpenters were divided into three groups regarding the activities that they conducted: interior, façade, and roof activities. The authors used two sources of evidence to compare the time that workers spent in production work categories and workspaces: (1) the work sampling technique to obtain time spent in work categories and (2) smartwatches to collect time spent in different workspaces. The authors used geographic data points provided by smartwatches worn by the carpenter trade to collect their location within the job site and developed a Python script to automatically group the data points into workspaces. Correlation analysis reveals a strong correlation (R^2=0.2473) and very strong correlation (R^2=0.7886) between time spent in VA workspaces and time spent on VA activities when the workers worked on interior and exterior activities, respectively.

KEYWORDS

Workspaces, construction site, production work, value-adding work.

INTRODUCTION

Automating the activity recognition process on construction sites has been the first step in numerous studies in the last decades that aimed to automatize the Work Sampling (WS) technique. The WS technique quantifies shares of time using a set of activity categories, classified into the Lean activity categorization of Value-Adding (VA) and Non-Value-Adding (NVA) activities (Dozzi & AbouRizk, 1993). Researchers have approached the issue from different angles, from exploring the use of bodyworn sensors to applying vision- or audio-based technologies either in a laboratory setting or on-site. Some studies have combined multiple technologies, and most use machine learning algorithms to analyze and classify data (Pérez et al., 2023).

Most of the papers found in the literature are part of a long-term research project conducted by researchers from the Indian Institute of Technology Madras (Joshua & Varghese, 2010, 2011, 2013, 2014). Joshua and Varghese conducted a series of studies focusing on recognizing masonry work activities using bodyworn accelerometers. Accelerometers measure acceleration, which in practical terms means human changes in speed or direction. These data streams are

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collected from sensors, for instance, inertial measurement units (Jacobsen et al. 2023). The first study (Joshua & Varghese, 2010) involved a subject posing as a mason performing instructed activities in a lab environment. Encouraging results led to an expanded study, where a mason performed productive tasks in both an instructed and uninstructed data collection mode. The accelerometer data patterns were observed to be repetitive and distinct for a particular class of activity, and supervised classifiers – in particular, neural network classifiers – confirmed a significant potential to classify masons' productive work activities using accelerometer data. This potential was then tested in a field situation studying iron workers and carpenters (Joshua & Varghese, 2014). The results showed a better classifying performance of iron worker activities than of carpentry, with an overall classification accuracy obtained for iron workers of 90.07% and for carpenters 77.74%.

Another approach was studied by Akhavian and Behzadan (2016), who used smartphones secured with a band on workers' upper arms to identify different construction tasks such as hammering and handling a wheelbarrow. Data from the built-in accelerometer and gyroscope in the smartphones were then analyzed through supervised machine learning algorithms to identify when workers were performing an activity and when they were being idle, achieving an accuracy of up to 97%.

Researchers from the Finnish University of Aalto (Görsch et al., 2022; Zhao et al., 2019) have explored the use of different technologies to track indoor workers' location and associate the positions with Direct Work (DW) or Indirect Work (ID) activities. Zhao et al. (2019) applied various tracking device placement strategies in three different cases to explore coverage and accuracy. Results showed that it is possible to obtain a real-time presence index using Bluetooth Low Energy (BLE) on construction sites when paired with heuristic rules, and suggested that uninterrupted presence is strongly correlated with time spent on VA activities. Görsch et al. (2022) continued this work through carrying out a time-motion study, combining the video data from head-mounted cameras and location data from indoor positioning BLE technology to understand the time spent in VA work when uninterrupted presence is detected by indoor positioning. However, the classification of the activities into DW, IW, and Waste Work (WW) was conducted manually based on the analysis of the recorded video.

Overall, it is evident that digital approaches to automizing the WS process have shown great potential, and this potential will increase as technology develops. In general, the literature review points to the existence of two approaches primarily used for activity recognition: sensor-based and video-based technologies. However, a significant limitation of both approaches exists in the data labelling process. Researchers need to select and classify a limited number of activities. Those activities are mainly associated with the specific activities of the construction process that the participants are doing (e.g., sawing, hammering, etc.) rather than a more generic classification into DW, ID or WW. In most cases, the activities are manually classified or classified using machine learning tools.

The literature about video-based technologies reveals that these technologies are based on monocular cameras or stereo cameras. Vision-based tracking of workers refers to retrieving the worker trajectories from recorded videos, which is a fundamental step for activity recognition (Jacobsen et al. 2023). In most of the studies, video annotation was used as an additional source of evidence to compare the results obtained from the sensors rather than using deep learning detection methods.

Lastly, these studies were applied on a reduced number of workers, involving between one and ten workers at maximum. In some cases, the subjects were academic participants simulating construction workers' activities in laboratories. So, the actual application on job sites and how practitioners could adopt the technologies have yet to be explored.

Regarding the studies that adopted tracking systems, they were conducted exclusively inside buildings. Other workspaces, such as material storage areas, transportation paths, and preparation workspaces, were not taken into consideration. So, these studies are limited to classifying work activities conducted in the production workspaces, avoiding the rest of job site areas.

In conclusion, there are currently three research gaps in the published studies concerning automation of the WS technique: (1) sensor-based technologies are limited to identify direct work activities previously labeled; (2) the activity recognition has mainly been conducted in delimited training areas; and (3) the studies were conducted with a limited number of participants, in most of the cases, subjects simulating workers' activities. Thus, a novel approach for automating WS is needed in job sites to deal with the abovementioned challenges based on indirect measurements.

To further investigate the possibilities of using sensor-based technologies in the construction industry to gain a better understanding of how workers spend their time, it was chosen to use smartwatches with Global Positioning System (GPS) sensors for the investigation. By using a GPS-signal the presence of the workers can be determined, which will give an insight into the workers presence at a construction site. Therefore, the following research question has been created to investigate the phenomenon:

- What is the possible relationship between the time spent in value-adding work found and the time in value-adding workspaces?

To address this question, the authors conducted a case study on a renovation project.

RESEARCH METHODOLOGY

The present paper adopts a Case Study (Yin, 2003) as the primary research method. The phenomenon of the study comprised construction workers' activities and locations. The real-life context is represented by the building project studied. The Case Study was carried out on a construction site in Fredericia, Denmark. The project studied is a social housing project consisting of 84 single-story apartments and a common house that are undergoing renovation. The apartments are divided into blocks, where there are three to six apartments in each block. The apartments were built in 1955 and the total building area is 8.600 m2. Ten of the blocks were under renovation when the data collection occurred. The focus of the data collection was on the carpenter trade. Their work consisted of internal and external activities in and around apartment blocks. The exterior work consisted of renovating the facade and roof.

The Case Study was conducted in week 9 and 10 in 2023. Data was collected for 10 workdays, where a full workday for the carpenters was from 06:30 to either 15:00 or 15:30. The carpenter observed mainly designed to perform three kinds of activities (Figure 1): (1) interior walls and ceilings; (2) façade; and (3) roof activities.

a b c

Figure 1: Carpenter main activities studied: (a) interior; (b) façade; and (c) roof activities

The authors used two sources of evidence to compare the time that workers spent in work categories and workspaces, those being (Figure 2): (1) the work sampling technique to obtain time spent in work categories and (2) smartwatches to collect time spent in different workspaces.

Activities	Collecting time in work categories	Collecting time in workspaces
Source of evidence/tool	Work Sampling Technique	Smartwatches
Steps	1) clarifying the work activities; 2) developing forms; 3) data collection; 4) deciding the accuracy desired; 5) data analysis.	1) clarifying the workspace categories; 2) data collection; 3) data extraction, aggregation and cleaning; 4) data classification and 5) data analysis.
Output	Time spent in Production work activities	Time spent in Production Workspaces
Analysis	Correlation analysis	

Figure 2: Research design

COLLECTING TIME SPENT IN WORK CATEGORIES

In this research, the WS procedure consisted of five steps previously developed by the present research team (Salling et al., 2022). The authors adopted that procedure to keep consistent with previous WS studies as part of a long-term research project. The steps are: (1) clarifying the categories of the activities to be measured; (2) developing data collection forms; (3) data collection; (4) deciding the confidence interval and the accuracy desired and calculating the number of observations needed; and (5) data analysis. Due to length limitations, this research methodology section will focus on describing steps 1 and 3. The other steps present the same structure as described in Salling et al. (2022).

During Step 1 – Clarifying the work categories, the authors classified the activities of the carpenter trade observed on the job site during the first day of job site visits, named as Day 0. In this study, a six-work categories classification was adopted, those are: (1) production; (2) talking; (3) preparation; (4) transportation; (5) walking; and (6) waiting.

During Step 3 – Data collection, the observations were made from the start of the carpenter's workday until the end (Figure 3a). The observations were collected in a general way in all the carpenters called "All activities" in Figure 3b. In addition, specific observations were made in three groups of workers. A stabilization curve of the share of observations of the production observation was created to provide a visual check of the accuracy of the collected data. The curve stabilizes at 28% after around 500 observations. Upon completion of ten days of data collection, a total of 1,661 samples (n) were recorded and distributed: 437 observations for the interior; 568 observations for the façade, and 663 observations in the roof activities.

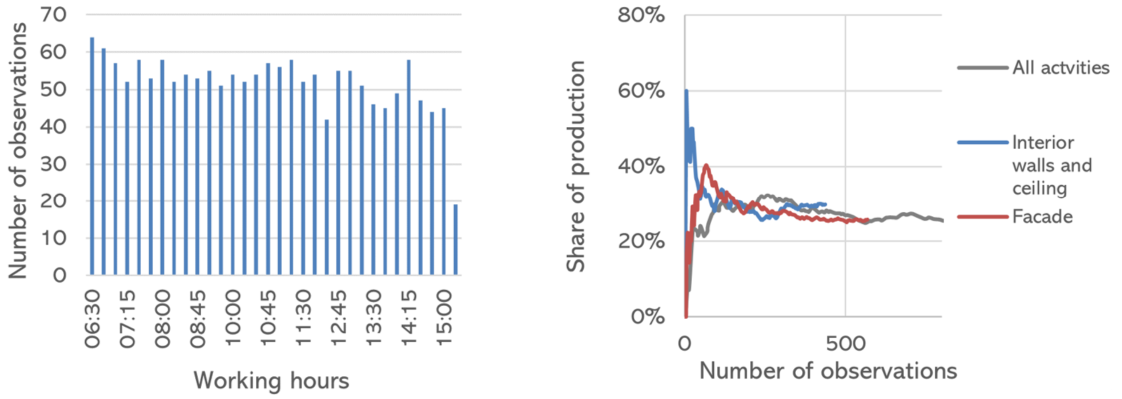

Figure 3: Sample characterization: (a) Distribution throughout the day; (b) curve stabilization.

COLLECTING TIME SPENT IN WORKSPACES

The procedure to collect the time spent in workspaces was previously proposed by the Pérez et al. (2022). The same procedure was adopted in this Case Study, which presents five steps: (1) clarifying the workspace categories; (2) data collection; (3) data extraction, aggregation and cleaning; (4) data classification and (5) data analysis.

Step 1: Clarifying The Workspace Categories

This study adopted a five-workspace categories classification for diving the job site (Figure 4), those being: (1) production; (2) preparation; (3) transportation; (4) storage; and (5) containers. It was chosen to consider all apartment blocks production workspace because the carpenters will only be able to perform VA work there. Since there is work being done on the facade it was chosen to extend the production zone one metre out from the building, so they also had some space to roam around in for their productive activities. The existing roads of the construction site were set to a transport workspace because the carpenters will be mainly transporting material and walking. The remaining zones of the construction site are the storage and container zones. The container zone is used for the breaks of the carpenters. The storage contained most of the tools and materials.

The classification of the job site areas into those five workspace categories used as an assumption that each zone has one single main purpose. For example, the storage workspace is mainly destined for storing material; however, talking and walking activities can be conducted in that area. A similar assumption can be made for the production workspace. The purpose of that area is to do VA activities. The behavior of the workers could not affect one of the categories of the workspace. It means the work activity conducted by the workers does not affect the purpose of the workspace.

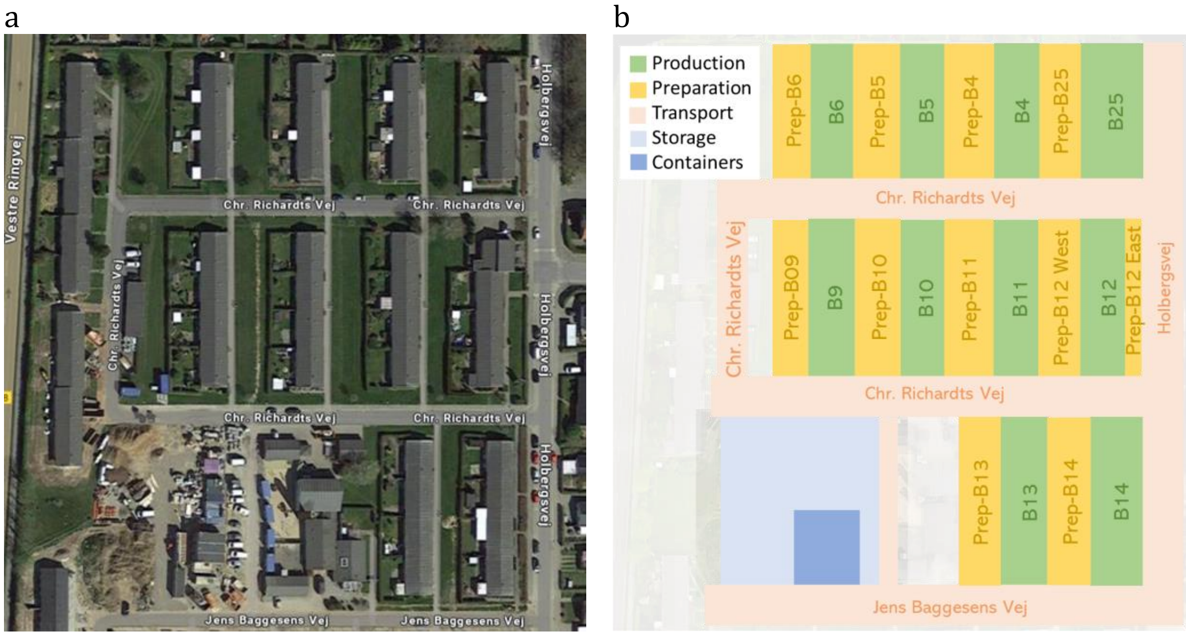

Figure 4: Jobsite (a) Aerial view; and (b) workspaces division into five categories

Step 2: Data Collection

To collect the time spent in the workspaces, ten carpenters were equipped with a Garmin Forerunner 255 smartwatch (named SW11 to SW20). The smartwatch collected carpenters GPS-positions throughout the day. The smartwatches collected data with a frequency of 1 to 30 seconds depending on whether they detected movement or not. Each smartwatch was marked with the carpenter's initials, so they would be wearing the same smartwatch throughout the data collection period. This allowed the authors to associate the data from each smartwatch with the activities conducted by each carpenter. The carpenters were classified into three groups according to the main activities that they conducted, those being: (1) interior walls and ceiling (SW 18 and 19); façade (SW 12, 13, 14 and 17); and roof activities (SW 15 and 20).

Step 3: Data Extraction, Aggregation and Cleaning

The data extraction consists of obtaining the datapoints collected by the smartwatches. For that, the smartwatches were collected at the end of the workday and synchronized to Garmin Connect using a USB-cable so that the data were stored for later analysis. The collected data can be exported from Garmin Connect in .gpx format (a GPS exchange file). The .gpx file is run through the "TCX converter"-program, which converts the .gpx file into a .csv-file. The .csv file is then transferred into an Excel sheet that cleans the data.

During the data aggregation, a dataset of each smartwatch for each day of collection (named SW11Day 1 to SW11Day 7) was created. The information that is stored in the .csv file is the latitudinal and longitudinal coordinates together with the time in Unix time format.

The data from the smartwatches are cleaned from breaks, which are from 09:00 to 09:30 and from 12:00 to 12:30. To clean the dataset from potential GPS errors, the following assumption have been used. If the speed travelling from two consecutive data is lower than 0,5 m/s, the worker is still standing, or higher than 1,5 m/s, the worker is running or caused by a GPS error (Pérez et al., 2022). If a datapoint exceeds these limits, the point is removed . The dataset was reduced greatly by using the speed assumptions. The datapoints still lie within the same region as can be seen in Figure 5, where the red points are the points discarded from the speed assumption and the blue points are the remaining in the dataset after the cleaning process. Most of the deleted datapoints seem to lie in a cloud around the remaining datapoints. Some of the datapoints removed are when SW18 is walking from one location to another, for example, on day 5 in Figure 5b.

Finally, it was decided to remove the first day of data collection since it does not reflect a full day of data collection. This entire data cleaning process resulted in the dataset going from a total of 414.997 raw datapoints to a total of 108.281 cleaned datapoints. The cleaned data files are transferred into a .csv-file so that the datapoints can be classified into a zone of the construction site using a Python script.

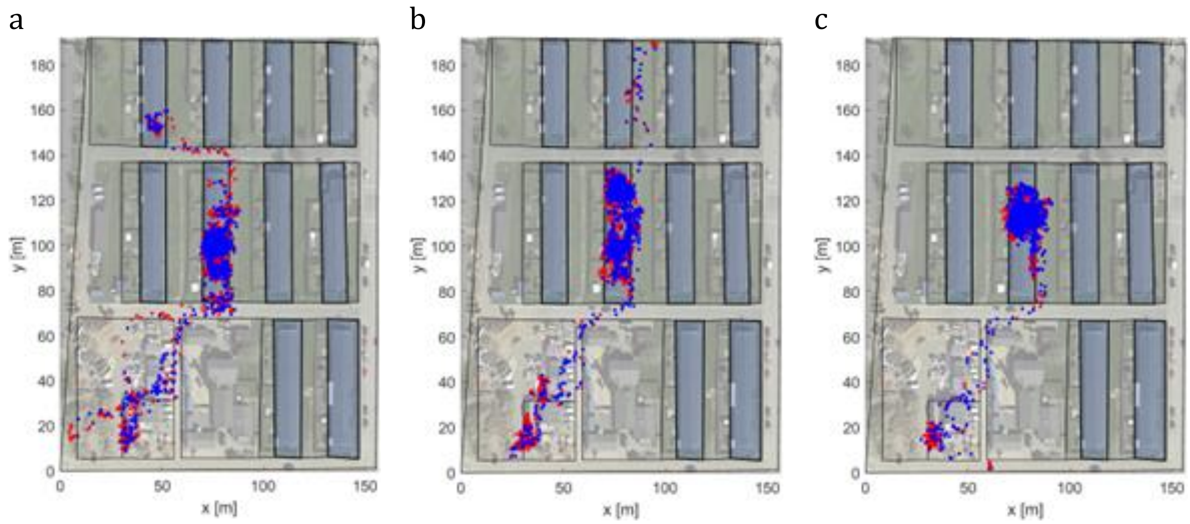

Figure 5: Data cleaned for SW18: (a) Day 5; (b) Day 6; and (c) Day7

Step 4: Data Classification

A Python script was created to sort the data points obtained by the smartwatches into the different workspaces of the job site. Python is a programming language that has many user-generated libraries, which give Python many uses and possibilities (python.org, n.d.). The script was written in Spyder version 5.1.5 which was accessed through Anaconda. The developed Python script was based on a script previously developed by the research team (Pérez et al., 2022). The developed Python script consists of nine steps: (1) Import packages i.e. numpy, pandas, shapely.geometry and matplotlib.pyplot; (2) Create a function to import the datapoints from the zones of the construction site and smartwatches; (3) Import the zones and smartwatches datapoints; (4) Create empty arrays to store the filtered datapoints; (5) Classify the datapoints into the right zones of the construction site; (6) Convert the data points into a "metric" system for the plot; (7) Plot the data points and zones; (8) Convert Unix time into a readable time stamp; and (9) Export the sorted data points into a .csv-file.

Step 5: Data analysis

The data analysis aimed to first visually present the data of time spent on work categories and time spent in workspaces to understand, compare, and validate the data. The analysis is based on three different types of work observed and monitored: (1) interior walls and ceiling; (2) façade; and (3) roof activities. Both the WS data, presenting data on time spent on work activities, and the SW data, presenting time spent in workspaces, apply to these three types of work.

Secondly, to analyze the relationship between time spent in VA workspaces and time spent on VA work activities. The data analysis aimed to test whether a possible relationship exists and is statistically significant. VA workspace is the production workspace, and VA activity is the production activity. The analysis was applied to the three types of works observed. The authors used the Statistical Package for the Social Sciences (SPSS) software for statistical analysis. This analysis was conducted as a linear regression analysis providing a linear regression and further an ANOVA analysis to reveal the statistical significance of the linear regression model's predictive capabilities. Common for the two tests are that they rely on interpreting the correlation coefficient (R). Previous recommendations (Cohen, 1988) outline that $R > 0.5$ reflects a large effect size. Research in the same area as this has previously used $R = 0.318$ as an acceptable level (Liu et al., 2011; Nevet et al., 2020; Wandal et al., 2023). Nonetheless, in this research, $R = 0.5$ is chosen as the minimum limit for accepting any relationship established through the statistical analysis. The R-value can be squared (R^2) to reflect the predictive capabilities of the independent variable in the analysis instead. The R^2 value corresponding to $R = 0.5$ is 0.25; thus, $R^2 = 0.25$ is the lower acceptance limit.

RESULTS AND DISCUSSION

The findings are divided into three main parts. First, the results from the WS application are presented regarding the kind of work conducted by the carpenter. Second, the smartwatch results concerning the location of workers in the different workspaces are analyzed. The last part comprises the comparison analysis considering the WS observations and the location data.

WORK TIME SPENT IN WORK CATEGORIES

The distribution of time spent into work categories is illustrated in Figure 6. The total number of observations (n=437) on the carpenters doing interior walls and ceiling activities are distributed with 30% on production, 16% on talking, 28% on preparation, 13% on transport, 12% on walking, and 1% on waiting. Those numbers are similar to the distribution obtained for the roofers. However, the main difference in their time allocation can be seen in the "gone" activity. The authors added that category because, in 6% of the observations made, they could not find the workers on the roof. Regarding the workers involved in the façade activities, the research team observed them doing preparation activities in 36% of the 568 observations registered. Those are the workers spending more time in this kind of work category.

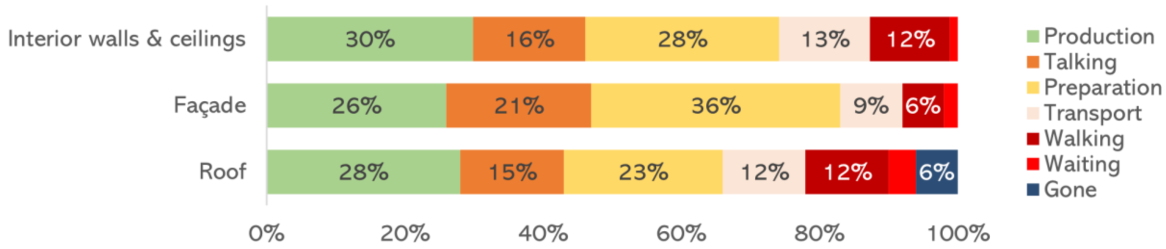

Figure 6: Distribution of time spent into work categories.

WORK TIME SPENT IN WORKSPACES

The developed script enables the classification of GPS data points from each worker into the specified workspaces (Figure 7). The analysis of the time spent in workspaces revealed that carpenters who worked on the interior walls and ceilings were the workers who spent more time in production workspaces. Those workers spent around 78% of their time in production workspaces in comparison to 50% spent by roofers. In contracts, the carpenters who worked on the façade had a wider range for their share of time in production zones, ranging from 25-60%.

The workers destined to conduct roof and facade activities spent more time in the preparation zones compared to the interior walls and ceiling activity. This can be caused because the carpenters who work on the interior walls and ceiling mainly did their preparation work within the production work zones, which is not necessarily possible for the other activities. The roofers spent most time outside of the site compared to the other carpenters. Most carpenters have roughly the same share of time in the transportation, containers, and storage zones.

	SW18	SW19	SW12	SW13	SW14	SW17	SW15	SW20
	Interior		Facade				Roof	
Production	78%	78%	61%	44%	60%	25%	50%	54%
Preperation	10%	7%	27%	42%	24%	56%	26%	19%
Transport	2%	2%	2%	3%	2%	3%	6%	6%
Containers	8%	12%	8%	6%	12%	13%	14%	14%
Storage	2%	1%	2%	4%	2%	3%	4%	4%
Outside site	0%	0%	0%	0%	0%	0%	1%	4%

Figure 7: Time spent in the different workspaces by the different smartwatches

Understanding the distribution of workers' time in the different workspaces can be useful to see where potential problems are, thus forming the starting point for discussion. For example, if workers spend a large quantity of time on transportation workspaces possible logistics and job site layout issues could be causing that situation.

CORRELATION OF DATA

The correlation analysis aimed to illustrate the relationship between the two datasets: (1) the time allocated to VA activities recorded by the WS application and (2) the time spent in VA workspaces tracked by the smartwatches. Figure 8 shows a visual interpretation of a possible correlation between the time spent in VA activities and the time spent on VA workspaces in which workers are involved in the interior (Figure 8a) and roof activities (Figure 8b).

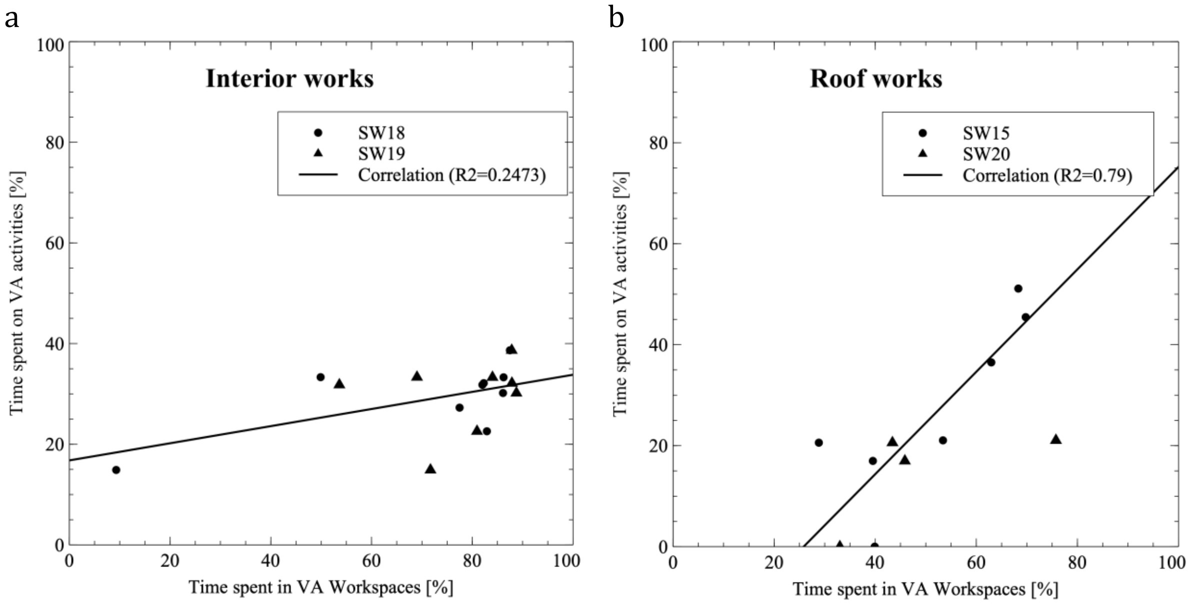

Figure 8: Comparison of time in Prod. Activities and Workspaces: (a) interiors; and (b) roof

In Figure 8, it can be seen that there is a medium to strong correlation between time spent in VA workspaces and time spent on VA activities for both interior works and roof works. For the facade work, no statistically valid correlation could be found. The result of the linear regression analysis can be found in Table 1.

Table 1: Correlation analysis between time spent in VA workspaces and on VA activities

Type of Work	Linear regression equation	R^2	correlation
Interior	y=0.1702x+16.792	0.2473	Medium/Strong
SW18	y=0.1702x+16.792	0.4699	Strong
SW19	y=0.1191x+20.336	0.0392	Low
Roof	=1.0138x-26.19	0.7886	Strong
SW15	=0.9192x-20.248	0.6798	Strong
SW20	=1.1415x-34.329	0.9690	Strong
Façade	=-0.013x+27.752	0.0019	Low
SW12	=-0.2241x+41.383	0.1307	Low
SW13	=0.1232x+21.917	0.1127	Low
SW14	=-0.0272x+28.749	0.0027	Low
SW17	=-0.2874x+34.210	0.2332	Medium

Interior work has an R^2 value of 0.2473, which is very close to the outlined threshold of 0.25 for a strong correlation. Roof work shows an R^2 value of 0.7886, which is a very strong correlation where it can predict almost all the independent variables. The relation analysis conducted in the time spent in VA activities and VA workspaces in the workers doing activities on the façade was unclear with a low to almost non-existent R^2 value of R^2=0.0019. The time that three of the four carpenters working on the facade (SW12, SW13 and SW14) spent in the production zone is not close to the share of time they spent on the production work category, which had an average of 26% during the two weeks. While their time in production zones range from 44% to 61%.

A plausible justification for the low correlation identified for the façade activities can be related to the boundaries definition of the zones created for classifying the GPS data points into workspaces. The authors used the same division of the job site into workspaces for the three groups of carpenters. That division into workspaces worked well when studying the interior (Figure 9a) and exterior activities (Figure 9c). However, when the workers conducted the façade activities, they worked on the boundary division into production and preparation spaces (Figure

9b). That situation could have impacted the distribution of data points identified in the preparation workspace.

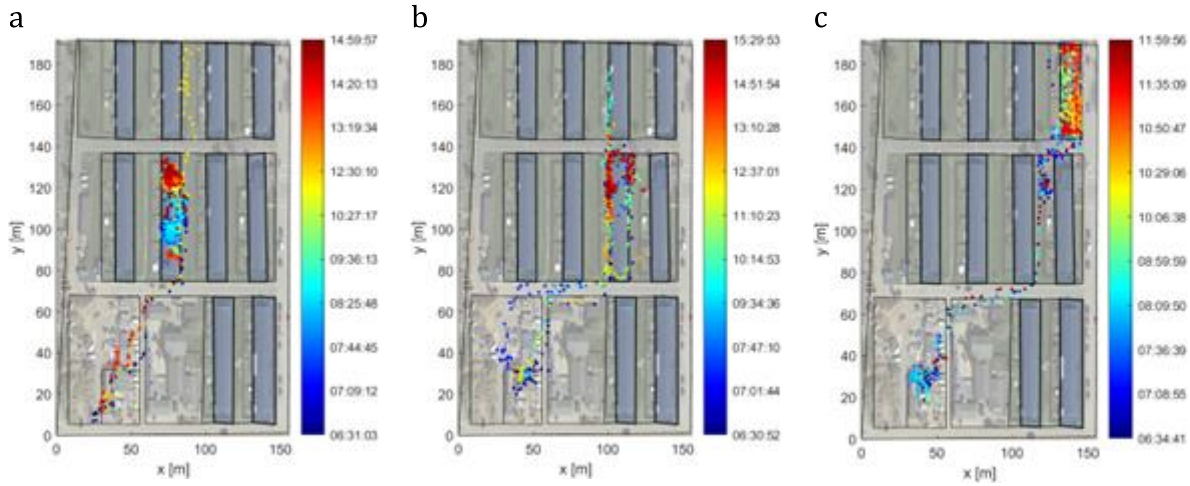

Figure 9: Example of GPS data points on: (a) interior; (b) façade; and (c) roof activities

CONCLUSION

The Case Study presented in this paper is part of an ongoing research project that aims to address the absence of established procedures for automatically measuring the distribution of time spent by workers on VA activities. This project is focused on the identification of workers' locations at the job site using smartwatches as an indirect way to understand how workers spend their time.

This paper aims to understand the relationship between workers' time spent on VA activities and time spent on VA workspaces. For that, the authors studied the activities conducted by a carpenter trade during the realization of a Case Study on a renovation building project. The carpenters were divided into three groups regarding the activities that they conducted (interior; façade, and roof activities). The authors collected their distribution of time on VA activities by the application of the WS technique and the distribution of time in VA workspaces by smartwatches. Correlation analysis reveals a strong correlation and a very strong correlation between time spent in VA workspaces and time spent in VA when the workers worked on interior and exterior activities, respectively. The correlation could not be proved when working on façade activities.

Hence, the primary contribution of this paper lies in the use of smartwatches to understand how workers spend their time indirectly by collecting their locations on the job site. The study results showed that, in traditional processes as studied in this paper, the amount of time workers spend in VA increases when there is an increase in time spent in VA workspaces. Previous studies stated that although presence in production workspaces is not equivalent to time spent on VA activities, it is a prerequisite. From the present study, the authors can conclude that it is true. The more time spent in production workspaces, the more time spent on productive activities, as concluded from the comparison analysis. However, the nature of the activity will impact workers' presence in the production workspace directly.

The primary limitation of this study is associated with the adopted workspace categorization used to classify zones into VA or non-VA. The authors opted for a three-workspace classification, and the assignment of certain locations to one category or another might have influenced the distribution of time analysis. An illustrative example was presented for the façade activities. Future studies should adopt different classifications of job sites for each activity. Lastly, the correlation analysis is limited to one single study. Thus, caution is necessary when generalizing findings to other contexts and other construction processes.

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LAST PLANNER SYSTEM IN THE OWNER'S PERSPECTIVE: CASE STUDY IN ONSHORE WIND ENERGY PROJECTS

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ABSTRACT

The race to reduce countries' carbon footprints has increased pressure to shorten the timelines of projects related to the construction of renewable energy parks. Projects of this scale require greater involvement between the representatives of the owner, who act in project management, and companies contracted to perform different scopes of the project. This study presents, through two case studies, the adoption of a model based on the Last Planner System from the perspective of the owner in onshore wind energy projects. It discusses current challenges within the management model of these projects and addresses tools and routines to be considered by companies participating in onshore wind energy construction. Among the main contributions of the research is the highlighted importance of the owner in the dissemination of lean within contracted companies, as well as the role of rituals such as control tower meetings and lookahead planning in improving communication and collaboration between sectors.

KEYWORDS

Lean construction, Last Planner System, owner, onshore wind energy project, collaboration.

INTRODUCTION

Energy supply has always been considered a critical aspect of modern life, playing a central role in the economic landscape of most countries and serving as the primary input to enhance social well-being and global development (Lima et al., 2013). In recent decades, concerned with total Greenhouse Gas emissions, an international alliance of countries has treated the global decarbonization process as a key element in addressing climate change (Souza, 2017). This initiative has led to an increasingly growing expansion in the search for renewable energy use (Irena, 2019).

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Regarded as clean energy in terms of its final product, wind energy has seen strong growth in Brazil in recent years. According to the Brazilian Wind Energy Association (ABEE), the first wind parks were installed in Brazilian territory in 2011, and last year, the country reached a milestone of 890 wind parks with about 25 GW of installed capacity, all produced in the onshore model. However, the current scenario presents more challenging aspects regarding the construction of new parks: (i) increased competitiveness, the global race for renewable energies has created challenges for the supply chain; (ii) tighter deadlines; (iii) parks in more inhospitable locations with significant infrastructure challenges; and (iv) complexity in the production and assembly of wind turbines, which are larger and with a generation capacity well above the initial models.

Aiming to improve their efficiency and competitiveness, companies involved in the construction of new wind parks have sought the adoption of planning methods that bring better reliability to the management of deadlines and costs (Lima et al, 2023). This movement is also identified outside Brazil, where a series of research demonstrates the advances in the adoption of methods such as the Last Planner System and Takt planning in offshore wind energy projects (Lerche et al., 2019; Lerche, 2020; Lerche et al., 2020; Lerche et al., 2022; Tommelein & Lerche, 2023). The Last Planner system (LPS) is a construction planning and control methodology that emphasizes collaboration and team commitment to improve project schedule reliability. It aims to enhance predictability and reduce waste by involving multidisciplinary teams in defining realistic work plans and proactively identifying constraints. However, it is possible to identify as a limitation of these studies the fact that the adoption of these methods from the Owner's perspective is scarcely discussed.

The construction of onshore wind parks holds great complexity and interface between different work scopes, including from obtaining licenses to the creation of road access, civil construction of tower bases and the substation, foundations, assembly of electrical transmission cables, and the assembly of wind towers and rotors (Gouveia, 2013). Normally, each work scope is the responsibility of different companies, according to competencies and expertise, which are contracted in the Engineering, Procurement and Construction (EPC) format. On a regular basis, the owner in these types of capital projects presents an in-house team responsible for contractual management, managing the owner's constraints, and supervision of issues related to service quality, occupational health and safety, and environmental aspects.

In the IGLC database, it is possible to notice the existence of articles that addressed the involvement of the owner in lean initiatives (Drysdale 2013; Knapp et al., 2014; Wirahadikusumah; Sulistyaningsih, 2013; Mota et al., 2019; Christensen et al. 2023). Knapp et al. (2014) highlighted that the owner plays a crucial role in facilitating the decision-making process in IPD projects. Toledo et al. (2014) presents a proposal for Bim-Lean implementation to improve the quality of information for project progress control and constraint management of the owner. Drysdale (2013) described the British highway agency's strategy for deploying lean improvement across the supply chain. Recently, Schöttle; Bocker (2023) proposes new integrations to the Last Planner System to increase common understanding of the project scope and goals within the owner, project teams, and stakeholders as the basis for reliable megaprojects delivery. However, there is still a gap regarding how to structure an owner planning model based on the Last Planner.

This paper presents a case study of lean construction implementation in major wind power projects in Brazil. The authors present the benefits, limitations, and opportunities identified from the development of lean construction in this case study. As the main contribution of this paper, it presents an adaptation of the Last Planner model from the owner's perspective.

METHOD

This research adopts a design science research methodology, and the artifact created is a planning method based on the Last Planner system, incorporating the perspective of the owner in a wind power project. The study was structured around three main phases: (i) diagnosis; (ii) development; (iii) evaluation. The diagnosis and development phases were conducted through two case studies within an onshore wind power project developed by Company X. The first three authors participated as consultants responsible for implementing lean concepts, and the last authors represented the company's planning sector.

Company X is an energy management firm which is responsible for managing land issues such as leasing and purchasing areas for the park's execution, monitoring environmental issues regarding fauna and flora, the approval and compatibility of engineering designs, and, finally, monitoring the execution of production through planning in collaboration with the quality and occupational safety sector, according to the norms established in contracts with contractors.

The diagnosis phase occurred in the first case study, located in the northeast region of Brazil, comprising 70 wind turbines. This phase began in September 2022 and concluded in November 2022. During this period, the authors conducted a Swimlane workshop, analyzed planning documents, performed direct observations of management routines, and interviewed representatives from Company X and its stakeholders. The purpose of the diagnosis phase was to understand the planning model utilized by Company X and identify the primary gaps.

The development phase spanned from March to December 2023 in the second case study, also situated in the northeast of Brazil and involving 188 wind turbines. For the construction of the Wind Complex, Company X hired four companies to execute the main work scopes. Contractor C was responsible for Civil and Earthmoving scopes; Contractor S handled the construction of the Power Substation and Medium Voltage Networks; Contractor O was in charge of the Transmission Lines; and Contractor V supplied and assembled the wind turbines. Figure 1 illustrates the organizational chart showing the principal responsibilities of each company.

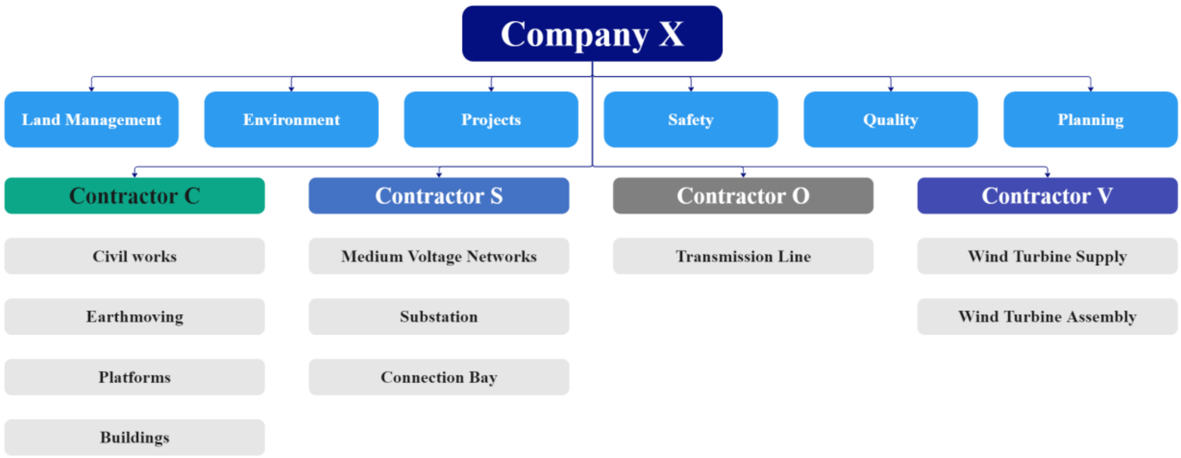

Figure 1: Organizational chart of Company X and the service scope of each company.

RESULTS

The findings are structured around the research's three phases: Diagnosis, Development, and Evaluation.

DIAGNOSIS – CASE STUDY 1

The project initiated with an in-depth diagnostic analysis of the company's current operational landscape, with the application of interviews with key department heads to identify critical issues and areas for potential enhancement. This process enabled the construction of a comprehensive swimlane diagram, delineating processes and responsibilities across various departments, including Business Development, Environmental, Land Management, Engineering, Planning, and Production, and proposed targeted improvements for each activity area. Figure 2 showcases the detailed swimlane diagram, illustrating the collaborative workflow and inter-departmental responsibilities.

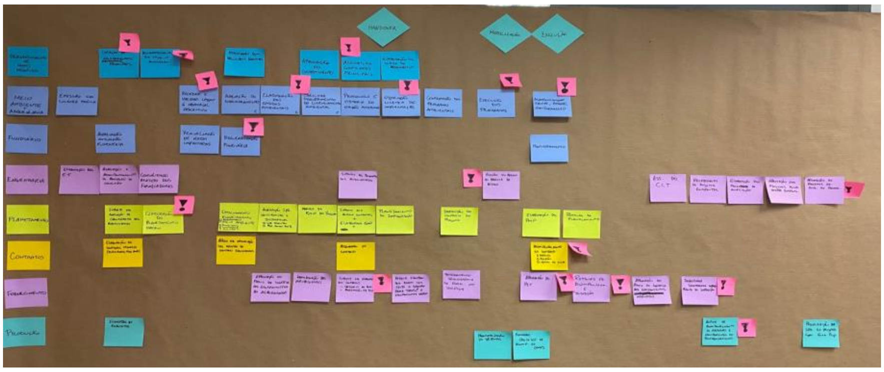

Figure 2: Project Development Flow

The consolidation of identified challenges revealed 63 areas for potential improvement, categorized by project phases. The Execution phase emerged as the most problematic, accounting for approximately 44% of the issues, followed by the Project Development phase at 35%, and the Commissioning phase at 21%.

The analysis of the execution phase pinpointed key concerns among the teams, predominantly centered around: (i) communication breakdowns with contractors; (ii) mismatches between weekly schedules and monthly replanning in the contractors' field planning; (iii) discrepancies between the agreed-upon timelines and contractors' actual scheduling efforts.

The planning department routinely faced the challenge of synthesizing progress updates from various contractors into coherent trend analysis reports. This task was complicated by the necessity to handle data from disparate sources, including MS Project, Excel, and WhatsApp, into a unified system, leading to inefficiencies and redundancies. Updated reports were then generated for executive management, providing insights into contractor performance. In instances of schedule delays, contractors were requested to submit action plans for review and incorporation into the project's master schedule, utilizing the critical path method for strategic adjustments.

Direct observation of management practices highlighted two main meetings: (i) the weekly contract meeting, focusing on contractual and procedural discussions with contractors and Company X's departmental representatives (safety, planning, environment, quality, production); and (ii) the monthly coordination meeting, serving a similar purpose but extending participation to contractors' directors and the client's executive team. These sessions, conducted separately with each contractor, were crucial for Company X to manage the interface between contractors' project scopes. Meeting minutes were meticulously prepared, encapsulating discussions and action items with each contractor.

A meticulous review of these meeting minutes revealed a dual categorization of discussion topics: operational constraints and contractual procedure adjustments. Analysis of resolution timelines for identified constraints showed a significant variance, ranging from 1 to 6.5 weeks across different areas, with outliers extending up to 18 weeks. Although data did not conclusively indicate the timeliness of constraint resolution, feedback from meeting participants suggested a reactive, firefighting approach to addressing issues, often aiming for resolution within the week.

DEVELOPMENT - CASE STUDY 2

The initial diagnostic phase provided insights into the operational dynamics of the company and identified key focus areas for development in the second case study. The development phase started with the creation of phase scheduling workshop to strategically visualize project phases and map out potential interferences and constraints with a broader anticipation horizon (12 to 21 weeks). For a more intuitive grasp of potential service scope interferences throughout the sub-parks, the Time-Location technique was employed.

The Time-Location tool, a form of location-based scheduling, utilizes the x-axis for production lots (park paths) and the y-axis for project time. This tool was instrumental in visualizing execution interferences in the field for Civil and Medium Voltage Networks activities, particularly due to the high number of rock detonations required throughout the project, which could impact nearby service executions within a 500 meters radius due to the need for temporary halts. Figure 3 illustrates the Time-location developed collaboratively with planning and production departments of the contracted companies and Company X.

Figure 3: Time-location for contractor C and S scopes.

After completing the time location chart, it was possible to pinpoint areas and times where interferences or a high volume of simultaneous services occurred. Table 1 lists the main points of concern identified in the planning.

Table 1- Time-location attention points

Id	Attention Points
1	Possible detonations for pole excavation concurrent with Base execution
2	Possible detonations for pole excavation concurrent with Platform Base execution
3	Possible detonations for pole excavation concurrent with Access Earthmoving
4	Possible detonations for pole excavation concurrent with Access Earthmoving
5	Services of RMT Suppression concurrent with Access Earthmoving

Only Contractor C was aligned with Lean culture, having embarked on their Lean journey in 2020 and adopting planning rituals based on the Last Planner system. Rounds of training and education on Lean Construction, Last Planner System, Takt Planning, and waste were conducted for both Company X employees and the other Contractors. Beyond theoretical discussions, the game Takt Planning - Wind Turbines was applied to practically implement Takt planning and develop the Time-location for a mini-park of 10 wind turbines. This activity involved 11 employees, 3 from Contractor C, 5 from Contractor S, and 3 from Contractor O (Figure 4).

Figure 4: Practical Application of Takt Planning and Time-location Concepts.

To enhance internal communication within Company X and establish a specific forum for discussing schedules and constraints, a Lookahead planning routine was implemented with a 6-week planning horizon and bi-weekly control meetings. These meetings involved planning departments of each Contractor and Company X, where Contractors were responsible for presenting their 6-week activity schedules and reporting constraints related to their scopes and those of Company X.

The constrains related to Company X were mainly due to land issues, such as land release that could impact the planned execution site or land embargoes; environmental issues, including wildlife, flora, and archaeological sites; factory inspections regarding the quality of products supplied by contractors, among other project management constrains. Additionally, constrains on the mobilization of labor and machinery by contractors were important for Company X to anticipate the necessary workforce for the swifter release of documentation. Furthermore, given the complexity of constructing a wind park, constrains related to the wind window for tower and wind turbine assembly were significant concerns, alongside the requisite training for workforce qualification in working at heights. Logistic constraints were also critical factors due to the large volume and magnitude of equipment involved.

The planning department of Company X critically evaluated the plans against the time-location, contractual items, and procedures. After these lookahead meetings, an internal session was held with the Safety, Environment, Quality, Land Management, and Production departments to review the contractors' proposed plans and identify potential sector-specific constraints (Figure 5).

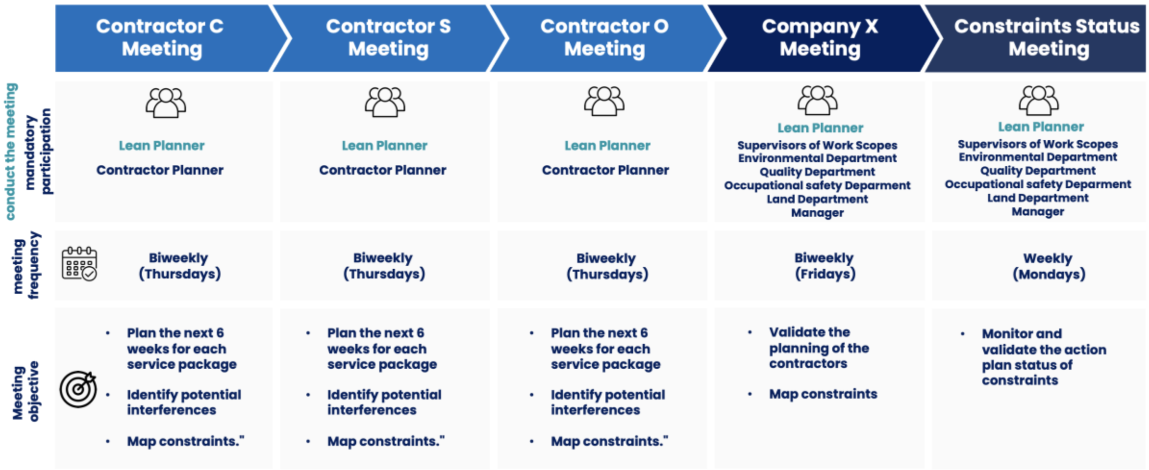

Figure 5 – Medium-term rituals workflow.

Lookahead planning meetings utilized visual management boards (Figure 6), where each contractor had a designated space for their 6-week plan. Activities were represented with post-its, and those with constraints were marked with a coded sticker indicating a constraint needing resolution. Action plans for removing identified constraints were highlighted on visual boards, specifying responsible individuals and deadlines for each Contractor. This approach emphasized constraint management, improving visibility and transparency of potential project impacts compared to the text-heavy minutes of weekly meetings.

Figure 6- Lookahead Management Panels (left) and Constraint Removal Plan (right)

The final element of the lookahead meeting was the constraint removal status routine, conducted alongside the Control Tower routine. The Control Tower was a weekly ritual involving representatives from the internal areas of Safety, Environment, Land Management, Quality, Planning, and Production, where each presented predefined indicators to the project manager and colleagues. This routine was crucial for aligning all company sectors, facilitating discussion, and presenting key elements for the project manager's decision-making. Furthermore, the weekly Control Tower meetings allowed for periodic monitoring of each department's indicators, fostering discussion and action plan formulation to achieve targets (Figure 9).

Figure 9: Control tower panels

EVALUATION

The initiative by Company X, the project owner, to implement the Lookahead planning routine along with its contractors led to the internal adoption of this practice by contractors S and O. For Company O, the adoption was voluntary, as the company's senior management and planning departments saw value in the ritual. However, Company S faced initial challenges in adopting the routine, largely because its leadership did not fully support the initiative, viewing it as beyond their contractual obligations, which affected the quality of the lookahead plans due to a lack of engagement and cooperation from support departments in creating more feasible plans.

To assess the maturity gained by the companies, analyses of key medium-term planning indicators were conducted: (i) Percentage of Constraint Removal (PCR) – evaluating the number of constraints removed on time against the total number of constraints for the period under review; (ii) Bi-weekly Adherence – assessing the number of completed packages compared to the planned work packages within a fortnight.

Figure 8 demonstrates the maturity level achieved by each contractor throughout the project, evidencing the effectiveness of the Lookahead routine in early constraint identification. The analysis covers two periods: the first from 03/07/23 to 14/08/23, and the second from 21/08/23 to 02/10/23, calculating the average Percentage of Constraint Removal (PCR) for each contractor across these periods.

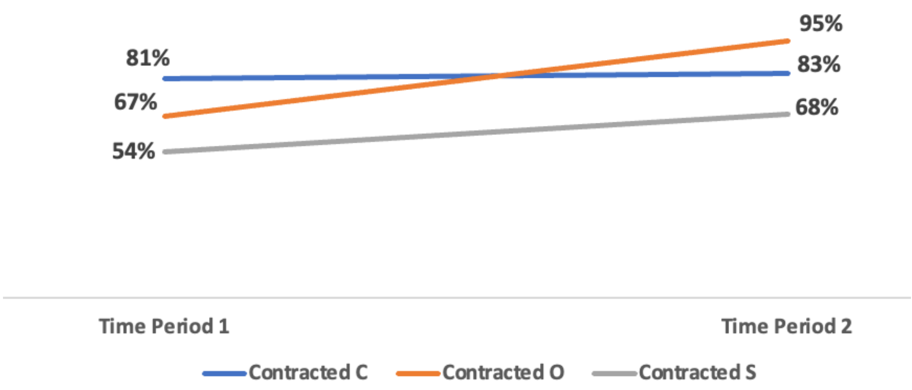

Figure 10- Evolution of Contractors' PCR Indicators

From Figure 8, it is clear that all three contractors improved in identifying and removing constraints on time. Contractor C's consistent performance was expected due to its internal adoption of the routine, leading to greater experience and maturity with the process over the project. Contractor O showed significant improvement, starting with an initial average of 67% and reaching 95% PCR in the last period analyzed. Contractor S also improved its Percentage of Constraint Removal, although it remained lower than the other contractors.

The Bi-weekly Adherence indicator for the defined medium-term plan packages showed a stable adherence rate across the project (Figure 11). Consolidating the packages from all three contractors yielded an average overall adherence of 78% for Contractor C, 77% for Contractor O, and 70% for Contractor S. A specific dip was noted in week 32, impacted by local holidays not initially accounted for, indicating a potential planning oversight for that week.

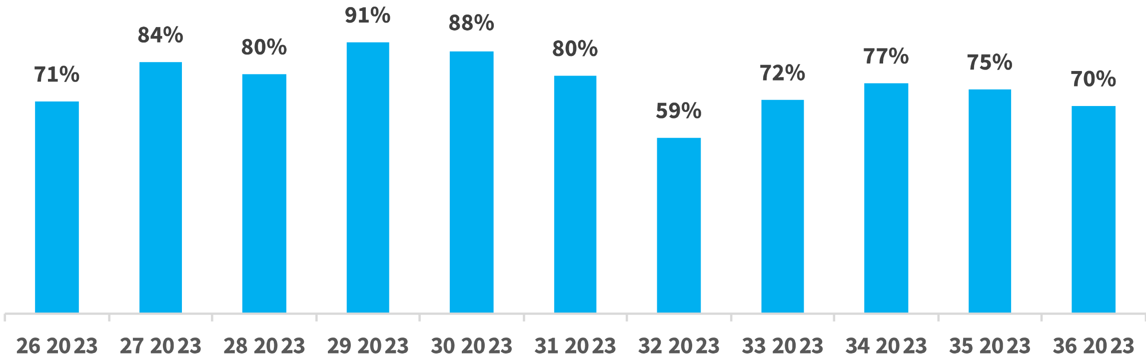

Figure 11- General Adherence Indicator

At the end of the project, in order to better understand and comprehend potential gains in the perception of those involved from Company X, a survey was developed and shared with the planning coordinator, who also was the main sponsor of the lean implementation journey. The questionnaire was designed with 6 open-ended questions, which can be viewed in Table 2.

Table 2- Post-implementation Lean Perception Questionnaire

Questions	Answers
How would you describe the effectiveness of communication between the contracted companies and the Company X team prior to the implementation of the Last Planner System?"	The communication was based on weekly meetings and highly reactive, focusing on project issues.
In your opinion, how has the Last Planner System improved planning transparency between the contracted companies and the Company X team? If so, provide examples if possible.	The LPS aided in the forward-looking view of activities, focusing on resolving problems and constraints before they impacted operations. An example is the approval of health and safety procedures and documentation prior to commencing activities.
Did the Last Planner System help identify and solve conflicts or obstacles more efficiently and with greater predictability during project execution? If so, provide an example if possible.	Yes, one example was with the contractor S, where we conducted a workshop and task force to identify issues and deviations from the planning in the final phase of the project, aiming to not impact commissioning activities.
In your experience, did the Last Planner System facilitate adaptation to unforeseen changes during project execution? If so, how?	Yes, the LPS proved to be a very useful tool for analysing scenarios and providing responses to changes and unforeseen events in the project.
What were the main perceived benefits of implementing the Last Planner System in the construction of the wind farm?	Increased predictability, greater integration between project areas, and improved communication with contractors were the main perceived benefits.
Did you notice an improvement in communication and transparency of relevant information among Engie's internal sectors for the project after the implementation of Lean? If so, provide examples if possible.	Yes, and the involvement of all areas in the lookahaed meetings greatly assisted in communication and understanding of constraints and critical points between the areas.

CONCLUSION

This study aimed to explore a planning and management model based on the Last Planner System from the owner's perspective in onshore wind energy projects through two case studies. The first case study shed light on the current challenges faced by the owner in managing onshore wind projects. One challenge stem from the traditional management and contract model, where the owner relies on an internal team for contractual management and coordination of interfaces between contractors, giving contractors full autonomy for planning and executing the project. This model has been questioned in literature and industry for not fostering collaboration among contractors, often prioritizing local optimization over global efficiency. Another challenge is the low maturity of contractors in adopting efficient planning practices based on Lean, such as the Last Planner System, and the third challenge relates to internal communication failures within the owner's team, with departments sometimes operating independently without aligning with project priorities.

The second case study showcased the adaptation of the Last Planner System from the project owner's viewpoint, implementing elements like Phase scheduling and Lookahead planning meetings. While phase scheduling aimed to identify hand-offs and potential risks to meeting deadlines using the time-location tool, the Lookahead meetings established structured sessions with contractors to proactively address constraints, whether from the contractors or the owner (Company X). This model created separate focal points for discussing each contractor's 6-week plan, followed by an internal alignment meeting to identify constraints, avoiding lengthy meetings and maintaining the quality of discussions despite varying Lean maturity levels among contractors.

A key outcome of the second case study was the enhanced Lean maturity among contractors, supported by internal training cycles and the structured Lookahead planning rituals implemented by the owner, which were disseminated among the contractors, improving their planning processes and proactive constraint management. This maturation was evidenced by indicators such as the Percentage of Constraint Removal and Bi-weekly Adherence of planned packages.

Another outcome was the implementation of the Control Tower ritual, aimed at fostering collaboration across departments, indicator-based management, and monitoring the status of departmental constraints. This ritual successfully integrated various aspects (land management, environment, safety, projects, quality) into production control.

Future research suggestions include exploring the adoption of BIM and 4D planning in onshore wind energy projects as mechanisms for identifying spatial constraints and conflicts. Another potential research area is the relationship between the implementation of integrated project delivery in onshore wind energy projects and the increased maturity in adopting Lean practices among contractors and the owner.

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AGILE RAMP-UP: A METHOD TO REDUCE PREMATURE CONSTRUCTION START

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ABSTRACT

It is understood that one of the main contributing factors to stagnant productivity in the construction sector is the haste of project teams to start construction without a thorough readiness assessment. With the aim of improving the sector's performance, recent research has turned to analyzing the consequences and challenges associated with the premature start of projects, showing a direction in the search for effective solutions to these issues. The purpose of this work was to present the application of an agile ramp-up method developed to mitigate cases of premature construction start in onshore wind projects. The method used in this article was Design Science Research and covers the following phases: awareness of the problem through understanding the concepts involved; artifact suggestion through the development of a diagnosis; development from the choice of appropriate tools for constructing the "Starting Right" method; evaluation through the impact, transparency, and statistical variance analysis in 16 projects, of which 6 applied the method; conclusion through the systematization of the main learnings. The "Starting Right" method significantly improved the performance of projects during the initial phases, with strategic tool use proving essential for effective responses to various scenarios.

KEYWORDS

Agile Ramp-Up, Lean construction, Wind Farm, LPS.

INTRODUCTION

The construction sector faces persistent productivity challenges, often compounded by the premature start of projects without a thorough assessment of construction readiness. This research, initially focused on onshore wind projects, reveals issues that are universally relevant across various types of construction, such as civil infrastructure, commercial buildings, and industrial developments. In this context, investigating the premature start of construction has

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proven critical to understanding how the pressures of deadlines and perceived benefits by stakeholders can compromise the success of a project in any of these areas.

In pursuit of enhancing the performance of the sector, some studies have shifted their research focus towards understanding the premature start of construction projects. (Griego;Leite, 2017; Abotaleb et al., 2019; Radzi et al., 2020; Ibrahim, et al. 2021). In this point, Ibrahim et al. (2021) suggest as a major reason of the stagnant productivity in the sector is that project teams often rush into construction without adequately assessing construction readiness.

Determining the right time to start construction is pointed out by Griego; Leite (2017) as one of the most important planning decisions on a major capital project. According to the same authors, this decision in many times is influenced by the fact of at least one stakeholder perceives a benefit from an early start construction, as result, project teams face pressure to begin construction, whether or not they are ready. The consequences of this decision could negatively impact a project outcome through frequent interruptions, rework, litigations, claims, disputes, out-of-sequence work, delays (Griego; Leite, 2017; Aboutaleb et al., 2019; Ibrahim et al., 2021).

This new line of research is led by the Construction Industry Institute (CII), which present two key terms: (i) premature construction start; (ii) construction readiness. The premature construction start is defined as "a decision, by at least one party, to start construction with at least one risk that exceeds an acceptable tolerance to a party, and which can result in an interruption to construction" (Griego; Leite, 2017). While construction readiness is defined as "a series of activities and procedures that should be completed or substantially completed prior to construction to productively start and sustain construction operations" (Ibrahim, et al. 2021). Despite the different definitions, it is implicit that the main purpose of both terms is to bring more clarity to the importance of avoiding interruptions right from the beginning of the projects.

It is possible to identify in the literature some research that has already addressed similar topics, but without the specific focus on the start of projects. For example, Koskela (2004) introduce the term making-do as a situation where the activity is started even without all prerequisites available. The relevance of the line of research led by CII is that when an organization experiences an interruption in the start, project teams react by spending additional capital on increased labor and speedier engineering documentation delivery in order to get the project back on track (Griego; Leite, 2017). In this point, the studies of Griego; Leite (2017) identified drivers, lead indicators and impact of premature construction start while Ibrahim et al. (2021) propose a model to assess the construction readiness. But even though advances have been observed in the respective research, there are still alternatives of methods that help companies reduce the cases of premature construction start.

In Lean construction, which highlights collaboration among teams to minimize waste and maximize value for stakeholders (LCI), the Last Planner System (LPS) stands out as a method that aligns closely with these goals. The main idea behind LPS is to establish a reliable and stable workflow through the preparation process (Ballard; Howell, 1998). Another aspect related to the Last Planner System tool is that it allows a global view of the project through three levels of planning: short, medium, and long-term (VIEIRA; BORGE; BARROS NETO, 2020). In this sense, the preparation process works to ensure that all prerequisites are available when the task is initiated, thus avoiding interruptions and lack of productivity. But, although this is the ideal to be pursued, in practice, some studies have shown that due the complexity of construction, unexpected contexts emerge that require adaptive decision-making, and the go/no-go decision to start an activity need to be applied (Pikas et al., 2012). These natural manifestations of resilience by team to respond an unexpected event require the appropriate support from the organization to create conditions to encouraging the diversity of perspectives when making decision, design slack, monitoring gaps between prescription and practice, or even anticipating and monitoring of small changes (Saurin; Sanches, 2014). Yet, although the benefits related to the application of the LPS, it is not exclusive to the construction start phase, requiring adaptations to its peculiarities.

In other industries, the Ramp-up phases presents similarities with the construction start phase, since the interruptions and the uncertainty are a common theme. The Ramp-up begins when the process is scale up from zero and ends at the stable production of full-volume (Christensen; Rymaszewska, 2016). This phase also encompasses the cases of manufacturing "start-ups" of new production lines or new factories, where the production output increase gradually (Glock; Grosse, 2015). Recently, a new way of managing the Ramp-up phase has emerged. This includes agile principles as an asset to combat the growth volatile and uncertainty of business environment (Kremsmayr et al., 2016; Mamaghani; Medini, 2021). According to DeVor et al (1997), agile manufacturing is described as the ability of a company to adapt and thrive amidst constant changes, including those in markets, technologies, and business relationships.

Historically, production management can be viewed from different perspectives, with the traditional approach linked to conversion, prioritizing aspects related to the transformation of inputs into the final product (COELHO, 2003). One important criterion of lean management is achieving the customer's needs. By entering lean management into the construction industry to reduce wastes in each process. Many innovative techniques developed by different individuals can be used for lean production, lean construction or agile methods in such a way that identifies wastes and tries to eliminate or minimize their impact (RASHID, HERAVI, 2012).

Therefore, understanding the complete production flow and identifying value-adding activities is crucial. One of the primary objectives of Lean Construction is the reduction of non-value-adding activities, further optimizing the production process.

The present study seeks to present the results of the application of an agile ramp-up method developed to mitigate cases of premature construction start in onshore wind projects. The methodology was developed based on 6 case studies.

AGILE RAMP-UP

Managing Ramp-up phase is a challenging task, due the complexity related to high uncertainty, resource availability, lack of process maturity and the involvement of several stakeholders from different backgrounds (Heraud et al., 2023). Another characteristic with negative impact is that the ramp-up process is normally designed based only on experiences from an existing production line (Mueller et el. 2020).

Recently several studies have presented agility as one of the main drivers of ramp-up management (Kremsmayr et al., 2016; Bergs et al., 2021; Mamaghani; Medini, 2021; Heuraud et al., 2023; Kadkhoda-Ahmadi et al.,2023). These studies highlight that the agile principles enable the companies to respond quickly to changes and to support continuous development and quality improvement during ramp-up phase.

Kremsmayr et al. (2016) allowed an advancement on the application of agility principles in ramp-up management. According to them, the agile ramp-ups could be characterized according four criteria (Figure 1):

- Proactive task prescheduling – Considers the principle of proactive through the application of possible scenarios as well as their effects on a Ramp-up phase. It also presents the concerns with mitigate risk and achieve time advantages.
- Acceleration of upscaling phase – The acceleration principle is achieved with transparent decision-making process and simplification of the major Ramp-up processes. The main idea is to remove unnecessary process steps and interion loops and organize efficiently the experience gained from previous ramp-ups.

- Flexible capacity adjustment – Involves the ability to undertake flexible capacity adjustment even shortly before starting or during Ramp-up activities. It highlights the necessity to determine and monitoring certain performance levels.
- Rapid response to change – Here there is a focus on the reduction of recovery time, since the system need to be able to quickly respond to unexpected disruptions and recovery to the initial schedule as soon as possible. Here the importance of an structured help chain in organization is implicit.

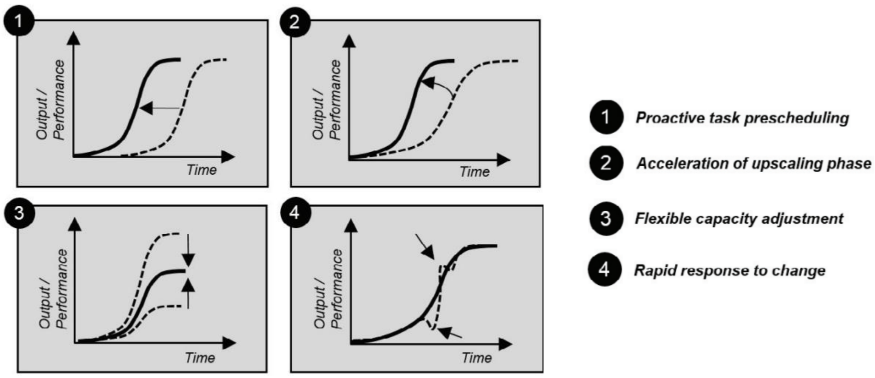

Figure 1: Four Criteria to Agile Ramp-up according Kremsmayr et al. (2016)

METHOD

For the development of the present study, the Design Science Research (DSR) methodology was employed. As highlighted by Bax (2014), the focus of DSR lies in the creation, investigation, validation, and evaluation of new artifacts, including constructs, frameworks, models, methods, and instances of information systems. The artifact developed in this article can be understood as a method for the accelerated initiation of wind farm projects, termed "Starting Right".

The aim of DSR is to create outputs that serve human purposes, and the critical point is to design a system that will address new challenges Kasanen et al. (1993) and create new perspectives for the current time (Lukka, 2003). DSR seeks to devise solution concepts, name artifacts, solve classes of problems (Van Aken, 2004; Holmstrom et al.2009), and, at the same time, provide a theoretical contribution to the field of knowledge (Kasanen et al., 1993).

The "Starting Right" methodology was developed based on the Agile Ramp Up structures used in the work of Kremsmayr et al., (2016), where these authors devised an artifact aimed at a hybrid industry of high-quality powder metallurgy. With this in mind, the "Starting Right" method, aimed at accelerating wind farm projects, utilized the Lean construction management philosophy, as well as tools such as the Last Planner System (LPS), visual management (Control Tower), risk matrix, and mobilization control spreadsheets. For this study, the LPS was integrated with key planning instruments: the Line of Balance for long-term planning, Six-week ahead planning for medium-term objectives, and Check Out meetings for short-term progress monitoring.

In this context, DSR played a crucial role in the design of this artifact, guiding its development through the steps outlined in Figure 02.

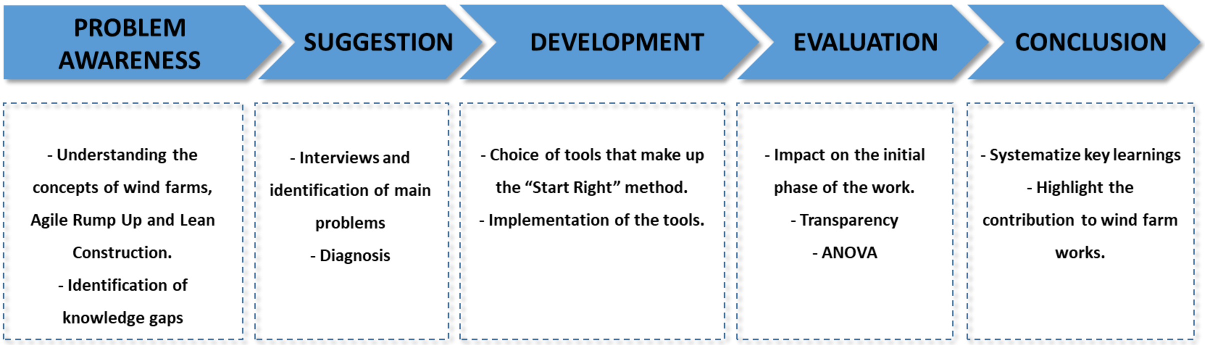

Figure 2: Methodological design

The development and implementation of the "Starting Right" method, as well as its deployment, were carried out by a management consultancy that began in 2020 at a wind farm construction company located in the northeast of Brazil. The Problem Awareness stage involved understanding the construction process of wind farms, studies on Agile Ramp Up, and studies on Lean principles. Furthermore, gaps in knowledge regarding these topics were identified. The selection criteria for the projects analyzed in this article required the project to involve the construction of wind farms, specifically the construction of access roads and concrete foundations (Table 1). Although there were other ongoing projects, such as building constructions and highways, the "Starting Right" method was applied exclusively to wind farm constructions, reflecting the constructor’s strategic decision to focus on this sector.

Subsequently, the Artifact Suggestion stage was carried out, in which the consulting firm conducted interviews with the engineers involved in the project "Project 11" (Table 1). The objective was to identify the main obstacles related to efficient management, culminating in the formulation of a diagnosis to be addressed.

Table 1: List of works analyzed

PROJECT	YEAR	TOWERS	METHOD	PROJECT	YEAR	TOWERS	METHOD
Project 01	2015	31	Conventional	**Project 09**	2019	121	Conventional
Project 02	2015	153	Conventional	**Project 10**	2019	49	Conventional
Project 03	2015	47	Conventional	**Project 11**	2020	120	*Start Right*
Project 04	2016	98	Conventional	**Project 12**	2021	76	*Start Right*
Project 05	2017	65	Conventional	**Project 13**	2021	93	*Start Right*
Project 06	2018	230	Conventional	**Project 14**	2021	70	*Start Right*
Project 07	2018	36	Conventional	**Project 15**	2021	123	*Start Right*
Project 08	2019	36	Conventional	**Project 16**	2022	188	*Start Right*

The Development phase involved selecting the most appropriate tools, taking into account the context identified during the diagnosis, followed by their implementation in "Project 11". This development process was subdivided into four parts, which were outlined as the initial guidelines of the "Starting Right" method. It is important to highlight that, after the implementation in "Project 11", this method was extended and applied to subsequent projects.

"STARTING RIGHT" RAMP UP METHOD

The "Starting Right" method encompassed 4 main pillars, which are: (1) Anticipating possible scenarios and mitigating risks as early as possible; (2) simplifying processes using a mobilization checklist; (3) making capacity adjustments before starting or during the initiation of activities; (4) reacting quickly to unexpected events through a structured support chain.

To facilitate the implementation of these guidelines, it was essential to determine the ideal timing for their application and identify the necessary tools for each situation, as described below:

Anticipate possible scenarios and mitigate risks as quickly as possible

Anticipating possible scenarios and mitigating risks are crucial elements for the success of any venture, especially in the field of wind farm construction. To address this challenge, two strategic tools were adopted: the Risk Matrix and Scenario Simulation. The Risk Matrix provides a comprehensive view of the potential challenges and opportunities that may arise throughout the project, allowing for proactive identification and an anticipatory approach. The Scenario Simulation, on the other hand, offered a global view of the project through long-term planning. For this purpose, the Critical Path Method and Line of Balance spreadsheets were used, which provided a clear visualization of milestone dates and resource allocation. Moreover, the combination of Scenario Simulation with the Risk Matrix contributed to better formulation and refinement of analysis at this stage.

Simplify processes using a mobilization checklist

The simplification of processes in the mobilization stage was crucial for the efficiency of the "Starting Right" methodology, being proactively incorporated through the use of a mobilization checklist spreadsheet. This spreadsheet not only simplifies the management of mobilization but also provides an effective channel to document and track new items that apply to a new project. The records obtained can be used in identifying patterns in the process. Thus, this simplification boosts operational efficiency and contributes to building a solid foundation for future ventures.

Make capacity adjustments before starting or during the start of activities

At this stage, the Carousel of Works control spreadsheet was employed, which facilitated the process of transferring a resource from one project to another. This approach aims to optimize the use of resources, ensuring proper allocation according to the needs of each project, providing greater flexibility and efficiency in the execution of simultaneous or sequential projects. For this purpose, mid-term meetings known as "Six Weeks Look Ahead" were utilized. These meetings were held periodically, occurring weekly or bi-weekly, with the goal of anticipating potential constraints in the planned activities over a six-week period.

React quickly to unexpected events from structured help chain

For effective management of emergency situations, it is essential to promptly address unforeseen events through a structured support chain. For this, Project Schedule Meetings, Check Out, Control Tower, and Management Meetings were utilized. The Project Control meeting involves discussions regarding the approvals and releases of executive projects, as well as analyzing specific aspects of the construction. This meeting takes place before the construction starts. On the other hand, Check Out, Control Tower, and Management Meetings occur at the beginning of the construction. The Check Out meeting provides a dedicated environment where operational teams meet with leadership daily to review critical events, share information, and make decisions, eliminating constraints for the next day. The weekly meeting called Control Tower presents an overview of all the project's information, with the participation of key leadership involved in the project's execution, aiming to present tactical indicators to the management. Concluding the support chain, a strategic meeting is held weekly, summarizing the main indicators and events for the board of directors. These four meetings enable quick and coordinated responses to minimize negative impacts, mitigate risks, and restore operational normality as quickly as possible.

Continuing with the DSR stages, the evaluation of the artifact took into account the Impact of the Starting Right method in the initial phase of the projects and the Transparency of the processes (Figure 02). The analysis of this impact is quantified by two aspects, first by the degree of deviation observed during the contractual progress of 25%, as exemplified in Figure 03, and by the level of challenges faced during implementation, classified as low, medium, and high.

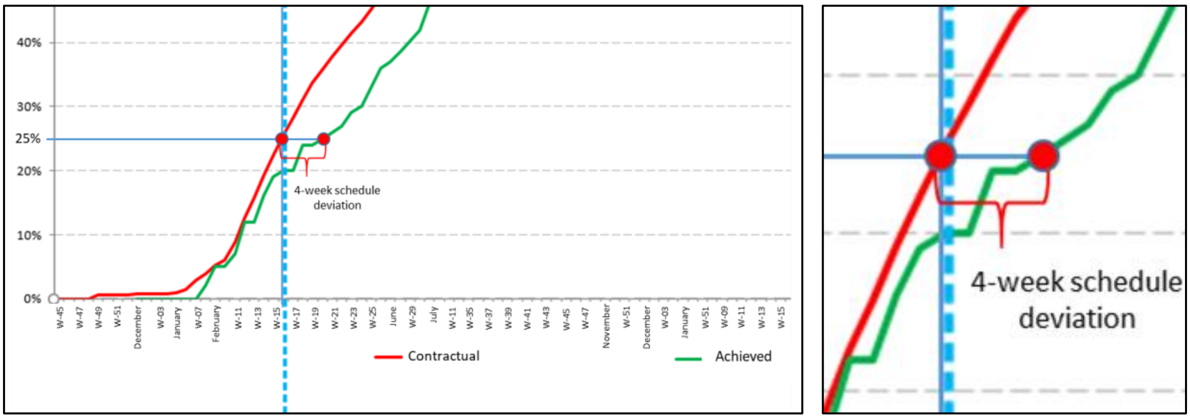

Figure 3: Example of S Curve for Project 7 Monitoring (left) and Zoom in on the 4-week schedule deviation (right)

Still pertaining to the Analysis phase, in addition to considering transparency as the ability of the production process (or its components) to facilitate communication with people (Formoso et al., 2002), robust statistical analyses were conducted to assess the effectiveness of the "Starting Right" method. According to Kerzner (2013), the technique of Analysis of Variance (ANOVA) is essential for comparing groups in project management studies. This technique was employed to quantify the schedule deviations during the Ramp-Up phase, comparing the performance of projects that used the conventional method with those that implemented "Starting Right".

In the final stage, the conclusion consisted of systematizing the main learnings, aiming to clearly highlight the method's contribution to wind farm projects.

RESULTS

In this section, we will discuss the results related to the development and evaluation phase of the artifact, presenting a representation of the method's structure, as well as analyses focused on the impact on the initial phases of the projects and the perception of the transparency of the implemented processes.

STRUCTURE OF THE "START RIGHT" METHOD

The "Starting Right" artifact represents an effective approach to the agile initiation of projects in wind farms. As illustrated in Figure 04, tools such as the Risk Matrix, Scenario Simulation, Mobilization Worksheets, LPS, "six weeks look ahead" meeting, Carousel of Works, Project schedule meeting, Check out, Control Tower, and Board meetings should be applied, especially in the initial phases of the project, until it reaches its production stability. It is worth noting that the continued use of these tools (1, 3, and 4) beyond the stability phase is indispensable, as they play fundamental roles in the ongoing management of the project.

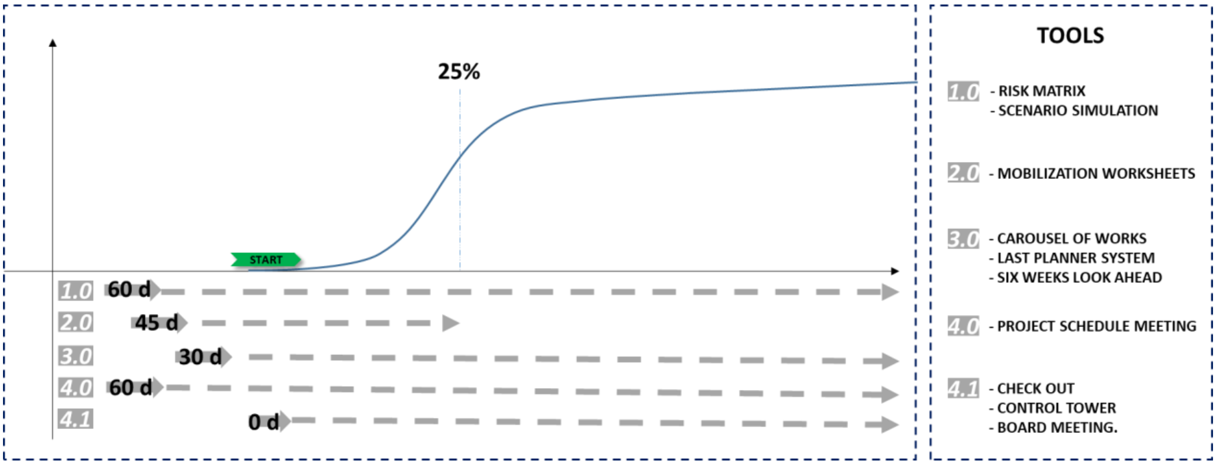

Figure 4: Representation of the Application of the method

Figure 03 also shows that each group of tools is initiated at a specific moment in the development of the project. This cadence is essential to ensure the success of the rapid startup of the venture.

Wind farm projects often occur in previously uninhabited locations, requiring the construction of accommodations, advanced campsites, and appropriate infrastructure. These constructions are necessary to ensure that the project can be started on schedule.

Details of the cadence for starting the tool groups:

- 60 days before the start of the project, the first group of tools is initiated
- 45 days before the start of the project, the second group of tools is initiated.
- 30 days before the start of the project, the third group of tools is initiated.
- 60 and 0 days before the start of the project, the fourth group of tools is initiated.

ANALYSIS OF THE METHOD'S IMPACT ON THE INITIAL PHASE OF THE PROJECT

Based on the analysis of the 16 projects monitored (Figure 04), it is observed that, in the period preceding the implementation, the occurrence of schedule deviations, resulting in delays in the initial phase of the projects, was more frequent. However, upon examining the period following implementation, it is noticed that the projects began to exhibit a superior performance pattern in their initial phase.

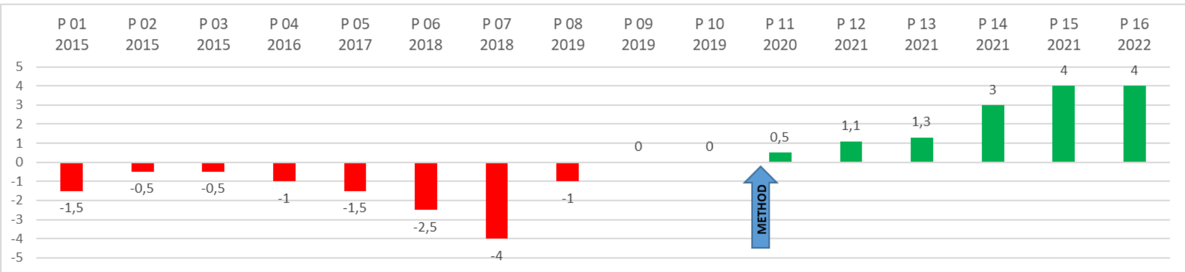

Figure 4: Timeline of the initial Ramp Up of ventures.

Considering this, an advancement in the method's maturity over the time of its application is noted. This progress is evidenced by the increase in the effectiveness of the "Ramp Ups" observed in the projects after the method's implementation (Figure 04). However, it is relevant to highlight the difficulties encountered during the implementation period, as can be seen in the initial performances of projects 11, 12, and 13. Among the difficulties that initially impacted the performance of the projects (Table 02), delays in the application of the tools and the lack of a database stand out.

Table 2: Impacts identified

Impact on Implementation	Level
Delay in applying tools	High
Customer Involvement in the Ramp-up process	High
Database shortage	Average

From this analysis, it was observed that the delay in the implementation of the tools had a significant impact on the adoption process of the new method. This situation arose mainly because the company's standard operational model did not anticipate a 60-day lead time for the start of these follow-ups. As a result, projects 11 and 12 started with only 30 days, compromising the available period for effective responses and identification of constraints, which ended up being identified too late. Despite these setbacks, projects 11 and 12 achieved positive outcomes. However, it is important to highlight that their performance, although satisfactory, did not reach the performance levels observed in projects 14, 15, and 16.

The presence and engagement of the client in the planning process and constraint removal are of vital importance, especially considering that various constraints emerge directly from their participation, such as license releases, project approvals, among other essential items for the construction's progress. In this context, the case of project 13 stands out, which, despite adhering to the 60-day advance preparation recommendation and achieving positive results, failed to replicate the high performance observed in projects 14, 15, and 16. This situation highlights the importance of effective collaboration with the client to overcome challenges and avoid delays, thus ensuring the smoothness and success of the construction process.

Another aspect that had a moderate impact was the lack of a comprehensive database on interferences and risk analyses, leading to a continuous refinement process. As the methodology was perfected over time, a notable improvement in the results of subsequent projects was observed, highlighting the continuous evolution of the method.

INFORMATION TRANSPARENCY AND THE VARIANCE ANALYSIS TECHNIQUE

When analyzing the tools implemented in the "Starting Right" method from the aspect of transparency, it is noted that, in general, all of them have the capacity to enhance communication among the involved parties. Particularly noteworthy is the integration observed between groups 3 and 4, as the support network structured by these tools continuously consulted the information surveys developed by tool groups 1 and 2. The discussions and analyses conducted through the support network played a crucial role, allowing the project to react agilely to unexpected events through active communication. However, during the implementation period, significant challenges were faced in attempting to establish a new culture within the company with the new routines. Many employees did not fully understand the proposed changes and, as a result, did not adhere to them as expected. It was essential for the construction engineers to provide regular guidance to their supervisors to ensure the adoption of the new practices until they could apply them independently.

It is important to highlight that, despite the initial positive results presented by the projects, it was essential to maintain the continuous use of the tools for the most part. This aimed to perpetuate transparency among the sectors, ensuring the sustainment of monitoring and control of the venture beyond the initial implementation period. It is worth noting that the tools were reused throughout the project, incorporating new analyses, risk identification, and proposition of solutions.

Moreover, a statistical analysis of variance was also conducted to further elucidate the effectiveness of the 'Starting Right' method. This analysis compared the schedule performances between two distinct groups of projects: those that did not implement the 'Starting Right' method and those that did. The data presented in Table 3 reveal a significant contrast between the groups, with the average of schedule deviations being negative for the group that followed the conventional method, indicating frequent delays, and positive for the group that adopted the 'Starting Right' method, reflecting earlier deliveries compared to the planned schedule.

Table 3: Variance analysis

Group	**Average**	**Variance**
Conventional	-1,25	1,51
Start Right	2,32	2,39

Interestingly, greater variance was observed in the projects that used 'Starting Right', particularly due to a substantial leap in performance between projects 11 and 15, where an improvement in schedule deviation from 0.5 to 4 weeks was recorded. This increased variance does not obscure the fact that, as evidenced by Figure 4, projects with the 'Starting Right' method consistently demonstrate superior results, underlining the method's potential to improve delivery during the Ramp-Up stage.

CONCLUSIONS

The "Start Right" method combines Lean construction principles with agile approaches, aiming to prevent premature project starts and achieve significant improvements in initial performance. Its application demonstrates the importance of strategically using tools for effective responses to various scenarios. The case studies addressed in this work showed that the application of the agile ramp-up methods, yielded positive results. The analysis encompassed 16 ventures, of which 6 adopted the new method. It became evident that determining the appropriate moment to start monitoring the constructions is of fundamental importance, highlighting the relevance of avoiding interruptions from the beginning of the projects.

The development of a database to document interferences and risks proved to be highly beneficial. Such a practice not only facilitated risk management but also significantly contributed to the enhancement and maturity of the method's implementation. However, it is important to note that, despite satisfactory results, the effectiveness of the method may be compromised in the absence of effective collaboration and joint planning with the client. This limitation was particularly evident in project 13, indicating that greater integration and alignment among all involved parties could have elevated the achieved results.

In this context, for the implementation of the Starting Right method, it is recommended to train employees on the presented tools, as well as to respect the appropriate time for the start of each phase. It is important to emphasize that the challenges faced by the construction sector vary according to its constructive characteristics, which can generate variations in the results. Therefore, it is suggested to expand the application of the method to other types of constructions in order to evaluate its performance. Additionally, fostering effective collaboration and joint planning with all stakeholders is essential for enhancing integration and alignment of th implementation. Continual evaluation and adaptation of the method should be carried out to align with the unique challenges and characteristics of each construction sector, accommodating variations in results and ensuring maximum efficacy.

The "Start Right" method combines Lean construction principles with agile approaches, aiming to prevent premature project starts and achieve significant improvements in initial performance. Its application demonstrates the importance of strategically using tools for effective responses to various scenarios.

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LEAN CONSTRUCTION IMPLEMENTATION IN THE CONSTRUCTION OF AN AIRPORT RUNWAY

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ABSTRACT

This study explores the application of Lean Construction in the expansion and restoration of an airport runway, a project marked by complexities and high demands. The aim of this paper is to address the following research question: "What is the effectiveness of the daily scheduling approach compared to the weekly horizon approach for short-term scheduling in complex and variable infrastructure projects?". To answer this question, an extensive literature review was conducted, anchored in the action research method. It was found that the adoption of daily schedules may be more efficient, as it allows for greater agility in responding to client needs, accommodating constant changes requested by stakeholders, and managing uncertainties inherent in infrastructure projects of this nature. The results highlight significant advances in long-term adherence and project management effectiveness, despite encountered obstacles such as coordination among different stakeholders and adaptation to variabilities. The Percentage of Constraint Removal (PCR) improved by 22% from the start to the end of the project, while maintaining a 93% adherence to the Master Planning.

KEYWORDS

Lean construction, Last Planner® System, variability, constraint analysis, lookahead planning.

INTRODUCTION

It is estimated that in Brazil, there will be an investment of over 10 billion reais in airport infrastructure over the next 30 years (Brazil, 2022). Specifically, for the year 2024, an investment of 3 billion is expected, which would represent an increase of 65% compared to previous years. This scenario of significant investment highlights the necessity and feasibility of applying Lean Construction techniques and the Last Planner System to optimize costs, meet deadlines (Mohan & Iyer, 2005), and ensure operational efficiency (Castillo et al., 2014) in large-scale projects.

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Lean Construction seeks to eliminate waste and maximize the value delivered to the client throughout the construction process (Koskela, 1992). The Last Planner System (LPS), in turn, is a methodology that integrates Lean principles for planning and controlling production in construction (Ballard & Howell, 2004). Both approaches have been successful in various sectors, however, when applied to infrastructure projects, they face specific challenges.

The present article aims to present a case in which Lean Construction and the Last Planner system were applied in an airport pavement project. Therefore, it intends to contribute to the development of Lean methodology in infrastructure projects. Thus, it seeks to answer the following research question: What is the effectiveness of the daily scheduling approach compared to the weekly horizon approach for short-term scheduling in complex and variable infrastructure projects?

LITERATURE REVIEW

For the diagnostic phase of the study, a comprehensive review of articles in the IGLC database was conducted to identify research addressing the challenges encountered in implementing Lean Construction and the Last Planner System (LPS) specifically within airport pavement projects. However, the search conducted on 05/04/2024 yielded no results for the term "Airport Runway". Upon broadening the search to the term "Airport", only seven results were returned. Of these, only one article (Herrera, 2018) directly addressed the challenges, while another (Tribelsky & Sacks, 2010) discussed waste management, emphasizing adaptability as a primary requirement and project issues such as "project overrun". These findings underscore the existing gap in the literature regarding the application of Lean Construction and the Last Planner System in infrastructure projects, as previously highlighted by Formoso et al. (2022) and Kassab et al. (2020).

Faced with this limitation, it was necessary to broaden the scope of the research, considering the similarities between airport pavement projects and complex infrastructure projects. Such projects encounter common challenges, including the presence of multiple stakeholders, varying levels of expertise, underground conditions, and the need for intensive coordination. Therefore, articles addressing the main challenges encountered in complex infrastructure projects were sought, aiming to develop a comprehensive strategy that meets all requirements and empowers the team in adopting the Lean philosophy. Existing literature highlights barriers such as the lack of support from senior management (Demirksen, 2019), communication problems (Opsahl et al., 2015), a lack of common understanding of the project's scope and objectives (Schöttle & Böker, 2023), and cultural resistance from those involved (Wandahl, 2014), were found in the literature.

Throughout the research, not only were the issues highlighted in the literature observed, but also successful aspects in projects. Authors such as Opsahl et al. (2015) emphasize the importance of engaging both employees and clients to ensure effective communication and trust development. Kassab et al. (2020) highlight the significance of maintaining commitment from all involved parties. The recommendations found in the literature were essential in guiding the implementation of Lean Construction and the Last Planner System in the journey presented in this article.

METHOD

This paper presents a methodological approach based on action research to assess the implementation of Lean Construction and the Last Planner System in an airport pavement project. The choice of action research as a method of investigation is grounded in the need for a practical and collaborative approach to solving specific problems in a real-world context (Eden & Huxham, 1996). By involving both researchers and action participants, this method allows for continuous assessment, iterative adjustments, and direct feedback, ensuring a thorough understanding of the implementation of Lean Construction and Last Planner System practices in the project.

The Action Research method is based on five main steps: Diagnosis, conducted during the literature review phase; Action Planning, evidenced in the pre-construction phase with the time location technique; Action taking, basing the work's success on Lean and LPS tools and routines; Evaluating, based on the indicators presented in the Results section; and Specifying learning, discussed in the Conclusion section.

BACKGROUND OF STUDY

PROJECT DESCRIPTION

The project carried out at Ministro Victor Konder Airport in Navegantes, Santa Catarina, Brazil, involved the expansion of the landing strip and the restoration of the existing pavement. Originally measuring 1700 meters in length and 45 meters in width, the runway underwent an extension to 1800 meters towards threshold 25. Additionally, threshold 07 was relocated, and Runway End Safety Areas (RESAs) were implemented at both ends. The runway, primarily composed of flexible pavement and rigid pavement at the ends, was adapted to support higher loads by replacing the flexible pavement with a greater thickness along the runway and widening the existing shoulder.

The scope also included the update of horizontal and vertical signage, lighting for low visibility operations, improvements in the drainage system, and a runway strip. Figure 1 presents a comparison between the existing runway and the proposed runway after the improvements are executed.

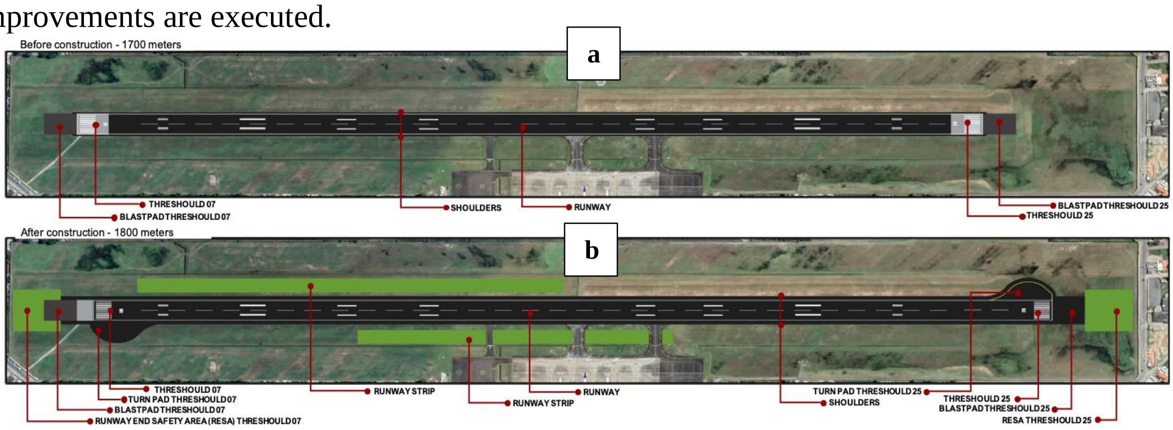

Figure 1: (a) Existing Runway; (b) Runway after the proposed improvements.

LEAN CONSTRUCTION JOURNEY

The Lean Construction implementation journey took place from May to November 2023. An implementation schedule for tools was conceived to introduce Lean Construction principles to project collaborators, as well as their practical application, monitoring, and continuous improvement. Figure 2 presents the timeline of Lean implementation in the Navegantes International Airport project.

In the first month the journey began with the execution of mobilization planning and priority plan studies. In the second month, the Last Planner System (LPS) was applied, integrating planning horizons and visual management tools, which were sustained throughout the entire project. In the third month, emphasis was placed on training and interactive activities about Takt Planning and focus on lessons learned and kaizens, more specifically on the definitive accreditation of collaborators and equipment. In the final months of implementation (four to seven) efforts were made for Pull Planning of drainage and lighting systems and detailed planning of micro-activities and commissioning.

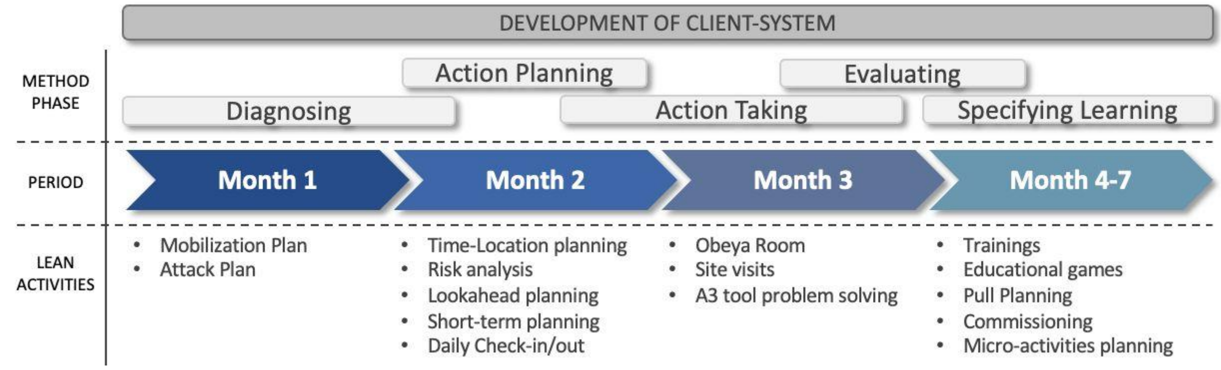

Figure 2: Timeline for LC implementation in the airport project

LEAN CONSTRUCTION IMPLEMENTATION

MONTH 1 – PRE WORKS

From the outset, the project was shown to be of high complexity due to the urgent need for mobilization to meet the contractual milestone with the client. Thus, a swimlane diagram was developed to map all activities (arranged chronologically) to be undertaken by the involved sectors (separated into lanes). These activities ranged from documentation and hiring of collaborators to the establishment of temporary facilities on site. This visual tool delineates the distribution of tasks and facilitates synchronized teamwork, ensuring transparency and cooperation among sectors, as demonstrated in Figure 3.

Figure 3: Swimlane diagram of activities for team mobilization; (a) routine execution; (b) final board

Simultaneously, a priority plan was developed aiming to establish a logical and efficient sequence of activities, with strategic allocation of resources to maximize productivity and reduce waste. This attack plan was developed using the Time-Location methodology to preliminarily map the temporal sequence and location of macro activities, offering clarity in understanding the project flow and facilitating the identification of potential conflicts and overlaps.

MONTH 2– LPS AND VM IMPLEMENTATION

The main challenge of the project was related to the restricted work window from 11:30 PM to 5:30 AM, due to the airport runway's operation during opposite hours. Any delay in production could interfere with the airport operations, making team efficiency a challenge due to time constraints and the need for daily mobilization to the airside of the airport. Recognizing that standard productivity rates in road projects would not be directly applicable in this scenario, studies of daily activities were necessary, focusing specifically on Hot Mix Asphalt (HMA) resurfacing service. The project demanded the application of HMA with different mixes and thicknesses, each presenting its own demands and challenges. Through scheduling scenarios, it was possible to identify an estimated daily productivity, considering time constraints and the processes of mobilization and demobilization. Figure 4 illustrates a pessimistic scenario of the daily schedule for asphalt resurfacing, considering the time constraints due to the continuous operation of the airport runway during opposite hours.

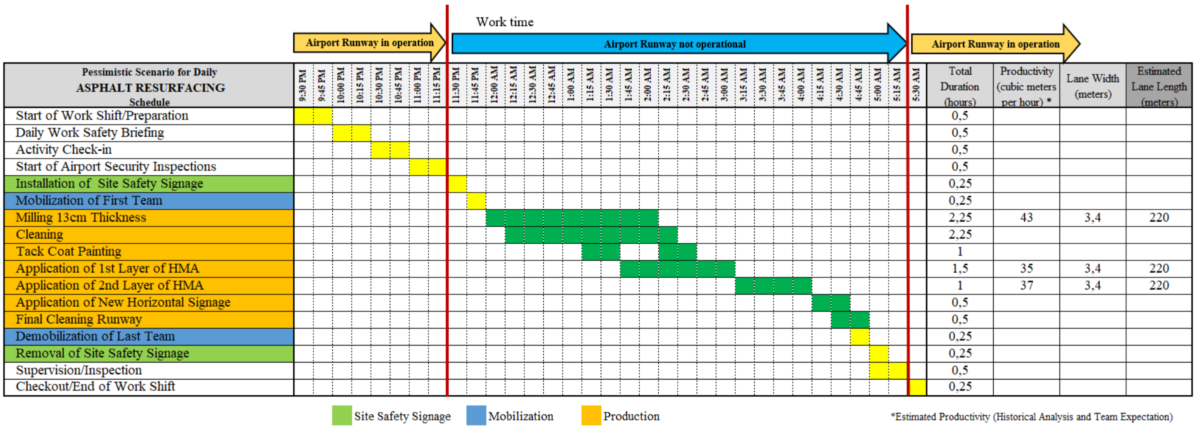

Figure 4: Daily schedule for asphalt resurfacing: pessimistic scenario

A workshop focused on risk identification was also conducted. This collaborative workshop allowed for the mapping of potential uncertainties, which, combined with the daily variation in productivity, was essential for constructing the master plan in a time-location format, integrating buffers into the schedule, and creating scenarios varying according to the identified risks and challenges. The strategy involved setting up macro work packages, as any service initiated had to be completed the same night. This master schedule was posted on the big room wall, as shown in Figure 5, to facilitate the visualization of the proposed attack plan by collaborators.

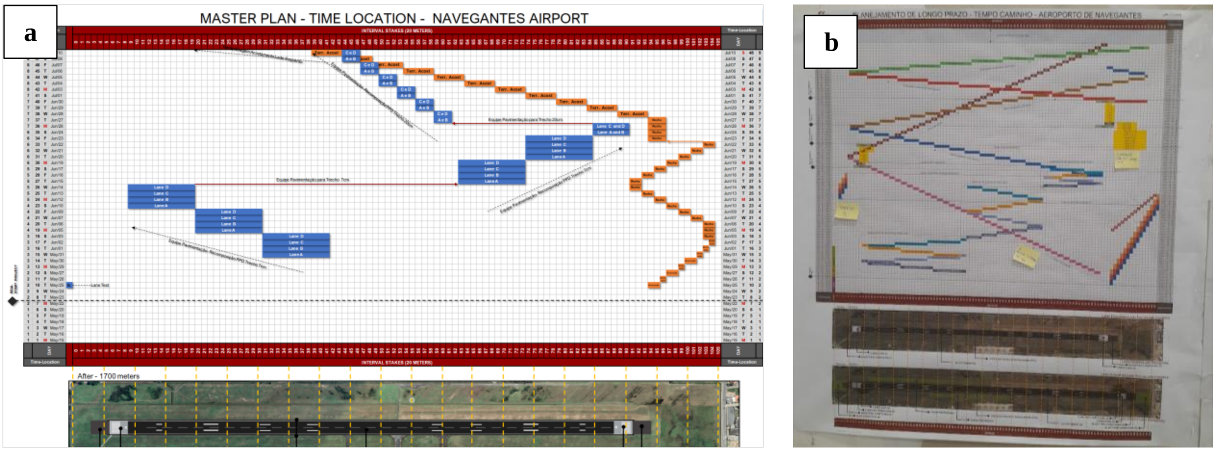

Figure 5: Time-Location master planning: (a) digital version; (b) printed version.

Within the implementation of LPS as a planning and production control system, medium-term, short-term, and learning dimensions were implemented, here represented by the Check-in/out routines as proposed by Ballard & Tommelein (2021). The Lookahead Planning was implemented with a six-week horizon, aiming for proactive identification of constraints and the generation of effective action plans to ensure uninterrupted workflows. From this medium-term routine, the Percentage of Constraint Removal (PCR) indicator was collected. The short-term, developed weekly in collaboration with production leaders, included the weekly activity plan. In this routine, the Percentage of Plans Completed (PPC) and adherence to production in quantity produced were collected. For daily control, daily check-in/out meetings were held for continuous monitoring of progress against the weekly plan, allowing for agile identification of deviations and interruptions for workflow efficiency.

These indicators, along with those developed with other sectors, were continuously presented in the Big Room or Obeya Room once a week for weekly performance evaluation, allowing the team to identify and prioritize the most critical issues. This approach enabled an improvement in collaboration between sectors, strengthening the support chain and its effective communication. All these control mechanisms were implemented due to the unique nature of this project, with constant plan changes from the client, continuity of Airport use during the day, and high variability of thickness with the removal of the asphalt layer. Figure 6 presents the high level of engagement and collaboration across all planning levels.

Figure 6: LPS meetings: (a) Lookahead planning; (b) Short-term planning; (c) Daily Check in/out

MONTH 3 – LESSONS LEARNED AND KAIZEN

Due to the expiration of the temporary accreditation deadline given by the airport administrator to the company, the definitive accreditation of collaborators and equipment became the main reason for the non-completion of scheduled activities. The critical period occurred between weeks 3 to 6, during which there was a peak in expirations resulting in up to 24% of workers being unavailable, as shown in Figure 7. This situation became particularly problematic because the unavailability of key operators from work fronts, such as paving, hindered the progression of activities.

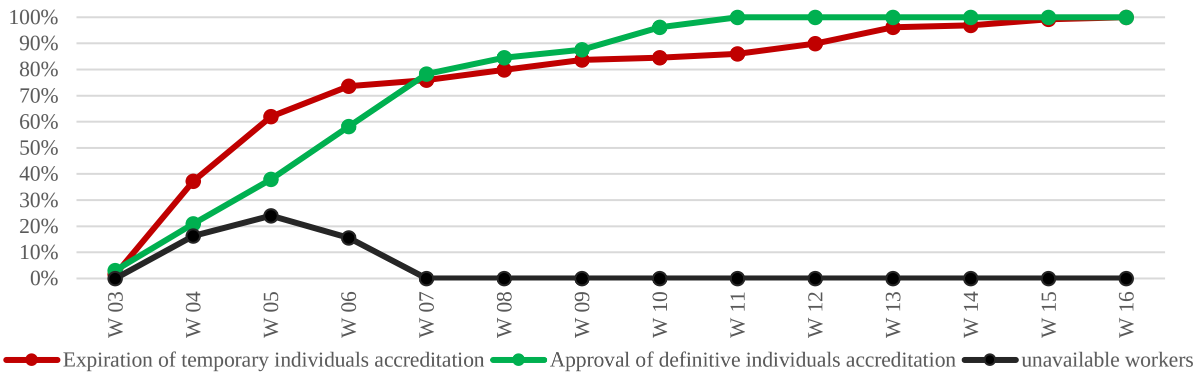

Figure 7: Expirations and Approvals of individual accreditation

Faced with the challenges of the temporary accreditation expiration and the subsequent need for definitive accreditation, the project team adopted proactive measures in August and September. The focus was directed towards training in problem-solving and the effective use of the A3 Tool for analysis and communication. This effort aimed not only to address the immediate issue of accreditation but also to strengthen the team's capacity to deal with future operational challenges. The client's uncertainty regarding accreditation processes exacerbated the situation, highlighting the need for a clear and effective action plan. To mitigate the negative impacts and optimize the accreditation process for the future, a detailed flowchart was developed, as shown in Figure 8, serving as an essential guide to simplify and expedite the accreditation procedure, demonstrating the commitment to continuous improvement and operational efficiency in the challenging context of airport projects.

Figure 8: Process mapping for individuals and vehicles airport accreditation: (a) digital version; (b) printed version.

MONTH 4 – 7 – PULL PLANNING SESSIONS

As the final step in the implementation of LPS, Pull Planning Workshops were conducted for training alongside third-party teams to study activities that were further removed from the long-term schedule. This approach involved teams responsible for the execution, aiming to map necessary tasks and their dependencies, identifying milestones, and establishing a logical sequence of activities to ensure efficiency in the workflow and meet the project deadline. In November, in the final phase, detailed planning of micro-activities focused on delivery and commissioning, tailored for the last three weeks. This meticulous elaboration ensured the identification, planning, and execution of critical tasks, guaranteeing an effective final inspection and the successful completion of the project. This slightly more detailed focus may deviate from the level of detail portrayed by the LPS literature, yet demonstrates that for this type of work, with high variability, it may be necessary to review the short-term planning horizon in order to enhance the predictability of service fronts.

DISCUSSION AND RESULTS

CHALLENGES DURING IMPLEMENTATION

Among the main challenges faced during the Lean Construction (LC) and Last Planner System (LPS) implementation journey, two stand out: the low performance of the Percentage of Constraint Removal (PCR) indicator and the low performance of the Percentage of Plans Concluded (PPC). Regarding the PCR, an average indicator of 54% was observed over the first 3 months of the project (June to August), a number also noted by Jang & Kim (2007) and Torre et al. (2021) in paving projects. This result can be explained by the various changes in the daily execution plan by the client. Despite the high climatic variability inherent to the region where the Airport is located, the change of plan corresponded to 22% of the reasons for non-completion of the week's activities, as presented in Figure 9. Such plan changes also led to an increase in the complexity of the service front (11%) and the lack of projects (10%), as there was not enough time for the prior study of the service front and the execution of the project. These difficulties are corroborated by Demirksen et al. (2019) who identified the main challenge for effective Lean implementation as the communication barrier among stakeholders, whether it be the difficulty in engaging the client or even the lack of effective information sharing and an integrated control of changes.

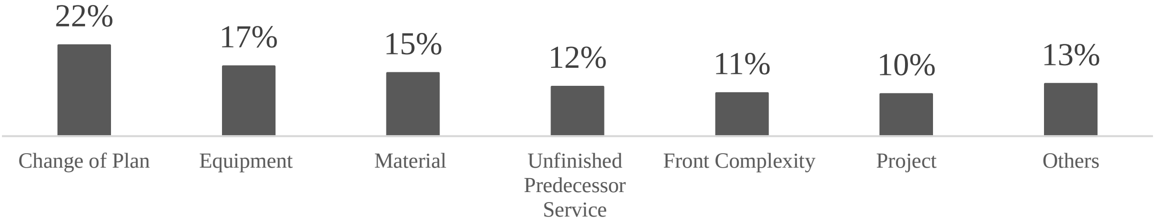

Figure 9: Main causes of interferences in the activities

This change of plan also resulted in not having enough time to identify and solve constraints in time. During the implementation, it was found that 69% of action plans in the lookahead planning were scheduled for the week following the identification date, as shown in Figure 10, indicating a challenge in effectively anticipating constraints. The six-week anticipation strategy, although implemented, proved to be potentially inadequate due to the high level of project uncertainties.

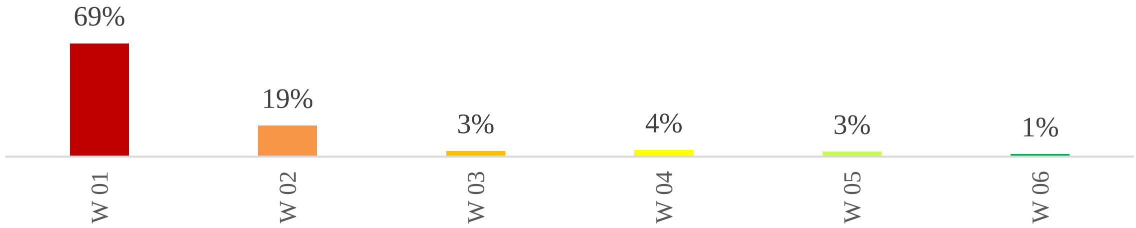

Figure 10: Average time of constraint identification in the lookahead planning routine

In light of this scenario, efforts were made to involve the client in the weekly lookahead planning meetings held in the Big Room. The room and the periodic meetings played a key role in engaging the client due to the transparency and visual management of the main pains felt by the service fronts. Thus, from month 5, a 22% improvement in the PCR indicator was noted, as shown in Figure 11.

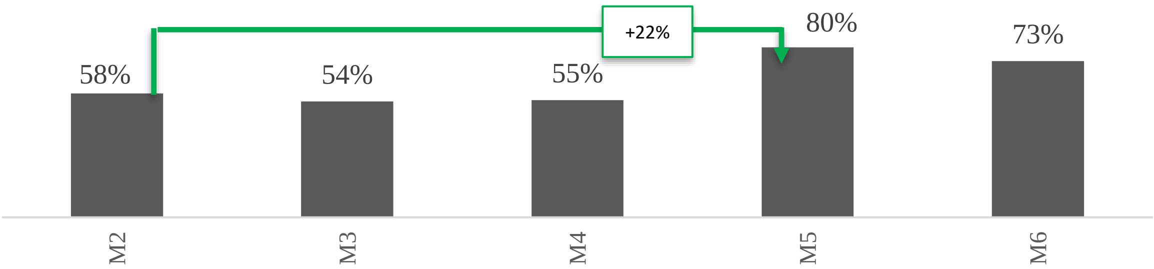

Figure 11: Monthly average PCR

Despite the correlation between PCR and PPC cited by Torre et al. (2021), the PPC did not follow the expected evolution, remaining at 41%, below the average found in the literature for paving works, namely 64% (Torre et al., 2021), 67% (Jang & Kim, 2007), and even 85% (Tezel et al., 2016). As mentioned earlier, most of the causes of non-completion are presented in the change of plan, demonstrating the high variability of the project.

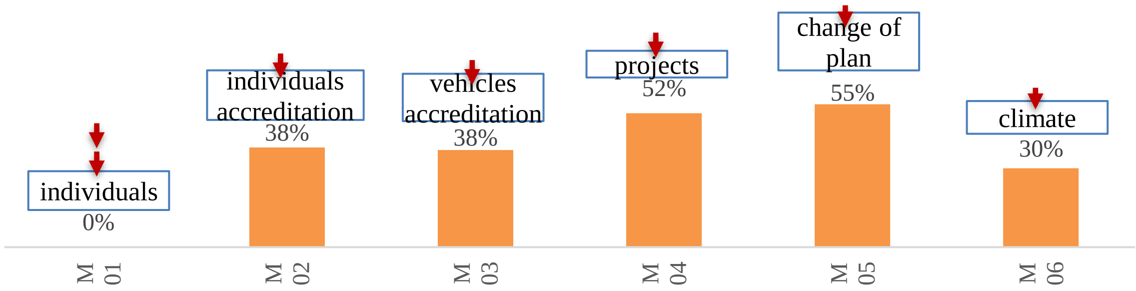

Figure 12: Weekly average PPC and problems

The low PPC indicator itself, coupled with satisfactory adherence to long-term planning, affected team morale. Therefore, a collection of weekly adherence based on the total quantity produced per day was initiated, which ended up raising team morale and maintaining satisfactory performance throughout the project. This adherence indicator showed an average performance of 75% throughout the project and also had an apparent correlation with the PCR indicator, as demonstrated in Figure 13.

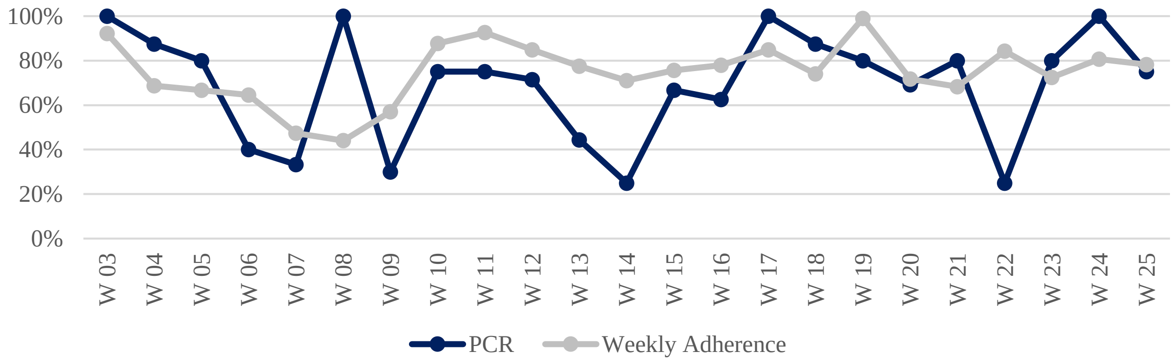

Figure 13: PCR and Weekly Adherence

OVERALL INDICATORS

Overall, the project was successful in the main long-term indicators, achieving 93% adherence to the planned long-term schedule and staying ahead of schedule in 27 of 29 project weeks. During the project, delays were identified only in weeks 2 and 9, with airport accreditation being pointed out as the main cause of these delays. However, the recovery plan effectively brought the project back on track after just one week. Week 21 marked the maximum advancement of the project, reaching 9% ahead of the planned schedule, as shown in Figure 14.

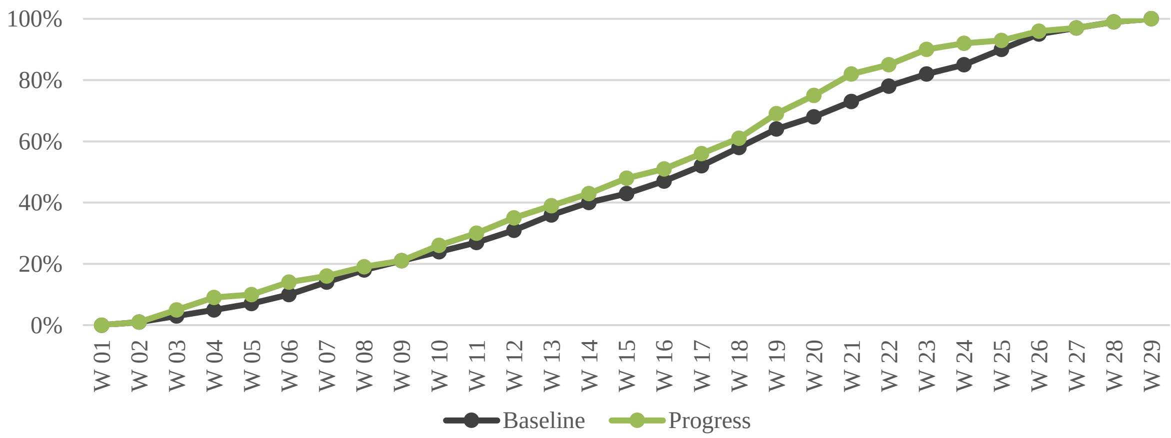

Figure 14: Physical progress chart of the project

CONCLUSIONS

The application of Lean Construction principles in an airport runway expansion and resurfacing project demonstrated significant improvements in schedule adherence and operational efficiency. The integration of strategies such as the Last Planner System and Pull Planning, complemented by visual management tools and collaborative work, resulted in more agile and adaptable project execution. Overcoming challenges such as accreditation constraints and climate variations highlights the importance of flexible planning and rapid response. The success achieved, marked by significant progress in scheduling and reduced variability in constraint removal, reinforces the value of Lean Construction in optimizing complex projects and promoting a culture of continuous improvement.

Analyzing the challenges faced during the project implementation, such as the low Percentage of Constraint Removal (PCR) and the Percentage of Complete Plan (PPC), resulting from low client engagement in routines, frequent plan changes, uncertainties related to accreditation, and local climate variations, questions the effectiveness of the weekly horizon approach for short-term scheduling in projects characterized by high complexity and variability, as addressed in this study. The analysis of the various stages developed over seven months addresses the research question proposed in this study, since that the adoption of daily schedules may be more efficient, as it better adjusts to the agility required by the client, considering the constant changes requested by all stakeholders and the uncertainties inherent to such infrastructure projects. It is also important to emphasize the need to seek mechanisms to engage the client throughout the project, as the active participation of all stakeholders is fundamental to ensuring the successful completion of the implementation journey.

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PRINCIPLES AND PRESCRIPTIONS FOR THE DEVELOPMENT AND IMPLEMENTATION OF PERFORMANCE DASHBOARDS

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ABSTRACT

Lean Production implementation in construction creates additional demands for Performance Measurement Systems (PMS), beyond what is typically suggested in general performance measurement literature. A PMS can support the implementation of Lean Production by evaluating the impacts of changes and providing information to guide organizations through this process. Some companies have adopted additional metrics during Lean implementation, but often limited to indicators related to the Last Planner System. Most companies still use traditional production control metrics, like cost, time deviation and project progress. There are opportunities for enhance performance measurement in Lean implementation programs, especially by incorporating leading indicators related to fundamental concepts and principles, such as pull production, work-in-progress, and continuous flow. Performance dashboards play a key role in achieving those objectives, facilitating information distribution across managerial levels, enhancing stakeholder communication, and encouraging participation. The main outcome of this investigation is a set of design principles (i.e. general recommendations that support decision-making in the design of a solution) and design prescriptions (i.e. suggested course of action for a given circumstance to achieve a certain effect) to guide the development and implementation of performance dashboards. This research is based on two empirical studies conducted in construction companies implementing lean production.

KEYWORDS

Dashboard, Performance Measurement, Indicator, Metric, Visual Management.

INTRODUCTION

The implementation of the Lean Production philosophy in construction creates additional demands for Performance Measurement Systems (PMS), in relation to what is suggested in general literature on performance measurement (PM) (Maskel, 1991). In fact, the literature suggests that the development of a PMS can play a major role in the introduction of any new managerial approaches, such as the Lean philosophy (Sarhan and Fox, 2013). PMS can support the implementation of Lean concepts and principles, by evaluating the impact of changes (Zanon et al., 2020) and providing information to guide organizations through this implementation process (Teh and Pang, 1999). A well-balanced PMS that contains a combination of leading and lagging indicators can contribute to cultural changes, reinforcing desired behaviours, values, and beliefs (Bourne et al., 2000; Naslund and Norrman, 2019). It also connects continuous improvement initiatives to strategic objectives, indicating

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opportunities for improvement or the need for changes (Kennerley and Neely, 2003). Most importantly, PMS can be used to highlight intermediate benefits, such as increased management capacity, reduced work-in-progress (WIP), faster identification of problems and a greater willingness to change (Crawford and Cox, 1990). It is important to highlight these improvements in order to maintain the motivation and support of different stakeholders in the change process, as some goals normally established in these programs, such as improving costs and time performance, require a long time to be achieved.

In general, construction companies face many problems related to PM: (1) most metrics are focused on results, being ineffective to support real-time decisions (Sarhan and Fox, 2013) (2) some PMS contain too many metrics, mostly focused on supporting rather than critical processes (Costa and Formoso, 2004); (3) the conception of PMS is often limited to the selection of isolated metrics (Beatham et al., 2004); and (4) PMS are poorly integrated into continuous improvement initiatives (Kennerley and Neely, 2003). Moreover, the inappropriate use of PMS is a critical factor in the failure of Lean implementation programmes in construction (Sarhan and Fox, 2013). Some still use traditional production control metrics, such as cost and time deviation, which are strongly based on the thermostat model; in that context control means to meet a predefined standard by correcting deviations, without putting much effort into identifying and eliminating the root causes of these deviations (Koskela and Howell, 2002). By contrast, PM in Lean Production systems should point out different types of problems and support a deep understanding of the main problems (Koskela and Howell, 2002), which can be considered as sources of creative tension for continuous improvement (Spear and Bowen, 1999). Moreover, PMS should provide information that will be used as a reference for improving and learning (Pavlov and Bourne, 2011).

Some companies often adopt additional metrics during the implementation of Lean Construction, but these are often limited to indicators related to the Last Planner System (LPS) (España et al., 2012; Sacks et al., 2017), such as PPC, effectiveness in constraint removal, and causes for the non-completion of plans. Therefore, there are opportunities for improving PM in Lean implementation programs, especially by using some leading indicators related to fundamental concepts and principles, such as pull production, WIP, and continuous flow. Performance Dashboards (PDs) also play a key role in the achievement of those objectives as they create information fields that support the distribution of information among different managerial levels (Waal and Counet, 2008), improve communication between stakeholders (Bititci et al., 2016), and foster people's participation (Greif, 1991). Through the combined analysis of indicators, PDs make it possible to carry out more consistent evaluations and scenario projections (Pauwels et al., 2009).

The research question that guided this investigation is "How to develop and implement PDs as a visual management device that supports Lean implementation in construction companies?". This investigation is focused on the performance of construction production systems which can be assessed considering different dimensions: efficiency, lead-time, quality, safety, environmental impact, etc. The main outcome of this investigation is a set of design principles and prescriptions that can provide guidance for the development and implementation of PDs. This study is part of a doctoral research study that aimed to propose a prescriptive knowledge framework that consists of a set of preliminary propositions for design principles and prescriptions for the development of PMS to support the implementation of the Lean philosophy in construction companies (Barth, 2023).

PERFORMANCE DASHBOARDS

The purpose of a PMS is to quantify the efficiency and effectiveness of the actions established (Neely et al., 2005). This objective can be analyzed in relation to the achievement of corporate strategies, in relation to improvement programs, or in terms of local improvements (Bourne et al., 2000). Besides, a PMS has the purpose of supporting decision-making and fostering learning and continuous improvement (Franco-Santos et al., 2007). In addition, PMS can contribute to increase process transparency, a core Lean principle, by making visible some invisible process attributes.

PDs are visual management artefacts that bring together important information to support the achievement of one or more objectives, consolidated and organized in a single interface, so that the information can be combined and quickly analysed by users (Yigitbasioglu and Velcu, 2012; Vilarinho et al., 2018). Visual devices are considered as a means for improving the performance of production systems (Valente et al., 2019), but it is through their effective use that this mechanism can achieve its full potential (Parry and Turner, 2006). As a visual device that supports PMS (Bititci et al., 2016; Eckerson, 2011), a PD has the functions of: (i) support decision-making process (DeBusk et al., 2003; Sarikaya et al., 2019); (ii) allow monitoring of projects toward goals and strategies (DeBusk et al., 2003; Cahyadi and Prananto, 2015); (iii) promote a flow of information supporting communication within the company (Pauwels et al., 2009; Vázquez-Ingelmo et al., 2020); (iv) facilitate prioritization (Yigitbasioglu and Velcu, 2012); (v) support improvement and learning (Parry and Turner, 2006; Cahyadi and Prananto, 2015; Vilarinho et al., 2018); and (vi) encourage the delivery of consistent information (Pauwels et al 2009; Yigitbasioglu and Velcu, 2012).

Like any visual management device, the development of a PD includes a visual and a non-visual portion (Nicolini, 2007). Developing a visual management system involves much more than just designing the device itself (Valente et al., 2019). Some authors use the image of an iceberg to illustrate that the visual device itself (PD) is the small portion of ice that arises above water, while most of the work remains submerged (Eckerson, 2011; Valente et al., 2019). In fact, Valente et al. (2019) suggests that the development of a visual management practice should start by the analysing of the process (identifying main problems, potential causes, and who is involved), then identify users' needs (which information is relevant and what is the purpose of the tool), integrate the visual device into the process or routine (whether it is necessary to perform coordination tasks and promote collaboration), and conclude by defining the attributes of the visual device (the only stage that involves visual work).

Knowing those attributes helps to design visual devices that are in line with the needs of users and the company (Cahyadi and Prananto, 2015). In terms of visual elements, PDs should communicate ideas clearly and effectively. The use of colours, signs, symbols, and graphs can support prioritisation, alerting the user to what needs more attention (Yigitbasioglu and Velcu, 2012). Visual elements should draw the user's attention to the content of the data, avoiding redundant or unnecessary information. Dynamic PDs can be used to show different levels of data granularity for users at different hierarchical levels (Cahyadi and Prananto, 2015). Lower-level PDs should provide additional information (details, views, and perspectives) that enable users to understand problems in more detail (Eckerson, 2011).

Regarding non-visual elements, it is important to devise a database that allows data to be properly organised in order to keep a historical report on the company (Cahyadi and Prananto, 2015). PDs must be integrated with this database so that users can access the information when necessary (Yigitbasioglu and Velcu, 2012). One important concern is the IT system to be used (Cahyadi and Prananto, 2015). Business Intelligence (BI) systems are often used to detail information and analyse scenarios (Eckerson, 2011). However, the wrong use of IT can lead to a loss of focus on what is most important and hinder the use of PDs (Nicolini, 2007).

Although PDs have become popular as management tools, the literature does not reflect this trend. Various publications aimed at professionals, such as articles in the business press (Miller and Cioffi, 2004) and textbooks (e.g., Eckerson, 2011 and Few, 2006) discuss the format for visualising information on PDs, how to monitor and measure business with PDs and how PDs should be designed. However, only a few studies on the use of PDs to support PM can be found in academic journals (e.g. Bititci et al., 2016; Cahyadi and Prananto, 2015; Pauwels et al., 2009; Vilarinho et al., 2018; Yigitbasioglu and Velcu, 2012), and even fewer studies related to construction companies. Only 5 papers discussing PDs have been found in the IGLC proceedings (Barth & Formoso, 2008; Wong et al., 2009; Bølviken et al., 2017; Amaral et al., 2020; Amaral et al., 2022), and only three of them deal directly with the development of PDs.

RESEARCH METHOD

Design Science Research (DSR) was the methodological approach adopted in this investigation. This approach has a prescriptive character, and consists of developing solution concepts, called "artefacts", to solve classes of problems (van Aken, 2004; Holmstrom and Ketokivi, 2009). The artefact proposed in this research consists of a set of *preliminary propositions for design principles and prescriptions* for the development and implementation of PDs. This research has explored the development of PMS to support Lean implementation programs, considering production management in construction companies as the application context. A *design prescription* can be defined as a suggested course of action for a given circumstance to achieve a certain effect (Ropohl, 1997), while *design principles* are categories of prescriptions, i.e., general recommendations that support decision-making in the design of a solution or artefact (Vaishnavi and Kuechler, 2007). The artefact was developed as the result of two empirical studies, through collaborative work with two companies. Therefore, the research method can be positioned as *action design research*, i.e., design, implementation, and evaluation of an artefact collaboratively with potential users (Sein et al., 2011).

The two companies (Company A and B) were chosen because both had been involved in long-term programmes for implementing Lean concepts and practices in production management and also due to their interest in improving their PMS. Company A, founded in 1922, is one of Brazil's largest retailers, specialised in the sale of apparel, and acts as a client for commercial building projects. Annually, this company has 40 to 60 small-sized, fast projects, most of them refurbishments. Company B, founded in 1965, is a large firm that develops and builds residential building projects for lower-, middle-, and upper middle-class markets in Chile. Power BI was the IT platform chosen by Company A to support PM and the use of PDs, while Company B managed their metrics by using MS Excel.

The two empirical studies were divided into three stages: understanding the problem in its context; developing and implementing the PMS; and analysing and evaluating the PMS. There were some iterations between those stages, as in any DSR project. Besides understanding the real problem, the first stage had the objective of raising awareness and formalise a plan to develop a PMS to support the Lean improvement programme. Development and implementation stage was made up of several cycles for the creation of the artefact: planning, action (gradual implementation of the artefact), evaluation and reflection, which are typical of the iterative cycles of action design research (Holmstrom and Ketokivi, 2009). In practice, there was no separation between development and implementation. Rather, there was an initial emphasis on the development (construction) of the PMS when it was being conceived. When the team felt that the prototype was ready to be tested, the emphasis shifted to action, evaluation, and reflection. What divided the development from the implementation was the decision by each of the companies to allocate an internal team in charge of implementing the PMS. The "analysis and evaluation" stage was carried out individually for each company, considering the prototype implemented.

At the beginning of each empirical study, a working group, named "PMS Group" was created, to support the development of this research. This group was made up of representatives from different departments of the organization and the first author of this paper. There were meetings every other week during the development of each empirical study. Occasionally, other company representatives were invited to support the discussion on specific topics.

The set of requirements for PMS proposed by Barth and Formoso (2021) was used as the basis for the development of the PMS Group's work. It began with the development of **maps of objectives and strategic actions** for the Lean implementation program in each company, with the aim of explaining and prioritizing implementation actions in the development of the PMS. From the elaboration of those maps, the PMS Group proceeded with defining the elements of PMS, which encompass not only the indicators themselves, but also PDs and cycles of learning and continuous improvement within the PMS. These cycles involve decision-making instances, reports, assigned responsibilities, frequency, and inputs and outputs for each stage. After several discussions among the PMS Group, a proposal of PMS emerged and was presented to representatives of each company. The proposal was refined based on the suggestions made from those professionals and moved on to implementation. The PMS Group continued to refine the PMS proposal along the implementation process.

In both empirical studies, the PDs were partially implemented due to time and human resource constraints on the part of the companies. At Company B, the **planning** and **operational PDs** were tested, but the proposed **tactical** and **strategic PDs** were presented to the company representatives in a mock-up format. At Company A, the **planning PD** was tested, and the **operational** and **tactical PDs** proposals were delivered in mock-up format. Strategic **PD** was not part of the research at Company A.

Multiple sources of evidence were used, including participant observation (LPS meetings, PMS Group meetings, and meetings with professionals from the companies studied), direct observation during visits to construction sites, individual and group interviews, document analysis, analysis of existing software tools and existing company databases. Table 1 summarises the time spent in each source of evidence for different research stages.

Table 1: Summary of hours spent in each source of evidence for different research stages.

Stage	Source of Evidence	Company A	Company B
Understanding	Participant observation	23,8hr	26,5hr
	Direct observation	6,0hr	13,5hr
	Individual and group interviews	12,5hr	5,0hr
Development and implementation	Participant observation	61,5hr	106,5hr
	Individual and group interviews	2,0hr	-
Analysis and evaluation	Participant observation	15,8hr	1,5hr
	Individual and group interviews	-	6,3hr
Total		121,5hr	159,3hr

RESULTS

MAPS FOR THE LEAN IMPLEMENTATION PROGRAM

The PMS Group developed maps of goals and strategic actions for the Lean implementation program, in the short, medium, and long term (Figure 1). Intermediate goals were defined based on long-term strategic goals, which were the point of departure to establish actions connected to the Lean implementation program. Those actions were distributed across seven managerial processes: (1) production, (2) quality, (3) design and BIM, (4) people, (5) costs, (6) supply chain, and (7) performance measurement and learning.

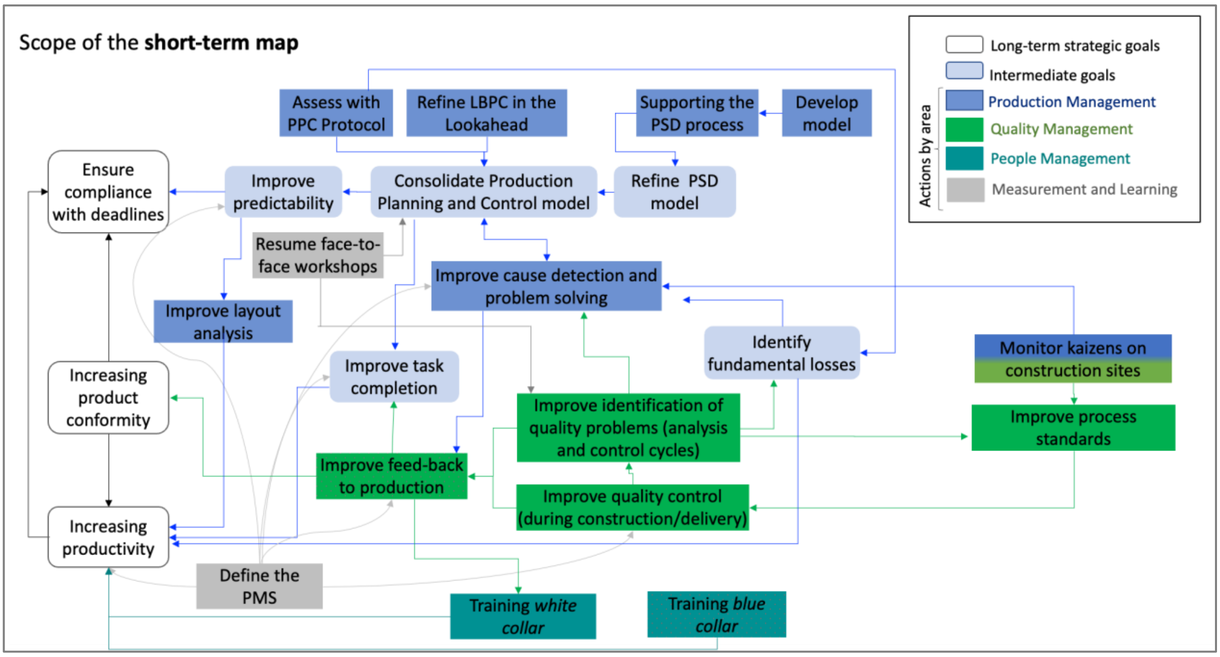

Figure 1: Example map of goals and strategic actions for the Lean program.

INCLUSION OF NEW INDICATORS

In an effort to assess the performance of production management, considering some core Lean principles, the PMS Group suggested the inclusion of new indicators. Adherence to planned batches, cycle time and tagging differentiated work packages (e.g. rework, non-planned work packages, etc.) were proposed to monitor WIP. Indicators were also proposed to assess the status of production, based on a tool named production status matrix, and to monitor the rhythm of activities being carried out (control of batch completion rhythm) (Barth and Formoso, 2021), as well as metrics for projecting the conclusion of the construction stage.

The planned batch adherence graph compares the planned start and finish of each batch with the actual start and finish. This graph also makes a projection of the expected start and finish dates on the basis of the data obtained on the same batch, allowing improvement actions to be taken in time to change unwanted results. The cycle time graph complements this information, in which variations can be monitored. Tagging differentiated work packages graph is a stratification of the work packages planned and executed in the short-term plan, which are labelled according to their nature (informal activities, rework activities, percentage of backlog activities that are executed, etc.). A high volume of informal work indicates that part of the workforce capacity is being planned informally and may be being used to execute activities that do not add value.

The development and implementation of these indicators was carried out in collaboration with its representatives of each company, in pilot projects. During those pilot projects, the need to develop a database to organize the information generated by the PMS was identified. The PMS Group was in charge of developing a database by using MS Excel spreadsheets, seeking to automate data collection based on existing controls. It is important to emphasise that most of the indicators proposed in this research work can be obtained from a small number of control tools, as there was a concern with limiting the data collection effort. Adherence to planned batches, cycle time, control of batch completion rhythm, project completion projection can be obtained from the status control matrix. Differentiated work packages can be identified in short-term plans.

PERFORMANCE DASHBOARDS

Based on the definition of new indicators and the construction of the database, each PMS Group devised a set of **planning PDs**, which evolved throughout discussions with representatives of different areas of the company. PDs were developed for the operational, tactical, and strategic levels. Moreover, some specific PDs were developed according to requirements of each company. Company A, for instance, chose to use a PD that grouped together short- and medium-term SLP indicators, while Company B chose to use a PD for each planning horizon. In Company B, in addition to the typical LPS indicators, the medium-term PD had a strong emphasis on location-based planning and control (LBPC) indicators (adherence to planned batches and cycle time). Due to space limitations, only operational and tactical PDs developed for Company B are presented in this paper. A complete description of all PDs is presented in Barth (2023).

The **operational PD** (Figure 2) groups together the indicators of one project divided into five zones: cost, labour efficiency, quality, project deadline and planning. A second interface of the operational PD also contains graphs of LBPC indicators for some processes considered critical to the projects. Moreover, the **production status matrix** is presented as part of the operational PD in company B (Figure 3), where it is possible to monitor fully completed batches, WIP, rework and interrupted work.

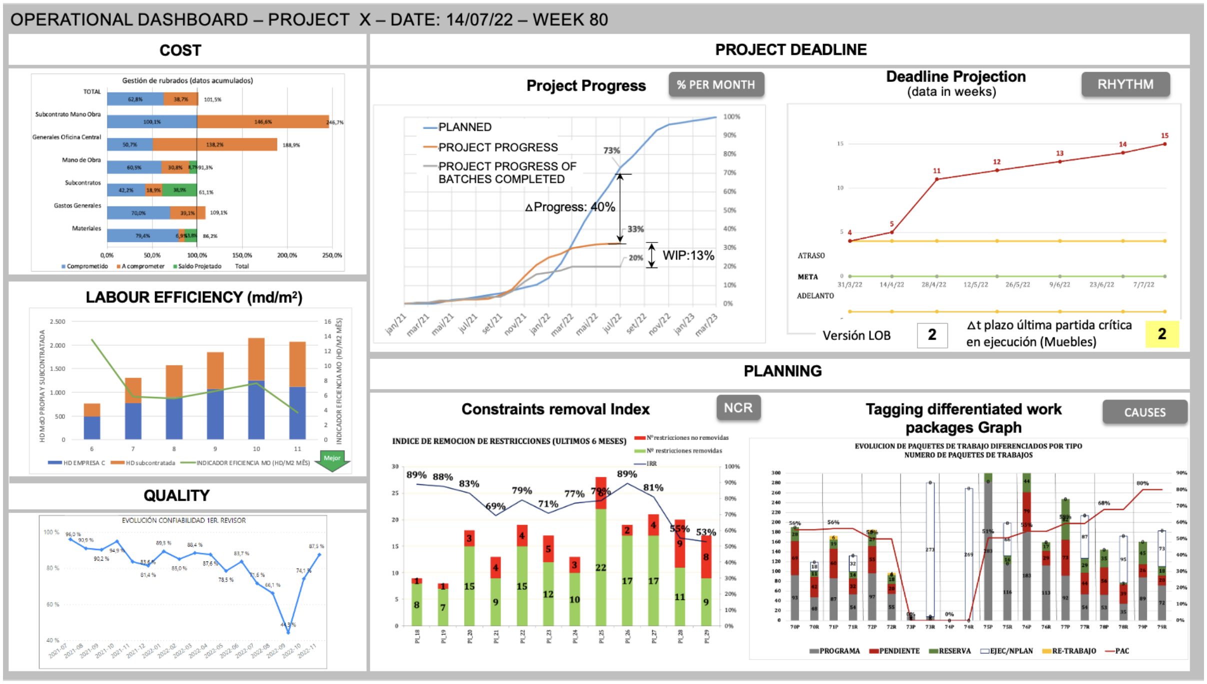

Figure 2: Example of Operational PD for residential building project.

LOCATION HIERARCHY		ACTIVITIES																													
IST LEVEL BATCHES (FLOORS)	2ND LEVEL BATCHES (APARTMENTS)	ACTIVITY 1	ACTIVITY 2	ACTIVITY 3	ACTIVITY 4	ACTIVITY 5	ACTIVITY 6	ACTIVITY 7	ACTIVITY 8	ACTIVITY 9	ACTIVITY 10	ACTIVITY 11	ACTIVITY 12	ACTIVITY 13	ACTIVITY 14	ACTIVITY 15	ACTIVITY 16	ACTIVITY 17	ACTIVITY 18	ACTIVITY 19	ACTIVITY 20	ACTIVITY 21	ACTIVITY 22	ACTIVITY 23	ACTIVITY 24	ACTIVITY 25	ACTIVITY 26	ACTIVITY 27	ACTIVITY 28	ACTIVITY 29	ACTIVITY 30
6	7	T	T	T	T	T	T	T	T	T	T	T																			
	6	T	T	T	T	T	T	T	T	T	T	T																			
	5	T	T	R	T	T	T	T	T	T	T	T		P																	
	4	T	T	T	T	T	T	D	T	T	T	T		P																	
	3	T	T	T	T	T	T	T	T	T	T	T		D																	
	1	T	T	T	T	T	T	T	T	T	T	T		P																	
	2	T	T	T	T	T	T	T	T	T	T	T		P																	
5	7	T	T	T	T	T	T	T	D	T	T	T	D	T	T	D															
	6	T	T	T	T	T	T	T	R	T	T	T	T	T	P	D															
	5	T	T	T	T	T	T	T	T	T	T	T	T	D	T	T	P														
	4	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	P														
	3	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	P														
	1	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	P														
	2	T	T	T	T	T	T	T	T	T	T	T	T	R	T	D	P														

Figure 3: Extract of the Production Status Matrix: part of the operational PD.

The tactical PD (Figure 4) enables comparisons between projects to be made, supporting meetings involving the whole production management staff, in which information is exchanged between site managers from different projects and the top production manager. The **tactical PD** was divided into six areas: cost, project progress, project duration, quality, labour productivity and safety management. The **strategic PD** was divided into four zones: planning (including time deviation, and project progress with and without batch completion), cost (cost deviation), quality conformance, and labour utilisation metrics (outcomes measured by area and monetary units).

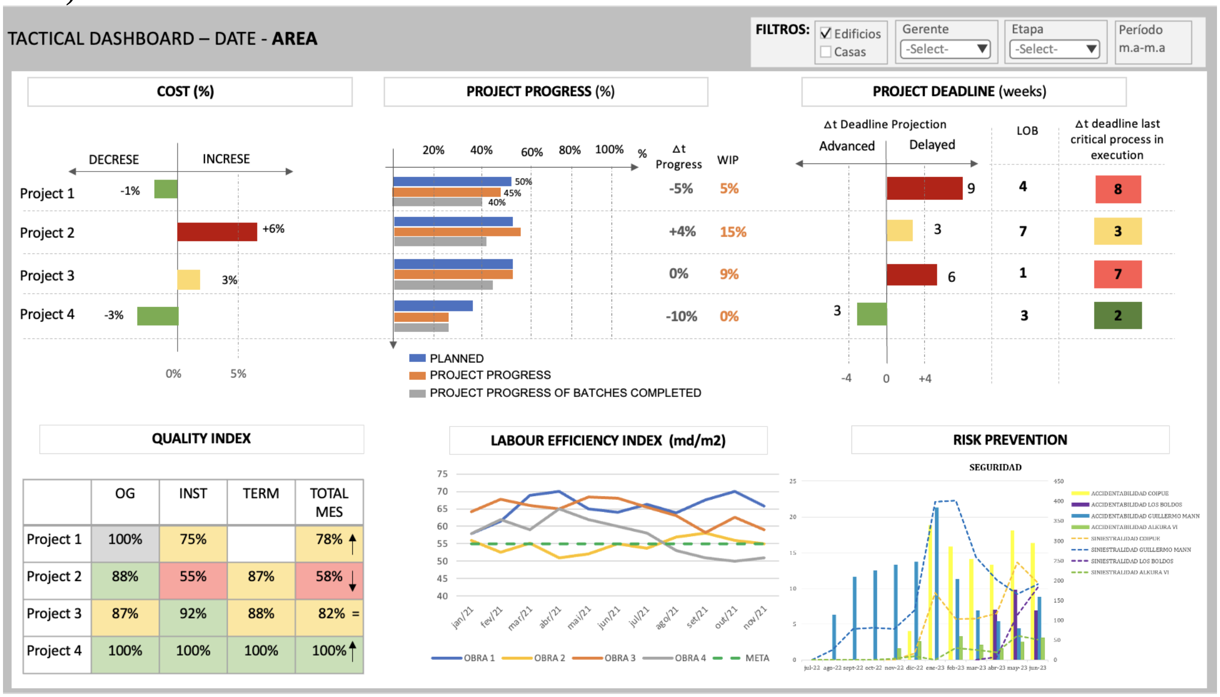

Figure 4: Example of Tactical PD for residential building project.

ESTABLISHMENT OF DECISION-MAKING INSTANCES

Some decision-making formal instances were defined in order to formally define control points and learning cycles for continuous improvement. Those control points must be regarded as moments for analysis and reflection, based on indicators connected via PDs. In fact, some regular meetings that already existed in the companies were adapted to include PD analysis. In Company B, the short-term planning PD was used to discuss the results at the weekly commitment planning meeting, whereas the medium-term planning PD was used in look-ahead meetings every fortnight. The operational PD was connected to a monthly meeting between the Site Manager and the Project Manager, named operational meeting. The tactical PD was used for a monthly meeting between each Project Manager and the company Overall Construction Manager, to present the results of the projects under the responsibility of the former. In addition, a lessons-learned meeting was held three times a year, in which Project Managers presented good practices and improvement opportunities identified in the projects completed during the period.

NON-VISUAL ELEMENTS

For each proposed PD, the PMS Group defined a person in charge for compiling the indicators and generating the reports. This is concern with the non-visual part of the PMS, that is necessary to generate an update version of the visual device (Valente et al., 2019). The flow of information generated by the PDs had to be made clear, to make reliable connections between operational, tactical, and strategic PDs. In this flow, the goals are broken down from the strategic level, through the tactical PD, up to the operational level. This allows a user at the strategic level to access detailed information by using the tactical and operational PDs, when necessary, as suggested by Eckerson (2011) and Cahyadi and Prananto (2015). At the operational level, goals and feedback are also disseminated among the construction site teams. The information generated by PM at the operational level, feeds back into the tactical and strategic levels, creating a bottom-up and top-down flow, as suggested by Bhasin (2012).

DESIGN PRINCIPLES AND PRESCRIPTIONS

Based on the literature review and the two empirical studies, five design principles and 8 prescriptions for developing and implementing PDs to support production management in construction companies was proposed. Some of the observed practices involved in the implementation of PMSs of the two empirical studies are presented as examples of the application of the set of principles and prescriptions.

Principle 1: Include a set of leading and lagging indicators that complement each other and help overcoming limitations of individual metrics.

Prescription: Use combined controls to anticipate future results. Practice identified: analysis of project progress (lagging indicators) combined with plan reliability (PPC), status of WIP and delivery projections (leading indicators) and rhythm curves.

Principle 2: Promote improvement and learning.

Prescription: Identify emergent connections between indicators as a way of learning. Practice identified: the users of the PD identified that the higher the degree of completeness of batches, the better the quality of the final product, considering that fewer assessment and finishing tasks needs to be carried out.

Principle 3: Support decision-making by providing meaningful and timely feedback to users.

Prescription: Identify the information needs of different stakeholders. The choice of indicators and the way they are displayed depend on the specific needs and knowledge of each user (e.g., managers, workers, and subcontractors). *Practice identified:* PDs were designed to include both the information required by their direct users and the information considered important by those who assess performance at different managerial levels.

Prescription: *Use PDs as visual management devices*. Visual devices must be designed for users and made available so that the necessary information is accessible (Valente et al., 2017). *Practice identified*: the use of dashboards to monitor production status, giving visibility to the situation in each production batch, and at the same time providing data on cycle time, WIP, and task completeness.

Prescription: *Connect PD analyses to a decision-making instance. Practice identified*: PDs need to be connected to formal meetings (e.g. LPS meetings), otherwise they are not systematically used. Note that this is a requirement, but simply connecting PDs to instances of analysis and reflection does not guarantee that they will be used for decision-making. The combination of different design principles is what makes it possible to achieve the desired effects.

Prescription: *Use IT to develop PDs and automate data collection and processing, and define the human resources for implementation.* IT helps to reduce the time and effort needed to collect and process data (Bhasin, 2012), but it is also important to assign tasks to those responsible for conducting this process. *Practice identified:* use of business intelligence software or spreadsheets to introduce automation in the generation of PDs. This prescription was partially implemented in the two empirical studies.

Principle 4: Show production status.

Prescription: Monitor production status by using the status control matrix. Monitoring the system status makes it possible to apply pull production, defined by Hopp and Spearman (1996) as authorising the release of work based on the status of the system, in order to avoid WIP. Practice identified: Use of leading indicators and visual devices (production status matrix) to monitor production status.

Principle 5: Provide information to deal with variability that cannot be removed.

Prescription: Give visibility to processes and results. Construction projects, like other complex systems, are characterised by a high degree of variability that cannot be fully removed (Williams, 1999). The PMS must provide information that makes complexity visible so that people can learn from information about anomalies and informal practices. *Practices identified:* Measurement of informal practices, represented in the differentiated work packages chart at the operational PD; making explicit non-visual work in the process of generating PDs and the staff responsible for that.

Some of the proposed prescriptions are related to the conception of PD, whereas others are concerned with their implementation, such as "identify emergent connections between indicators as a way of learning", "use PD as visual management devices", and "connect PD analyses to a decision-making instance".

CONCLUSIONS

The main outcome of this research work is a set of 5 design principles and 8 prescriptions for the development and implementation of PDs to support production management in construction companies. Those PDs have played an important role in the Lean implementation programs of the companies involved in this research study, as they have made the use of PM more systematic, and introduced a number of metrics related to Lean concepts, which are not usually adopted in construction companies. The implementation of the PDs required explicit planning of the non-visual activities needed to generate the necessary metrics, as well as the establishment of formal meetings for analysis and reflection. The use of these visual management devices made it possible to explore connections between the indicators, resulting in analyses more consistent with the reality of the projects. The use of PDs was promoted by connecting them to decision-making instances (LPS and other formal meetings), which encouraged the frequent updating of the indicators that were part of the PMS. In addition, the PDs made it possible to make the flow of information between the different hierarchical levels transparent.

Further work is necessary in the assessment and refinement of the proposed knowledge framework (design principles, prescriptions, and practices) so that it can be widely used in the implementation of Lean Construction. This is considered the main limitation of the proposed artefact.

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PROPOSAL FOR A DEADLINE DEVIATION INDEX BASED ON LINE OF BALANCE AND RHYTHM DEVIATION DATA

Marcus P. Sterzi[1] and Fabiana Bonesi[2]

ABSTRACT

The line of balance (LOB) plays an important role in the implementation of Location-Based Planning and Control (LBPC), inducing most activities to be carried out at only one production rate and enabling the established deadlines to be met. Monitoring deviations from these deadlines is essential for project success, particularly in the construction industry. Rhythm deviation, an indicator rooted in Lean Construction principles and closely linked to LBPC, reveals the interference of critical tasks with other project activities and enables the analysis of how rhythm deviation of critical activities affects the project's deadline deviation. Analysing deadlines using the LOB technique in combination with rhythm deviation helps identify which activities are associated with project delays and advancements, allowing for corrective actions to improve workflow. However, this topic receives limited attention in the literature. The aim of this research is to propose a Deadline Deviation Index for monitoring and projecting delays and advancements in construction projects based on LOB and rhythm deviation data. This paper adopts an Action-Research methodology within a Case Study Approach. It presents findings from a case study involving 12 residential building projects that utilized location-based methods for scheduling and control, alongside rhythm deviation for monitoring critical processes. The results underscore how integrating the LOB technique with rhythm deviation enhances workflow and deadline management, thereby refining the sector's ability to estimate delays and advancements.

KEYWORDS

Location-Based Planning and Control (LBPC), Takt planning (TP), Line-of-Balance, Rhythm Deviation, Deadline Deviation.

INTRODUCTION

Traditionally, companies in the construction industry have relied on physical progress (a metric based on the Earned Value Management) as an indicator to measure project performance and progress (in terms of the volume of work carried out) over time (Kim & Ballard, 2002). However, result indicators, such as physical progress, tend to be reactive, focusing on the past and inefficient for supporting decision-making (Sarhan and Fox, 2013). Additionally, this indicator does not reflect time deviation, or a deadline projection based on Lean principles. Analysing the performance and progress of a project based on Lean principles should consider a set of factors: causes of problems, waste elimination, continuous improvement, zero defects,

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just-in-time, multifunctional teams, variability, and cycle time of critical processes (Karlsson & Åhlstrom, 1996; Koskela, 1992). In this way, process indicators can enhance the reliability of result indicators, as they focus on assessing performance at intermediate stages while providing information during execution to identify possible losses and problems (Braglia et al., 2019).

In this context, LBPC can address the shortcomings of traditional models. LBPC can be defined as a planning and control approach that allows for: (i) identifying critical construction processes in a time-location-context relationship; (ii) explicitly managing workflows on-site; (iii) supporting decision-making at different planning levels (Lucko et al., 2014). LBPC involves a set of techniques, including the line of balance (LOB), which represents the master plan (Ballard & Tommelein, 2021).

Adopting the Location Breakdown Structure (Kenley & Seppänen, 2010) and applying the LOB technique enables a better understanding of a project composed of repetitive activities because it allows for adjusting activities' production rates. It facilitates a smooth and efficient flow of resources and requires less time and effort to produce than network schedules (Arditi & Albulak, 1986). The LOB technique provides a clear overview of the project's overall status by quantitatively representing the cumulative completions of activities associated with a planned number at a given time (Suhail & Neale, 1994). It graphically reveals any imbalances that suggest a deviation from the plan due to the uneven progress of activities, enabling management to focus on assessing the deviation quantitatively (Khisty, 1970). The major benefits of the LOB are that several concepts related to Lean Production Philosophy are explicitly used, such as batch size, work-in-progress, cycle time, and the rhythm of processes (Schramm et al., 2006).

The rhythm deviation of critical activities is a performance indicator that incorporates lean concepts, strongly related to LBPC, specifically to Takt Time Planning (TTP) (Barth et al., 2019). According to Barth et al. (2019), the rhythm deviation control represents a form of critical process control, considering only fully accomplished tasks (batches). Each team must complete their work in a specified batch within a certain amount of time, also called takt time (Frandson et al., 2013; 2014). In this context, monitoring the rhythms of critical activities and their impacts on other activities can provide the trend of completing the last critical process (Barth et al., 2019), and consequently, the deadline projection.

Studies on LBPC (Kala et al., 2012; Seppänen et al., 2013; Frandson et al., 2013; 2014) have not extensively explored integrating LOB technique with performance indicators, such as the rhythm deviation of critical processes, to analyse deadline control in construction projects. Managing workflow through LOB technique alongside analysing rhythm deviations has the potential to proactively control delays and overruns in a production planning and control system based on Lean principles. So, this research aims to propose the application of a Deadline Deviation Index for monitoring delays and advancements in construction projects, as well as to establish a graphical representation indicating deadlines based on LOB and rhythm deviation data.

CASE STUDY

With 60 years of history, the company under study is currently the largest real estate group in Chile and one of the largest in South America. It is a fully integrated company that acquires land, designs, and constructs projects, and sells the end products. Most of residential building projects delivered by the company exhibit a high degree of repetitiveness, such as horizontal housing estates and vertical buildings. This company operates in 13 out of the 15 regions of Chile and sells more than 3,000 units per year. The company initiated a significant transformation process that resulted in a larger corporation with different brands focusing on distinct customer segments.

PREVIOUS RESEARCH AND PRACTICE

A Lean Implementation Program has been carried out in the company with the support of a consultancy firm and a research institution, both from Brazil. Previous research (Barth et al. 2019; Barth et al. 2020) reported the implementation process and presents a preliminary assessment of the impacts of the Lean implementation program.

RESEARCH METHOD

The methodological approach adopted in this investigation was Action-Research, based on a Case Study Approach. Action-Research is an approach that allows the active participation of the researcher in the observed phenomenon (Thiollent, 2005). Thiollent (2005) defines action research as a specific type of empirical-based research that is conceived and carried out through action in which researchers and some participants in the situation or problem are involved cooperatively. According to Dick (1993), action research has two objectives: action to bring about change in organizations and research to increase understanding of the topic under study.

A Lean Implementation Program was conducted within the company with the assistance of a consultancy firm. The researchers, who also acted as consultants and facilitators, were actively engaged in executing interventions or modifications based on the research findings, collaborating closely with company stakeholders to drive change. Additionally, the researchers maintained a continuous process of reflection to refine the research methodology and gain deeper insights into the identified challenges and potential solutions. Lastly, they disseminated the findings of the action research to pertinent employees, thereby enriching the collective knowledge base and potentially catalysing further initiatives.

The proposed Deadline Deviation Index has been tested and refined in 12 projects undertaken by the company. Ten out of the twelve projects had implemented Last Planner System (LPS) and LBPC, as well as the rhythm deviation of critical activities for analysis of the project deadline. Multiple sources of evidence were utilized in each project: interviews with site engineers and project managers, participant observations in (LPS) meetings, direct observations of the construction site, and analysis of planning documents.

The steps used to implement this Index are as follows: (a) train individuals to comprehend the significance of measuring rhythm deviation based on Lean concepts and principles; (b) designate responsibility for data collection and analysis; (c) create a rhythm deviation matrix and charts; (d) gather data; (e) utilize visual aids to disseminate information; (f) generate the Deadline Deviation Index; (g) analyse data, discuss rhythm deviations, deadline deviations, and establish corrective actions; and (h) report to various hierarchical levels within the company.

DISCUSSION AND RESULTS

LINE OF BALANCE DELIVERY STAGES

One of the fundamental stages in the development of LOB is the identification of Delivery Stages or milestones of the construction project. These Delivery Stages play a crucial role in referencing and predicting potential project delays or advancements in relation to the existing Master Plan. Therefore, the LOB model implemented in the studies must effectively demonstrate the different stages of delivery. The first delivery stage was associated with rough construction; the second delivery stage involved raw finishes. The third delivery stage addressed punch list items, and the fourth delivery stage focused on client delivery. The Figure 1 illustrates the workflows and delivery stages (both partial and final) using the LOB technique.

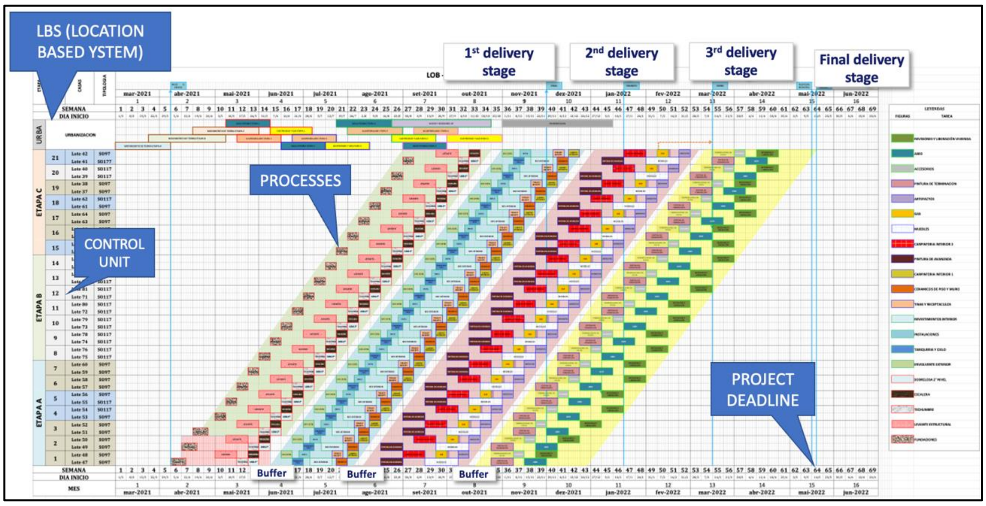

Figure 1: Example of Definition of workflows (whole project) and Delivery Stages (partial and final) through the LOB technique

RHYTHM DEVIATION FOR CRITICAL PROCESSES

The LOB developed for the construction projects under study, along with their respective delivery stages, provided the data that served as input for the creation of rhythm deviation control charts. In this context, planned and real completion dates, as well as the corresponding quantity of planned and real batches completed within a specific period, were compiled into an integrated database that allowed for the generation of rhythm deviation control charts. The rhythm deviation encourages the entire team, including subcontractors, to prioritize batch completion alongside integrated quality control measures. In this study, all 12 residential construction projects analysed applied the rhythm deviation in monitoring critical activities.

Figure 2 illustrates the rhythm deviation chart developed for a critical activity. The rhythm deviation is represented by the difference (in weeks) between the planned date in the current LOB and the real execution date of the critical activity. This allows monitoring the actual pace of the activity in relation to the planned pace in the current LOB, as well as projecting the execution pace until the completion of the activity based on resource analysis and constraints of each critical activity. The data enable the analysis of strategies and resources needed to reduce pace deviation in future weeks.

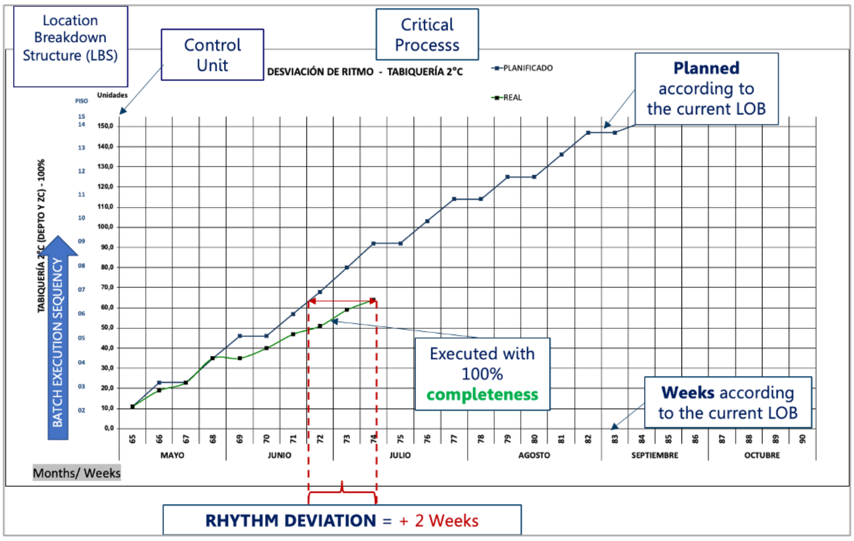

Figure 2: Example of a chart to monitor the rhythm deviation of one critical construction process.

Figure 3 illustrates the integrated rhythm deviation chart of different critical activities, enabling monitoring of the effects that critical tasks have on other activities. The following analyses can be conducted: (a) checking for possible clashes between critical activities based on real paces and projections, (b) analysing the paces of projections in a consolidated manner, and (c) examining the impact of real paces and projections on the intermediate plan. Considering the pivotal role many of these activities play in production, both in terms of time and cost, any adjustment in the pace of a process line justifies a comprehensive analysis of its impact on others.

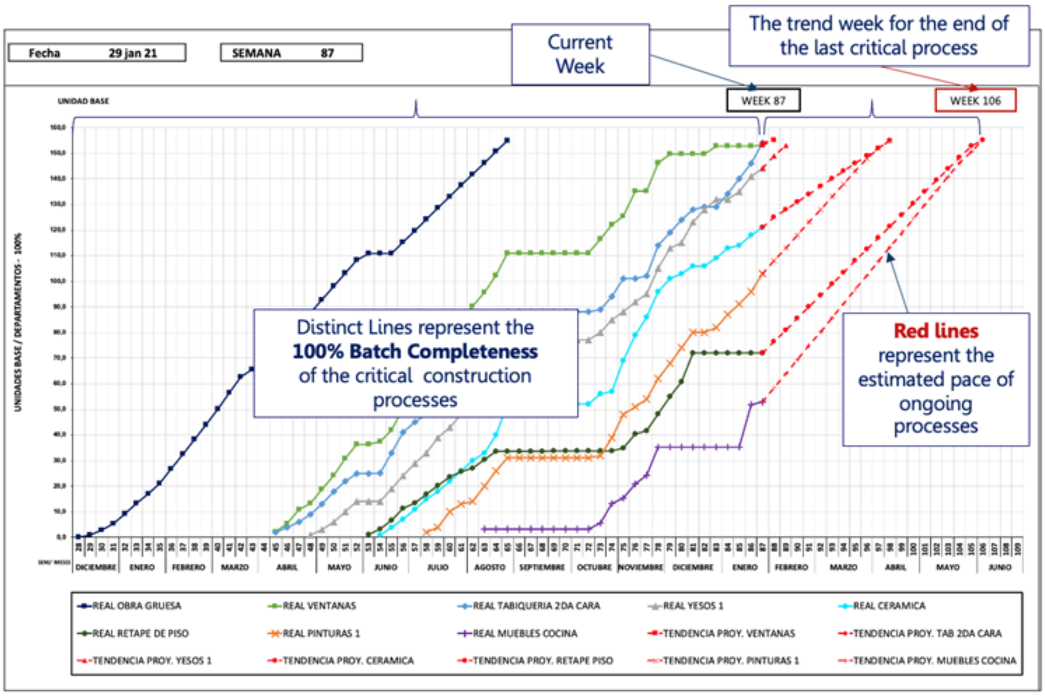

Figure 3: Example of an integrated chart to monitor the rhythm of different critical construction processes.

DEADLINE DEVIATION INDEX AND PROJECTION CHARTS

The data generated by the rhythm deviation provided the necessary information to generate the Deadline Deviation Index. In this context, data can be collected weekly by the construction site manager or by someone experienced in planning and control, simultaneously with the weekly plan data, to optimize data collection and processing. Both individual and integrated rhythm deviation charts facilitate data visualization for calculating the Deadline Deviation Index.

Deadline Deviation Index is calculated by the ratio of the sum of weighted delays and advances in critical processes (measured in weeks) to the total duration of critical activities on site, according to the formula outlined in Equation 1.

$$DD = \frac{\left[\sum \text{Number Weeks late X processes duration} - \sum \text{Number Weeks in advance X processes duration}\right]}{\sum \text{processes duration}}$$

Equation 1: Deadline Deviation Index Formula.

Lower and upper limit charts were employed to depict and monitor the Deadline Deviation index over the course of the project. These charts enable the establishment of delay or advancement thresholds tailored to each delivery stage. In the case of the company under study, upper and lower limits of 4 weeks were set as triggers to prompt the formulation of an action plan or adjustment of strategy within the lookahead planning process. This proactive approach aims to primarily address project delays identified through this indicator. Figure 4 illustrates an example of a Deadline Deviation Index Chart utilized during performance management meetings.

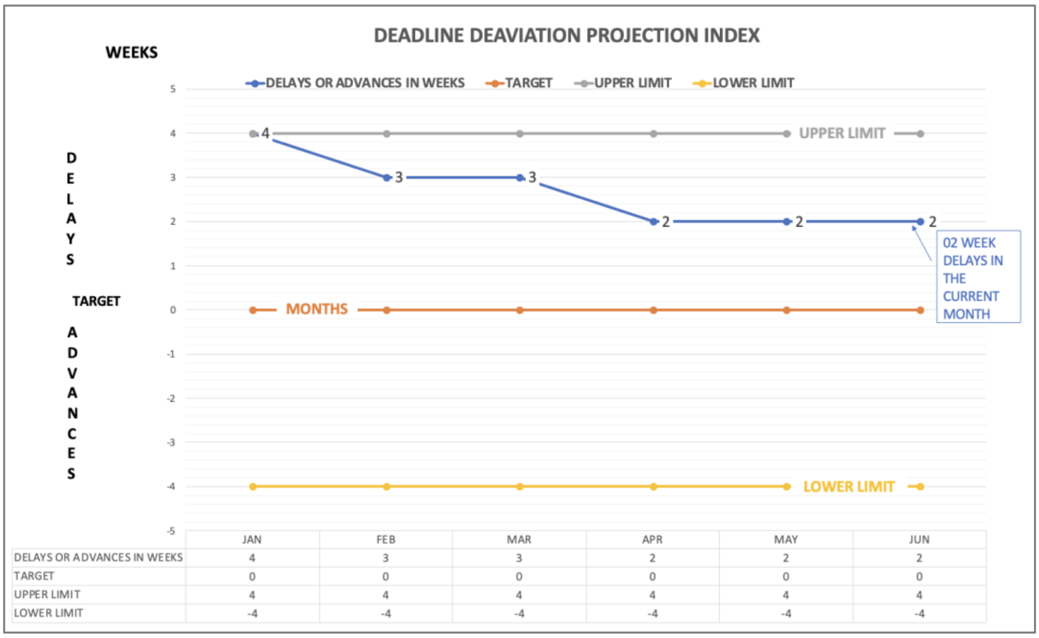

Figure 4: Deadline Deviation Index Chart applied in performance management meetings (example)

INDEX APPLICATION PROCESS

Throughout this study, data regarding the Deadline Deviation Index was examined across 12 construction projects. This indicator was precisely captured at the time of each delivery stages to visualize its progression throughout each project. This facilitated a flow of information supporting decision-making for both the project managers and the group of researchers, aiming to address identified delays and redirect the project's trajectory.

The implementation of the Deadline Deviation Index necessitates prior adoption of the LOB Technique and rhythm deviation charts. Initiating this tool involves training relevant personnel, emphasizing the advantages of maintaining accurate data and ensuring complete batch execution. The application process encompasses data collection, processing, and analysis.

Data Collection: Completion data should be gathered weekly by a qualified professional to assess task fulfillment and quality. This assessment can be synchronized with weekly task monitoring to minimize additional time for data processing. Recorded data should feed into a control table to generate rhythm deviation charts.

Data Processing: Processing involves data storage, visualization, and dissemination. Processed data yields actionable insights for decision-making across various analysis scenarios. Information should be presented in an accessible format for all stakeholders. Indicators and charts derived from rhythm deviations support analytical processes.

Analysis of Data and Information: Analysis of rhythm deviations primarily aligns with medium-term planning, although time projection analyses occur during specific meetings to assess project performance. For residential projects exceeding 12 months (typical in this study's sample), performance review meetings are held monthly. Thus, it's advisable to conduct time projection analyses more frequently to ensure timely intervention and course correction.

INFORMATION AND DATA ANALYSIS

An initial evaluation of the implementation of the Deadline Deviation Index was conducted across the 12 projects under study. This assessment utilized four distinct classifications based on the stage of Lean implementation within each project: Prior Lean implementation (PL), Early Lean implementation (EL), Basic Lean (BL) practices implementation, and Initial Stability (IS) achieved with Lean. Figure 5 illustrates the outcomes for each project categorized under one of these four implementation stages.

Furthermore, for this analysis, Deadline Deviation data was collected at the four distinct stages of project delivery. Since the projects did not occur simultaneously, it was necessary to establish a comparable timeframe for this evaluation. Projects 1 and 2 were analysed prior to the introduction of Lean practices within the company. Projects 3 and 4 were in the initial stages of implementing lean practices. In contrast, projects 5, 6, 7, 8, and 9 fully engaged in the implementation of fundamental Lean practices. Projects 10, 11, and 12 can be considered the most advanced in terms of Lean implementation compared to the others, having achieved an initial level of stability. Figure 5 displays the outcomes of the Deadline Deviation Index across four distinct delivery stages for 12 projects.

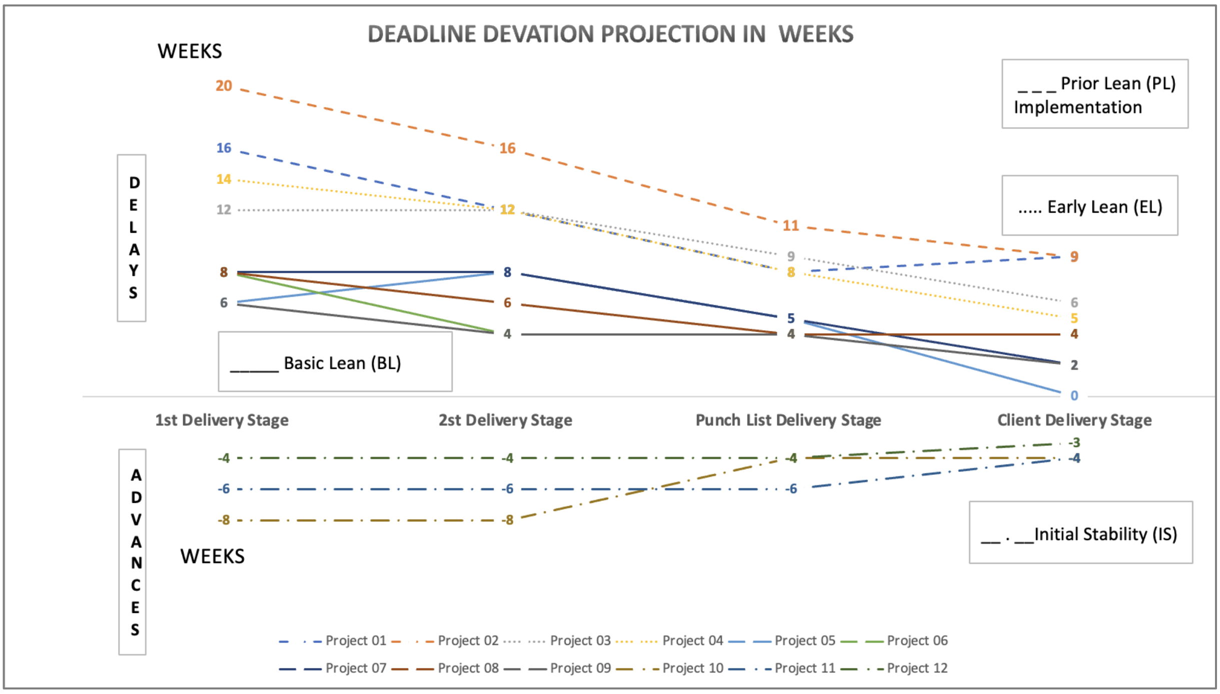

Figure 5: Results of Deadline Deviation Index during 4 different deliveries stages, for 12 projects.

From the analysis of the chart presented in Figure 5, it is noticed that the Deadline Deviation data exhibit greater variability across different delivery stages for projects executed before the implementation of Lean practices in the company and for projects in the early stages of Lean implementation, such as Projects 1, 2, 3, and 4.

As the Lean implementation stage progresses, there is a decrease in variability in the Deadline Deviation data across different delivery stages. For Projects 5, 6, 7, 8, and 9, which were fully engaged in implementing Lean practices, the variation in the Deadline Deviation index is lower than for Projects 1, 2, 3, and 4.

Finally, the Deadline Deviation data remains more stable across different delivery stages for Projects 10, 11, and 12, i.e., for projects in a more advanced stage of Lean implementation.

In this context, it is observed that for projects further advanced in Lean implementation practices, the Deadline Deviation index obtained from LOB data and rhythm deviation data provides a fairly accurate projection of the real project completion, regardless of the project stage. The indicator, therefore, proves effective in monitoring delays and advancements in construction projects, reflecting the Deadline Deviation based on Lean principles.

CONCLUSIONS

The research methodology employs an Action-Research approach within a Case Study framework, demonstrating the practical application of the proposed Index in real-world construction projects. This research has proposed and tested an index that may be used to monitoring and projecting delays and advancements of construction projects that integrates the Line of Balance technique with rhythm deviation analysis. This index represents an approach and, like other indexes, should not be analysed in isolation. Combining it with other information such as cycle time, batch adherence, batch completeness index, and percentage of plans completed (PPC) provides a more accurate project status.

LBPC is a critical aspect of Lean construction, allowing for the explicit management of workflows on-site and supporting decision-making at different planning levels. By integrating LBPC with the proposed Deadline Deviation Index, the paper contributes to advancing knowledge in the field of Lean construction management.

The findings of this study expose on the effective utilization of 12 residential building projects management tools, notably the Line of Balance technique, Rhythm Deviation control, and the Deadline Deviation Index, within construction projects. The Line of Balance technique, when coupled with the identification of delivery stages, serves as a valuable predictive tool for managing project timelines and mitigating delays. Likewise, Rhythm Deviation control, integrating lean principles, emphasizes the completion of tasks within specified timeframes, fostering a culture of efficiency and quality across project teams.

The findings of this study expose on the effective utilization of various project management tools, notably the Line of Balance technique, Rhythm Deviation control, and the Deadline Deviation Index, within construction projects. The Line of Balance technique, when coupled with the identification of delivery stages, serves as a valuable predictive tool for managing project timelines and mitigating delays. Likewise, Rhythm Deviation control, integrating lean principles, emphasizes the completion of tasks within specified timeframes, fostering a culture of efficiency and quality across project teams.

The implementation of the Deadline Deviation Index, alongside these techniques, offers a comprehensive approach to performance monitoring and decision-making. By systematically gathering and analysing data at different project delivery stages, stakeholders can identify trends, anticipate challenges, and proactively address deviations from planned timelines. The paper introduces practical tools such as lower and upper limit charts, coupled with the Index, provide actionable insights for timely intervention, strategy adjustments, performance monitoring and decision-making thereby enhancing overall project management effectiveness.

The analysis of research results further highlights the importance of Lean implementation stages in influencing project performance. Projects exhibiting Initial Stability with Lean practices demonstrate improved resilience to timeline deviations compared to those at earlier stages of implementation. This underscores the significance of continuous improvement efforts and organizational learning in optimizing project outcomes.

Future studies could explore the application of the proposed tool in non-repetitive projects, to further expand knowledge and understanding in the field of Lean construction management. This aspect contributes to the ongoing discourse on continuous improvement and innovation in construction practices.

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COLLABORATIVE PLANNING OF SUBCONTRACTORS USING THE LAST PLANNER SYSTEM AND BIM: A CASE STUDY ON A GAS SUBCONTRACTOR IN REPETITIVE HOUSING PROJECTS

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ABSTRACT

The objective of this study is to adapt the Last Planner System (LPS) for managing subcontractors in natural gas installations within repetitive housing projects, using BIM technology for enhanced modeling and efficiency. Our methodology was applied to a large-scale, multi-family, low-cost housing project in Lima, Peru. Through this application, we achieved high Percent Plan Complete (PPC) values and improved collaborative planning practices. This paper makes distinct contributions to the subcontractor management literature: (1) it demonstrates the practical integration of LPS with BIM to streamline subcontractor activities in a real-world setting; (2) it offers a novel approach for determining optimal Takt Time Planning for daily and weekly schedules, enhancing the predictability and reliability of subcontractor work; and (3) lessons learned from the implementation provide a roadmap that can be adapted to other subcontractor management scenarios.

KEYWORDS

Last Planner System, subcontractor management, gas facilities management, continuous improvement, BIM.

INTRODUCTION

The efficient management of subcontractors turns into a challenge in contracts with fixed prices and very short terms. Non-conformances due to poor deliverables are common, generating delays and cost overruns for all parties involved, especially for the main contractor (Akintan and Morledge, 2013). It is a very common practice in construction projects that the main contractor contracts subcontractors to transfer cost and deadline risks to it with the aim of not losing money. However, it is still necessary to analyze the relationship of subcontractors and contractors to improve their performance (Ribeiro et al., 2017). The Last Planner System (LPS)

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is a production system that shows multiple workflows, identify deficiencies or wastes and promote continuous improvement (Aslam et al, 2020). In addition, LPS is a control system with the principal goal to reduce variation and uncertainty in construction activities (Hamzeh et. al, 2012). In addition, LPS is a collaborative tool that promotes continuous flow, teamwork and reliability (McConaughy and Shirkey, 2013). LPS encourages people to coordinate multiple activities and resolve problems with team agreements (Pavez and Gonzalez, 2012). However, there is still little information about successful results in the management of subcontractors. (Akintan and Morledge, 2013). The most frequently used system to implement the Lean philosophy in project works is the LPS (Smith and Ngo, 2017) and there is much evidence that projects with a Lean approach allow contractors to have better productivity, deadlines, and prices, among other indicators (McGraw Hill, 2013; Hasle et al., 2012). Nevertheless, with no adequate education and training, there could be resistance to change in subcontracting companies, and they would refuse to use Lean systems (Emuze et al., 2021).

With the implementation of Building Information Modeling (BIM) and Lean Construction, the AEC industry is making an important transformation. These are different initiatives, but both are making a great impact on the industry (Heigermoser et al 2019). According to recent studies the LPS is used in combination with 4D models in order to improve the project progress, and to prepare and show a better visualization during the planning meetings (Sacks et al., 2011; Toledo et al., 2014). The use of LPS becomes a potent tool when practitioners incorporate automated BIM workflows. With this incorporation, decisions and feedback are based on optimized information from the BIM models for the constrain analysis, identification of tasks, sizing, and sequencing (Gerber et al., 2010). Although Building Information Modeling (BIM) is utilized in this project for enhanced visualization and planning, the main focus of our research is on the application of LPS. We explore how LPS can be adapted to the unique demands of subcontracting within the construction sector, particularly in projects involving repetitive tasks like those seen in housing developments.

The Last Planner System (LPS) has been increasingly recognized for its potential to enhance subcontractor management in construction projects. LPS, a lean construction tool, focuses on reducing the variability in production planning and increasing the reliability of scheduling, which are critical for the efficient management of subcontractors. By involving subcontractors in the planning process, LPS facilitates improved communication and coordination, which helps in aligning their work with the project's main schedule and objectives. This collaborative approach not only mitigates the risk of delays but also enhances the overall project execution by integrating subcontractor inputs early in the planning phase. Despite its advantages, the literature reveals several gaps in the application of LPS in subcontractor management. Firstly, there is limited empirical evidence on the quantitative benefits of using LPS specifically for subcontractor management as opposed to general project management. Secondly, the strategies for effectively integrating technology, such as Building Information Modeling (BIM), with LPS to optimize subcontractor performance are not well-documented. These gaps underscore the need for more targeted research to explore and validate the use of LPS in enhancing subcontractor management across different types of construction projects. Therefore, the main objective of this research is to propose a method that adapts the LPS to the subcontract management, as well as to apply it for subcontracting natural gas installations in a highly repetitive housing project, which was modelled by using BIM technology.

LAST PLANNER SYSTEM (LPS)

LPS is a collaborative stakeholder system that combines tools, techniques, and practices to manage projects by reducing variability (Ballard, 2000); LPS proposes that planning and programming be considered as a system, performance be measured, and programming errors be analyzed, identifying the root causes of non-compliance, and adopting corrective measures, evaluating their impact (Ballard, 2000; Daniel et al., 2017). During the planning phase, LPS recommends that the level of detail for every activity should be increased as the execution date approaches; collaborative meetings, called Pull Planning, include subcontractors and contractor support areas (Verán and Brioso, 2021).

The LPS elements are the following: Master Planning: the general schedule is developed, deadlines and milestones are agreed, and construction processes are defined (Ballard, 2000). Pull Planning Phase Session: a meeting where all the support areas and subcontractors have to identify the "handoffs" and agree on the Takt Time Planning (TTP) and sectorization; TTP consists of defining the production units to be executed on a daily basis and their sequence; Sectorization consists of dividing the work areas or volumes into several sectors to create a balanced production line and define the limits between sectors. Agreements must be fulfilled as part of the subcontractor's contract (Elfving, 2021; Murguia and Brioso, 2016); Lookahead Planning: it is planned by time windows that usually have some weeks according to their variability (Ballard, 2000). Constraint Analysis: every week of the Look-ahead is analysed. A constraint can be defined as a previous requirement of an activity that can stop the production flow if it is not considered (Ballard, 2000; Brioso, 2011). Weekly Work Planning: compliance with the first week of the Lookahead is optimized and buffers are used according to variability and complexity (Ballard, 2000). Daily Programming: the maximum scheduling level is reached, and the use of common equipment is agreed with subcontractors (Ballard, 2000; Brioso, 2011). Learning (Reliability Analysis): performance measurements are made for every task and subcontractor, the root cause of a non-compliance is analysed, and corrective measures are adopted as soon as possible. LPS measures the weekly and daily plan performance through the percent plan complete (PPC), which is the number of completed tasks divided by the number of scheduled tasks (Ballard, 2000).

SUBCONTRACTORS MANAGEMENT AND LAST PLANNER SYSTEM

There is little information about subcontractors' management in projects that implement the LPS. A study shows that the perception of subcontractors about phase collaborative planning is positive, and that teamwork and a sense of collaboration are developed (Ribeiro et al., 2017). Other research shows that there are still barriers in the implementation of LPS in finishing subcontracts in the USA (Smith and Ngo, 2017). LPS cannot be implemented until changes are made through education and training (Emuze et al., 2021). Regarding the application of LPS and Lean concepts in the gas industry, there is very little information. A study proposes the use of the collaborative tool First Run Studies to Develop Standard Work in the ongoing remodeling of a Liquefied Natural Gas Plant (Hackett et al., 2015). On the other hand, another study explains that the use of Lean tools could be useful in Offshore Oil and Gas Construction (Lerche et al. 2019). In addition, other research indicates that the application of Lean concepts and tools in the oil and gas industry is still undeveloped and lacks details; however, it proposes that digital transformation and Lean concepts could complement each other to improve the collaborative engineering review process at Oil and Gas EPC Projects (Matta et al. 2022). Nevertheless, no results have yet been presented on the application of LPS in the execution of gas subcontracts in urban areas. Additionally, in recent years, various studies have been published showing that LPS has been implemented by different general contractors in Peru with successful results, showing performance indicators of the structure and finishing phases (Brioso et al., 2016; Brioso and Calderon-Hernandez, 2019). However, no information on subcontracts for gas installations in building projects in urban areas has been published.

BUILDING INFORMATION MODELING (BIM)

BIM is a work methodology based on 3D modelling that offers the necessary information and tools to stakeholders to plan, design, build and manage buildings and infrastructures (Cortijo et al., 2021). By the year 2003, the General Services Administration (GSA) of United States with the support of the Public Buildings Service (PBS), created the National 3D-4D-BIM Program. Then, in 2007, the GSA established, for all the major projects, that spatial program BIMs be the minimum requirements for submission to the Office of Chief Architect (OCA) (Edirisinghe and London, 2015). In addition, in the year 2007, the National Building Information Modelling Standards of United States (NBIMS-US) published the first BIM standards. After this publication, BIM protocols were used as addendum for construction contracts with the support of the American Institute of Architects (AIA) (Sarı and Pekeriçli, 2020). By the year 2007 appeared similar initiatives in the United Kingdom AEC industry. The UK government published Publicly Available Standards (PAS) to describe BIM services (Sarı and Pekeriçli, 2020). A few years later, in 2016, the government established that level 2 BIM is obligatory for all public projects. Also, the UK government developed a BIM committee to support contractors during the transformation process to BIM. Besides that, in order to accomplish embrace BIM in the projects, the British Standards Institute (BSI) defined information sharing standards called PAS 2292:2 and the UK government created a roadmap for public projects. (Edirisinghe and London, 2015).

BIM integrates the 3D model of a project with geometric and/or parametric information and is described as the digital representation of the physical and functional characteristics of any object (Sacks et al., 2018). BIM improves the projects design, encourages an efficient workflow and reduces errors during the process (Lévy 2011). The 3D model for a construction project has to be linked with data building elements or components. The information of elements or components are obtained from the level of development (LOD) specification (Lévy 2011). The BIM approach is based on collaborative planning, reasoning, discussion of ideas, decision-making, transparency, improvement of understanding, among other factors, which help employees develop soft skills (Brioso et al., 2022).

The use of Lean Construction and BIM is not restrictive between each other. The interaction of Lean and BIM permits different opportunities to make an efficient workforce and an effective process in the construction projects (Oskouie et al. 2012, Hamdi and Leite 2012, and Dave et al. 2013). An important contribution of the interaction between Lean and BIM is the LC-BIM matrix, which includes 56 positive interactions that support waste elimination and adding value concepts (Sacks et al. 2010). Literature describes some steps for the interaction between LPS and BIM. These studies presents a framework that integrates BIM with LPS at Master planning Level, Lookahead Planning and Weekly Work Planning in order to seek the reduction of waste and to increase collaboration with the project stakeholders (Bhatla and Leite 2004). Also, these studies describe the interactions between LPS and BIM functions, for example: Master Plan with 4D models; Lookahead Planning with Request for Information, Weekly Work Planning with Systematic registration of demands for information, among others (Garrido et al. 2015). Another study presented the advantages of the interaction between LPS and BIM for mechanical, electrical, plumbing and fire protection functions (Tillmann and Sargent, 2016). In this study, significant interaction between LPS and BIM were identified, which are presented in this case study.

METHODOLOGY

Figure 1 shows the research methodology. It is proposed to adapt the LPS processes to manage a natural gas subcontractor in a highly repetitive housing project located in the city of Lima, Peru.

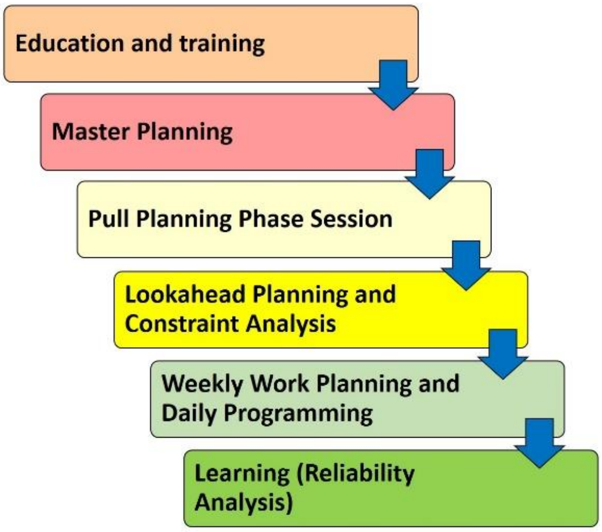

Figure 1: Research methodology

The steps are the following:

1. Education and training: subcontractor personnel, including foremen and site managers, were provided with a series of training sessions on the principles of the Last Planner System (LPS). These sessions included interactive workshops and simulations to demonstrate the practical application of LPS tools such as Pull Planning and Lookahead Planning. The aim was to ensure that all team members understood how to implement these methods in daily construction activities to improve scheduling accuracy and reduce waste.
2. Master Planning: The project's master schedule was developed using collaborative input from all key stakeholders, including subcontractors. This stage involved the use of BIM software to visualize project timelines and critical milestones. By integrating subcontractor schedules into the master plan, we aimed to align all activities and minimize conflicts in the workflow.
3. Pull Planning Phase Session: During these sessions, subcontractors and the main contractor's management team met to discuss and agree on the workflow and sequence of operations. The use of BIM models helped to identify potential logistical issues and sequence tasks effectively. These meetings were essential for establishing a clear and shared understanding of the project's operational demands and for enhancing the temporal and spatial coordination of tasks.
4. Lookahead Planning and Constraint Analysis: Subcontractors were required to submit detailed four-week lookahead plans, which were reviewed weekly to identify and address potential constraints such as resource limitations or scheduling conflicts. This proactive approach allowed for timely interventions, ensuring that project milestones were met without delays.
5. Weekly Work Planning and Daily Programming: Detailed daily work plans were created, specifying the tasks to be completed, the resources required, and the expected outcomes. These plans were adjusted based on real-time feedback and project developments. The daily updates provided a mechanism for continuous improvement and allowed for flexibility in response to on-site challenges..
6. Learning (Reliability Analysis): At the end of each week, a review session was conducted to assess the accuracy of the work planning and the reasons for any deviations from the plan. This analysis helped in identifying consistent patterns of issues that could

be addressed in future cycles. This stage was crucial for learning from experiences and for making systematic improvements to the planning and execution processes.

Regarding the case study, the main construction company has over 20 years of experience constructing buildings of all kinds in Peru, including massive affordable housing projects. In addition, the company has over 15 years of experience implementing LPS concepts and tools. On the other hand, the natural gas subcontractor has 20 years of experience and is the main gas supplier in Peru. It has also participated in projects where LPS has been implemented; however, it is usually informed about the general contractor's schedule at short notice which consequently leads to inefficiency and very low PPC values, with 70% on average.

The methodology was applied to a massive multi-family affordable housing project, which was modeled with BIM technology, Revit 2021 software. The project is located in the city of Lima, Peru, with a built area of 7,372 92 m2. It consists of 4 housing buildings with 16 floors, 512 apartments of 49.50m2 and 50.40m2 of covered area. The structure of every building is made of reinforced concrete and has low-cost finishes and installations. Figure 2 shows the typical floor plan of a building.

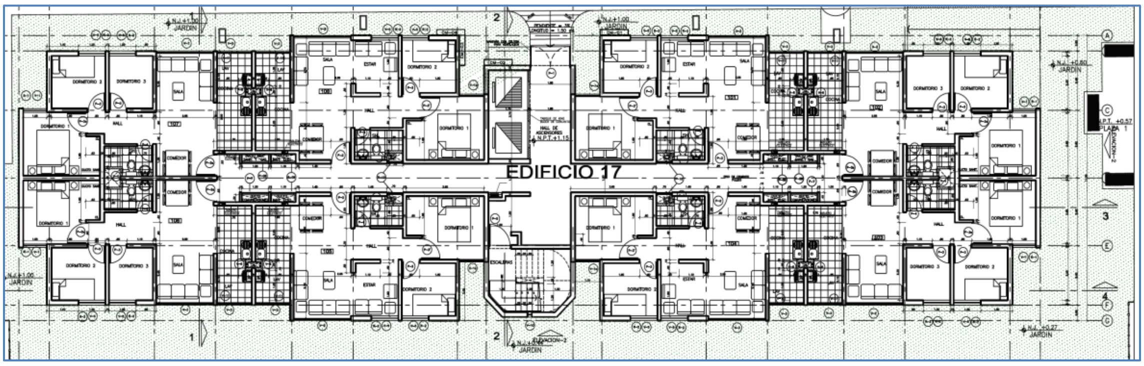

Figure 2: Typical floor plan of a building

The project natural gas installations will be divided by the stud, from the primary regulators that will be located on the first floor. The secondary regulators that will feed the individual lines in every apartment will be connected from the studs.

RESULTS AND DISCUSSION

The Lean Construction philosophy will be applied in the project of gas installations. Consequently, the project will be classified first to present the measurements of the project, the master planning, and develop a constraint analysis that will result in the released programming.

1. Education and training: the subcontractor's stakeholders, such as the coordinator and foremen, were educated and trained in LPS concepts, tools, and techniques. They were instructed in the dynamics of collaborative meetings that would be implemented from the start of the work. Its objective is to reduce waste in the construction processes.
2. Master Planning: the general contractor has extensive experience in this type of projects, so phase milestones and deadlines are precisely defined. The construction of every building lasts 7 months. The subcontractor became aware of this information and planned the following activities to complete them within the defined deadlines:

- Foundation slab: (a) Layout for ground gas network; (b) Excavation of trenches for network; (c) Placement of gas installations on the slab.
- Structure: (a) Layout of gas network; (b) Placement of valves and gas installations in walls and slabs.

- Finishes: (a) Placement of valves and accessories in the finishes; (b) Placement of protection against impacts and dirt.
- Common Areas: (a) Placement of risers, pipelines, regulatory cabinets and gas meters; (b) Execution of quality tests.

3. Pull Planning Phase Session: the subcontractor participated in the collaborative meetings where they agreed on the Takt Time Planning and the general sectorization of the phase shown in figure 3. The BIM model was used on every level of the gas installations, improving the understanding and analysis of the resources to be used.

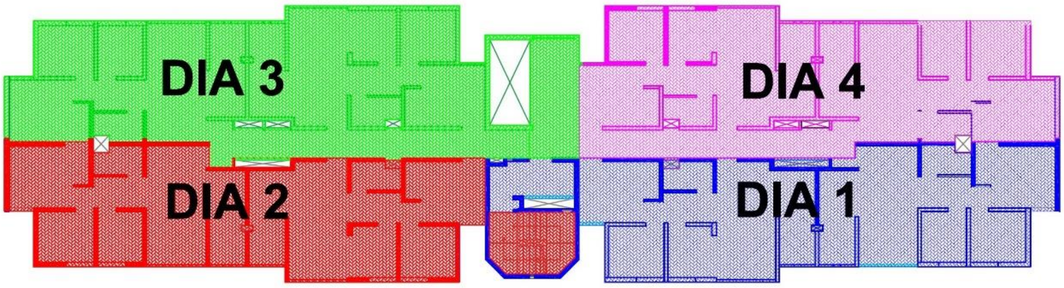

Figure 3: General sectorization of the phase

4. Lookahead Planning and Constraint Analysis: every week, the subcontractor schedules the activities for the next four weeks. The BIM model of every sector is analyzed on a daily basis (see figure 4) and the resources and quality tests of the activities to be conducted are determined. Figure 5 shows the pressure test. For every task, it is determined the constraints of materials, equipment, labor, safety and health, information, previous activities, design, environment, suppliers, subcontractors, among others.

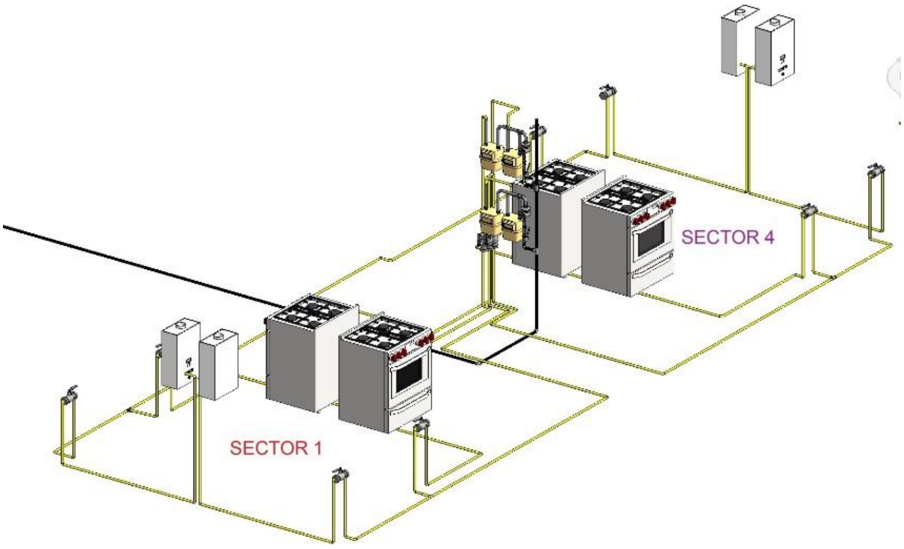

Figure 4: BIM model of every sector

Figure 5: Pressure test

5. Weekly Work Planning and Daily Programming: the subcontractor defined all the tasks that are ready to be executed in the week. Figure 6 shows the takt-time schedule (four sectors, S1 = Sector 1). BIM models are used, daily classifications are approved, and the resources corresponding to every day of the week are analysed.

TASKS/DAYS	1	2	3	4	5
Vertical Rebar	S1	S2	S3	S4	
Vertical Piping Installation	S1	S2	S3	S4	
Vertical Electrical Installation	S1	S2	S3	S4	
Vertical Natural Gas Installation	S1	S2	S3	S4	
Vertical Formwork		S1	S2	S3	S4
Horizontal Formwork		S1	S2	S3	S4
Horizontal Rebar		S1	S2	S3	S4
Horizonal Piping Installation		S1	S2	S3	S4
Horizontal Electrical Installation		S1	S2	S3	S4
Horizontal Natural Gas Installation		S1	S2	S3	S4
Vertical and Horizontal Concrete Pouring		S1	S2	S3	S4

Figure 6: Takt-time schedule of structural work

Throughout all the processes, collaboration was received from the following stakeholders: construction supervisor, subcontractor coordinator, two foremen, and several operators. Among the most remarkable contributions, we can say: (1) The supervisor observes the drawings since the distances to the electrical points and hot water pipelines cause rework, and this situation originates gas installations shutdown; (2) Previous activities cause delays in several stages since drawings are not updated; (3) The natural gas subcontractor assures that the best system is updating the information on the drawings regarding the changes that could occur on site. This facilitates the work on the required items of gas installations. However, there are several companies that do not meet these updates; (4) The poor communication between the parties involves causes many losses, damages, and defects in the items; (5) Operator 1 observes that, in the structure and finishing stages, there are delays due to rework. This situation is due to the lack of knowledge of the regulations of gas installations; (6) Operator 2 indicates that, in the finishing phase, accessories must be secured with masking tape for better protection; (7) Operator 3 observes that for the best operation of installations network, pressure tests must be conducted: (a) during the structures phase, and (b) at the end of the finishing phase during the installation of valves and risers. After that, the root causes of non-compliances are analysed, corrective measures are adopted, and their effectiveness is monitored. For example, all gas installations must have their respective identification from the manufacturer, to avoid the misuse of other brands of accessories and the incompatibility of materials.

Finally, the weekly and accumulated PPC are measured, and their positive performance is verified. Table 1 shows the results of the following 9 weeks. It is observed that in week 2 there were 2 non-compliances, due to lack of materials and lack of quality tests. Corrective measures were immediately adopted, and a person was assigned for every measure to implement it. The routine was then repeated every week, promoting continuous improvement. This methodology leads to efficiency and very high accumulated PPC values, with 96% on average.

Table 1: Weekly and accumulated PPC

WEEK	SCHEDULED TASKS	COMPLETED TASKS	WEEKLY PPC	ACCUMULATED PPC	GOAL
1	10	10	100.00%	100.00%	85.00%
2	10	10	100.00%	100.00%	85.00%
3	10	8	80.00%	93.33%	85.00%
4	17	16	94.12%	93.62%	85.00%
5	24	24	100.00%	95.77%	85.00%
6	26	26	100.00%	96.91%	85.00%
7	27	27	100.00%	97.58%	85.00%
8	33	32	96.97%	97.45%	85.00%
9	34	31	91.18%	96.34%	85.00%

The integration of the Last Planner System (LPS) with Building Information Modeling (BIM) has significantly advanced subcontractor management in our case study project. Key improvements include:

- Enhanced Planning Accuracy: The use of BIM in conjunction with LPS allowed for more accurate and detailed planning schedules. For instance, the visualization capabilities of BIM helped in identifying potential scheduling conflicts early, which LPS methods then addressed through proactive adjustments. This integration led to a marked increase in Percent Plan Complete (PPC) values, from an average of 70% before implementation to 96% post-implementation.
- Improved Resource Allocation: By leveraging detailed BIM models at various planning stages, subcontractors could better predict and allocate resources. This was particularly evident in the weekly and daily planning phases where BIM’s detailed visualizations complemented LPS's structured scheduling approach.
- Increased Subcontractor Collaboration: LPS’s emphasis on regular and structured communications among all project stakeholders was enhanced by shared BIM models. This facilitated a more collaborative environment and improved the subcontractors' commitment to the project timelines and quality standards.
- Feedback and Continuous Improvement: The integration provided a feedback loop where BIM visualizations helped identify non-conformances quickly, and LPS protocols were used to implement corrective actions swiftly. This continuous improvement cycle significantly reduced rework and increased operational efficiency on site.

CONCLUSIONS

The integration of LPS and BIM allows more detailed processes and a better understanding of the natural gas project. BIM and LPS are synergetic, when they interact understanding is improved, decision-making is automated, and transparency is increased. Gas installation subcontractors could generate lower losses using LPS, since it allows better planning and scheduling of the different items identified. It is important that all parties involved are educated and trained in LPS and know the scope of the project. When the implementation of the planning is conducted from the master plan, it is necessary that all collaborators participate in the agreement from the beginning. It is essential to take the respective safety measures to create an environment of confidence to work safely. The most frequent root causes of non-conformances were determined, and this information was fed back into the collaborative planning of the following, determining the optimal classification, Takt Time Planning, subcontractor restrictions, weekly and daily schedules, and finally, the lessons learned from the implementation of the LPS for future projects, which can be adapted to other types of subcontracts.

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A SYSTEMATIC APPROACH TO MAKING PEOPLE, PROCESSES & PROJECTS READY FOR MAKE-READY

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ABSTRACT

Project management methods like risk management (RM), production planning (including make-ready) and continuous improvement (CI), are often considered in isolation of each other. The literature recognises how teams struggle with implementing these methods according to known current best practices and standards. The purpose of this paper is to report the on-going development of a research artefact called IRMA 360^0 (Integrated Risk Management Approach) through a Longitudinal Action Case Study over four cases between 2016 and 2024. There is a particular focus on Case 4 – an ISO 18404 Certified Alliance.

In summary, this research has identified links between RM, make-ready planning and CI, and proposes IRMA 360^0 as a model to advance the Last Planner® System (LPS) by feeding what 'might' happen or might be possible through 'should, can, will, did, learn' functions. We conclude that both effective RM and make-ready are required to create and protect value which includes reliable workflow. However, to embed RM and make-ready planning a safe and collaborative environment is desired. In theory, RM is complex as it deals with uncertainty. On the other hand, make-ready is a relatively straightforward activity to 'just' screen tasks for constraints. However, in practice both are extremely difficult to implement.

KEYWORDS

Risk Management, Make-Ready, Last Planner® System, IRMA 360^0, Alliancing.

INTRODUCTION & BACKGROUND

Much has been written about the benefits of the LPS (e.g., Fauchier & Alves, 2013) but less about practical implementation challenges (Ebbs et al., 2018) or underpinning theories that support the LPS. During IGLC30, Ballard delivered a keynote speech titled 'The Last Planner System and the Waste of Making-Do (Koskela, 2004): a Research Proposal'. This was a broad call for research into three areas 1) Improve input flows; 2) Reduce incentives for making do; and 3) Improve the process for deciding what to do when timely delivery of standard input fails.

Eighteen years of research bookends Koskela's original paper on Making-Do and Ballard's call to focus on these research areas at IGLC30. Many scholars, practitioners and standards have made contributions to the LPS (incl. make-ready), RM and flow. The 8 Pre-requisite Flows

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of Lean Project Production have largely emerged from Koskela's (2000) Transformation, Flow, Value (TFV) Theory, Ballard's (2000) Directives, Bertelsen et al., (2007) Preconditions, and Pasquire's (2012; 2017; 2018) work on Shared Understanding. The 8 Flows appear in slightly different guises but for this paper they are: 1) Information; 2) Equipment; 3) Materials; 4) People/Workers; 5) Prior Activity; 6) External Conditions; 7) Safe Space (Physical Space & Wellbeing); and 8) Shared Understanding.

The aim of this paper is to investigate the links between the 8 Flows, RM, make-ready planning and CI. The objectives of this paper are to:

1. Evaluate the practical challenges associated with embedding RM and make-ready planning on projects and programmes.
2. Assess the relationships between collaborative RM, make-ready planning, CI and project/programme reliability.

The remainder of this paper is structured as follows. Firstly, the literature of relevant concepts is reviewed. Secondly, the research methodology used to develop, test, and implement IRMA 360^0 is outlined. Thirdly, the key outputs from four cases are discussed which includes how IRMA 360^0 emerged from Ebbs and Pasquire's (2018) Flow Walk; an overview of IRMA 360^0 with a specific focus on RM and advancing make-ready; a summary of IRMA 360^0 participant feedback; and, how the rich data generated was used for both CI and to develop the DR.PAMPPSS (Design, Resources, Procurement, Access, Materials, Plant, Permits, Shared Understanding, Safety) make-ready codes and process aligned to the 8 Flows in Figure 3. DR.PAMPPSS built upon O'Connor's (2020) DRAMPPS constraint management technique by adding another 'P for Procurement' and 'S for Shared Understanding' during Cases 3 & 4.

LITERATURE REVIEW – RM & LPS

The RM literature is extensive, and much is beyond the scope of this research. The role of culture, organisational change (Mu et al., 2014; Olechowski et al., 2016), the need to collaborate at the 'fuzzy' front end (Pinto & Winch, 2016; Akerman et al., 2014), understand linguistics (Aven, 2012; Flores, 2013), avoid ignoring risks (Kutsch & Hall, 2010), and improve opportunity management within a holistic and iterative process is recognized (ISO 31000:2018). However, it is clear more case studies on collaborative approaches to RM are required.

There is a plethora of LPS (Hamzeh et al., 2007; Ballard & Tommelein, 2016, 2021; Ebbs & Pasquire, 2019; Mossman, 2020) and Collaborative Planning (CP) guidance (Highways England, 2020) freely available. However, while the LPS Guides provide some detail on how to screen tasks, the CP Guides generally focus more on constraint management than make-ready for every task. Many scholars have reported incomplete LPS implementations (e.g. Daniel, 2017; Hamzeh, 2011; Fireman & Formoso, 2013; Dave et al., 2015; Ebbs & Pasquire, 2018). They observed that whilst project teams may be enthusiastic about the LPS they seem to be unable to grasp the full depth of the system. Furthermore, Daniel (2017) identified that the technique entitled CP is frequently mistaken for the LPS in the UK and that its implementation often stalls at the level of make-ready. Differing epistemological and ontological views of the LPS may be contributing factors to the inconsistency in deployment.

The case study reported by Kamal et al. (2023) represents a recent example of misinterpreting the LPS as they included LPS within 'Collaborative Target Programming' alongside 'pull planning' and 'make-ready' rather than referring to LPS as the overarching system of interconnected parts (Ballard & Tommelein, 2016). Whilst they noted the use of DRAMPPSS make ready planning, they did not credit the sources (O'Connor 2020; Pasquire & Ebbs, 2017; Ebbs & Pasquire, 2018) related to its development.

The research and reporting of make-ready deployment (Ballard & Howell, 1998; Ballard, 2000) is not always explicit and appears limited to a few areas namely lookahead planning (e.g., Alves and Britt, 2011), constraint analysis and management (e.g., Lindhard & Wandahl, 2012), Tasks Made Ready (TMR) and Tasks Anticipated (TA) (e.g., Hamzeh et al., 2016), and the operating environment (Britt et al., 2014). Other IGLC literature from Emdanat and Azambuja (2016) and Samad et al., (2017) questioned the impact of many LPS metrics but propose even more LPS metrics that are beyond this paper's scope. Examples of 'making do' are reported by Koskela (2004), Fireman and Formoso (2013), and others. The cost of rework is also widely discussed but outside the boundary of this paper. Whilst both are not explicitly make-ready related, one could argue that making do and rework are symptoms of not making ready.

Regarding integrating RM and LPS, Ballard and Tommelein (2021) recommend conducting project RM in the Project Definition Function with risk mitigation strategies contained on the Project Execution Plan. Additionally, they maintain that the purpose of the LPS is for the Last Planners to create and maintain reliable workflow in pursuit of project objectives. To support this from a RM perspective, ISO 31000:2018 states that effective RM protects the effect of uncertainty on objectives and its purpose is to create and protect value (through opportunity and threat management) by leveraging the input of experts who have knowledge of risks. The eight RM principles listed in ISO 31000:2018 emphasize how critical collaboration is for effective RM and this may also explain why other RM scholars (such as Aven, 2012; Pinto & Winch, 2016) recognise implementation challenges.

In summary, when comparing both RM and LPS there appears to be significant relatedness from both a systems approach and implementation challenges. Both may benefit from closer alignment and learning from some common denominators such as people and available time.

RESEARCH METHODOLOGY

The struggle with make-ready was found in practice (Ebbs & Pasquire, 2018; Ebbs et. al., 2018) and from anecdotal conversations with experienced LPS practitioners at IGLC conferences. As a result, the original singular Case Study methodology was extended to a Longitudinal Case Study (Yin, 2018) using Participatory Action Research (Mackenzie et al., 2012) alongside some Design Science (van Aken, 2004), and post-rationalisation including a literature review of Collaborative RM, Make-Ready, and other RM domains such as Supply Chain RM.

Between 2016 and 2024 data was collected from many workshop participants (n=c.1000) across 15 infrastructure projects. The extensive primary data was analysed using Braun and Clarke's (2006) thematic analysis framework alongside Ebbs and Pasquire's (2018) approach to measure the Level of Conversation (LOC) of each risk and the risk categories that emerged. The LOC was established by totalling the number of survey responses, workshop scribbles, and dots used to prioritise and summarise risks captured through Steps 1-4 of the Flow Walk in Figure 1. Using excel, risks were then mapped to their relative risk categories that were developed through the Flow Walk's Step 5 to define the LOC of each IRMA 360^0 category.

THE CASE STUDIES – OVERVIEW, RESULTS & DISCUSSION

The Longitudinal Case Study ran between 2016 and 2024. It involved 21 action-research cycles within four case studies to develop the IRMA 360^0 artefact. Cases 1-3 are detailed briefly to articulate the key findings used as the foundation for nine action-research cycles in Case 4.

Researchers Background, Experience and Roles

The authors are divided into several groups. Author 'A' is a PhD Researcher and ISO 18404 Lean Expert. 'B' is also an 18404 Lean Expert who collaborated with 'A' on make-ready deployment since 2019. 'C' is an ISO 18404 Lean Leader who worked with 'A' on the 3rd and 4th Case Studies. 'D' and 'E' academic supervisors since 2019 and 2021 respectively and Pasquire (2012; 2017; 2018) was 'A's' academic supervisor from 2016-2021. Whilst developing the artefacts the ontological viewpoint shifted from positivist in 2016 to relativist in 2021 which reflects the complexity and difficulty of deploying RM and the LPS in full and the ontological and epistemological dimensions that emerged as the artefact was developed.

Case Study 1: UK Organisation X (n=150)

The research began in 2016 whilst ‘A’ (supported by Pasquire) was embedded in a UK Client Organisation (X) for 30 months to design, develop and test a Lean Project Delivery System that addressed the root cause of delays and disruption. Organisation X operated in a highly regulated and confidential environment. Some of the main findings were in relation to the need for clarity of purpose, shared understanding, and the challenges sustaining all aspects of LPS deployment - particularly the make-ready process. Ebbs and Pasquire’s (2019) ‘Facilitators’ Guide to the LPS’ was one of the outputs and Ebbs and Pasquire’s (2018) ‘Flow Walk’ emerged as an artefact to help formalise make-ready but also integrate RM into the LPS using the 8 Flows.

Case Study 2: UK Transport & Infrastructure Division (n=145)

With ‘A’ acting as a Lean Coach for a Global Engineering Firm, the Flow Walks went through another four action-research cycles (projects) which formalised as IRMA 360^0 in 2019. In hindsight, the Flow Walks were a macro-RM approach to make-ready rather than a specific task screening approach (micro). The data collected during all 5 Steps of the Flow Walk in each of the projects proved to be very rich. Whilst the participants noted how overwhelming the data was, this also highlighted the complexity of projects, the need for the right people to be involved early, and the value of the collaborative conversations and shared understanding triggered by the Flow Walk. The Covid Pandemic began shortly before the 4th action-research cycle in Case 2. This required the physical ‘Flow Walk’ to move online which resulted in significantly more data input from the participants during Step 1. Subsequent data analysis identified 272 ‘risks’ within 15 bespoke risk categories. This was circa 3x more ‘risks’ than previously identified.

‘Risks’ in the context of this research include opportunities, threats, assumptions, and pre-requisite make-ready items (typically known as constraints in LPS literature). This categorisation clarified there was more to the Flow Walk and RM than threat management.

IRMA 360^0

IRMA 360^0 emerged from iterations of the Flow Walk in 2019 and primarily supports Ballard’s first IGLC30 call “to improve input flows” by using the 8 Flows to trigger conversations about flow. IRMA 360^0 is proposed as an advancement of Ballard and Howell’s (1998) LPS (not a replacement) to further integrate RM with production planning and control and help structure CI initiatives with RM. Ebbs and Pasquire (2018) report how the development of IRMA 360^0 started in practice by recognising how teams struggle with make-ready and the concept of flow.

Figure 1 shows how the 8 Flows trigger conversations about what ‘might’ happen or be possible during the Steps 1-5 of the Flow Walk using divergent thinking during Step 1 & 2 to identify ‘risks’, and convergent thinking during Steps 3 - 5 to prioritise ‘risks’ and develop IRMA 360^0 categories. Figure 1 also shows how the 8 Flows are important triggers for learning and action within the other LPS functions and how the outputs from the Flow Walk inform the development of collaborative milestone, phase, and make-ready plans. For example, whilst phase pull planning what ‘should’ happen, the 8 Flows are helpful triggers to identify predecessors and ‘risks’. To ensure tasks ‘can’ happen as planned, every task must be screened for ‘risks’ during make-ready planning - the 8 Flows or DR.PAMPPSS make excellent prompts. Commitments are made for what ‘will’ be done after tasks are made ready and shared understanding is established. After reviewing what ‘did’ happen, missed commitments (delay and disruption) data can be trended against the bespoke IRMA 360^0 categories developed during the Flow Walk’s Step 5 ‘Categorise’. When teams need to ‘learn’ from missed commitments for example using a fishbone problem solving template, the 8 Flows are very effective at drawing out causes and effects of a specific problem. In summary, the emergent data that makes up the IRMA 360[0] categories after the Flow Walk, supports many conversations during general problem-solving workshops and the deployment of LPS ‘should, can, will, did and learn’ functions. The use of IRMA 360[0] data is discussed more in Cases 3 & 4. See Pasquire and Ebbs (2017), Ebbs and Pasquire (2018; 2019) for more on the development of IRMA 360[0].

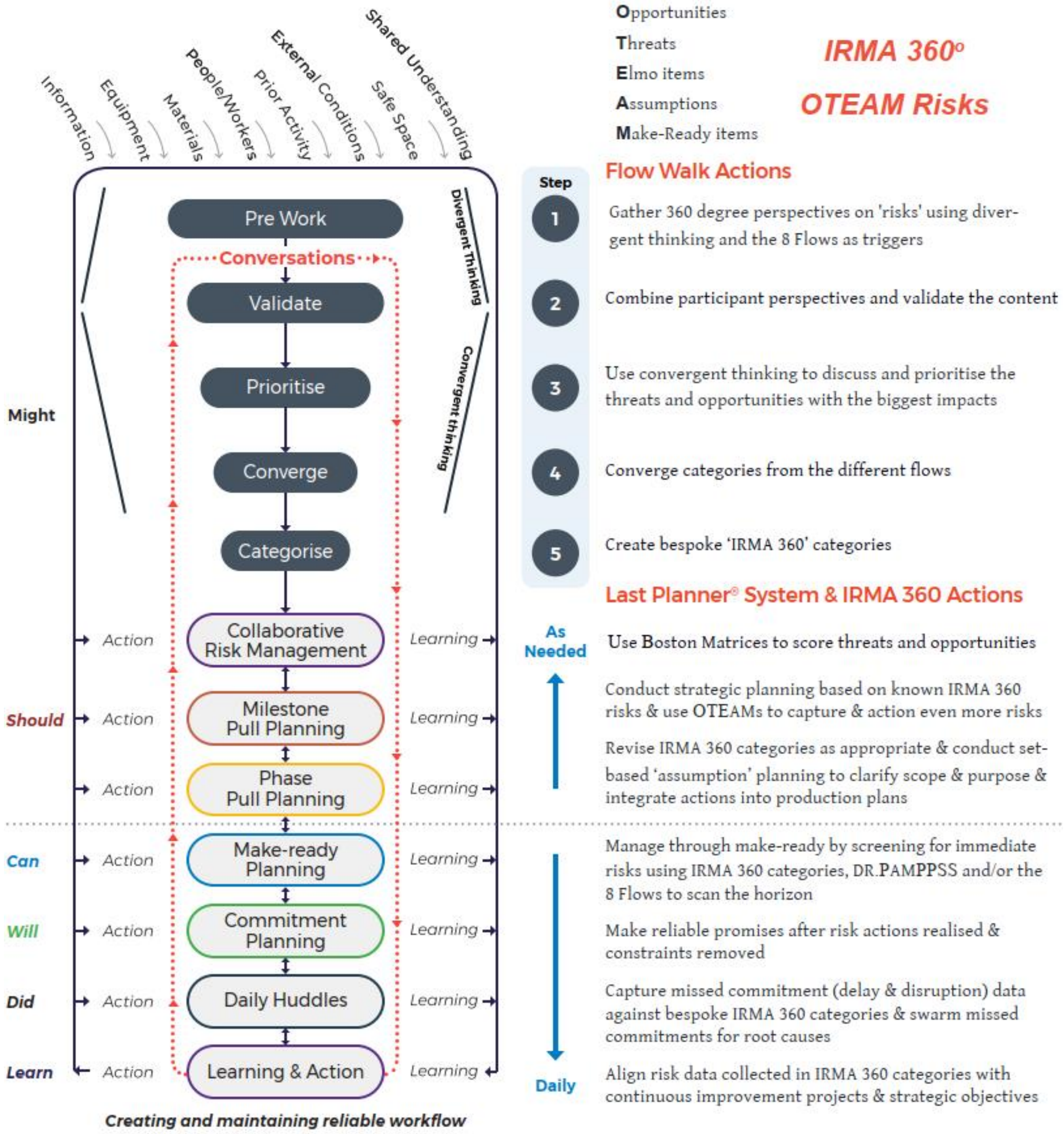

Figure 1: IRMA 360[0] Framework (after the Last Planner System)

CASE STUDY 3: MIDDLE EAST LOCAL INFRASTRUCTURE PROGRAMME (N=200)

After ‘A’ joined this programme with responsibility for lean deployment a clearer link between IRMA 360[0] and make-ready emerged. In practice O’Connor’s (2020) DRAMPPS process was less formal than the task-by-task screening approach documented in literature (Howell & Ballard, 1998; Hamzeh et al., 2007; Ballard, 2000; Ballard & Tommelein, 2016). Nonetheless, it was effective and another ‘S’ was added to include ‘Shared Understanding’ as a screening criterion for teams. Teams were also encouraged to map their DRAMPPSS to specific tasks to elevate their timely removal. Kamal et al. (2023) reported the use of DRAMPPSS in a micro tunnelling improvement project but did not acknowledge O’Connor (2020) or ‘A’ as the sources.

In parallel to continuing DRAMPPSS deployment, four IRMA 360[0] Flow Walks were conducted on four projects at various stages. During these, two more ‘stations’ were added to the 8 Flows to capture ‘Stakeholders’ and ‘Biggest Concerns’. The output was consolidated through a workshop (n=15) into 22 bespoke IRMA 360^0 programme categories. After a final round of thematic data analysis 410 specific 'risks' emerged within these 22 categories. This data was used on two more projects to develop risk registers from scratch, improve the quality of risk registers and align with programme delay and disruption data collection. Building on ISO 31000:2018's categorisation of RM, reflection upon the RM literature and practical observations of RM, it became clear that opportunity management was not given the same level of attention that threats were – in practice 'risks' are typically only viewed as threats. Furthermore, following Case 2, IRMA 360^0 'risks' were defined as opportunities, threats, assumptions, and make-ready (OTAM) items. Elmo (enough let's move on) was introduced in Case 4 and OTEAMs emerged as a useful framework for capturing 'risk' conversations requiring action during milestone and phase pull planning workshops. OTEAMs are discussed more in Case 4. The following findings were noted after post-rationalising Case 3. These fed into the action-research cycles of Case 4:

- The Last Planners are also the Last Risk Managers
- Nobody knows more about risks than everybody and everyone is a Last Risk Manager
- Thoughtful early stakeholder selection and team engagement helps avoid threats
- Leveraging multiple perspectives on risks creates rich 'current state' data
- Teamwork and diversity are critical to RM
- The IRMA 360^0 database is a checklist for projects when planning collaboratively
- Major risks are common across similar projects on an infrastructure programme
- The IRMA 360^0 categories and specific risks are sources for focused CI
- IRMA 360^0 supports requirements of ISO 31000:2018, 44001:2018 and 18404:2015
- Integrate Risk Managers into IRMA 360^0 workshops to leverage inputs/outputs and encourage the effective use of the rich data generated

CASE STUDY 4: UK HIGHWAYS ALLIANCE (N=220)

Figure 2 is a team identifying 'risks' during the 3rd Flow Walk action-research cycle of Case 4.

Figure 2: IRMA 360^0 Last Risk Managers during a Flow Walk in Case 4

Ebbs and Ward (2024) share more about Case 4 but in short, the Alliance is an enterprise of 7 partners and a diverse supply network delivering UK highway infrastructure upgrades. Building on feedback from the RM Lead after the 2nd action-research cycle, opportunity management was also incorporated into Step 3 of the Flow Walk illustrated in Figure 2, and into a subsequent mini workshop that used a simple Ease/Benefit Boston Matrix to evaluate opportunities. This was the first time the Flow Walk was used pre-contract award and the feedback noted "good team alignment on threats and opportunities and re-focusing Step 3 to prioritise threats and also opportunities helped shift the mood in the room". The output was used to create the initial programme risk register and improve collaboration within the Alliance. The RM Lead noted "by bringing risk, planning, and learning into one workshop where all stakeholders are present has reaped endless rewards. Not just from an engagement perspective but from a lean perspective by pulling all strands together and providing that golden thread between them in one forum. It has enabled all parties to look at the bigger picture and the required interfaces between different work disciplines and third parties and has helped to break down silos. As all parties are involved, this has really set the scene to ensure they are all bought into the same vision and mission. It also helps the understanding of key constraints held by all."

Like Case 3, the Alliance projects were all at various lifecycle stages. This supported building from Case 3's approach to rationalise the data under 'Alliance' Categories but without the need for a workshop. The categories developed by each project was consolidated by 'A' into Alliance IRMA 360^0 Categories using the LOC technique. The categories in Table 1 summarise the data analysis from across the Alliance. Note that Category #1 is not more important than #16, it only articulates how much conversation took place in relation to the 'risks' in each category. Ultimately, the LOC is dependent on who is present to have the conversations.

Table 1: Case 4 Alliance IRMA 360^0 Categories (n=200)

Rank	Category	Level of Conversation
1	Traffic Management & Roadspace	577
2	Labour & Skills Availability	555
3	Procurement, Logistics & Plant Management	509
4	Collaborative Planning & Programme Management	417
5	Design Information Management	383
6	Expectations, Leadership, Culture & Communication	348
7	Approvals & Governance	299
8	Material Management	299
9	Surveys & Existing Conditions	299
10	Stakeholder Management	269
11	External Conditions	246
12	Safety, Health, Wellbeing & Environment	223
13	Information & Quality Management	137
14	End User/Customer	114
15	Technology	70
16	Commercial Management	68

A similar IRMA 360^0 Category Framework in Table 1 was developed for Case 3 but 22 categories emerged. The top four categories in Case 3 were 1) Material Management; 2) Labour Availability and Skills; 3) Planning & Coordination and 4) Residents' Concerns. Case 3 categories provide an interesting correlation between category #2 in Table 1, but also with category #4 which indicates production planning 'risks' ranked highly in both Case 3 & 4, albeit the Cases are from different geographical regions and slightly different contexts.

Using IRMA 360^0 Data for CI & RM

The combined data from four action-research cycles underpins the categories in Table 1. The data was used for various purposes. For example, the first action-research cycle was a highway technology retrofit programme where Traffic Management and Roadspace booking constraints meant several shifts were lost per month. The team used Step 1 of the Flow Walk to collate appropriate data in relation to the 8 Flows. However, due to geographic and Pandemic constraints and rather than attempting a Flow Walk online, 'A' sorted the data into themes. A 2hr online structured problem-solving workshop followed with 20 key stakeholders using the themes created in Step 1. This resulted in no lost shifts and over £500k cost avoidance.

Like Case 3, the other action-research cycles were either during conceptualisation, mid-way through or during the construction (assembly) mobilisation period. The 9th action-research cycle in March 2024 used the 16 IRMA 360^0 Categories in Table 1 and the 8 Flows to trigger immediate 'risks' in each category. Three teams (n=19) from the same programme used this approach during a 1.5 hrs facilitated workshop. Each team worked independently but reported back to the collective group with the Risk Manager recording 49 'risks'. During the subsequent pull planning session (n=31) another 59 OTEAM 'risks' were identified. Whilst there was some cross-over on risks during both workshops, an additional 9 threats and 12 opportunities were added to the risk register. These workshops also helped to identify 37 mitigations to the 21 new risks, whilst also identifying a further 18 mitigations to 12 threats already on the risk register.

Make-Ready Action-Research Cycles

The roll out of a structured make-ready process shown in Figure 3 was part of a larger 18404 Lean Strategy and involved five action-research cycles. In Dec 2022, 29 OTEAM risks and 39 DRAMPPSS were identified during and after a pull planning workshop. In Feb 2023, 'A' facilitated a workshop with cross-functional site staff (n=12) using the question "what are the typical reasons why tasks are stopped or disrupted in relation to each of the 8 Flows?". 34 'reasons' emerged which ranged from not conducting a 24hr weather check to requiring an RFI.

Assembly Make Ready Codes (N=68)

	D	R.	P	A	M	P	P	S	S
	Design	Resources	Procure-ment	Access	Materials	Plant	Permits	Shared Understanding	Safety
Monthly	1 TQs	5 Personnel TBC	62 Req's	6 Traffic Mgmt	8 Acquisition Requests	10 Deliveries	13 Enviro & Ecology	16 Site Visit	14 RAMS
	2 RFIs	64 Inductions		7 Roadspace	9 Available	11 CCTV Req's	63 Dig	17 Handover & Maintenance	15 Temp Work Req's
	3 Inspection Test Plans					12 Preventative Maintenance Schedule	65 Quality Plan	18 Stakeholder Engagement	60 Working Area Width
	4 Survey Info						66 Load	59 Contracts	
	68 Inspections						67 O'head	61 Prior Lessons Learned	

Figure 3: Sample Alliance Assembly DR.PAMPPSS Make Ready Codes (February 2024)

The 34 codes were piloted, but feedback suggested "there were too many, DRAMPPSS is enough". In March 2023, a version of Figure 4 emerged with another team. The 34 reasons were mapped under DRAMPPSS but aligned to the colours/flows used in Ebbs and Pasquire's (2018) Flow Walk. By April 2023, the 'codes' increased to 55 and DR.PAMPPSS subsequently emerged after the team identified 'Procurement' as a critical make-ready prompt. By February 2024, through workshops to mobilise teams safely, effectively, and efficiently 68 make-ready codes emerged. The DR.PAMPPSS codes were used as prompts to screen 60 tasks in 1.5hrs. Figure 3 is a snapshot of the Assembly make-ready screening codes but without the weekly and daily codes (not shown for brevity). Figure 4 illustrates the make-ready screening process using both OTEAMs (captured during and following pull planning) and the DR.PAMPPSS make-ready processes. The numbers in the dashed red box on the pull planning post-it on the left of Figure 4 reflect the codes from Figure 3. The different coloured dots with numbers inside reflect the OTEAMs that were captured on a flip chart during a pull planning workshop and then mapped to specific tasks to identify when the risk actions needed to be completed by.

Figure 4: Examples of OTEAMs & DR.PAMPPSS mapping to phase pull plans

In parallel to the 'Assembly' roll out of make-ready, another retrofit programme had to identify and design 138 highway emergency areas within a constrained period. Four of the leadership team were on their I8404 Lean Practitioner journeys which collectively exposed them to various lean principles, theories, and techniques such as flow, change curve thinking, batch size reduction, LPS (incl. make-ready), visual management, and de Bono's Six Thinking Hats (Ebbs & Ward, 2024). As a result, there was significant coordinated 'pull' for lean. The Practitioners (supported by 'A') facilitated a series of workshops over 6 days in June and July 2023 to leverage perspectives and help projects mobilise safely and faster (n=80) whilst standardising approaches to design where possible. Following these workshops, the Design Lead asked "ok, so what's next for lean?", one of the answers was make-ready. Recognising that 'not every nail requires a hammer' a bottom-up approach to 'Pre-Assembly' make-ready was implemented. However, rather than conduct a workshop, an 8 Flow survey was conducted (n=24). This resulted in 28 initial codes that increased to 35. These were also structured under DR.PAMPPSS to maintain some consistency with the 'Assembly' codes. Some interesting observations emerged. Whilst the leadership were fully supportive and engaged with make-ready and the individual leading make-ready deployment was too, in hindsight, the pre-assembly teams' understanding of make-ready and the LPS in general was insufficient. 'Code #31' was added to capture and trend tasks 'not screened'. By Nov 2023 #31 equated to 60% of 4,500 tasks. Additionally, there was also reluctance to share the initial 'poor' TMR scores because it was assumed the 'wrong' reaction might be provoked. This knowledge provided more focus on the screening process and transparent reporting of TMR data.

In Nov 2023, the 'make-ready' lead then undertook the 18404 course reported by Ebbs and Ward (2024). During their Sponsor session in Dec 2023, they noted "I now know why you were asking me to do all these things including collecting and sharing the data, had I known what I know now I would have been even more disciplined with the roll out of make-ready, huddles and visual management. To be honest, I was only doing it because you asked me to [and I trusted what you were doing]". Furthermore, during the Stage 1 ISO 18404 External Audit in Feb 2024, the Auditor asked to see TMR Pre-Assembly data, but it transpired the make-ready lead had left the Alliance and the data trail was not updated for 3 weeks, which suggested some people relaxed their approach to make-ready without leadership. Overall, from September 2023 to Jan 2024 initial Pre-Assembly make-ready deployment data analysis showed TMR increased from 15% to 62%, and LEI (Lookahead Execution Index) went from 54% to 72%. LEI is a client measure of programme certainty. It takes the planned starts and finishes within a reporting period and records if those planned starts and finishes were achieved. The practical output of this and general lean deployment in the Alliance, which was heavily focused on RM, make-ready, and CI, reduced some project initiation to mobilisation periods by approximately 50%.

Elevating the Importance of Make-Ready: Moving the focus from Did to Can

The background to elevating the importance of ‘make-ready planning’ was in part related to deploying ISO 18404 to embed a lean culture and make lean normal practice. However, it was also vicariously related to IRMA 360^0 deployment as the rich data generated included many make-ready items within the ‘risks’ which highlighted the need for a more structured make-ready approach. The Alliance created a Single Page Lean Strategy with more detailed plans to support and structure deployment of critical elements such as training and coaching, visual management, the LPS, and specifically make-ready. The Alliance also created a ‘rich picture’ to show a programmatic and outcome-based intent. This evolved as the Alliance and lean competencies matured. For example, ‘Progress Tracking’ was replaced with ‘Make-Ready Planning’. Whilst the focus on make-ready formed part of a wider lean deployment through an 18404 framework to develop the lean competency of key mid-senior leadership, the make-ready pilots also influenced more strategic updates to the Alliance strategy (Ebbs & Ward, 2024).

CONCLUSION

The primary contribution of this research demonstrates how to improve input flows through the IRMA 360^0 framework based on the collective input from the ‘Last Risk Managers’. Within a complex project delivery or organisational improvement paradigms, significant thought and collaboration is required. Projects, strategic objectives, and improvement activities are realised from many conversations which constantly occur between the Last Risk Managers. Outcomes are ultimately the result of establishing shared understanding between people, however, the process of realising outcomes inherently involves RM, production commitments, rework, making do, and learning. Whilst the theory of make-ready ‘to screen every task for constraints prior to committing to production’ is relatively simple, this research highlights that embedding make-ready planning (and the ‘full’ LPS) is much more complex. Many contributing factors require consideration such as the operating environment, contract model, and knowledge and understanding of the LPS which includes make-ready and linguistics.

Aven (2012) emphasized the need to understand linguistics in RM and Flores (2013) articulated how we invent the future through conversations. IRMA 360^0 is a system that helps facilitate conversations to understand risks and concerns before making commitments. The common denominator in conversations is people, however, their ontology naturally differs based on their socio-technical constructs. Therefore, the more of the ‘right’ people in the room, to have the right conversations at the right time, the richer the conversations. You don’t know, what you don’t know until you know it, and knowledge of risks alone does not equate to understanding and in some cases as Kutsch and Hall (2010) posit, leads to ignoring them.

In conclusion, we propose that an integrated approach to collaborative RM and make-ready within a LPS framework to trigger and capture the conversations that emerge with the required commitments for CI is useful. Furthermore, for effective production planning and control RM, make-ready planning, and CI cannot be considered in isolation of each other. Whilst IRMA 360^0 appears to support this integration, a collaborative systems thinking environment is also desired (such as the Alliance model reported in Case 4) to help people feel safe to become ready for make-ready and integrate RM with the LPS. Whilst the generalisation of the case study findings of this research may be harder without further independent testing of IRMA 360^0, the implementation challenges of RM, make-ready and the full LPS are well recognised. There is a plethora of guidance and research on RM, LPS and CI but the empirical evidence provided here suggests IRMA 360^0 may help integrate these approaches and provide the framework to not only formalise make-ready planning at the heart of project conversations but also integrate RM with the LPS as a standalone [risk] management system that ISO 31000:2018 calls for.

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PROMOTING HEALTH AND SAFETY ON UK CONSTRUCTION SITES USING LEAN CONSTRUCTION STRATEGIES

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ABSTRACT

Poor health and safety (H&S) conditions in the construction industry are linked to ill-defined social and economic factors. To mitigate poor construction H&S performance, it has been widely recommended that Lean Construction (LC) strategies be adopted. Existing literature shows a strong correlation between implementing LC and improving construction H&S performance. However, limited research utilises qualitative research based on primary data to understand the perspectives of experts with real-world experience on the LC/H&S relationship. To address this gap, we conducted a novel study interviewing eight highly experienced LC experts to gain insights into how LC can enhance H&S in construction projects. Going beyond theory, we conceptualised a model linking key LC methods to root causes of H&S accidents to enable tangible improvements. This model intends to guide construction professionals in adopting and implementing LC strategies to foster safer construction workplaces. Our findings affirm and extend prior research by emphasising the efficacy of LC methods in improving H&S performance in construction projects.

KEYWORDS

Lean Construction, Health and Safety, Accidents, Waste, Flow

INTRODUCTION

Construction is one of the most dangerous industries, with a higher death rate among its workers (National Safety Council, 2023). This does not include fatalities from suicide – of which this industry also has one of the most. Accidents in this industry often result in death or serious injuries. Every year, a significant percentage of employees are temporarily or chronically disabled due to injuries sustained on construction sites (Health and Safety Executive, 2023). According to the United States Bureau of Labor Statistics (2021), the annual number of deaths in the construction sector in 2020 was 1,008, which accounted for 21% of all deaths among US workers. In Great Britain, Construction-related fatal injuries jumped

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by 55% from 29 to 45 in the 2022/23 reporting year and it remains the sector with the highest number of deaths, according to the Health and Safety Executive (HSE, 2023). The most common types of fatal accidents in the United Kingdom (UK) in 2022/23, as reported by the HSE, are as follows:

- Falls from a height.
- Struck by moving object.
- Struck by moving vehicle.
- Trapped by something collapsing/overturning.
- Contact with moving machinery.

Construction-related accidents lead to productivity losses and increased construction expenses due to project delays, employee absences, healthcare procedures, employee health coverage, legal costs, reimbursement costs, and recovery sessions. These social and economic losses have an overall effect on human well-being (Schaefer et al., 2008).For these reasons, several research studies have suggested various techniques and approaches to improve the Health and Safety (H&S) performance of the construction industry. Lean Construction (LC) has been among the key research themes to enhance the H&S aspects of construction. According to LC principles, accidents are causes of process waste in terms of duration, budget, and workforce productivity, which obstruct workflow and impact product quality. Therefore, from a productivity perspective, injuries must be avoided (Mitropoulos et al., 2007) As a rule of thumb in LC, it is essential to ‘stop production whenever it feels unsafe’. In addition, ‘Respect for People’ is a core principle in LC. Several studies suggested that implementing LC principles across worksites can offer an opportunity for construction professionals to improve the H&S of construction work environments (Salem et al., 2007; Antillon et al. 2019, Melo and Costa, 2023). At the same, it has been argued that a focus on H&S from an early stage in projects, using LC, can also help companies achieve their sustainability targets and objectives (Emuze and Smallwood, 2013; Sarhan et al., 2021) and improve project value delivery (Gomez et al., 2020). This paper investigates the value of LC in tackling H&S concerns, specifically the root causes of construction project worksite accidents.

During the past two decades, the efficacy of LC practices towards enhancing H&S has been a source of considerable discussion. However, the topic has been primarily investigated for individual LC methods with limited investigations on the conceptual relationship between LC and H&S. There is little known about how LC tools and techniques could actually help to improve H&S performance on construction sites. The novelty of this study is through its distinctive methodological approach, which aims to inductively explore professionals' knowledge, opinions, and observations to unfold a phenomenon and pinpoint the link between LC and H&S. The paper contributes to knowledge and practice by providing a better understanding of the value of LC in reducing common construction site accidents. The paper is structured to start with a background section, followed by the methodology and the rationale behind the choice, the results, and closing with the overall discussions and conclusions.

BACKGROUND AND RESEARCH OBJECTIVES

An occupational accident is an unexpected event that leads to personal harm or illness, damage to assets, resources, equipment, the environment, or any impact on business opportunities (Hughes & Ferrett, 2012). The nature of construction activities, fluctuations in workplace conditions, climate impact, construction materials, and the constant need for mobility are among the challenges linked with construction worksites (Perttula et al., 2003).

As a result of such circumstances, employees are more likely to be engaged in various types of injuries.

Numerous studies have been conducted to identify the various causes of workplace accidents in the construction industry. Defects and engineering issues can introduce potential hazards, which can stem from inaccurate design or execution flaws (Bellamy et al., 2008;). Weak planning and supervising, poorly maintained worksites, and lack of expertise within the workforce are among the project management-related causes of accidents (Bellamy et al., 2008). Moreover, human-related issues such as the psychological state, training, physical and emotional abilities, and motivational factors, are among the key causes of accidents (Bellamy et al., 2008; Kletz, 1993; Sawacha et al., 1999). Administrative failures and the lack of implementation of H&S standards are also contributing factors (Toole, 2002). Overall, these findings highlight the multifaceted nature of construction-related accidents and the need for a holistic strategy that encompasses management, training, compliance, and a safety culture.

One of the fundamental concepts of LC is to constantly optimise operations to reduce waste, such as non-value-adding activities and other interruptions within the flow of operations. It is well established that reliable workflow in construction operations cannot be achieved without safe work practices. Hence, every event that can impact employees' well-being and obstruct the flow of value-adding activities can be viewed as a 'source of waste' that should be eliminated (Sarhan et al., 2018). Accidents often lead to a variety of consequential wastes, lower efficiency, economic losses, and project delays. Therefore, workplace H&S management can minimise the adverse impacts of accidents such as loss of work time and compensatory payments (Jang & Kim, 2007). Aside from the productivity perspective, a key aspect of LC is promoting 'respect for people' (Emiliani, 2008; Liker, 2011; Korb, 2016) and incorporating ethical responsibility towards maintaining employees' physical and mental health (Rother, 2010; Akers, 2011; Gomez et al., 2020). Therefore, from a theoretical standpoint, LC and H&S are well-aligned and interrelated. It is already well-established that the effective application of LC can promote H&S in the workplace and minimise accidents. However, this study contributes to knowledge by addressing the following research objectives:

- Identifying the most common causes of accidents on UK construction sites and investigating their root causes,
- Exploring the relationship between LC and H&S performance,
- Providing practical insights from industry experts on the barriers and enablers of adopting LC for improving H&S performance on construction sites, and
- Developing recommendation for construction firms and professionals on how LC can be used to tackle these identified issues.

Several LC methods have the potential to improve H&S performance in construction projects. For example, the Last Planner System (LPS) can enhance workplace safety by empowering employees, aligning tasks with individual abilities, and promoting collaboration. Through pre-construction hazard assessments and regular monitoring, it proactively addresses potential causes of accidents, including ineffective practices, anxiety, and poor cooperation (Saurin et al., 2001; Sacks et al., 2005; Leino and Elfving; 2011; McHugh et al., 2021). Another example is the 5S method, which emerges as a potent safety tool by fostering a clean and organised workspace, enhancing comfort, and effectively managing resources. It directly addresses potential causes of accidents such as bottlenecks, inadequate work conditions, and workplace risks like slips, falls, and operating in narrow spaces (Ng et al., 2012). Visual management has been shown to be instrumental in advancing workplace safety through improved visibility, risk management, and clear warning signals. It directly addresses potential causes of accidents by enhancing communication, strengthening monitoring and scheduling, fostering site expertise and shared understanding, and promoting compliance with legislation. This proactive approach minimises the risk of accidents arising from weak communication channels, inadequate monitoring, lack of expertise, misunderstandings, and faulty decision-making (Melo and Costa, 2023). Other lean approaches for reducing onsite accidents include the use of standardised work (Mollo et al., 2019), Five Whys (Leino and Helfenstein, 2012), leading performance measurement indicators (Ng et al., 2012), Kanban (Jang and Kim, 2007), prefabrication and supply-chain management (Arbulu et al., 2005; Adekunle et al., 2023), BIM (Etges, 2020) and unmanned aerial systems (Melo and Costa, 2023).

METHODOLOGY

As indicated earlier, the main purpose of this study is to investigate how the application of LC can enhance H&S performance on construction sites. An inductive approach for qualitative data analysis was adopted in this study to gain a better and more practical understanding of the relationship between LC methods and H&S performance. Semi-structured interviews were conducted with eight UK industry experts in the field of LC. These experts were selected based on their extensive experience and expertise in implementing lean practices in construction projects. A snowballing technique was adopted, where each expert was asked at the end of every interview to recommend the next interviewee with relevant expertise and knowledge. Snowball sampling is an effective research method that is commonly used in social science research when the population under investigation is either hidden or difficult to reach (Browne, 2005; Waters, 2015). Table 1 provides details about the selected experts in terms of their profiles, years of relevant experience, and current work location. Interviews were conducted online and recorded for data analysis purposes after taking consent from the participants. Each interview lasted for about 30-45 minutes. The qualitative data collected through these interviews were analysed using thematic analysis (Braun and Clarke, 2006), aiming to identify patterns, themes, and key factors that contribute to the intersection of LC and H&S performance. A qualitative data analysis software (i.e. NVivo) was used to support with data coding and analysis, following the guidelines provided by Sarhan and Manu (2021).

Table 1: Interviewee Details

Expert no.	Professional's profile	Work experience	Work location
E1	Lean Construction Consultant	20 Years	Global
E2	Head of Project Planning	11 Years	UK
E3	Lean Construction Leader	19 Years	UK
E4	Lean Practitioner	8 Years	UK
E5	Productivity and Performance Manager	32 Years	Europe
E6	Senior Project Manager	28 Years	UK
E7	Chief Executive	46 Years	UK
E8	Director of Lean Consultancy	18 Years	Global

The choice of semi-structured interviews allowed for a flexible and systematic exploration of the experts' insights, experiences, and observations. The interview questions were designed to elicit detailed responses regarding specific lean tools, methodologies, and practices believed to influence H&S performance in construction. Four main open-ended questions were used for this purpose, as follows:

- **Q1.** What are the most common H&S problems / issues on construction sites?
- **Q2**. What are the main causes of these accidents or related H&S problems?
- **Q3**. How can lean construction help to improve H&S performance in construction?
- **Q4**. Which Lean construction (LC) tools or strategies could be used to address H&S issues in construction projects, and how?

RESULTS

In this section, the outcome of the thematic analysis of the collected data is provided. Four themes were identified based on the responses of the interviews. Two were related to H&S in construction and two were focused on their views on the interrelationship between LC and H&S. The following sub-sections present the results of the four identified themes.

COMMON H&S ISSUES ON CONSTRUCTION SITES

In order to set the context for the interview, the experts were asked about their experience with H&S and what they perceive as the most common H&S issues within the industry. Different types of H&S issues were highlighted. E1 and E7 found that falls from height are the most common, indicating that improper Personal Protective Equipment (PPE) compound this safety hazard. E2, E4, E5, E7 and E8 consider slips, trips and falls the most common issue. E2 also mentioned tiredness and fatigue, especially towards the end of the shift when workers may be making decisions that lead to injury. This aligns with findings of research by Turner and Lingard (2020) that investigated the impact of the physical demands of the construction work and (experienced and anticipated) bodily pain on the mental health and productivity of construction workers. E3 considered chemical hazards, obstructions on the site of vehicles, and the motion of people as major issues. While E4 mentioned that in the last 6-7 months of their work, utility strikes came up as a safety issue on construction sites. E6 stated that they are currently working on a highway project, and their team identified people-plant interference as the biggest hazardous factor.

CAUSES OF CONSTRUCTION SITE ACCIDENTS

The next question was intended to support the focus of the research on addressing the root causes of accidents. Therefore, the experts were asked about their views on the causes of site accidents. E1 indicated that poor planning is among the key causes of accidents. They stated that *"when the work methods are not agreed, the operational definitions are not established, and the first run studies are not done, these will cause on-site accidents".* E3 made a similar notion by suggesting that "*the most common cause of accidents is a lack of site planning because a lot of the hazards are identified within planning before workers go to the site…and to be honest, many people don't see these hazards individually*". E2 considered fatigue and lack of experience as causes of accidents, highlighting the role of human error in worksite accidents. This may also suggest the need for considering the implications of occupational stress and job-burnout on workers' safety performance (Sarhan *et al*., 2023). A similar finding was mentioned by E4, who indicated that personal behaviour is a major cause of accidents. They also explained that *"Employees know that what they're doing is wrong. They're taking the shortcut there, trying to do things quicker whether that is driven by targets or whether that's driven by intentionally, but it causes accidents*". E6 asserted that human behaviour is a main cause of accidents by saying that *"H&S starts at home, it starts with the individual. People forget having things in their minds and being under pressure to go out and do their day-to-day work, and they end up with safety issues. And this is where behaviour change is* *required”.* It is important, though, to consider how project and organisational systems (e.g. contracts, payment methods and performance measurement systems) influence behaviours. E5 pointed out that lack of awareness and communication gaps play a major role in accidents. They added that untidy workplaces, unsafe working environments, and misunderstanding of information cause a large number of onsite accidents. E8 also identified poor communication as a key cause of accidents. E7 mentioned several general causes including employees behaviours, resources, activity management, planning and scheduling. They also indicated that among the causes is that *“people are reluctant to develop a plan at work, and when developed, they are reluctant to stick to that plan”.*

THE ROLE OF LC IN IMPROVING THE H&S PERFORMANCE IN CONSTRUCTION

When it comes to the participants’ views on the role of LC in improving H&S, E3 considered that a key concept in LC is about dissecting the activities into small activities and ensuring that each activity feeds into and adds to pre-identified value with the project stakeholders. The concept of flow is also essential and the interdependency between activities should not be overlooked. They asserted that the correct application of the Transformation-Flow-Value generation (TFV) concept can enhance H&S performance in construction. In addition, they indicated that the use of digital tools along with the Last Planner System (LPS) provides good results in terms of identifying the H&S hazards. They also highlighted that collaborative planning addresses H&S, as employees can know which machines/equipment are going to be used, the number of people working, and the motion of the machine and workers. E2 explained that a lean strategy ensures that the risk assessments and methods statements are delivered in time, so that employees can assess them for accuracy and workability. E4 and E5 see that visual management plays a big part in advancing H&S in construction, as it enables transparency and information sharing. As per E6, LC has a major effect on H&S risks. Based on their experience, proper planning can reduce unnecessary machinery movement by 50% and reduce carbon emissions, which are considered a hazard to the employees, surrounding people, and the environment. E1 described that *“there is a lot more to lean construction than the last planner, but that’s how firms choose to write it up. The last planner has lots of planning conversations. The first conversation is about risk analysis and safety at construction sites. Also, 5S is very important as it will reduce trip hazards and so on, and another thing which I think would make an enormous difference going it would improve productivity along with reducing hazards”.* E7 and E8 affirmed that collaborative meetings, daily briefings, and safety checks as part of a LC strategy can help to minimise H&S hazards. E7 provided an example by indicating that *“to identify potential areas for risk as part of activities, we ask a series of questions for each planned activity like: have you got the detailed design? have you got the resource or access? Safety considerations about materials, plant permits, and are they all identified?”.* These are the necessary pre-conditions for starting any construction activity on site, which are conceptualised in LC literature as the seven flows needed to avoid the ‘Making-Do’ kind of waste (Koskela, 2004; Kraemer et al., 2007).

BENEFITS AND BARRIERS OF IMPLEMENTING LC TO IMPROVE H&S

A key objective of the interviews was to understand the correlation between LC and H&S performance to establish practical solutions for H&S improvement through LC. Therefore, the final group of questions focused on identifying the benefits and barriers of LC implementation to enhance H&S performance in construction projects. E1 mentioned that the focus of LC on value generation is a key benefit to H&S as LC will enable a systemic process for holistic improvement considering the complexity of construction systems. E2 indicated that *“the way you plan your work better through LC means that you're eventually improving H&S in a proactive way”.* However, they shared their concerns that although the benefits of

LC have been evident over more than two decades, the market is not yet mature enough to understand the correlation between LC and H&S, due to the general perception that lean is about time and cost savings. E3 confirmed a similar notion that a key barrier is related to industry culture. They asserted that there is a lot to do in terms of embedding LC into current industrial practices and challenging the traditional perception of lean as a mere productivity enhancement tool. They also highlighted the importance of change management to influence current practices and provide evidence of the overlap between LC and H&S. E7 supplemented this view by stressing the problem of aging workforce that are usually resistant to changes. They emphasised the role of project leadership in promoting LC practices and demonstrating their benefits to the H&S of construction workers.

E4 highlighted transparency as a key strength of LC to help construction teams in minimising H&S hazards. They also indicated that the availability of data through LC tools can play a key role in establishing Key Performance Indicators (KPIs) for H&S monitoring and control. E5 considered the behaviour change as both a benefit and a barrier in terms of H&S improvement. They clarified that the ability of LC to influence behaviour towards a safer work environment can highly improve H&S performance of construction projects. However, they highlighted the risk of disruptions and confusion caused by new initiatives, especially in traditional industries such as construction, which might create safety hazards that impact the overall H&S performance. E6 provided an interesting view of the role of LC in using modern production methods in construction, such as modular construction and Just-In-Time, which are generally safer methods of construction compared to traditional hazardous heavy site activities.

In summary, the key benefits identified from the interviews were related to transparency, look-ahead collaborative planning, communication improvement, risk reduction, enhanced efficiency, modern methods of construction, and prioritisation of workers' wellbeing. On the other hand, the main barriers were related to the industry culture, behavioural aspects, time and cost of implementation, and standards and guidelines.

DISCUSSION

In exploring the complex relationship between LC and H&S performance in construction projects, our findings align with the acknowledgement that the causes of poor construction H&S are multifaceted. The expert interviews emphasised that LC practices directly counter several root causes of H&S accidents. LC can provide practical solutions to enhance H&S in construction projects. For example, collaborative planning emerged as a powerful mechanism fostering a shared understanding of construction activities (Pasquire and Court, 2013) and identifying hazards proactively. Daily huddles were identified as reinforcing safe procedures and enabling transparent discussions of risks. Visual management was recognised for its effectiveness in risk management by monitoring and eliminating hazardous actions on construction sites. These mechanisms collectively address human errors, oversight, miscommunication, and noncompliance – prevalent causes of H&S accidents on construction sites.

Importantly, LC practices were perceived not only as a group of tools and methods but as a catalyst for deeper cultural and systemic changes within the construction industry. They instil a sense of order, efficiency, and collective responsibility while flagging hidden risks. Participant experts highlighted the connection between LC and modern building techniques by emphasising their inherently safer nature. Utilising LC to create ecosystems centred on worker well-being was identified as an effective means to elevate the priority placed on accident prevention. As opposed to the traditional view of the workforce, which visualises individual employees conducting work along their linear career paths to create value for their organization, a workforce ecosystem is considered a more inclusive and integrated approach for strategically managing a diverse group of internal and external workers. The concept of a workforce ecosystem can be defined as "*a structure focused on value creation for an organization that consists of complementarities and interdependencies. This structure encompasses actors, from within the organization and beyond, working to pursue both individual and collective goals*" (Altman et al., 2021, p. 1).

Despite the evident benefits of adopting LC for improving H&S performance in construction projects, a key emerging barrier is the ingrained industry mindset that safety, profit, and efficiency represent competing aims. LC is often viewed as a set of solutions for waste reduction and productivity augmentation rather than an ethos enabling both safer and more productive job sites concurrently. Overcoming this scepticism requires leadership commitment, active worker engagement, and measurable H&S gains linked to LC adoption. The participants stressed that meaningful change management relies on demonstrating the compatibility of safety, profit, and efficiency within a LC strategy.

Based on the findings from the literature review and semi-structured interviews, we formulated a conceptual model that links the root causes of accidents, as reported in Haslam et al. (2005), with LC methods (see Figure 1). This developed conceptual model provides general guidelines to support H&S improvement in construction projects but is not intended to be a comprehensive approach. It serves as a steppingstone for further research and practical implementation by providing a framework for construction professionals, project leaders, and policymakers to enhance safety protocols by adopting LC principles.

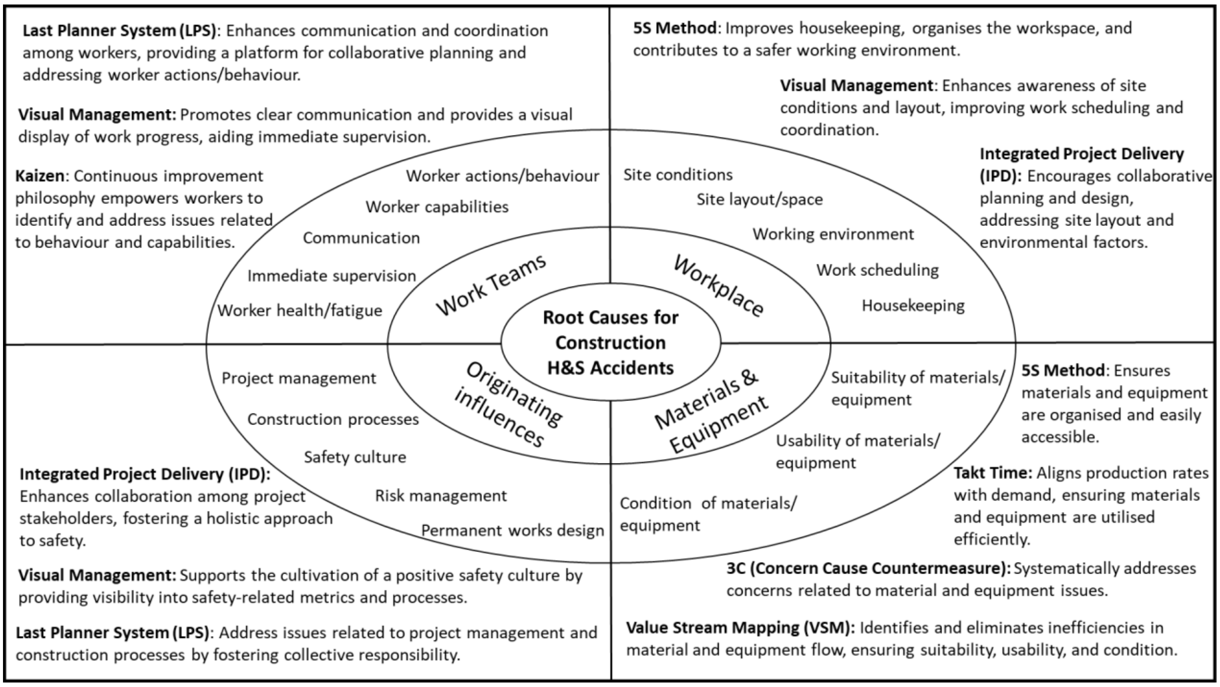

Figure 1: Conceptual model linking LC methods with root causes of construction accidents.

CONCLUSION

Poor health and safety performance remains a critical issue in the construction industry leading to injuries, fatalities, social and economic impacts. Prior research has connected LC principles of waste reduction and continuous improvement to enhanced safety outcomes. This study sought to elucidate the practical mechanisms underpinning this relationship based on insights from eight LC experts sharing their knowledge and suggestions from decades of first-hand industry experience.

Key findings reveal tangible methods by which the LPS, Visual Management, 5S among other LC methods proactively identify hazards while fostering orderly, transparent work ecosystems centred on worker wellbeing. Beyond isolated techniques, a lean culture and holistic systems approach was perceived to drive safer practices across different project dimensions. However, barriers related to industry culture and the prevailing views of cost, schedule, and safety as competing priorities persist. It is recommended that leadership commitment to worker-centric ecosystems is critical for successful implementation of LC to improve H&S performance.

The study concluded with a conceptual model that connects the root causes of onsite accidents with tailored LC countermeasures to provide actionable guidance for health and safety enhancement. The findings of this provide guidance to construction project managers and professionals on how to effectively use LC concepts, tools, and techniques to avoid or minimise the occurrence of accidents and related H&S problems on construction sites.

As an exploratory qualitative study based on interviews with a small purposive sample of industry experts, the findings are not meant to be generalisable without further validation. Quantitative examination is suggested to statistically correlate LC adoption maturity levels to H&S metrics such as incident rates and safety culture index. Comparative case studies of projects using varying degrees of LC methods would shed further empirical evidence on direct and indirect impacts on H&S outcomes. Future research avenues may also explore the longitudinal impact of LC adoption on the industry H&S performance and investigate the dynamics of such implementation within construction companies. Finally, further research is also needed to investigate how LC can help to tackle and minimise mental health issues in construction.

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AN EXPLORATORY STUDY ON VISUAL MANAGEMENT AND PROCESS TRANSPARENCY IN CONSTRUCTION

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ABSTRACT

Several managerial approaches have emerged to address current construction challenges. Among them, information management addresses construction hurdles through process transparency, a core function of Visual Management (VM). Research on VM in construction has focused on its theoretical development and practical implementation. Conversely, research on process transparency has focused on highlighting its significance for construction through transparency strategies. This study aims to extend the research on process transparency and VM by identifying their current applications, measuring their degree of implementation, and highlighting their impact on team performance in two case studies based on observational protocols in Peru.

The main findings are: (1) Process transparency implementation was mainly driven by internal team efforts for job facilitation, while VM primarily served job facilitation, site signage and transparency functions, (2) One site had a higher degree of process transparency while the other had a slightly higher degree of VM, and (3) team performance improvement was associated with visual practices serving the functions of transparency and job facilitation. Some recommendations for the implementation of VM systems on construction sites and for future research were also presented.

KEYWORDS

Lean Construction, information management, process transparency, Visual Management, team performance.

INTRODUCTION

Construction is a project-based industry with relatively high complexity and low efficiency (Vrijhoef & Koskela, 2008). Construction projects often face problems such as misunderstanding of tasks, lack of process integration, delays, and unfulfillment of quality requirements (Galsworth, 2017). Researchers have studied different managerial approaches to mitigate the current challenges of the construction industry, e.g., safety management (Levitt & Samelson, 1987), production management (Koskela, 2000), risk management (Mills, 2001). Among them, information management (Adekunle et al., 2022) is of high relevance given that:

1. Construction projects involve a vast and dynamic amount of information often limitedly displayed or inefficiently updated (Valente & Costa, 2014; Saldias, 2010).

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2. Every task within a construction project should be fully understood to ensure that the overall production system operates as a continuous stream of activities (Brady, 2014).
3. Reassignment of personnel between work sectors, changes in product specifications, and adjustments to construction site settings make the immediate and accurate dissemination of information necessary (Formoso et al., 2002).
4. Information deficit in the workplace is highly associated with production waste (waiting, defects, over-processing, etc.) in construction processes (Formoso et al., 2002).

Information management aims to provide all project stakeholders with up-to-date, accurate, accessible, understandable, and relevant information (Reinbold, 2020). Enhancing process transparency increases information availability by making the attributes of construction processes visible to everyone. It is defined as "the ability of a production process (or its parts) to communicate with people" (Dos Santos et al., 1998). Process transparency seeks to deal with poor process orientation, ineffective decision-making, and prominent levels of waste and variability in construction processes (Formoso et al., 2002).

Tezel et al. (2016b) presents the improvement of process transparency as one of the main functions of a sensory strategy for information management called Visual Management (VM), which aims to "improve organizational performance through connecting and aligning organization vision, core values, goals, and culture with other management systems, work processes, workplace elements, and stakeholders, by means of stimuli" (Tezel et al., 2009a). The improvement of process transparency through VM is expected to have an influence on waste reduction (Koskela, 1992; Formoso et al., 2002), which enhances team performance for quality during process execution. This paper presents the first findings of an extensive research project that aims to assess the impact of implementing a visual management system on process transparency and team performance for quality in construction. The scope of the paper is limited to presenting the findings of analyzing the current applications, degree of implementation, and impacts on team performance of process transparency and VM in 2 construction sites from a railroad project in Peru.

LITERATURE REVIEW

VISUAL MANAGEMENT

VM is a managerial strategy that emphasizes short-range sensory communication (Tezel et al., 2016b). Communication is not limited to visual messages, but involves all 5 senses: taste, touch, smell, hearing, and sight (Liff & Posey, 2004). VM is achieved in visual workplaces (Galsworth, 1997). A visual workplace presents an information field integrated with the work setting, where the actual information need might occur, thus extending access to information to a larger number of people (Tezel et al., 2011). VM supports managerial practices (Tezel et al., 2009a) such as Health, Safety, Security & Environment (HSSE), production, quality, inventory, and knowledge management. VM also provides specific functions at an operational level: (1) transparency, (2) discipline, (3) continuous improvement, (4) job facilitation, (5) on-the-job training, (6) shared ownership, (7) management by facts, (8) simplification, and (9) unification (Tezel et al., 2009b).

Taxonomies and typology

Numerous VM taxonomies have been proposed based on its purpose, such as regulating human behavior (Galsworth, 1997) or presenting information to users (Bititci et al., 2016). For instance, Tezel et al. (2015) proposed a taxonomy of visual practices, which are visual elements implemented in the field to improve a specific aspect of construction operations (see Table 1).

Table 1: Taxonomy of Visual Practices (Adapted from Tezel et al., 2015).

Purpose	Examples
Removing visual barriers	Site layout organization, using chain-link fences, etc.
Standardize identification and location	Marked pathways, site maps, ID cards, etc.
Systematic site order	5S implementation.
Production control	Material tag control, scaffolding control, Kanban, etc.
Production leveling	Heijunka boards, simple colored beats, etc.
Prototyping and sampling	Product prototypes, material samples, etc.
In-station quality	Colored boards, Andon boards, etc.
Site signage	Safety signs, safety information, desired practices, etc.
Performance management	Overall progress boards, productivity metrics, etc.
Improvising Visual Management	Aids for on-site quality control and assurance.
Work facilitation	Visual work instructions, project drawings display, etc.
Mistakeproofing	Poka-yoke devices.
On-site prefabrication	Prefabricated construction elements.
Distributing system-wide information	Visual information for the workforce.

By integrating VM taxonomies, Brandalise et al. (2022) proposed a typology that classifies visual elements by complexity and context dependence in 3 levels and 7 attributes (Figure 1).

Level 1: Device	A visual display designed to achieve a certain degree of control by its visual appeal only for a certain period (e.g. permanent safety signals).
(1) Degree of control	*Visual indicator,* which shares information with voluntary compliance. *Visual signal,* which catches attention and generates a reaction. *Visual control,* which impacts behaviors by limiting physical quantities. *Visual guarantee,* which ensures desired outcomes by mistake-proofing.
(2) Visual expression	Static (immutable) or dynamic (updated over time).
Level 2: Practice	A visual device designed to fulfill a specific function with a communication, collaboration, or managerial integration role (e.g. Kanban, Andon, 5S).
(3) Main function	Control artifact, execution procedure, target specification, material delivery, prototype, or others (specified in Tezel et al. (2015)).
(4) Communication role	One-to-one, one-to-many, many-to-one, or many-to-many.
(5) Collaboration role	Collaborative (stimulating interactions) or non-collaborative.
(6) Integration role to management routines	Integrated or not integrated.
Level 3: System	Two or more integrated visual practices with greater impact on the project.
(7) Integration of practices forming a system	Integrated or not integrated.

Figure 1: Typology of Visual Elements (Adapted from Brandalise et al., 2022).

Visual Management Implementation

Some VM practices adapted for construction projects are well described in the literature, such as 5S (Tezel & Aziz, 2016), Kanban (Costa & de Burgos, 2015), and Andon (Kattman et al., 2012). At the beginning of its adoption in construction, VM was mostly applied in site offices to support managerial decisions, and only health and safety warning boards, focused on information giving, were usually found in construction site working areas (Tezel et al., 2016a). However, recent studies have shown the application of many other visual practices in construction sites (Moser & dos Santos, 2003; Tezel & Aziz, 2016; Tezel et al., 2015).

PROCESS TRANSPARENCY AND LEAN

Lean Construction, guided by Lean Thinking, aims for continuous improvement and value flow (Womack & Jones, 1996). To achieve this, construction processes should be easily understood by everyone involved (Dos Santos et al., 1998). Process transparency involves making the main process flows visible and comprehensible from start to finish (Koskela, 1992), allowing for easy problem identification within the production system (Moser & dos Santos, 2003).

Koskela (1992) outlines six strategies for enhancing transparency: (1) reducing interdependence between production units, (2) using visual artifacts that allow immediate recognition of process status, (3) making the process directly observable, (4) incorporating information into the process, (5) maintaining a clean and orderly work site, and (6) representing invisible attributes through measurements. Formoso et al. (2002) suggested 10 performance indicators to evaluate process transparency (see Table 2).

Table 2: Process Transparency Indicators (Adapted from Formoso et al., 2002).

Transparency indicator	Definition / Criteria
(1) % of workstations presenting no interference from another process	Sharing space, equipment, or materials with other crews.
(2) Number of visual indicators	They only provide information.
(3) Number of visual signals	They aim to generate a response.
(4) Number of visual controls	They limit physical quantities.
(5) Number of visual guarantees	They ensure outcomes through mistake-proofing.
(6) % of process stages observed from the most favorable viewpoint	Stages clearly observed throughout the whole process.
(7) % of process stages clean and tidy	Minimum material waste and visually organized.
(8) Number of process performance indicators collected regularly	Adress the ease to collect indicators from the process.
(9) Number of workstations analyzed	Required for the 1st indicator.
(10) Number of process stages	Required for the 2nd indicator.

METHODOLOGY

This paper presents an exploratory research based on two case studies of construction sites in Peru using 3 sources of evidence: participant observation, document analysis, and unstructured discussions (Yin, 1994). Participant observation was selected due to the role of the first author as field supervisor, with data primarily collected during quality inspections. Unstructured interviews, characterized by undetermined questions and answers (Minichiello et al., 1990), complemented participant observation and involved conversations with site managers to enhance data collection. Documentation consulted included field notes, photos, daily reports, and weekly reports.

The first author collected data from the Site A from January 3rd to January 13th, 2024, and from the Site B from January 15th to January 28th, 2024. The scope of study for VM analysis was the construction field and its execution procedures. For transparency analysis, two main construction processes were sampled from each site, taking time constraints into consideration.

Data on VM and process transparency was compiled in observation protocols. The VM protocol (Figure 2) classified visual elements through a checklist (Tezel et al., 2009a; Brandalise et al., 2022; Galsworth, 1997; Bititci et al., 2016; Tezel et al., 2015), and analyzed them through guided questions (Valente et al., 2019). The process transparency protocol (Figure

3) identified transparency indicators (Formoso et al., 2002) along with transparency strategies (Koskela, 1992). Team performance for quality was assessed through field notes on defects and rework activities. A grading system is provided to ease the comparativeness of the units studied. Inferences were drawn from the relationships between the indicators, potential causes of significant results, and the primary VM functions observed in the field.

VISUAL ELEMENT			
Name:		**Location:**	
Affects processes? Which ones?	◉	◉	◉
CLASSIFICATION			
Function (Tezel et al., 2009a): Select all that apply.	☐ Transparency ☐ Discipline ☐ Continuous improvement ☐ Job facilitation ☐ Unification ☐ On-the-job training ☐ Shared ownership ☐ Management by facts ☐ Simplification		
Level (Brandalise et al., 2022):	☐ Visual device	☐ Visual practice	☐ Visual system
Degree of control (Galsworth, 1997)	☐ Visual indicator ☐ Visual signal ☐ Visual control ☐ Visual guarantee		
Visual expression (Bititci et al., 2016)	☐ Static ☐ Dynamic		
Purpose (Tezel et al., 2015)	☐ Removing visual barriers ☐ Standardize identification and location ☐ Production leveling ☐ Systematic site order ☐ Performance management ☐ Work facilitation ☐ Mistakeproofing ☐ Prototyping and sampling ☐ Distributing system-wide information ☐ On-site prefabrication ☐ Improvising Visual Management ☐ Site signage ☐ In-station quality ☐ Production control		
Role of communication	☐ One-to-one ☐ One-to-many ☐ Many-to-one ☐ Many-to-many		
Role of collaboration	☐ Collaborative ☐ Non-collaborative		
Role in managerial routines integration (If so, in which ones?)	☐ Integrated with management routine ☐ Not integrated with management routine ☐ HSSE ☐ Production ☐ Quality ☐ Inventory ☐ Knowledge ☐ Other: ____________		
Other practices of the system	◉	◉	◉
ANALYSIS (Valente et al., 2019)			
1) Visual attributes	- What is the content to make available?	- Which kind of coding is used?	
2) Visual implementation	- What is the frequency of use?	- Who is responsible?	
3) Visual information	- Which type of data is used?	- Where is information placed?	
4) Problem solving	- Which type of problems are avoided?	- Is there a standard procedure?	

Figure 2: Visual Management Protocol (Summarized).

CONSTRUCTION PROCESS					
Name:			**Location:**		
Stages (Indicators #6, #7 and #10 - Formoso et al. (2002)):	**O**	**K**		**O**	**K**
1)			3)		
2)			4)		
O: Observable from the most favorable viewpoint | **K**: Kept clean and tidy					
Transparency approaches (Koskela, 1992)					
Reducing interdependence between production units. *(If identified, how is it applied?)*					
Using visual artifacts that allow immediate recognition of process status. *(If identified, how is it applied?)*					
Making the process directly observable. *(If identified, how is it applied?)*					
Incorporating information into the process. *(If identified, how is it applied?)*					
Maintaining a clean and orderly work site. *(If identified, how is it applied?)*					
Representing invisible attributes through measurements. *(If identified, how is it applied?)*					
Transparency indicators (Indicators #1 to #5 - Formoso et al. (2002))					
1) Is there an interference with other processes? Which ones?			2) Is process information displayed? How? (Visual indicators)		
3) Are there any visual signals? Which ones?			4) Are there any visual controls? Which ones?		
5) Are there any visual guarantees? Which ones?					

Figure 3: Process Transparency Protocol (Summarized).

RESEARCH FINDINGS

Two construction processes were analyzed at each construction site and a total of 19 different visual elements were identified, 8 of them being observed in both sites.

PROCESS TRANSPARENCY

In both sites, the execution of masonry walls of concrete blocks was studied. Site A was re-starting activities after a pause period, so only the first stages of its processes could be studied. The denomination for each process is shown below:

- (A1) Execution of off-site prefabricated slabs and on-site compression slabs in Site A.
- (A2) Execution of masonry walls of concrete blocks in Site A.

- (B1) Waterproofing and backfilling of street-level slab in Site B.
- (B2) Execution of masonry walls of concrete blocks in Site B.

Figure 4 and Figure 5 illustrate some stages of the construction processes mentioned above.

Figure 4: Main Stages of the Construction Processes A1 and A2.

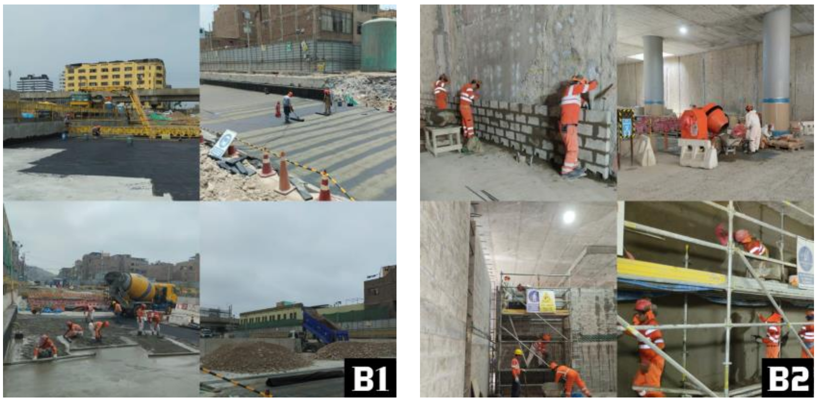

Figure 5: Main Stages of the Construction Processes B1 and B2.

The application of the six transparency strategies is verified through a check/cross marking and their specific ways of implementation are explained if the strategy is applied (see Figure 6).

TRANSPARENCY APPROACHES OF PROCESSES A1, A2, B1, B2					
1) Reducing interdependence between production units.			4) Incorporating information into the process.		
A1	✓	Use of safety barriers in the surroundings of the process.	A1	✓	Labeling of precast slabs.
A2	✓	Use of safety barriers in the surroundings of the process.	A2	✓	Markings for block positioning.
B1	✓	Use of safety barriers / Labeling of materials.	B1	✗	
B2	✓	Use of safety barriers in the surroundings of the process.	B2	✓	Markings for block positioning, wall height, concrete pouring level, span dimensions, and inspection status.
2) Using visual artif. that allow immediate recognition of p. status.			5) Maintaining a clean and orderly work site.		
A1	✓	Sound alarms during lifting.	A1	✓	Identification of a waste disposal area.
A2	✗		A2	✓	Identification of material collection area.
B1	✓	Lateral markings to identify layers of backfilling.	B1	✓	Material waste constantly disposed.
B2	✓	Markings for inspection status.	B2	✗	
3) Making the process directly observable.			6) Representing invisible attributes through measurements.		
A1	✓	Illumination improvement / Rebar markings for anchorage.	A1	✗	
A2	✓	Rebar markings for anchorage.	A2	✗	
B1	✗		B1	✗	
B2	✗		B2	✓	Metrics for placed blocks (not too clear).

Figure 6: Transparency Strategies of Processes.

Figure 7 shows the identification of transparency indicators #6, #7 and #10. Each one of the process stages studied is verified according to its compliance with the observability and cleanliness indicators through a green check (complies) or red cross (does not comply).

	Stages (Indicators #6, #7 and #10):	O	K		O	K
A1	1) Arrival of prefabricated slabs	✗	✓	5) Hook release	✓	✓
	2) Preparation for lifting	✗	✓	6) Concrete chipping of the main slab	✓	✓
	3) Lifting of slabs	✗	✓	7) Perforation of holes for steel anchorage	✓	✓
	4) Positioning of slabs	✓	✓	8) Steel anchorage in main slab	✓	✓
A2	1) Scarification of concrete at the base of the walls	✓	✓	4) Preparation of mortar mixture	✓	✓
	2) Perforation of holes for steel anchorage	✓	✓	5) Application of mixture and placement of blocks	✓	✓
	3) Vertical rebar anchorage in slab	✓	✓	6) Horizontal reinforcement between block rows	✓	✓
B1	1) Repair of cracks and imperfections on concrete surface	✓	✓	5) Waterproofing test	✓	✓
	2) Priming of bituminous material	✓	✓	6) Placing of geotextile	✓	✓
	3) Placing of 1st waterproofing layer	✓	✓	7) Mortar pouring	✓	✓
	4)Placing of 2nd waterproofing layer	✓	✓	8) Backfilling and compacting	✓	✓
B2	1) Scarification of concrete at the base of the walls	✓	✓	9) Steel reinforcement in pilasters and beams	✓	✓
	2) Perforation of holes for steel anchorage	✓	✓	10) Formwork for pilasters and beams	✓	✓
	3) Vertical rebar anchorage in slab	✓	✓	11) Concrete pouring in pilasters and beams	✗	✓
	4) Preparation of mortar mixture	✗	✗	12) Formwork stripping of pilasters and beams	✓	✓
	5) Application of mixture and placement of blocks	✓	✗	13) Scarification of concrete on pilasters and beams	✓	✓
	6) Horizontal reinforcement between block rows	✓	✓	14) Preparation of mortar mixture	✓	✗
	7) Preparation of liquid concrete	✗	✗	15) Wall plastering	✓	✓
	8) Concrete pouring in wall cavities	✗	✗			

O: Observable from the most favorable viewpoint | K: Kept clean and tidy

Figure 7: Transparency Indicators of Process Stages.

Table 3 enumerates the transparency indicators #1 to #5 of each process and presents an interference rating (IP, 0 = With interference, 1 = No interference), and a visual display rating (VD, 0 = not implemented, 0.5 = partially implemented, 1 = well implemented). To quantify the degree of process transparency, Table 4 presents a general 5-scale rating.

Table 3: Transparency Indicators of Construction Processes.

Process	Process interf.	Visual indicators	Visual signals	Visual controls	Visual guarant.
A1	No (1)	Slab labels (1)	Safety signs (1) Sound alarm (1)	Steel marks (0.5)	No (0)
A2	No (1)	Slab marks (1)	Safety signs (0.5)	Steel marks (0.5)	Prototype (0.5)
B1	No (1)	No (0)	Hot work sign (1)	Layer marks (0.5)	No (0)
B2	No (1)	Wall marks (0.5) Span marks (1) Status marks (0.5)	Safety signs (1)	Pouring level (0.5)	No (0)

Table 4: Process Transparency Observation Results.

Process	Fraction of observable stages (OS)	Frac. of stages clean/tidy (SK)	Fraction of implemented strategies (IS)	Interference rating (IP)	Sum of average VDs (SVD)	Total process transparency degree (TD)
A1	5 / 8	8 / 8	5 / 6	1	2.5 / 4	4.08
A2	6 / 6	6 / 6	4 / 6	1	1.5 / 4	4.04
B1	8 / 8	8 / 8	3 / 6	1	1.5 / 4	3.88
B2	11 / 15	10 / 15	4 / 6	1	2.2 / 4	3.62

According to the grading system, process A1 is the most transparent (TD = 4.08), while process B2 is the least transparent (TD = 3.62).

VISUAL MANAGEMENT STATUS

Out of the 19 different visual elements identified, Site A presented 4 unique elements, Site B presented 7, and both sites presented 8 repeated elements. Both construction sites had implemented visual systems for HSSE management, and some visual practices for quality and performance management. A single visual device without managerial role was also identified in site B. Figure 8 presents the elements classified according to their level and location.

Level	Site A	Site B
System	(1) Color coded safety signs, (2) Labelling of enclosed areas, (3) Safety cone retractable barriers for enclosed areas, (4) Plastic jersey barriers, (5) Solid waste storage signs, and (6) Inspection elements of scaffoldings.	
	(7) Labeling of liquid materials, and (8) Visual reminders for safety meetings.	(9) Safety plan board on-site.
Practice	(10) Markings for block positioning, and (11) Construction element labeling.	
	(12) Markings on steel rebars for anchoring, and (13) Temporal prototype of concrete block reinforcement.	(14) Lateral markings for backfilling layers, (15) Markings for masonry wall height, (16) Concrete pouring level, (17) Markings of span dimensions on masonry wall, and (18) Markings for metrics of placed blocks.
Device	-	(19) Markings of inspection status.

Figure 8: Visual Elements Identified.

Figure 9 presents the functions (Tezel et al., 2009b) and purpose (Tezel et al., 2015) of each element identified.

Level	Element	Site	Functions	Purpose
System	(1)	A and B	Discipline	Site signage
	(2)		Transparency / Job facilitation / Shared ownership	Standardize identification and location
	(3)		Discipline	Removing visual barriers
	(4)		Discipline	Standardize identification and location
	(5)		Transparency / Discipline	Site signage
	(6)		Transparency / Discipline	Production control
	(7)	A	Transparency / Job facilitation	Standardize identification and location
	(8)		Transparency / Discipline / Simplification / Unification	Distributing system wide information
	(9)	B	Transparency / Discipline / Simplification	Distributing system wide information
Practice	(10)	A and B	Transparency / Job facilitation	Work facilitation
	(11)		Transparency	Standardize identification and location
	(12)	A	Transparency / Job facilitation	Work facilitation
	(13)		Transparency / Job facilitation / On-the-job training	Work facilitation
	(14)	B	Transparency / Job facilitation	Work facilitation
	(15)		Transparency / Job facilitation	Work facilitation
	(16)		Transparency / Job facilitation	Work facilitation
	(17)		Transparency / Job facilitation	Work facilitation
	(18)		Transparency / Continuous improvement / Management by facts	Performance management
Device	(19)	B	Transparency	-

Figure 9: Functions and Purpose of Each Visual Element.

A 20-scale rating was developed to assess the degree of VM of each element:

- *Level:* Visual device = 2, visual practice = 4, and visual practice of a system = 8.
- *Degree of control:* Visual indicator = 1, visual signal = 2, visual control = 3, and visual guarantee = 4.
- *Visual expression:* Static = 0, and dynamic = 1.
- *Role of communication:* One-to-one = 1, many-to-one = 2, one-to-many = 2, many-to-many = 3.
- *Role of collaboration:* Non-collaborative = 0, and collaborative = 2.
- *Role in managerial routines integration:* Not integrated = 0, and integrated = 2.

Figure 10 presents the remaining classification and VM score of each element identified.

Level	Site	Element	Degree of control	Visual expression	Role of communication	Role of collaboration	Role in managerial routines integration	VM Score
System	A and B	(1)	Visual signal	Static	One-to-many	Non-collaborative	Integrated	14
		(2)	Visual signal	Static	One-to-many	Non-collaborative	Integrated	14
		(3)	Visual control	Dynamic	One-to-many	Non-collaborative	Integrated	16
		(4)	Visual control	Dynamic	One-to-many	Non-collaborative	Integrated	16
		(5)	Visual signal	Static	One-to-many	Non-collaborative	Integrated	14
		(6)	Visual signal	Dynamic	One-to-many	Non-collaborative	Integrated	15
	A	(7)	Visual signal	Static	One-to-many	Non-collaborative	Integrated	14
		(8)	Visual signal	Dynamic	One-to-many	Collaborative	Integrated	16
	B	(9)	Visual indicator	Static	One-to-many	Non-collaborative	Integrated	13
Practice	A and B	(10)	Visual control	Static	One-to-one	Non-collaborative	Not integrated	8
		(11)	Visual indicator	Static	One-to-many	Non-collaborative	Not integrated	7
	A	(12)	Visual control	Dynamic	One-to-one	Non-collaborative	Not integrated	9
		(13)	Visual guarantee	Static	One-to-one	Non-collaborative	Not integrated	9
	B	(14)	Visual control	Static	One-to-one	Non-collaborative	Not integrated	8
		(15)	Visual control	Static	One-to-one	Non-collaborative	Not integrated	8
		(16)	Visual control	Static	One-to-one	Non-collaborative	Not integrated	8
		(17)	Visual indicator	Static	One-to-one	Non-collaborative	Not integrated	6
		(18)	Visual indicator	Static	One-to-one	Non-collaborative	Not integrated	6
Device	B	(19)	Visual indicator	Static	-	-	-	6

Figure 10: Classification and VM score of visual elements.

According to the rating system, elements (3), (4) and (8) have the highest VM score in the study.

TEAM PERFORMANCE FOR QUALITY

The team performance study was addressed by observing the incidence of defects or rework during the execution of construction processes and the quality inspection of process stages.

- *Process A1*: One defect in the alignment of pipe holes on the precast slabs and one rework activity due to vertical displacements in 5 anchorage perforations were observed.
- *Process A2:* No defects or rework were identified. However, we observed overprocessing and overproduction wastes on the scarification of concrete at the base of the walls by covering larger areas and exceeding roughness requirements.
- *Process B1:* Four defects of lack of adherence of waterproofing layers were identified.
- *Process B2:* There were 4 defects pertaining to the depth of holes for rebar anchorage, 2 exposed horizontal reinforcement of masonry walls, excess height on 2 walls, excess thickness on 1 beam, and excess scarification in 2 pilasters.

DISCUSSION

Regarding the applicability of process transparency, the following inferences are drawn:

1. No interferences were observed among the studied processes during the period of observation, facilitating smoother operations and improved cleanliness, as noted by Formoso et al. (2002). However, process B2 exhibited significant untidiness (SK = 10/15), which was attributed to simultaneous work in sectors of the same process, highlighting the relevance of minimizing interferences within the process itself.
2. Stages not observable from an optimal viewpoint, indicated the existence of visual barriers (Formoso et al., 2002), observed in processes A1 (OS = 5/8) and B2 (OS = 11/15). In A1, distant lifting equipment was an unremovable barrier, while in B2, drum mixer location was a removable barrier and built masonry walls were unremovable.
3. We observed some systematic applications of the 1st and 5th transparency strategies within the visual systems in HSSE management, promoting continuity, standardization, and overall improvement. However, the 2nd strategy, seen in processes A1 and B2, lacked consistency to be considered systematic. Meanwhile, subcontractor initiatives drove the implementation of the 3rd and 4th strategies, aimed at facilitating construction

processes. Solely process B2 adopted the 6th strategy, employing simple markings to indicate daily block placements, but their clarity and comprehensibility were limited.

4. Processes studied at Site A exhibited higher process transparency (4.06) than Site B (3.75). This difference may stem from Site A having fewer processes, facilitating better management. Adjusting results for the total number of processes may be necessary.

The main VM functions applied where transparency, discipline, and job facilitation. Meanwhile, both sites presented standardized identification and location, work facilitation, and site signage as main purposes. The total VM score of site B (159) was slightly higher than site A (152).

The study identified visual systems associated with the HSSE managerial practice, highlighting the advantages of integrating visual systems with managerial routines. The quality of the system design was driven by external safety and environmental regulations. However, the implementation followed a rigid top-down approach, as found in Tezel et al. (2015).

Addressing performance deficiencies observed during the study involved implementing visual practices and transparency strategies. While process B2 (TD = 3.62) presented 4 defects pertaining to the depth of holes for rebar anchorage, A2 (TD = 4.04) prevented them by a transparent control through marks in the rebars (VM score = 9). Similarly, exposed horizontal reinforcement in masonry was detected twice in process B2, while A2 clarified it through a displayed prototype (VM score = 9). Within process B2, exceeding wall height was prevented with reference markings (VM score = 8), and excess beam thickness was controlled by marking pouring levels (VM score = 8). Further structured analyses are needed to validate these findings.

Finally, we highlight that implementing VM implies structuring the site as a visual workplace aligned with management agreements, while process transparency requires a particular focus on construction processes and their relationships. Therefore, studying each independently clarifies their distinct features, enabling more efficient analysis and application.

CONCLUSIONS

Past research on process transparency and VM provides a solid basis for methodically studying transparency strategies and visual practices on construction sites. Their applications are process-oriented and site-oriented, respectively. Process transparency strategies were identified as an indirect consequence of internal team efforts for job facilitation, considered a basic level of implementation lacking systematization and visual communication. On the other hand, VM implementation mainly addressed the functions of transparency, discipline, and job facilitation.

The ratings developed to measure the degree of process transparency and VM allowed the comparison between the sites studied. Processes studied at Site A presented a higher degree of process transparency than Site B. However, the global VM score of Site B was slightly higher than Site A. Therefore, we conclude that implementing process transparency and VM do not imply a single effort, but different methods of development.

Improvements on team performance were observed in the prevention and control of defects and rework wastes associated with the implementation of visual practices serving the functions of transparency and job facilitation, and with the implementation of the transparency strategies of incorporate information into the process and make it directly observable.

The exploratory study provided a basis for further research on the influence of VM and process transparency on team performance. Its main contributions are the individual parallel analyses of process transparency and VM to address their differences, the development of observation protocols based on existing indicators and parameters from the literature review, and the introduction of a grading system to measure the degree of process transparency and VM for both study inquiries and implementation efforts. Furthermore, it highlighted the importance of visual systems integrated into management practices that lack visual representation in the field such as production management, knowledge management, and quality management.

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LEAN REFLECTION PRACTICES AND ORGANIZATIONAL KNOWLEDGE MANAGEMENT: A GENERAL CONTRACTOR CASE STUDY

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ABSTRACT

This paper is the sixth in a series discussing the transition of a self-performing general contractor (GC) towards early systems of measurable collaboration to achieve more reliable outcomes. This approach, known as a Systems Approach to Quality (SAQ), enhanced project performance and team culture. This paper investigates the impact of the Monday Quality Calls (MQC) initiated by the Quality Leadership Team (QLT) in 2015 as a forum for reflection, learning, and collaborative tacit knowledge sharing to build SAQ competencies and support organizational change efforts. The research aims to understand the characteristics of the MQC portfolio, evaluate the influence of the QLT, and assess trends in content development over seven years. Findings reveal the MQC's representation of the GC's work and highlight opportunities to enhance geographic and role diversity in participation to support further organizational efforts. Moreover, the paper underscores the value of the MQC as a multi-modal knowledge-sharing platform, facilitating team coaching, onboarding, and refining organizational strategies and processes. The study proposes future research and advocates for similar metrics tracking and knowledge-sharing initiatives in the industry. Ultimately, this paper contributes to refining organizational approaches to quality management and fostering collaborative learning in the Architecture Engineering Construction industry.

KEYWORDS

Systems Approach to Quality (SAQ), Knowledge Management, Capability-building, Organizational Change, Action Learning Research

INTRODUCTION

KNOWLEDGE MANAGEMENT TO INFORM THE REWORK PROBLEM IN THE CONSTRUCTION INDUSTRY

This paper marks the sixth installment in a series of works authored by the current authors and others, aiming to document, analyze, and learn from the journey of organizational change undertaken by a prominent "self-performing General Contractor (GC) focused on highly

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complex and technical projects” (DPR homepage 2024). Central to this contractor's ethos is the commitment to "Exist to Build Great Things" (DPR homepage 2024), not solely in project deliverables but also in fostering excellence in individuals, teams, and relationships. Nonetheless, as Spencley et al. 2018 outlined, this GC faced recurring rework issues common within the construction industry. These issues manifested as unpredictable variations in project outcomes, with instances where work was completed per plans and specifications but did not meet client expectations, thus necessitating rework. Furthermore, warranty issues occasionally demanded post-completion rework, and there were other cases where substantial resources were expended to address punch list items before project closeout (Spencley et al., 2018).

The crux of the problem lies in the entrenched operational practices within the industry, characterized by significant silos among key stakeholders—owners, architects, designers, general contractors, and subcontractors—and challenges with knowledge sharing resulting in knowledge fragmentation and loss during transmission (Spencley et al., 2018; Gil, 2002). As Gil (2002) describes, knowledge and information are distinct; while information has been collected, documented, and referenced, knowledge expresses understanding from experience or education and can be explicit or tacit. Explicit knowledge is documented where tacit knowledge exists in the minds of individuals (Gil, 2002). Gil describes tacit knowledge as having “operational and logistic dimensions” and how knowledge transference amongst stakeholder firms is problematic, leading to assumptions and uninformed decisions (Gil, 2002). These challenges contribute to deliverables not meeting stakeholder expectations (Spencley et al., 2018). Therefore, the challenge is establishing a way to “signal know-how between architects and builders” (Gil, 2002) and the seamless flow of knowledge and information from those with technical, logistical, and operational expertise to designers and owners while minimizing the loss of translation of expectations to those executing the work (Spencley et al., 2018).

To address these challenges, the GC’s approach centered on promoting measurable collaboration early in project lifecycles (Spencley et al., 2018) to “signal know-how” (Gil, 2002). Subsequently, Gordon et al., 2021a recognized this approach as a systematic application of principles encompassing leveraging existing knowledge and information, understanding expectations through identifying Distinguishing Features of Work (DFOW) from each stakeholder’s perspective and aligning them to measurable acceptance criteria at key Points of Release (PoR) across project phases. This approach to sharing tacit knowledge aimed “to develop means and methods for enhancing high-competence contractors and supplies to signal- and designers to retrieve-know how along AEC product development” (Gil, 2002) with the customer. Collaboration facilitates bridging information and knowledge sharing, mitigates risks, supports adaptability to late design changes, improves supply chain efficiency, and fosters product design innovations (Gil, 2002).

Termed a Systems Approach to Quality (SAQ), this methodology yielded promising results, as evidenced by a 2021 case study comparing SAQ-implemented projects with a control group that implemented a prescriptive compliance-based quality approach. The SAQ intervention group demonstrated superior performance across critical success factors for cost, schedule, change management, and quality and fostered more collaborative work cultures (Gordon et al., 2021a). Further studies by Gordon et al., 2022 and 2023 unearthed additional insights. The GMP sign date as a percentage of the overall project timeline, staffing and resourcing patterns, and communication variances in RFIs and PCIs are performance predictors desired by this GC.

Gordon et al. (2021b) describes the organizational change implementation efforts to integrate SAQ into the GC’s approach to work between 2013 and 2020. This paper focuses on how building from tacit knowledge was foundational to their organizational change strategy. Gil 2002 highlights how knowledge transference within companies is also complex. Thus, to address this struggle, the QLT initiated the Monday Quality Calls (MQC) in 2015. The MQC forum aimed to understand, articulate, and disseminate project strategy and SAQ execution principles from different types of projects, including scale, geographies, customers, and core markets, from perspectives of diverse roles at standard phases in the project lifecycle to further support, and develop organizational change endeavors. Through the MQC, the QLT organizational change strategy sought to make tacit knowledge of project team implementation strategies explicit. Within the standard project lifecycle timeline, project teams reflected and shared successes, challenges, and opportunities for improvement on their overall project approach and specific deliverables.

After seven years of MCQ production, the main research question the authors wanted to explore is: What can be learned from the MCQ information and knowledge gathered to inform our organizational change journey moving forward, and what insights can be provided to others embarking on this journey? Specifically, this work sought to answer the following questions: 1) What are the characteristics of the portfolio of work captured in the MQC, and does it represent the GC's body of work? 2) What insights do the characteristics of calls offer regarding the influence of Quality Leadership? 3) Are there observable trends in the development and maturity of the content of the calls?

The remainder of this practice-oriented paper will describe the theoretical framework for the MQC, the IGLC literature review related to this topic, the methodology for investigating the research question, the data collection process, analytical findings, data limitations, discussion of findings, and formative conclusions.

THEORETICAL FRAMEWORK

SYSTEMS APPROACH TO QUALITY (SAQ)

The MQC described the project and organizational strategy and the creation and execution of SAQ. SAQ focuses on understanding and identifying key Points of Release when work will be released to the subsequent phases, as well as building from knowledge and information to inform stakeholder expectation discussions. After identifying project stakeholders and accountable decision-makers, SAQ involves conversations to understand DFOW, which are areas of the work that require increased attention to ensure the work is built right the first time from each stakeholder's perspective. Through conversations, the stakeholders document DFOW alignment to Measurable Acceptance Criteria (MAC) before releasing work for production. When production work is completed, it is evaluated to ensure it meets the agreed MAC before release to the next phase. If deliverable outcomes do not meet documented MAC, causal analysis is performed to understand the breakdown in the process and develop solutions to prevent the issue's reoccurrence (Spencley et al., 2018; Gordon et al., 2021a).

THEORY INFLUENCING MONDAY QUALITY CALLS (MQC) STRATEGY

A few key concepts influenced the MQC strategy. In mid-2019, the Lean and Integrated Delivery Leader, the fourth author of the paper, challenged the first author to consider the QLT and Quality Leadership Network's (QLN) strategy to build the organization's competencies to implement SAQ. The Lean and Integrated Delivery Leader provided the first author with the Competency Development Model (Ortiz & Reed, 2015). Ortiz and Reed delineated competence levels ranging from unawareness to awareness, from awareness to understanding, from understanding to capable, and from capable to mastery. They proposed a developmental approach aimed at elevating competency across these levels, commencing with informing, followed by educating, training, coaching, and ultimately, mentoring, to achieve mastery. Additionally, their model described the message content and focus for fostering competency through each developmental pathway (Ortiz & Reed, 2015).

To build the organization's competencies, from unaware to aware, the first and fourth authors decided to build a "You are Here Map" for project teams based on a standard project workflow. In each phase of the project lifecycle, pursuit, preconstruction and design development, design development and coordination, fabrication, installation, and construction, the strategy was to provide teams with basic information. This included project strategy to implement SAQ, considering if they had started this approach from the beginning of the project or were starting at that phase in the project lifecycle. Examples of process workflows, tools, and scripts for how to have the conversation and examples of DFOW and MAC that other teams had produced for that phase and work would also be provided. The MQC would be a pivotal tool to provide examples of what operationalizing SAQ at different stages in the project life cycle looked like. While no two projects are identical, and each has unique challenges, the MQC aimed to provide enough examples of emerging operational and strategic trends.

The MQC relied on understanding and capturing the knowledge of those who understood and mastered SAQ principles in their work and were leading others. The purpose was to learn from these leaders and teams and assist others in competency states of unawareness, awareness, or understanding but not yet capable of integrating SAQ in their approach to work. In McKinsey's 2015 article on the "Four Building Blocks of Change," the importance of seeing leaders behave differently encouraged the authors to include storytelling and modelling as critical components of the MQC. The vision and strategy for moving the organization through competencies included focusing on knowledge capture, project team competency building, integration of SAQ principles into organizational processes, and communication of successes and learning. The QLT worked toward supporting business unit quality strategies and developing more quality coaches who could assess and work with project teams through coaching, modelling, flipped classroom activities, and other tools (Gordon, 2019).

IGLC LITERATURE REVIEW

Our review of the IGLC database identified 21 papers pertinent to the query "knowledge management." While numerous papers outlined theoretical frameworks for capturing project knowledge, and some offered case studies, none specifically addressed the longitudinal process of documenting and disseminating project team knowledge within an organization. Consequently, our paper fills this gap in the literature, offering valuable insights for scholars and practitioners initiating similar endeavours.

METHODOLOGY

The research methodology can be described through Saunders, Lewis, and Thornhill's Onion Model; the research philosophy's outer layer is realism, a scientific inquiry approach (Saunders & Tosey, 2013). The authors examined the MQC series by drawing from the design and systems thinking innovation lab hosted by the Center of Innovation in Design & Construction Industry (CIDCI 2022). The web of abstraction tool was utilized to frame and re-frame the question: How might we learn from what we did to understand, capture, and share project team successes, challenges, and opportunities for improvement to support the quality organizational change initiative? Questions from the web abstraction exercise and discussions with industry colleagues were categorized to understand the problem better. Three distinct categories of investigation emerged.

The first category of questions sought to ascertain whether the calls represented the GC's body of work by geography, core market, and contract value and whether the series adequately represented the diverse roles within project teams.

The second category of questions aimed to assess how the MQC documented the Quality Leadership Team's (QLT) corporate change journey, how the calls reflected their influence, and what could be learned to inform future strategy. Questions grouped into this category included: Did the geography of the teams delivering on the calls align with QLT's presence and their coaching with project teams, or were other organizational mechanisms influencing SAQ implementation? Would there be an observable increase in the number of team members participating in sharing their project team implementation story as SAQ became more ingrained in the operational framework? Also, of interest was exploring the patterns of project DFOW production, an output of SAQ project implementation (Gordon et al., 2021b), compared with previous organizational data findings. Furthermore, what could be derived from understanding the demographics of attendees in these calls?

Finally, the third category of questions sought to learn whether the knowledge and content reflected organizational goals and if it matured over time. The call content could be mapped to cost, schedule, safety, quality, team culture, and strategic goals, reflecting standard areas for project metrics as documented in Gordon et al. (2021a, 2022, and 2023). The authors sought to understand if there had been a noticeable change in the topics or presenter characteristics.

The following research layer used a multimethod qualitative and quantitative design (Saunders & Tosey, 2013). The qualitative data, including MQC recordings, presentations, and internally published narratives, assessed content characteristics. The quantitative data of presenter characteristics, attendance records, project characteristics, and project DFOW files were also evaluated.

The third layer of research is described by action research, as the authors worked with practitioners to gather and document their explicit and tacit knowledge to “bring about organizational change” (Saunders & Tosey, 2013). The fourth layer of this research is longitudinal, as the work studied spanned from 2018-2023. Finally, the inner layer of research, the data collection, is described in more detail in the following section. The data analysis entailed mapping the data about each call to the respective categories of questions. Visualizations were subsequently generated to analyze the data for each category of questions. Finally, the data analysis was compared with previous research based on the company’s implementation of SAQ and juxtaposed against the development of the QLT and QLN.

DATA COLLECTION

The QLT started the MCQ in 2015. The content included discussions about developing a quality objective, a standard quality implementation plan reflective of SAQ, processes, and systems to support SAQ, practitioners' experiences, project implementation stories, and coaching from leaders. In September 2019, the first author led the series' relaunching, focusing mainly on project implementation stories. A standard set of questions related to how the project team implemented SAQ was developed with the QLN to help the teams reflect on their journey and prepare for sharing on the MQC. The QLT, QLN, Operations/Business Units, and Corporate Services selected projects and presenters for the MQC that had implemented SAQ principles. The first and second author interviewed teams to understand their project's story, and the project teams presented their stories in a virtual forum. Questions and discussion were encouraged. The calls were open to everyone, and the QLN distributed call invites to their networks.

Also, the MQC shifted to a platform with advanced collaboration features like call recording, transcriptions, chat messaging, file sharing, and news article publishing. Recordings and summaries were shared via email and stored in an online searchable notebook. In 2021, the authors reviewed the process with organizational leaders. They decided to improve dissemination by publishing summaries as news articles and developed a standard PowerPoint to aid call production.

DATA FINDINGS

PREVIOUS RESEARCH

In previous research, Gordon et al. 2021b assessed the implementation of SAQ by counting the projects with DFOW files in the project folder enterprise system. The results presented by year the project mobilized and DFOW project revenues as a percent of annual sales for the year:

- 2016: 3 projects, DFOW project revenues as percent of annual sales is 5%
- 2017: 17 projects, DFOW project revenues as percent of annual sales is 29%
- 2018: 37 projects, DFOW project revenues as percent of annual sales is 31%
- 2019: 66 projects, DFOW project revenues as percent of annual sales is 42%
- 2020: 67 projects, DFOW project revenues as percent of annual sales is 55%

The results presented by region:

- Central: 17 projects with DFOW files, 24% of revenue as a percent of regional sales
- Northeast: 31 projects with DFOW files, 44% of revenue as a percent of regional sales
- Northwest: 60 projects with DFOW files, 39% of revenue as a percent of regional sales
- Southeast: 49 projects with DFOW files, 36% of revenue as a percent of regional sales
- Southwest: 34 projects with DFOW files, 28% of revenue as a percent of regional sales

Additionally, the results were presented by the core market, which refers to the market of the GC's customers:

- Advanced Technology: 34 projects with DFOW files, 33% of core market sales revenue
- Commercial: 42 projects with DFOW files, 41% of core market sales revenue
- Healthcare: 37 projects with DFOW files, 23% of core market sales revenue
- Higher Education: 13 projects with DFOW files, 42% of core market sales revenue
- Life Sciences: 44 projects with DFOW files, 42% of core market sales revenue
- Other: 20 projects with DFOW files, 24% of core market sales revenue

DATA FINDINGS FOR MONDAY QUALITY CALLS (MQC)

Between 2017 and 2023, 76 MQC focused on a project implementation story. In each year, a few project teams presented more than once. Only distinct project numbers were used to assess the work portfolio by contract value. Of the distinct project numbers that were shared, 19% had contracts greater than $250 million, 17% had contracts between $100 - $250 million, 19% had contract values from $50 - $100 million, and 33% had contracts between $10 - $50 million and 12% had contracts less than $10 million. The graph on the left shows the percentage of calls from each region for each year. The graph on the right shows the percentage of calls from each core market presented each year.

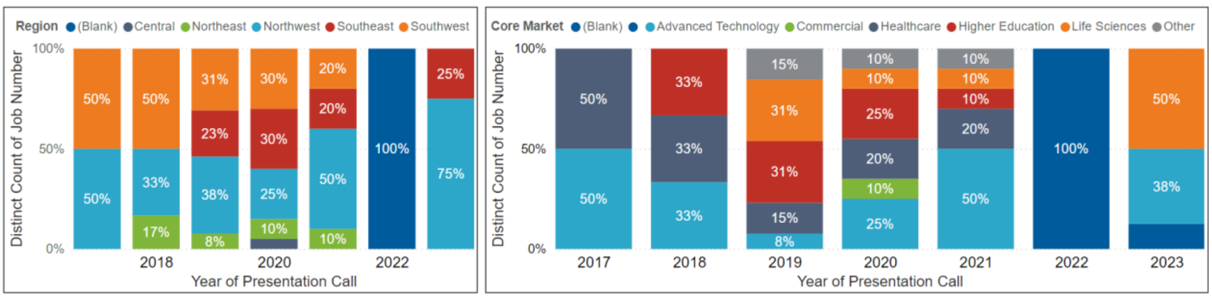

Figure 1: Percentage of MCQ from each region and core market by year.

In Figure 1, the chart to the left shows that all regions contributed a story to the calls during the seven years. Aggregate analysis reveals that Central had the lowest percentage of participation in the MCQ series, with two calls, and the Northwest had the largest percentage of participation, with 38%. Southeast contributed 22% of all calls, Southwest 24%, Northeast 12%, Central 3%, and Blank 1%. The chart to the right shows that all core markets are represented in the MQC. Advanced Technology core market comprised 33% of all calls, Higher Education 20%, Life Sciences 17%, Healthcare 16%, other 9%, Commercial 3%, and 1% blank.

Furthermore, for each year, the count of MCQ Project Implementation story and attributes of the call, including the median contract value, whether the project had DFOW files, the median value of the count of DFOW files in the project repository, and the median and count of presenters for all calls that year were tallied. The information was also compiled for seven years.

Table 1: Attributes of MQC Project Implementation Stories presented each year.

Year	Count of Project Stories	Median Value for Contract Value	% of calls with DFOW files	Median value for Count of DFOW files	Median number of presenters	Count of presenters
2017	2	$292.4M	50%	111	1.0	2
2018	7	$260.4M	43%	111	1.0	7
2019	17	$61.1M	76%	62	1.0	17
2020	25	$74.7M	64%	13	1.0	37
2021	16	$159.4M	38%	7	1.5	34
2022	1	$100.0M	0%	0	1.0	1
2023	8	$84.6M	75%	4	2.0	24
Total	*76*	*$110.0M*	*59%*	*14*	*1.0*	*122*

The median value for the project contract ranges varies over the years, and the larger contract values reflect the GC's large project portfolio being showcased more frequently. Most of the projects presented had DFOW files readily accessible in the enterprise repository. The data also shows that the median value of projects with DFOW files fell drastically over the years while the median number of presenters increased slightly.

In Figure 2, the graph on the left visualizes the percentage of MQC presenters from each workgroup each year. The resources are as follows: DM = Design Integration Management, VDC = Virtual Design and Construction, SPW = Self-Perform Work, RISQ = Risk, Insurance, Safety Quality, Precon = Preconstruction Services, PM = Project Management, MEP = Mechanical Electrical and Plumbing, Field = Superintendent and foreman. The graph on the right shows the percentage of standard work topics covered, including team culture, cost, planning and scheduling, quality, safety, and the company's strategic focus areas.

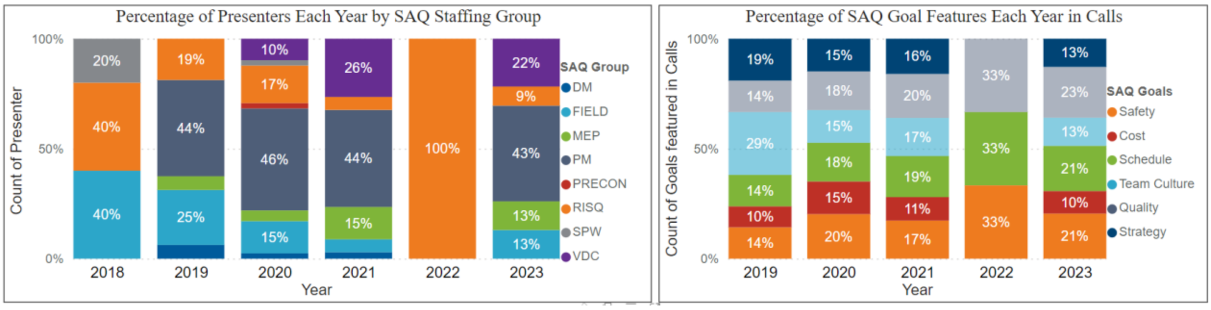

Figure 2: Presenters by SAQ Staffing Groups and SAQ Goals featured by Percentage.

Figure 2 shows that all roles had the opportunity to present their perspective over the years. The distribution of roles presented on the calls was highly uneven. The project management group had the most visibility on the calls to share their experiences with 36% representation, and the preconstruction dedicated resources had the least time with only one presenter. The calls' content was analyzed yearly, and all workgroup topics were discussed, except for 2022. In 2022, there was one call with a Quality Manager, and only three topics were discussed. Of the 117 presenters, 21% were repeat presenters, and 17% had graduated from an online 4-week quality training course, which began at the end of 2020.

Figure 3 shows the number of participants in the MQC Project Implementation Stories by region each year. The superimposed line graphs also show the number of unique attendees compared to the total attendees each year. Overall, 3137 participant hours were logged for 895 unique participants, an average of 3.5 hours per participant.

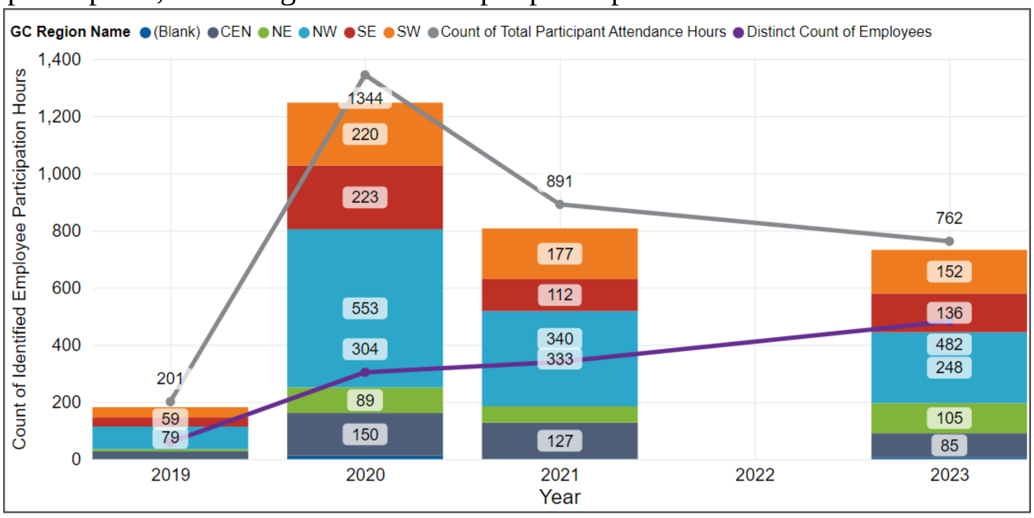

Figure 3: Shows the count of attendees by region and the difference between unique attendees and total counts.

Each year, attendees on the calls represent all regions. The data shows more attendees but fewer unique attendees each year. This gap starts to close in 2023, with a more even distribution of attendees in 2023 across all regions.

LIMITATIONS OF THE DATA

Limitations of the data include 1) The Study sample reflects 131 Monday Quality Calls (MQC) documented from 2017 to 2023. 2) Only MQCs focused on a single Project Implementation Story with job numbers in the Excel MQC tracker were analyzed. 3) Other MQCs demonstrating SAQ principles across multiple projects describing process implementation and other trainings and discussions were excluded from the analysis. 4) DFOW file counts were tallied if accessible in the enterprise project document control repository. Some projects had

DFOW files maintained in customer systems, and these were not counted. 5) Presenter roles were counted if they existed and were categorized based on previously defined classifications from Gordon et al., 2022. 6) Attendee tracking commenced in the fall of 2019 with the transition to a new collaboration platform. 7) Attendee roles represent current positions and include all 131 MQCs, not solely Project Implementation Stories. 8) Not all attendees of the MQCs were able to be related to employee records, which is why the participation hours exceeded the employee records in each instance. This analysis also highlights gaps created when the organization relies on manual records processes. For example, the primary recorder could not attend the 2022 call. Thus, the participation records were not recorded.

DISCUSSION

The data shows that the MQC Project Implementation stories represented the GC's work by core market and size of the project contract. The calls did not adequately represent the geography of the regions. The Central region accounted for 3% of MCQ; however, the previously collected data on DFOW file production shows that Central had 24% of all project revenue from 2016-2020 implementing SAQ. The Northwest region accounted for 38% of calls and was documented as having a similar distribution of projects with DFOW files through 2020. This finding aligns with the geographical region of most of the QLT from 2013-2020. The percentage of participation in the MCQ from each region represents how strongly the individual members of the QLT and QLN value capturing and sharing this knowledge across the company. Geographical participation in knowledge capturing and sharing is essential for evaluating strategic implementation.

Gordon et al. (2021b) show DFOW file findings distributed across all core markets. Similarly, the MCQ has project examples distributed across all markets. Also, the percentage of MQC with DFOW files reflected similar results observed during the organizational results documented by Gordon et al. (2021b). Organizationally, 2019 and 2020 had the highest percentage of projects with DFOW files. Similarly, there were more MCQ projects with DFOW files in those years. These observations suggest that the MQC reflected the GC's portfolio of work. While 2023 shows that 75% of MQC had DFOW files, 60% of calls that year were nominated by a leader the first author had worked with on several projects, highlighting the importance of tracking who nominated the calls.

When looking at presenter characteristics, the MCQ does not adequately reflect all the roles in the company. There was one preconstruction workgroup presenter during the seven years. While all roles, DIM, PM, VDC, MEP, RISQ, and Field, participated in the preconstruction phase, the data shows that the dedicated preconstruction role was absent. This highlights an opportunity to describe further how these dedicated resources can support and lead SAQ implementation through their daily work streams. Furthermore, in this study of presenter characteristics, participating in the 4-week online quality training was not a determining factor for those teams who implemented and presented.

The data also shows a wide range of attendees and that key influencers attended every call. The audience attending the calls is vital to show who is participating in these calls and to reflect on why. The first three years of data, 2019, 2020, and 2021, show a higher number count of attendees but fewer new attendees due to the frequency of the calls. In 2019 and 2020, calls were weekly; in 2021, they shifted to twice monthly; in 2023, there were calls approximately 4-6 weeks. Specifically, 2020 demonstrates a solid base of extended QLN regularly attending the calls and supporting the company in implementing the DFOW process in the early years, as documented in Gordon et al. (2021b). In 2023, 60% of the calls originated from the Northwest; however, that year shows that the attendees of the calls were evenly distributed across all regions. These changes can be attributed to the change in communication and frequency of the information. Last year, instead of relying solely on the QLN to distribute the calls, the first author marketed the MQC in company-wide communication channels. Thus, it is also essential to track and understand how changes in communication and frequency of calls affect attendance.

All the company goals and strategic focus areas were addressed each year, except for 2022, when there was only one call by a quality manager. This demonstrates that describing a project's results and process to achieve those results must consider all workstreams: safety, quality, cost, schedule, and team culture. While the number of presenters increased each year, reflecting a maturity of the call content to share more project role perspectives, reviewing the information by overall implementation or deliverable implementation, assessing the type of workflow process discussed, and the phase in the project lifecycle would aid in assessing patterns in content and maturity of content.

CONCLUSION

The present study highlights the benefits of documenting organizational change management efforts and project team implementations in a multi-year and multi-modal process to refine the understanding, language, and presentation of SAQ. The MQC process and coaching platforms have helped teams describe their interdisciplinary and multi-factored approach to achieve improved and more reliable performance outcomes. Repeat presenters matured in their project team implementations and demonstrated their growth and development. Providing a coaching platform facilitated reflection on the continuous improvement and learning process. This has enabled the authors to refine and standardize their approach to helping project teams describe the complex and dynamic situations (Bertelsen 2003a, 2003b) they face from different standard project team roles. This forum was essential for the diffusion of ideas across the organization and promoted innovation, as teams could build off the work and knowledge of others. Additionally, this foundation of knowledge has proved immensely helpful in mapping the content to maturing language in the organization to articulate company goals better.

The value for other practitioners is understanding that this work formed an information network that weaves and cascades through the organization. These modes allow for storytelling and modeling through video recordings, slide deck presentations, and SharePoint summary news items that "signal know-how" (Gil, 2002) of project teams. This foundation facilitates team coaching, connects peers to peers for relatable knowledge building, onboard new team members, and prepares external marketing and communication materials. MCQ content has been shared at conferences such as Lean Construction Institute and Advancing Construction Quality to advance the knowledge and practices of the industry. The QLT saw this knowledge capture as a foundation to support learning and development frameworks while raising the competency of individuals who developed project and organizational systems reflective of SAQ. However, it has been difficult for the organization to incorporate this new knowledge into existing learning and development materials.

The authors recommend expanding the work to ensure the discussed MCQ processes are captured and reflected in organizational standards. Additionally, the authors recommend further developing learning and development experiences to build the competency of measurable collaboration alongside technical training as the organization matures in SAQ adoption. To support organizational competency growth, skill-building is essential. The authors suggest that others embarking on this journey track similar metrics, including project attributes, presenter roles, attendees, and topics, as metrics to gauge their influence and inform their strategy. Furthermore, the authors recommend tracking the motivation or driving factors of the teams that implemented and shared in this forum. Understanding what assisted them in creating the strategy and routines for implementation and who nominated them could help the QLT gain insight into the channels for spreading ideas and the influencers of organizational change, which can aid in refining strategy. Additionally, analyzing the data collected on the MCQ enabled the authors to understand the portfolio of work captured through the calls, presented gaps in the content, revealed where geographically more focus was needed, and began to track the maturity of the content. A deeper understanding of the captured processes is needed to quantify the maturity of the content.

For further research, the authors suggest conducting a similar investigation to quantify project performance outcomes and contributing factors described by Gordon et al. (2021b, 2022, and 2023) to the MQC projects. Additionally, the authors suggest broadening the MCQ analysis to consider the processes discussed on the calls to assess content maturity. Finally, the authors believe there are opportunities to leverage emerging Artificial Intelligence capabilities to capture knowledge and provide knowledge transference to assist teams in understanding the strategy and actions necessary to achieve predictable outcomes.

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WHOSE GAME IS IT? DO SMALL AND MEDIUM SIZE ENTERPRISES WIN ALLIANCE CONTRACTS?

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ABSTRACT

This empirical archival study investigates the distribution of alliance contracts (ACs) between small and medium-sized enterprises (SMEs) and large enterprises (LEs). Previous research has identified concerns about ACs in relation to the participation of SMEs in public procurement markets in the construction sector. The aim of this study was to understand how these contracts are distributed in the construction sector and to provide additional information for industry players on ACs. The study analyzed 80 investment alliance projects from 2011 to 2023, demonstrating a decreasing trend in SME participation against an increase in LE involvement. The findings revealed a concentration of ACs among a few LEs, with a significant portion of SMEs not participating in these alliances. While 81 SMEs have engaged in Finnish ACs, this number is small compared to the total number of SMEs in the industry, pointing to an imbalanced contract distribution favoring LEs. The study also noted a steady rise in the relative share of alliances in the overall construction market. This research sheds light on the challenges of asymmetric AC distribution and offers valuable insights for public works procurement bodies, industry consultants, and AC participants and researchers, highlighting the need for balanced contract allocation.

KEYWORDS

Lean construction, alliance contract, archival study, enterprise

INTRODUCTION

In many countries, the alliance contracting format, which originated in Australia, and integrated project delivery (IPD) developed in the United States, have become widespread in construction projects, often combining lean construction methods and elements into these collaborative contracts (Lahdenperä, 2012; Young et al., 2016). IPD is a contractual and operational approach that unifies the various parties involved in a construction project, including their contracts, procedures, and operating principles. IPD incorporates numerous aspects of lean construction (Lahdenperä, 2012). An alliance contract (AC) is employed for collaborative contracting in

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various construction scenarios, where the emphasis may not be solely on lean construction principles. Instead, these contracts prioritize shared risk sharing, joint decision-making, and enhanced collaboration between the parties involved (Davis & Love, 2011). However, there are some indications that large enterprises (LEs) are engaging in ACs, while small and medium-sized enterprises (SMEs) are not as prominently involved (Dainty et al., 2001; Davies, 2008; Tezel et al., 2018). SMEs are expected to generate a relatively high number of jobs and minimize changes in income distribution (Ayyagari et al., 2007). Therefore, the European Union (EU) includes the participation of SMEs in public procurement markets among the objectives of its public procurement legislation (The European Parliament and the Council of the European Union, 2014). In Australia, similar legislation aims to promote the public procurement of SMEs, indigenous communities, and local industry (Hoekman, 2018). According to Kidalov (2011), in the United States, at the federal level, the Small Business Administration seeks to encourage the participation of small minority and women-owned businesses in federally funded road projects. As the aim is to involve a wider range of firms in growth while ensuring the most efficient use of public funds, the involvement of SMEs in the construction sector is socially and economically significant (Thai, 2017). This rationale is grounded in economic theories, whereby the public entity benefits from a combination of the lowest price, preventive corruption, and a fair playing field for all construction actors (Anechiarico & Jacobs, 1995; Thai, 2017).

The project alliance model originated in the 1980s when the oil and gas industry decided to develop a collaborative contractual model for investment projects (Olsen et al., 2005). Oil and gas companies adopted this approach in the 1990s, and with the success of these projects, the alliance model began to spread to infrastructure maintenance and construction (Rahmani et al., 2016). Alliances establish an integrated project organization between the contractual parties, usually the client, contractors, architects, and other designers. The aim of establishing a joint organizational structure is open communication, information sharing, and joint problem-solving (Lahdenperä, 2012). The main objectives of the alliance are to create an open culture of agreement and cooperation between the contracting parties, which will allow for a more holistic perception of the risks and benefits of the project and enable joint decision-making and risk and benefit sharing (Rahmani et al., 2016).

In the EU, public procurement contracts significantly impact the economies of its member states, representing over 16% of the EU's gross domestic product (GDP) (The European Parliament and the Council of the European Union, 2023). Similarly, in the United Kingdom, the construction industry is a major economic contributor with an annual turnover exceeding £100 billion, nearly 10% of the UK's GDP; approximately 40% of this turnover is attributed to the public sector (Menteth et al., 2014). Public entities are therefore seeking more value for money in their construction projects, and in this respect, alliance contracting has set high expectations (Love et al., 2010).

Recognizing the challenges and complexity of traditional procurement methods, particularly in managing significant risks, public procurement has played an important role in seeking alternative contracting models (Lahdenperä, 2015; Walker & Jacobsson, 2014). Experiments with public procurement entities began in Australia, where the model was adapted to different types of projects and local markets (Rankohi et al., 2023; Sanderson et al., 2018; Valkama et al., 2019). In countries where alliances have been promoted, public procurement authorities have been the drivers of change and have adopted alliance model practices in their procurement policies and procedures (Walker & Jacobsson, 2014). The role of the public sector has been a key factor in the development of the alliance model and its increasing use in the construction industry. Therefore, the rationale behind selecting ACs has primarily been based on the characteristics of the project and the type of client.

Many studies identify the benefits of alliances for the contracting parties and for the public entity in terms of improved liaison, adherence to budgets and schedules, and the achievement of objectives important to the client, reducing the disputes and litigation typical of the sector (Davis & Love, 2011; El-adaway et al., 2017; Young et al., 2016). Despite the importance of public procurement and the role of ACs in public construction projects in countries where the model has been adopted, there is limited research on how ACs are distributed in the market between SMEs and LEs. Understanding the distribution of contracts can reveal market conditions and barriers that may have an impact on reducing competition, such as oligopolies and monopolies. This study presents a comprehensive sample of the Finnish construction market and the parties to ACs and contributes to answering the question of how ACs are distributed in the construction business landscape. The aim of this study is to shed light on the current situation through a geographically limited but comprehensive sample of the Finnish dataset and to encourage similar research in other countries. The findings of the study could be used by policymakers to target the use of public funds in the construction sector more precisely to relevant groups of companies. For the lean community, the study contributes to mirroring the economic and social impacts of lean construction.

This research endeavor will also provide a modest contribution to the relationship between lean construction and ACs. It presents novel insights into the implementation of lean methods within Finnish ACs, including the utilization of the "last planner system," the "big room" approach, and other lean methods. This is intriguing because ACs have not originally been seen as a distinct characteristic of lean construction. For example, Miles and Ballard (1997) contended that alliance-like partnerships were not established with the intention of enhancing efficiency, productivity, speed, or the smooth flow of production in a construction project; therefore, they have a logical link to the productivity ethos of lean construction. They reasoned that the applicability of an alliance-type collaboration to lean construction is therefore uncertain (Miles & Ballard, 1997). In subsequent years, the relationship between alliances, namely IPD initiatives, and lean construction has been further reinforced, indicating that these two advancements in the construction industry are useful concepts together (Lahdenperä, 2012; Young et al., 2016).

METHOD

Archival research was chosen as the research method (Das et al., 2018) and was encouraged by the researchers' sufficient access to the research data, which was possible in the Finnish context. The research relies mostly on quantitative data. The research study data were collected from all ACs implemented in Finland from 2011 to 2023. The data were first collected using a publicly available catalog from a consultancy specializing in alliances (Vison Ltd., 2023), which provided basic information on alliances. This basic information included the name of the project, the name of the client, and the budget. The names of the projects and companies investigated were anonymized. Numerical codes 1–80 were used for projects, and the letter-number combination C-1 to C-112 was used for companies.

Based on these data, the researchers sought the following additional information on these projects from public and available sources (news, Internet search, Finnish research databases): 1) which companies were contractors in the alliance, 2) the turnover category of these companies (i.e., which companies are SMEs and which are LEs), 3) the time schedule of the ACs, and 4) any indication of the lean methods used in the project. In this study, in line with the EU convention, SMEs are defined as enterprises with fewer than 250 employees and an annual turnover not exceeding EUR 50 million, which are independent of enterprises that do not qualify for the definition of an SME (The Commission of the European Communities, 2003). Tezel et al. (2018) also used this method of dividing firms in their study of SMEs.

The researchers inserted the data into an Excel spreadsheet. Projects related to maintenance or other service ACs were excluded from the data. The number of excluded projects was 14. After screening the data, 80 construction investment alliance projects remained to be analyzed. The total budget value of the selected projects is €9.049 million. Details of the analyzed projects are presented in Table 1.

Table 1. Details of the projects

Project No.	Project type	Timeline	Client	No of SMEs	No of LEs	Budget [M€]	Lean methods used
1	Railway renovation	2011–2015	Public entity	0	1	80	BR, LPS
2	Housing renovation and expansion project	2011–2013	Public entity	1	1	18	BR
3	Road construction project	2012–2016	Public entity	2	1	192	BR, LPS
4	Office and laboratory building project	2019–2021	Public entity	3	1	18	NA
5	Health care building project	2014–2016	Public entity	5	1	51	BR
6	Travel center project	2014–2016	Public entity	2	1	19.2	NA
7	Power plant project	2015–2017	Public entity	1	2	50	NA
8	Courthouse and police headquarters building project	2014–2017	Public entity	0	1	31	NA
9	Office and laboratory building project	2014–2016	Public entity	0	1	30	NA
10	Housing façade renovation project	2014–2018	Private company	2	1	23.3	BR, LPS
11	Housing project	2014–2016	Private company	5	2	13	NA
12	Expansion project of the health care building	2015–2017	Public entity	3	3	14	NA
13	Airport paving works project	2015–2016	Public entity	1	3	20	LPS
14	Tramway construction project	2017–2021	Public entity	0	4	266	BR, LPS, TVD, VM
15	Hospital building project	2018–2021	Public entity	3	5	265	BR
16	Hospital building project	2015–2021	Public entity	0	3	153	BR, LPS
17	Airport expansion project	2015–2020	Public entity	0	1	100	BR, LPS
18	Renovation project of the cultural center	2015–2017	Public entity	0	1	30	NA
19	School building project	2015–2017	Public entity	1	4	20	BR, LPS
20	Police headquarters building project	2015–2016	Public entity	0	1	20	NA
21	Housing project	2015–2022	Private company	2	1	120	NA
22	Road construction project	2015–2017	Public entity	0	3	76	BR
23	Railway renovation project	2015–2017	Public entity	0	1	74.6	BR, LPS
24	School building project	2015–2018	Public entity	1	2	23.7	NA

BR = Big Room, LPS = Last Planner System, TVD = Target Value Design, VM = Visual Management, TP = Takt planning, CBA = Chosen by Advantage, NA = Information not available

Table 1 (continued). Details of the projects

Project No.	Project type	Timeline	Client	No of SMEs	No of LEs	Budget [M€]	Lean methods used
25	Office and multipurpose building project	2015–2017	Public entity	1	1	25	BR
26	School renovation project	2015–2020	Public entity	2	0	10	BR
27	School renovation project	2015–2017	Public entity	5	2	10	NA
28	School and multipurpose building project	2016–2021	Public entity	2	1	42	BR
29	Housing and commercial building project	2016–2021	Private company	1	3	52.1	NA
30	School and multipurpose building project	2016–2018	Public entity	1	3	22	NA
31	Renovation project of the service tunnel	2017–2018	Public entity	0	2	7	NA
32	School building project	2017–2019	Public entity	2	1	32	NA
33	Tramway construction project	2017–2023	Public entity	0	5	508.5	BR, LPS
34	Hospital building project	2017–	Public entity	3	2	321	NA
35	Airport expansion project	2017–2021	Public entity	2	2	300	BR, LPS, TP
36	Road construction project	2017–2023	Public entity	0	4	258	BR, LPS
37	Hospital building project	2018–	Public entity	3	6	164	BR
38	Hospital building project	2017–2022	Public entity	2	3	141	BR
39	School building project	2018–2021	Public entity	1	4	36	BR
40	School building project	2018–2020	Public Entity	2	1	32.5	BR, CBA
41	Housing renovation project	2018–2021	Private company	2	2	8	BR
42	Church building project	2018–2020	State church	1	1	44	BR
43	Housing renovation project	2018–2021	Public entity	6	0	25	TP
44	Office and multipurpose building project	2018–2020	Public entity	1	1	22.3	BR
45	Hospital expansion building project	2021–2023	Public entity	3	4	118	NA
46	University building renovation project	2020–2023	Public entity	1	1	28	BR, LPS
47	Housing project	2019–2021	Private company	2	3	15	BR
48	Church building project	2018–2021	State church	2	3	10	NA
49	School and daycare building project	2018–	Public entity	4	1	53	NA
50	Hospital building project	2020–	Public entity	3	5	375	BR, LPS, TP
51	Sports stadium building project	2019–2023	Public entity	1	1	60	NA
52	Church building renovation project	2019–2021	Independent state church	2	2	13	NA

BR = Big Room, LPS = Last Planner System, TVD = Target Value Design, VM = Visual Management, TP = Takt planning, CBA = Chosen by Advantage, NA = Information not available

Table 1 (continued). Details of the projects

Project No.	Project type	Timeline	Client	No of SMEs	No of LEs	Budget [M€]	Lean methods used
53	Tramway construction project	2019–	Public entity	0	5	370	BR
54	Housing and commercial building project	2021–	Housing foundation	1	3	118.6	NA
55	School building project	2019–2021	Public entity	0	1	25	NA
56	Soccer hall project	2019–2020	Sports association	2	0	3.7	NA
57	Tramway construction project	2020–	Public entity	0	5	300	BR
58	Office renovation project	2021–2023	Public entity	2	2	22.9	NA
59	Hospital building project	2021–	Public entity	0	2	500	BR, LPS
60	Theatre building renovation project	2020–2023	Public entity	0	1	61.4	NA
61	School building project	2020–	Public entity	1	3	14	NA
62	Hospital building project	2022–	Public entity	3	5	225	BR
63	Police headquarters building project	2020–	Public entity	0	1	130	NA
64	Concert hall building project	2021–2023	Public entity	1	2	62.2	BR
65	Hospital building project	2022–	Public entity	5	7	838	BR
66	Housing renovation project	2022–	Non-profit foundation	2	0	10	NA
67	Museum building extension project	2022–	Public entity	0	1	55	NA
68	Prison building extension project	2021–	Public entity	0	1	56	NA
69	District heat seasonal storage project	2022–2023	Public entity	0	2	108.8	NA
70	Road construction project	2022–	Public entity	2	2	96	NA
71	Housing renovation project	2021–	Public entity	4	0	10	TP
72	Sports arena building project	2022–	Public entity	2	3	50	BR
73	Power plant project	2021–	Public entity	0	2	60	NA
74	Housing and multipurpose building project	2023–	Public entity	3	3	190	BR, TVD
75	Pedestrian and light traffic road project	2023–	Public entity	0	2	30	NA
76	Seawater heat extraction project	2022–	Public entity	0	2	496	NA
77	Multipurpose building project	2023–	Public entity	1	2	39	NA
78	Road construction project	2021–	Public entity	0	1	128	BR
79	Tramway depot building project	2023–	Public entity	2	3	275	BR
80	Tramway construction project	2023–	Public entity	0	4	335	BR

BR = Big Room, LPS = Last Planner System, TVD = Target Value Design, VM = Visual Management, TP = Takt planning, CBA = Chosen by Advantage, NA = Information not available

The data were analyzed as follows: 1) the alliance contractor companies were divided into SME and LE categories, 2) the groups were divided into two subgroups: contractors and designers, 3) the alliance contractor companies were summed by subgroup in step 2. The analysis allows for an estimation of the number of SME partners in alliance projects and the distribution of ACs in Finland. By linking the timeline of ACs signed, it is also possible to assess how the involvement of SMEs in alliances has evolved over time in Finland.

In the last part of the analysis, the relative share of ACs in the total construction market was analyzed using public statistical data from Statistics Finland (SF) and the database of the Finnish Association for Quality in Construction (Finnish Association for Quality in Construction (FAQC), 2023). The aim of the analysis is to link the data to the research questions and provide explanations both quantitatively and over time. SF's data were used to estimate the size of the construction market, and FAQC's data were used to compile SME and LE data for analysis. The FAQC's data on certified construction companies in different turnover categories are reliable and, as required by the Finnish public procurement function, comprehensively cover the entire SME sector and LEs operating in the market.

FINDINGS

The mean budget value of the ACs in these projects was €113.1 million, and the median was €50.5 million. In terms of project value, Figure 1 shows the distribution of contract values of ACs in euros.

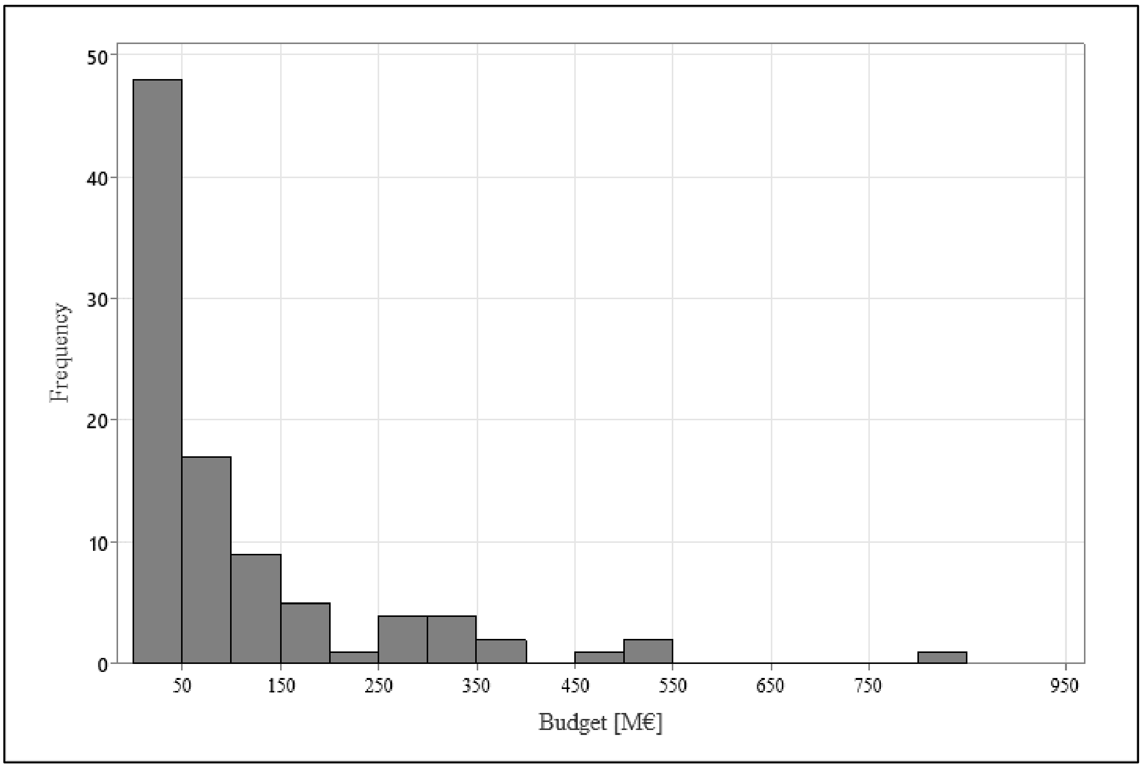

Figure 1. Distribution of the value of alliance contracts

Of the total, 40% of the parties to the ACs were SMEs, and 60% were LEs. There was a downward trend in the number of parties in the SME group, while there was a clear upward trend in the number of parties in the LE group. At the peak, the share of SME parties was 67% in 2012 and 2014, but the mean of the last four years of observation was 33% for the number of SME parties. The trends and relative proportions of AC parties by year are shown in Figure 2.

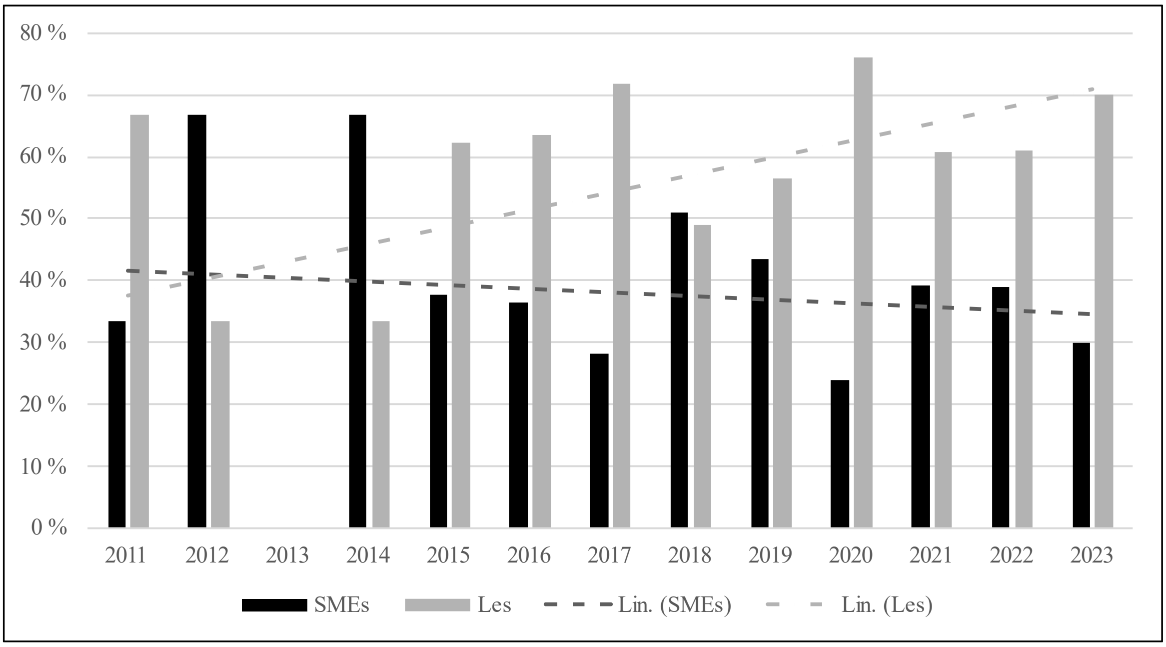

Figure 2. Distribution of ACs between SMEs and LEs

In the analysis phase, the same companies were identified as recurring alliance partners. Table 2 summarizes the 15 companies with the highest number of ACs.

Table 2. Distribution of ACs among companies

Company code	No. of alliance contracts	SME	LE	Contractor	Designer
C-19	21		X	X	
C-37	16		X		X
C-26	13		X		X
C-2	12		X	X	
C-7	12		X	X	
C-35	11		X		X
C-45	11		X		X
C-5	10		X		X
C-14	8	X			X
C-40	7		X	X	
C-18	6		X		X
C-42	6		X		X
C-11	5		X	X	
C-15	5	X			X
C-31	5		X	X	
Sum	148				

As demonstrated in Table 2, 15 companies, of which only 2 were SMEs, were selected 148 times out of 292 as contract partners. This means that 51% of the ACs have been signed with only 15 companies. Of these 15 companies, only 2 were SMEs, and both were architecture firms. In addition to this group of firms, ACs have been signed with 97 other firms, of which

79 are SMEs and 18 are LEs. In total, 292 AC parties were involved, with 115 individual firms in the surveyed data. This indicates that just 11% of the companies (all LEs) have signed more than half of the ACs. When considering contracts with a maximum budget value of €50 million, there were 67 SMEs and 65 LEs as contractors in these contracts, so the contracts were evenly split between the groups.

For the analysis period, the relative share of the budget value of ACs in the revenue value of the overall construction market was also assessed. In 12 years, the annual budget value of ACs has risen from €15 million to €1 billion. The revenue value of the construction market varied over the period from EUR 11.6 billion to EUR 12.9 billion (Statistics Finland, 2023). The relative share of ACs in the Finnish construction market has steadily increased, as illustrated in Figure 3.

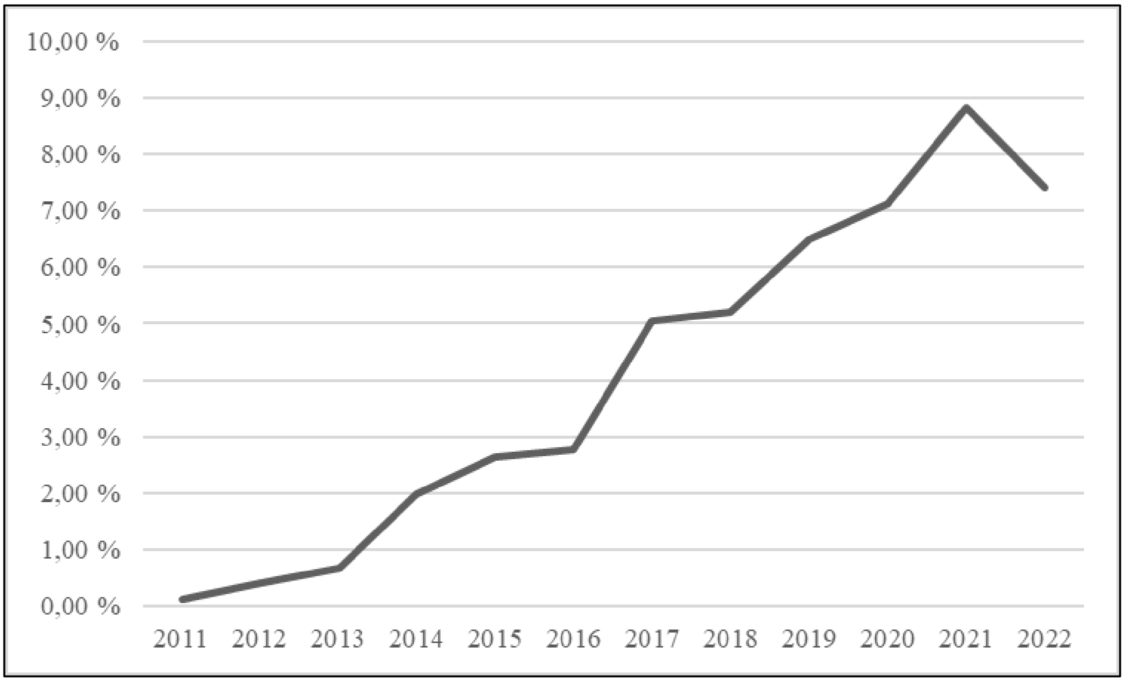

Figure 3. Relative share of ACs in Finland's total annual construction market

While the findings of this study suggest that ACs are mainly distributed among LEs already present in the market, only 81 SME companies have participated in ACs. However, this number represents about 9% of the total number of these SMEs in the construction sector, which was 857 in Finland in 2022 (FAQC, June 2023). For LEs, 31 out of 77 companies (about 40%) have participated in ACs in the period under review. According to the FAQC (June 2023), there were 77 LEs in Finland in 2022. The evidence indicates that a significantly higher number of LEs than SMEs have been awarded ACs. For 2022, the downturn in the construction sector in Europe caused by the pandemic and Russia's invasion of Ukraine is likely to be reflected in the downward trend in Figure 2.

The most often employed lean methods in AC projects were the "big room" and "last planner system." The latest lean construction innovation, "takt planning," was implemented in three projects, whereas "target value design" was utilized in two projects. "Visual management" and "choosing by advantages" were each utilized in a single project. Out of the 80 projects, 38 did not have any reference to the utilization of lean methods in public sources.

DISCUSSION

Alliance projects have been shown to bring many benefits to contracting parties, but there are limited studies available on how ACs are distributed among firms in the market. The three main findings of this study from the projects studied are as follows: 1) the distribution of ACs in the group studied is skewed toward LEs, 2) a significant proportion of ACs is distributed among a few LEs, and 3) the relative share of ACs has increased relative to the size of the construction market throughout the follow-up period. Each of the three findings and their significance are discussed separately below.

One explanatory factor for the distribution of ACs to LEs may relate to the fact that the alliance model was mainly developed for large and complex construction projects (Hietajärvi et al., 2017). Large, risky, and complex construction projects inherently exclude smaller companies with a limited capacity to bear the risks of the project, regardless of the contract model. On the other hand, although large projects require large firms as contracting partners, the construction sector globally depends on SMEs, which, in practice, also do most of the work of these large firms, including work in alliance projects (Akintan & Morledge, 2013; Kale & Arditi, 2001). This has generated debate in the sector and in research on how trade contractors should be considered in the alliance model (Aslesen et al., 2018; Dainty et al., 2001). One issue raised by the data is that actors in the SME sector, such as smaller architectural and engineering firms, participate in alliances using traditional contracts with alliance partners, thus distributing the value of the alliances to the SME sector. More research is needed on these issues.

However, the findings indicate that the mean size of ACs was just over €100 million and the median was about half of that. The ACs studied included many smaller school and housing projects as well as renovations. Nevertheless, these contracts were also disproportionally awarded to LEs. These findings suggest that the objectives of public procurement in terms of enhancing SME opportunities may not be achieved as intended in the alliance model. Based on the data, SMEs seem to be mainly smaller design firms. The share of design costs in construction rarely rises above 10–20% of the contract value, so the question arises: Are alliances in practice large construction contracts for one large construction company? These observations open an interesting question for further research: Are these phenomena observed only country- or market-dependent, and what other factors are behind this observation?

The distribution of a significant proportion of ACs to just a few LEs also raises interesting questions. Are these actors pioneers and forerunners of the industry and, therefore, overrepresented in the survey (Holt, 2015)? Has the alliance model been a strategic choice for these companies, and their success in doing so is reflected prominently in the study (Kim & Park, 2006)? Is the alliance model a form of Schumpeterian hypothesis-like innovation to which only large companies can typically afford to dedicate their resources, and would this also explain the findings of this study (Nam & Tatum, 1989)? Does this finding suggest that relations between individuals in the sector (including decision makers in procurement entities) and large companies were already strong before the alliance model emerged and that cooperation has been further strengthened by the collaborative nature of ACs (Blayse & Manley, 2004)? Is it a game-theoretic setting where, as cooperation flourishes, an oligopolistic mechanism prevents the entry of the SME sector (De Valence, 2010)? Oligopolistic competition focuses on competition based on specialization in certain types of projects or forms of procurement in the construction sector or on alliances or partnerships with customers (Contractor & Lorange, 2002; De Valence, 2010). Instead of looking at these individual factors, further research, such as multivariate analysis, is recommended to seek these answers (Rencher, 2005).

The contribution of this empirical study is relevant since it also shows that the relative budget value of alliances is increasing in one local construction market, but on the opposite side of this trend, the share of SME companies in alliances is decreasing. Hence, more and more budget value is being transferred from ACs to LEs. However, this study cannot answer the question of why these differences have emerged and are growing between SMEs and LEs. Nevertheless, our research indicates that as a few major companies secure a larger portion of ACs, including those smaller ACs, there is potential for dominant industry leaders to exploit their market power in a highly competitive setting. The market may thus progressively form toward oligopolies, leaving small and medium-sized businesses with diminishing opportunities to form partnerships with companies of similar scale. Therefore, we consider it important to investigate and record this issue, especially because many advocates and practitioners of alliances have emphasized the significant benefits of alliance agreements in public discussions and among researchers and practitioners (Davis & Love, 2011). These advantages include transparency, collaboration, and, among other benefits, the implementation of lean construction principles and practices (Schöttle et al., 2014).

The discovery that lean methods were not publicly emphasized or mentioned in nearly half of the projects suggests that the Finnish realization of alliance and lean may not always involve a combination of the two. Instead, it appears that certain ACs are executed without incorporating lean methods. However, the discovery that the "big room" and "last planner system" were the most frequently employed lean methods indicates that lean construction has indeed had an influence on Finnish alliance projects. It is also possible that ACs are perceived by contracting parties primarily as simply cooperation agreements, with no prerequisite for a lean component, and that the primary goals of alliances, which are frequently improved collaboration, joint decision-making, and joint risk sharing, are sufficient for many of the projects studied (Rahman & Kumaraswamy, 2002). Nevertheless, the data we gathered are not entirely comprehensive and conclusive. Specifically, in cases where there are no publicly available references for a project, conducting interviews or surveys might offer supplementary insights into the methodologies used. Further qualitative research is necessary to gain more clarity regarding the impact of lean in Finnish ACs.

LIMITATIONS

This study is not a statistical analysis of the randomness of the observed phenomena; therefore, a more detailed and statistically rigorous further study on a larger sample of projects is recommended. However, in many studies, it can be difficult to randomly allocate companies to experimental conditions, although this study has managed to obtain a complete sample of all ACs in one country over a 13-year period. Despite the geographical limitations, the complete sample size enhanced the reliability of the conclusions.

The main limitation of the study is its interpretation based solely on numbers without qualitative background data. However, there are intentions to gather qualitative data on the entire dataset in a later phase of the research project. Unfortunately, this qualitative data cannot be and is not included in this short conference paper. Another obvious limitation relates to the geographically limited market and language area. The reliability of the study is enhanced by the open data availability of the study to other researchers. Researchers are also willing to share data on request. The researchers also stressed the internal validity of the study by underlining the possibility of competing explanations. The study would benefit significantly from combining qualitative research with the numerical data currently being collected.

Another limitation is the comparison of the budget value with the revenue value of the construction sector. In reality, the budget value is spread over several years after the contract year; therefore, comparing the budget value to the annual turnover value as a relative figure is not absolutely correct. However, the approach used to present the time series contributes to minimizing this error.

One limitation of the reliability of the study is that the research sample was obtained from a company involved in the alliance facilitation business. It is therefore possible that the list is not exhaustive or that there are contracts on the list that are not ACs. The researchers have tried to mitigate this limitation by identifying the details of each contract from public sources, and some of the contracts on the list were other types of contracts (e.g., project management contracts) and have been excluded from the data. On the other hand, a company that has collected information on its ACs has also included ACs in which it was not involved, which suggests neutrality in maintaining the list.

CONCLUSION

This study is motivated by a research gap on the role of SMEs and LEs in ACs. The study was carried out as an archival study covering all alliance construction projects in Finland over a period of 13 years. In addition, the relative change in the budget value of Acs in this market was assessed. The aim of this study is to stimulate debate among researchers and practitioners on the distribution of ACs in the construction sector and to encourage further quantitative and qualitative research.

The survey indicates that the number of ACs awarded to a group of LEs is clearly higher than to SMEs. The study's findings, with an even split between SMEs and LEs and a median contract size of just over €50 million, also raise a question about the effectiveness of the alliance model in promoting SME opportunities in public procurement. This difference suggests that further research is needed to understand the market-specific factors influencing this phenomenon and to assess whether the alliance model disproportionately benefits larger firms.

From the projects examined, it was found that a significant proportion of ACs are distributed among a few LEs. These LEs may be pioneers in their field, strategically choosing an alliance model of lean construction to succeed, or their dominance may be the result of innovation dynamics in which only large companies can afford to invest significant resources. Whatever the speculated reasons, in order to clarify these aspects, we encourage other researchers to explore the phenomenon in more depth than this short paper, which focuses on numbers and a limited geographical area, is able to accomplish.

The third central finding revealed that the relative budget value share of ACs has been increasing relative to the size of the construction market for 13 years and is approaching one-tenth of the total market. However, the share of SMEs in these alliances is decreasing. This trend suggests that the budget value of ACs is increasingly being transferred to LEs, which raises serious questions about the differences and opportunities between SMEs and LEs in the sector. The limited sample and data available in this study are not sufficient to assess the reasons; therefore, this study serves as an inspiration for further investigation into the dynamics of ACs, especially from the perspective of SMEs in the construction sector.

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RECONCEPTUALIZING A MODEL FOR LEAN CONSTRUCTION SUPPLY CHAIN

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ABSTRACT

The inefficiency of construction projects in Tanzania made popular cost overruns, extensive delays, reworks, defects and accidents, including resource waste within the construction supply chain. Although scholars have proposed diverse ways to combat supply chain problems, these efforts lack an integrated lean construction supply chain (LCSC) model. Given the persistent resource constraints characterizing the construction industry, this study reconceptualizes an LCSC model for deployment to drive out waste. A critical review of relevant literature was conducted to identify which lean supply chain model predominates in construction in order to develop an LCSC model that integrates lean construction tools and supply chain strategies that were found to proffer better solutions. The paper offers novel theoretical insights that lay a foundation for subsequent empirical and practical implications for LCSC efficiency.

KEYWORDS

Construction, Lean, Supply Chain, Model, Project

INTRODUCTION

Research on the application of supply chain management started first to be investigated in manufacturing industries (McSharry et al., 2023). Given its usefulness, studies on the framework have now taken its course on construction projects. Substantial studies have been carried out on the applicability of supply chain management for construction projects (Chauhan et al., 2022; Cigolini et al., 2022). Further, lean construction practices and principles are widely researched and reported in construction (Koskela et al., 2020; McSharry et al., 2023). Construction supply chain research has also integrated lean project delivery approaches (Le & Nguyen, 2023; Sarhan et al., 2018). Vigorous integration of lean and supply chain strategies can address construction project productivity and resource efficiency problems (Koskela et al., 2020; Le & Nguyen, 2023). However, most of these studies have only focused on applying lean principles, with little emphasis on integrated lean supply chain approaches (Sarhan et al., 2018). These two phenomenological approaches (i.e. construction supply chain and lean construction) have been constantly and distinctly deployed on their own merits.

While lean construction aims at meeting customer needs, continuous improvement, and resource waste minimization (Demirkesen & Bayhan, 2020; Meng, 2019), construction supply chain integration helps with commitment and communication to enhance synergy and co-value creation (Koskela et al., 2020; Le & Nguyen, 2023). Supply chain integration increases

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collaboration and networking of key actors (contractors, consultants, developers) aligned in project delivery (Ballard & Elfving, 2020; Le & Nguyen, 2023). This dyadic synergy is key for lean construction supply chain (LCSC) efficiency at both inter- and intra-organisational levels, which will benefit these LCSC actors. Various studies have been expedited to provide solutions to the current construction supply chain problems in various regions, both in traditional and other project delivery paths. For instance, prior studies were carried out to test the use of traditional construction supply chain to reduce delays because of pre-construction deficiencies in construction projects (Koskela et al., 2020; Meng, 2019).

Although the Architecture, Engineering and Construction (AEC) industry contributes an average of 11% to the GDP of Tanzania's economy (Kikwasi & Escalante, 2020), studies suggest that the development of the industry in Tanzania is hindered by various factors including time/cost overruns, inadequate productivity, insufficient professional knowledge capital, competencies, skills, innovation, building codes, and the industry's supply chain fragmentation (Kikwasi & Escalante, 2020; Kikwasi & Sospeter, 2023; Lello et al., 2023; Bajjou & Chafi, 2020). To address these deficiencies, a robust study is required. At the same time, an LCSC model is lacking in Tanzania. Such a model will also curb challenges related to defects, rework, waste, lack of a common base for project information, lack of standard work, lack of collaboration, and lack of teamwork (Kikwasi & Escalante, 2020; Kikwasi & Sospeter, 2023; Lello et al., 2023). This will contribute to improvements in the construction industry compared to traditional management methods (Koskela et al., 2020; Meng, 2019). Therefore, drawing on the lean and supply chain integration theories, this paper addresses the following research question: *What model will promote lean construction supply chains in Tanzania?*

AN OVERVIEW OF RELATED LITERATURE

Given the construction challenges stated above, this study contends that robust lean tools integration, supply chain integration, lean innovative capability, and stakeholder support (conducive industrial policies, building codes, standards and IT systems embedded within LCSC) can significantly address resource limitations, thus offering positive practical consequences and innovations (i.e. LCSC efficiency) in construction projects. Prior research also indicates that construction projects constitute only 62% of value-adding activities and 12% of support activities (Demirkesen & Bayhan, 2020). This suggests that non-value-adding activities still dominate most of the current project works. Although policy recommendations by experts (e.g. Kikwasi & Escalante, 2020; Kikwasi & Sospeter, 2023; Lello et al., 2023) have been issued recently, comprehensive research efforts to eliminate waste in construction (given the persistent resource limitation) have not been thoroughly carried out. In addition, studies that have empirically investigated the supply chain of projects delivered through lean tools (i.e. using an integrated LCSC model) are scanty (Le & Nguyen, 2023). As an integral part of a major PhD research project, this study reconceptualises an initial integrated LCSC model, which will be tested and validated for deployment basing on sample data from Tanzania's construction industry.

THEORETICAL CONSTRUCTS OF THE MODEL

Considering the nature of construction problems and their proximal effects, this subsection proposes the following study constructs based on lean and supply chain integration (SCI) theories to guide the proposed LCSC model (see Figure 1):

Resource limitation. Resource constraints (e.g. finance, human capital and other tangible assets, such as equipment and supplies) will continue to shape organisational dynamics and routines as resources continue to be scarce. Drawing insights from lean theory, the primary driver of efficient production in the construction industry is its efforts to synthesize and deploy variables for novel project undertakings (Johnson et al., 2023; Zimina & Pasquire, 2011). As stated earlier, "lean" refers to generating value for clients while using less resources (Drevland & Lohne, 2023; Mossman, 2018). It involves a set of principles, axioms, techniques, tools and ways of thinking (sub-theories) that, when combined and applied, can assist individuals and teams in enhancing the processes and systems in which they operate (Koskela et al., 2020; Mossman, 2018).

Supply chain integration. Based on the *SCI theory*, the study opines that robust internal and external supplier and customer integration (Li et al., 2022; Perdana et al., 2019) has potential to leverage supply chain problems inherent in the construction industry. It aims at eliminating traditional functional silos and integrating the functional departments of a company into a single entity in order to meet the requirements of customers at the lowest system-wide cost (Li et al., 2022; Perdana et al., 2019). SCI scholars (e.g. Lello et al., 2023; Li et al., 2022; Perdana et al., 2019) advocate that all the nodes in the network and innovation ecosystems, whether inside or outside the firm, should focus on communicating, exchanging and sharing key information at various sub-systems, activities, relationships and operations.

Lean tools integration**.** Lean tools in construction are viewed as techniques, methods and principles that when strategically deployed have the potential to address resource waste and efficiency challenges. These include: the Last Planner System (LPS), Building Information Models (BIM), Integrated Project Delivery (IPD), Target Value Design (TVD), Lean Project Delivery System (LPDS) model, Choosing by Advantages (CBA), Just in Time (JIT), and the like. Drawing insights from lean theory and the dynamic capability literature, this study contends that construction organisations which can develop dynamic capabilities in effectively and efficiently deploying lean tools, enhances them to integrate, construct, and reconstruct internal and external resources to cope with the fast-changing environment (Johnson et al., 2023; Li et al., 2022).

Lean innovative capability**.** Johnson et al. (2023) define Lean Innovation Capability (LIC) as “an organization’s ability to achieve sustainable innovation performance that meets core customer needs while constantly iterating offerings to validate and learn by continuous market feedback-all via the effective leveraging and mindful embracing of resource limitations” (p. 3). In this context, firms must innovate by developing new processes, organizational forms and business models to achieve differentiation (Li et al., 2022; Manda et al., 2023).

Stakeholder ecosystem support. Based on the supply chain integration and stakeholder resource-based view literature, firms can acquire sustainable competitive advantages by establishing sustainable relationships with key stakeholders (Li et al., 2022; Manda et al., 2023). This enables them not only to capitalize on supply chain resources, but also sail through multiple stakeholder limitations and needs. For instance, while strategic IT vendors can offer supporting technologies (such as BIM, AI, business-to-business (B2B) platforms, blockchain, machine learning, etc.), the government/regulatory institutions can provide valuable policies, professional fee tax incentives and building codes that aim at achieving LCSC efficiency.

Lean construction supply chain efficiency**.** Performance (of organisation or project) is a multi-faceted phenomenon which in general depicts the level of effectiveness and efficiency of previous acts (Lello et al., 2023). The traditional view of project or organisational performance, has been expanded to include the modern dimensions of environmental and societal performance pillars. Therefore, according to Lello et al. (2023), a company’s performance is assessed not only by its capacity to satisfy and keep customers, but also by demonstrating its level of profitability and sustainability. This study focuses on efficiency outcomes that entail making best use of available resources such as project capital/life cycle cost limits, equipment and time saving in project execution. Effectiveness (e.g. visually appealing facilities, etc.) and commercial aspects (the “absolute values” of business performance such as profitability, cash flow and market share, patent counts, etc.) are not the scope of this work.

METHODOLOGY

The conceptual paper is based on the preliminary literature review of lean and supply chain integration (SCI) theories. The conceptual framework developed is the preliminary stage of a major research project (doctoral study) expected to solve the challenges impeding LCSC efficiency experienced in construction operations. The keywords for the search included "lean" AND ("construct*" OR "construction" OR "building" OR "built environment" OR "civil engineering" OR "engineering") AND ("supply chain" or “supply chain integration” or “supply chain network*” or “supply chain collaboration” or “supply chain allianc*” or “supply chain coordination”) AND (“model*” or “framework”)”. The search was dominated by, but not limited to, Web of Science (WoS) and publications in the International Group of Lean Construction (IGLC) repository. The WoS is considered the most reputable peer-reviewed database, with science citation indexed journals. The IGLC database was selected due to its lean-focused research direction. While there were articles addressing global LCSC concerns, preference was made for articles relating to developing countries (emerging economies) as the study context is characterized more by them. Although an attempt was made to consider the latest articles, the retrieved articles ranged between 2000 and May 2023 based on the PRISMA[3] exclusion/inclusion criteria. Initial search resulted in 381 articles. After limiting to subject area and relevance (i.e. engineering & construction building technology), 49 articles were finally obtained from WoS. These were supplemented with additional relevant articles from the IGLC repository. Content analysis was employed to extract relevant information on which lean supply chain model predominates in construction that feeds into developing the conceptual LCSC model that addresses supply chain problems as shown in Figure 1.

RESULTS

This section presents the literature review results on various supply chain models that have been explored in LCSC research in order to identify a model that predominates in construction. This synthesis has broadened and deepened our understanding of how these lean efforts have contributed to the theoretical and empirical examination of the phenomenon. Further, unpacking the extent of exploration in this discourse will aid the development of an integrated LCSC model and increase our awareness of proposed solutions to Tanzanian supply chain problems that alleviate their effects and proffer guidelines on policy recommendations.

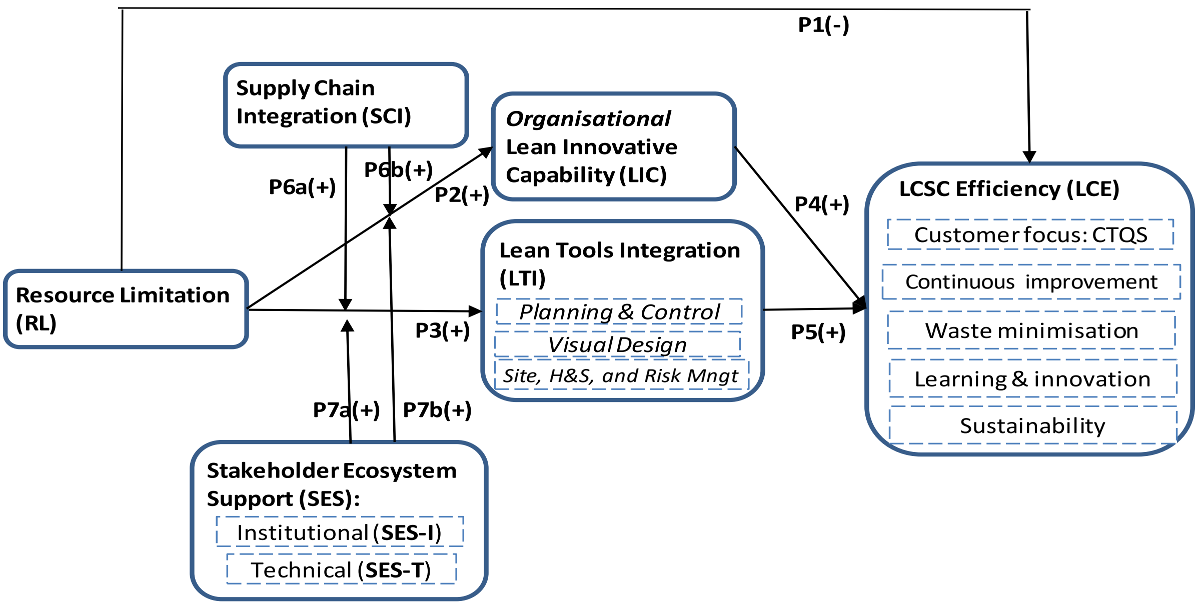
Prior studies have presented various model relationships (see Table 1). For example, a hypothetical LCSC model that employed the study between the applicability of lean principles, construction supply chain collaboration and project performance, centred on key elements (customer focus, continuous improvement, learning and innovation, waste minimization) for lean construction success was established by Meng (2019). However, the impact of the relationship on each construct was not tested and lacked validation. Demirkesen and Bayhan (2020) explored lean construction success factors and clustered them into; financial, managerial, technical, workforce, culture, government and communication. Their results revealed that lean training, availability of lean tools and techniques and market share were lean implementation's most important success factors. Although their findings demonstrated potential to improve efficiency, their study offered little understanding on how resource limitation among project actors could be addressed by vibrant supply chain integration, stakeholder ecosystem support and lean innovative capability of AEC organisations. Table 1 summarizes other models and their contributions adopted by various researchers in construction. LCSC models related to other industries (such as manufacturing) were excluded in this study.

[3] Preferred Reporting Items for Systematic Reviews and Meta-Analyses

Table 1. Summary of previous LCSC models

Author(s)	Model Main Constructs	Methods/Theory	Contribution
Meng (2019)	Applicability of lean principles, lean CSC collaboration, and project performance.	Interviews and descriptive statistics	Lean principles are found to apply to various types of construction projects. Lean management has an impact on project performance.
Demirkesen & Bayhan (2020)	Success factors are clustered as financial, managerial, technical, workforce, culture, government, and communication.	Analytical Network Process (ANP) model based on Importance Weights	These constructs are considered key lean implementation success factors.
Le & Nguyen (2023)	Virtual design construction (design integration), project planning and control, onsite construction and safety management, and sustainable CSC performance.	Integrated Delphi – Fuzzy AHP Process	Proposed a strategic and operational framework for Lean Construction (LC) practices' contributions to sustainable CSCM trends in the forthcoming years.
Asadian & Leicht (2022)	Construction teams, LPS procedure, social interactions, team dynamics, and planning performance.	"Interaction Process Analysis" (IPA)	Proposed an untested hypothesized model.
Zhang & Wu (2011)	Implementation ability, process management, lean degree of employee, lean improvement culture, and adaption ability.	Analytical Network Process (ANP)	Offered an appraisal model to improve Lean implementation ability in China's construction industry.
This study	Resource limitation (RL), Lean tools integration (LTI), Supply chain integration (SCI), Stakeholder ecosystem support (SES), Lean innovative capability (LIC), LCSC efficiency (LCE)	Theory of constraints, lean and supply chain integration theories; structural equation/regression modelling	Proposes a strategic and pragmatic (operational) model for an integrated LCSC in construction. Its successful deployment is instrumental in achieving LCSC efficiency (LCE).

The synthesis summarized in Table 1 suggests that models that integrate lean approaches and construction supply chain constructs are lacking. In addition, a considerable chunk of studies on the phenomenon was conducted adopting mainly; integrated Delphi – Fuzzy AHP process and related Multi-criteria Decision-making (MCDM) methodologies. However, despite substantial attempts to utilize MCDM models, these studies were dominated by conceptual and relatively few empirical studies. They lacked other logics that may further expand and enrich our understanding on theoretical and empirical implications. Moreover, models that employed structural equation modelling and multivariate regression analysis techniques were lacking in these studies. Therefore, this study proposes an initial LCSC remodeling that is more comprehensive and pragmatic for value addition, which will be tested and validated by employing these techniques. To achieve an integrated LCSC model and to limit the envisaged empirical investigations and discussions, we select six (6) constructs (see Figure 1) as key predictors influencing LCSC efficiency. Referring to the research question and drawing on the proposed theoretical framework, the selected theoretical constructs include: (1) resource limitation, (2) lean tools integration, (3) supply chain integration, (4) lean innovative capability, (5) stakeholder ecosystem support and (6) LCSC efficiency. Although there could be diverse ways of remodeling LCSC, the basis for selecting these constructs is anchored on two basics: (1) the model aims at addressing the identified supply chain problems in Tanzania, and (2) the theoretical underpinning is backed by conceptual model building literature which underscores that, models (conceptual, numerical, statistical) are simplifications (reductions) of complicated real-life scenarios (Bernard & Ryan, 2010; Imenda, 2014). The combined effects of these two basics support pragmatists' view in which the behavior of one construct impacts another construct (Imenda, 2014; Greene et al., 1989), thus concretizing LCSC efficiency. For example, it can be noted that; the identified problems and effects (i.e. inappropriate delivery practices, delays, rework, waste etc.) can be addressed by integrating sufficient lean tools pegged on the lean theory. Resource limitations (such as finance, knowledge, technologies etc.) could be swiftly leveraged by the aura of lean innovative capabilities (Johnson et al., 2023; Meng et al., 2019). Further, inefficient procurement systems can be improved through effective integration of supply chain strategy that involves key resourceful supply chain actors/partners grounded on supply chain integration theory. Moreover, inadequate capital and a lack of industrial policies, building codes, and incentives can be intervened through stakeholder support systems (institutional/technical) based on stakeholder resource-based view (RBV) theory. The model will benefit contractors, consultants, and developers. The subsections that follow expound these constructs along with propositions.



Note: H&S – Health & Safety; Mngt. – Management; CTQS – Cost, Time, Quality, Safety; P – Proposition.

Figure 1. Proposed conceptual model

DISCUSSION

PROPOSITION ONE

Johnson et al. (2023) indicate that innovation requires human capital and other assets, such as equipment and supplies as resources (Johnson et al., 2023). While some firms do better than others, it stands out that with no strategic resources, there will be no innovation (Johnson et al., 2023; Li et al., 2022). Empirical studies have employed different theoretical frameworks and have developed various conceptual models to probe the effect of resource limitation on LCSC efficiency (Johnson et al., 2023; Koskela et al., 2020). This study contends that the problems related to defective design, poor quality, inferior working conditions and low safety arrangements, coupled with resource constraints, have a detrimental impact on LCSC efficiency. As stated earlier, empirical studies on slack and its effects on innovation suggest that performance increases as resources increase up to a point where incremental costs exceed benefits, resulting in an inverted-U shape metric (Johnson et al., 2023). In contrast, an opposite trend occurs as resources get diminished. Prior research substantiates that innovation decreases relative to cases where resources are plentiful, in which firms with low levels of slack had the lowest innovation levels (Johnson et al., 2023; Troilo et al., 2014). This will in turn negatively impact LCSC efficiency. Thus, it can be postulated:

P1: Resource limitation has a negative impact on LCSC efficiency.

PROPOSITION TWO AND THREE

As discussed, the lean concept is centred on creating value for customers with fewer resources (Drevland & Lohne, 2023; Mossman, 2018). It optimizes resource efficiency and time/schedule constraints and ensures the budget is not exceeded, thus satisfying the customer (client/employer) (Mossman, 2018). According to Meng (2019), "wasteful processes and activities consume resources but do not add value to the final deliverables" (p. 3787). Therefore, lean, innovative efforts to remove all non-value-adding processes and activities are vital for lean construction (Koskela et al., 2020; McSharry et al., 2023; Meng, 2019). Prior empirical studies on slack (plentiful resources) and its effects on innovation suggest that performance increases as resources increase to a point where incremental costs exceed benefits, resulting in an inverted U shape (Johnson et al., 2023). However, circumstances in which resources are constrained (similar to having lower slack/munificent resources "relative" to other industry players) but where organizations continue to innovate successfully reflect conditions of lean innovation (Johnson et al., 2023; Troilo et al., 2014). This lean innovative capability enhances organisations achieve innovation performance with limited resources. At the same time, to achieve this aim in the AEC project context, the integration of lean tools comes into effect. For example, planning and controlling tools such as LPS are confirmed to have far superior project results (Liu et al., 2022; Warid & Hamani, 2022). Their main strength is their ability to handle uncertainties by increasing planning reliability and predictability, thus decreasing workflow variability (Liu et al., 2022; Warid & Hamani, 2022). Hence, it is propositioned:

P2: The negative impact of resource limitations/constraints is positive when lean innovation capability is high.

P3: The negative effects of resource limitations/constraints turn positive when lean tools integration is high and robust.

PROPOSITION FOUR

As stated earlier lean innovation capability (LIC) of an organization is its ability to achieve sustainable innovation performance that meets core customer needs while constantly and effectively leveraging resource limitations (Johnson et al., 2023). Drawing insights from this perspective, we argue that AEC firms (especially start-ups), usually characterized by a financial, human, and material resource shortage, fail to achieve LCSC efficiency. These effects constrain construction production, exchange, and consumption (Johnson et al., 2023; Koskela et al., 2020**;** Troilo et al., 2014). LICs (such as product-market fit, experimentation culture, mission-oriented leadership, and network learning capability) can significantly improve LCSC efficiency (Hong et al., 2019; Johnson et al., 2023). For instance, visionary leadership provides clear and decisive directions for an organisation, symbolizing strategy and culture on what to do and why (Johnson et al., 2023; Lello et al., 2023). Prior research showed that innovative companies under resource constraints had managers who focused on translating innovation strategies into strategic goals, objectives and performance (Hong et al., 2019; Johnson et al., 2023; Meng, 2019). We also argue that we can use the LIC construct to set a baseline effect to test for positive mediation in leveraging the negative effects of resource limitation, thus improving LCSC efficiency. Therefore, we opine:

P4: LIC has a significant and positive impact on LCSC efficiency.

P4a: LIC positively mediates the relationship between resource limitation and LCSC efficiency, such that the negative impact of resource limitation turns positive when LIC is high.

PROPOSITION FIVE

To achieve LCSC efficiency (i.e., value creation for end customers, waste minimization, etc.), lean tools integration (LTI) plays a vital role. It includes key tools that a main contractor can use to improve predictability, eliminate variability in production (Liu et al., 2022; Warid & Hamani, 2022) through standardization, and reduce lead time (Broft, 2019). As previously described, these key lean tools include the last planner system, building information modelling, target value design, choosing by advantages, just in time, to mention a few. Studies indicate that effectively using these tools has significantly improved lean construction performance (Broft, 2020; Koskela et al., 2020; Le & Nguyen, 2023). Scholars (e.g. Le & Nguyen, 2023; Liu et al., 2022) grouped these lean tools into four categories: design and engineering, planning and control, construction and site management, and health and safety management. This study also suggests that the negative impact of resource limitation on LCSC efficiency is leveraged by LTI mediation. Studies that have examined this relationship are limited. Remodelling resource limitation and LCSC efficiency without factoring LTI cannot yield the envisaged LCSC efficiency. Thus, it can be opined:

P5: LTI has a significant and positive impact on LCSC efficiency.

P5a: LTI positively mediates the relationship between resource limitation and LCSC efficiency, such that the negative impact of resource limitation turns positive when LTI is high.

PROPOSITION SIX

The lean approach challenges scholars to fundamentally rethink value from the customer's needs (Broft, 2020; Koskela et al., 2020). According to Broft (2020), this includes the identification of the 'entire' value stream. The value stream is "the set of all the specific actions (including key project stakeholders) required to bring a specific product or service through the critical management tasks of any business" (Broft, 2020, p. 280). In supply chain integration (SCI), all key supply chain actors need to be able to make a full contribution to ensure that the client's needs are fulfilled and that value creation is maximised (Broft, 2019; Li et al., 2022; Malaeb & Hamzeh, 2018). Drawing on the flow model of production perspective, where production is conceived as a flow of materials and semi-products leading to an integrated final product (Koskela et al., 2020), the analysis of these construct relationships argues that both internal and external SCI can positively moderate the relationship between resource limitation and lean tools integration as well as between resource limitation and lean innovative capability. According to Koskela et al. (2020), any form of waste, i.e., non-value-adding activities existing in the production system of the organisations within the supply chain, will need to be reduced or removed. Vibrant organisation and governance of key supply chain actors (suppliers,

specialized subcontractors, etc.), processes and activities can lead to high productivity and fast delivery (Ballard & Elfving, 2020; Broft, 2019; Le & Nguyen, 2023). To achieve this effect, robust lean tools integration is inevitable. However, to effectively plan, design and control (by employing lean tools) the works (material handling, site logistics and productivity, etc.), strategic engagement with key supply chain actors should be considered (Dakhli & Lafhaj, 2022; Le & Nguyen, 2023). This can positively leverage any negative impact of resource limitation on both lean tools integration and lean innovative capability. Prior research demonstrated that a 7% to 8% improvement is attributed to construction site logistics and supply chain management (Dakhli & Lafhaj, 2022). Thus, SCI has the potential to act as a critical vector and catalyst between resource limitation and lean tools integration as well as between resource limitation and LIC, where innovative lean tools coupled with lean innovative capability must be orchestrated. Therefore, it can be suggested:
P6: SCI moderates the relationship between resource limitation and lean tools integration (**6a**) and between resource limitation and lean innovative capability (**6b**).

PROPOSITION SEVEN

Stakeholder research in AEC focuses mainly on key inbound (direct/core) supply chain actors such as customers, suppliers, and subcontractors (Koskela et al., 2020; Lello et al., 2023; Li et al., 2022). Outbound (indirect/peripheral) supply chain actors, such as government institutions, have been overlooked in LCSC contexts. Given the resource constraints that characterize the AEC industry, construction organisations are always under pressure to deliver projects successfully. This is attainable when these organisations employ innovative lean tools (Koskela et al., 2020; Le & Nguyen, 2023) and lean innovative capability (Johnson et al., 2023). However, strategic integration with peripheral partners (such as institutional stakeholders and IT vendors) can greatly foster corporate flexibility and quick responsiveness (Johnson et al., 2023; Malaeb & Hamzeh, 2018). The delivery of AEC projects involves knowledge- and service-intensive undertakings usually regulated by third-party stakeholders (government/regulatory organs) (Lello et al., 2023; Yip et al., 2019). These stakeholders provide strategic policy frameworks, such as building codes, environmental certifications, and safety guidelines (Lello et al., 2023; Yip et al., 2019), influencing lean tools integration and lean innovative capability. To attain this, AEC designers must seek ways to incorporate all stakeholder interests and then transform the interests into clear design specifications for the new product/service development process (Lello et al., 2023; Yip et al., 2019).

Data science innovations are widely considered as unequivocal vectors for supporting not only SCI but also information sharing, knowledge/skills and innovation networks. For instance, IT vendors, which are also key stakeholders, play a pivotal role in providing the necessary supporting IT infrastructure (e.g. BIM, AI, blockchain, big data analytics, etc.) (Adekunle et al., 2023; Dakhli & Lafhaj, 2022; Liu et al., 2022). In the current digital era (industry 4.0 & 5.0), this technical support employing big data and Internet of Things provides innovative methods that aid organizations in developing high-performing teams and a culture that is performance-focused (Adekunle et al., 2023; AlBalkhy et al., 2023). Nascent studies are now shedding light on the application of technical supports to deal with the problem of lack of synchronization, which has constantly hindered creation of a stable flow in the production system, thus degrading performance and value creation (Lello et al., 2023; AlBalkhy et al., 2023). This will thus leverage the negative impacts of resource limitation on both lean tools integration and lean innovative capability. It can be postulated:
P7: Stakeholder ecosystem support (both institutional and technical) positively moderates the relationship between resource limitation and lean tools integration (**7a**) as well as between resource limitation and lean innovative capability (**7b**).

No prior research has proposed such an integrated model (see Figure 1). In this context, its realization will unfold a novel contribution to theory and practical implications. Moreover, to measure/test and validate the theoretical constructs, the proposed LCSC remodeling will use indicators well-established in previous studies in the literature. For instance, scholars will identify these variable indicators mainly based on the Integrated Delphi – Fuzzy AHP Process (e.g. Le & Nguyen, 2023; Demirkesen & Bayhan, 2020). One of the advantages of this approach is the ease of comparison among alternatives and easy adjustment (Demirkesen & Bayhan, 2020).

CONCLUSIONS

Achieving LCSC efficiency of the AEC projects has been hindered by the lack of an integrated and pragmatic LCSC model that can aid in the alleviation of cost overruns, time overruns, supply chain quality concerns, environmental and safety challenges. Based on a critical literature review approach, this study was conceptualized to solve the mentioned problems to eliminate resource waste (non-value adding activities) through LCSC. Drawing on insights from the lean theory and SCI view, six (6) theoretical constructs were identified as key variables in developing a novel LCSC model for deployment by the AEC actors (e.g. contractors, consultants, developers etc.). Future studies will examine the seven (7) propositions closely to gauge if hypotheses that can be measured can then be developed and tested. In this study, a proposition tries to suggest a link between two or more concepts that may not be tested scientifically while a hypothesis can be tested to estimate the impact of these relationships on LCSC efficiency. Undertaking this endeavor is instrumental in identifying, understanding and removing constraints in operations thus aiding work progress. Therefore, this study presents not only a preliminary step of a doctoral study but also lays a potential foundation on how the theory informs future empirical investigation in eradicating LCSC problems using sample data from Tanzania, thus contributing to and advancing the LCSC literature. The research will further elicit responses from industry participants to answer the research questions and draw up recommendations for the main study. It will further aid theoretical, empirical, practical and policy implications in achieving LCSC efficiency in the construction industry.

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DIGITAL TWIN BASED INTEGRATED DECISION SUPPORT SYSTEM FOR ENHANCED DECISION-MAKING IN THE LAST PLANNER SYSTEM

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ABSTRACT

This paper discusses the enhancement of decision-making within the Last Planner System (LPS) through digitalization, emphasizing the role of a Digital Twin-based Integrated Decision Support System (DT-IDSS) aligned with Lean Construction 4.0 principles. The proposed conceptual framework DT-IDSS aims to address the challenges in LPS decision-making in terms of autonomation, data integrity, user-centricity, and decision-making rapidness, by integrating user-centric design with advanced technologies such as Digital Twins, Internet of Things, Blockchain, and Artificial Intelligence. It features a decentralized reality capture flow for data processing and storage, and an information loop fostering collaborative stakeholder engagement. The system's user-centric development loop adopts an agile, iterative approach, meeting the dynamic needs of construction projects. The integrations of workflows and technologies in the proposed framework has a huge potential in addressing challenges in the deficiency in system integration, which are essential to effectively support information, computation, visualization, and services, thereby enabling stakeholders to make informed decisions. Future research will focus on assessing decision-making effectiveness, enhancing system scalability, improving data management security, and achieving interoperability with existing management systems. This research contributes to the digital transformation of decision-making process, aiming to provide guidance for future developments in this rapidly evolving field.

KEYWORDS

Last Planner® System (LPS), Lean Construction 4.0, Integrated Decision Support System (IDSS), Digital Twin, Smart Digital Technologies (SDTs)

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INTRODUCTION

In the field of Lean Construction, the significance of efficient and accurate decision-making cannot be overstated. The Last Planner System (LPS) is a Lean-based production planning and control system that aims to reduce variability in workflow, improve the predictability of planning, and decrease the waste of production; while acting in tandem on the social and technical aspects of planning and control in projects (Ballard, 2000). This system highlights the importance of "last planners," the individuals responsible for planning the tasks of those executing the work, such as builders and subcontractors, which empowers these planners to have a greater impact on planning and decision-making processes (Babalola et al., 2019). Hamzeh (2009) identifies key decision-making activities in the LPS are:

- **Master scheduling:** Value proposition translation, milestone setting, schedule development, and integration of master scheduling.
- **Phase scheduling:** Milestone planning, collaborative planning, reverse phase scheduling, and schedule adjustment.
- **Lookahead planning:** Lookahead filtering, constraint identification, constraint removal, and operation design.
- **Weekly work planning**: Task selection and assignment, quality criteria application, and learning from failures.

For over three decades, the LPS has become one of the most popular tools within Lean Construction, contributing a multitude of benefits to the construction industry (Sbiti et al., 2021). However, similar to various other construction project management approaches, LPS can be considered to fall under the category of the gambling paradigm. In this paradigm, decisions are made under conditions of uncertainty, where the outcomes are not certain, but the probabilities are known (Blackwell, n.d., Chapter 1). This type of decision-making often indicates that not all available information is being used effectively or in a timely manner. As a result, decision-makers may oversimplify their process, failing to gather and integrate all the relevant information (Fox et al., 2015).

This lack of comprehensive information utilization is a significant factor contributing to some of challenges that the LPS implementation faces in construction projects such as partial implementation issues (Babalola et al., 2019; Lindhard & Wandahl, 2015), the failure to involve key people in decision-making (G. Ballard et al., 2020), the inherent projects’ complexity (Altan & Işık, 2023), underestimation of the social processes impact on technological adoption (Ballard, 2000; Noueihed & Hamzeh, 2022), and the limitations of applying deterministic planning in uncertain project environments (Ballard, 2000; Singh et al., 2024).

To address these challenges, digitizing the decision-making process has become one of the primary areas of focus in construction and engineering project management. Although there has been extensive research on developing digital decision support systems, challenges persist in implementing automated solutions that maintain data integrity and prioritize user-centered design (Boje et al., 2020; Rane & Narvel, 2022; Sacks et al., 2020). Previous studies have concentrated on integrating technologies such as Digital Twins (DTs) (Huang et al., 2021), Internet of Things (IoT) combined with Blockchain (Rane & Narvel, 2022), and computer vision (Mavrovounioti et al., 2015; Reja et al., 2022) to enhance decision-making in project management. However, the practical integration of these complex systems remains a major challenge (Boje et al., 2020). Therefore, a decision support system framework that facilitates the practical application of these technologies in the field is necessary.

Liu et al. (2010) investigated the effectiveness of Integrated Decision Support Systems (IDSS) in improving decision-making within the project management domain. IDSS are defined as interactive computer-based systems that aid in decision-related tasks and are essential in harmonizing data, processes, and technology to facilitate timely and accurate decisions (Liu et al., 2008; Shim et al., 2002). Their research delves into various integration aspects, including data, processes, and technology, culminating in a summarized framework depicted in Figure 1. This framework promotes a unified, interconnected, and user-friendly approach to decision-making (Ren et al., 2023).

For instance, when planning weekly tasks in the Last Planner System (LPS), decision-makers require various supports: information (e.g., progress updates, resource availability, task details), visualization (e.g., aerial site views, task flowcharts), computation (e.g., feasibility studies, cost estimation, risk management), and services (e.g., planning boards, documentation software). In an IDSS, these supports are enhanced: information support through service integration (e.g., shared drives, data management platforms) ensures data accessibility; visualization support through process integration links logical relationships; computational support through data integration converts computational data into decision-making data; and service support through presentation integration reduces cognitive load. These integrations are vital in facilitating an effective decision-making process and can be effective in addressing challenges for the decision-making process associated with the LPS. However, choosing a suitable theoretical framework to guide the IDSS development and pinpoint effective technologies and methodologies for decision-making support in the LPS, continue to be a matter that requires further investigation.

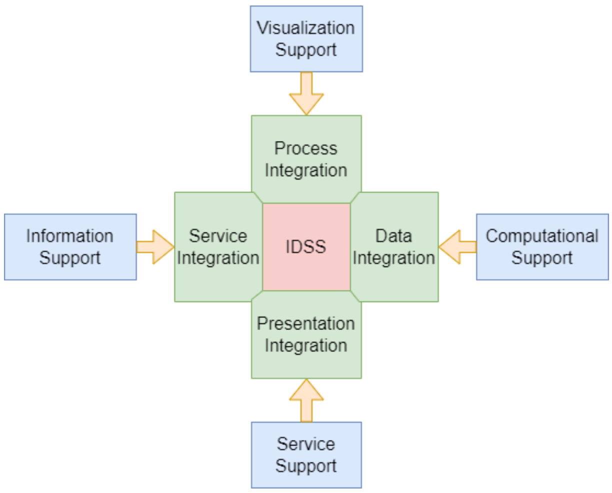

Figure 1 Integrated Decision Support Systems (IDSS) Framework, adapted from Liu et al. (2010)

Lean Construction 4.0 (González et al., 2022) presents a promising theoretical framework that reflects on some of the fundamental technology, production and people/culture shifts in the Architecture, Engineering, and Construction (AEC) sector. This framework combines the production principles of Lean Construction with Industry 4.0-inspired smart and digital technologies (SDTs), underpinned by human-centered design. This synergy aims to enhance and expedite the AEC industry's digital transformation not only by applying Lean Construction principles in tandem with SDTs, but boosting the effectiveness of decision-making processes within AEC organizations. Lean Construction 4.0 also cultivates a project management style that is both more efficient and sustainable, centered on human requirements, which leads to an effective manner to deal with the unique challenges of large-scale infrastructure projects. Through this integrated approach, Lean Construction 4.0 opens new avenues for optimizing resource utilization, mitigating risks, and accomplishing project objectives with an unparalleled level of precision and efficiency.

Building on the foundation of Lean Construction 4.0 (González et al., 2022), this paper presents a novel approach: a Digital Twin-based Integrated Decision Support System (DT-IDSS) to support the LPS implementation. The aim is to weave Lean Construction 4.0's SDTs into LPS's decision-making processes. This involves enhancing key decision-making activities in the LPS by utilizing an IDSS in crucial areas such as data collection, data analysis, decision-making application development, and information flow. The objective is to not only tackle current challenges in digital decision support systems but also to pave the way for future advancements in the development of digital IDSS in Lean Construction domain.

A BRIEF REVIEW OF DECISION SUPPORT SDTS AND INTEGRATIONS

The concept of Digital Twin (DT) has become a fundamental element in revolutionizing decision support systems among various industries. Essentially a DT serves as a digital reflection of physical entities, systems, or processes, facilitated by ongoing and timely information exchange (Sacks et al., 2020). In construction, DT goes beyond the simple digital representation of project products and processes to offer a dynamic and real-time link between the physical and digital realms. This connection enables continuous monitoring and analysis, providing deep insights and control over infrastructure projects. Creating a DT involves developing a virtual model of a physical asset, integrating real-time data from sensors and IoT devices to accurately replicate the asset's behaviour and performance (VanDerHorn & Mahadevan, 2021). Populating the DT requires continuously updating the model with live data, enabling real-time monitoring, analysis, and optimization of the asset's operation and maintenance (Boje et al., 2020). This offers a dynamic and holistic view of construction projects, integrating real-time data and predictive analytics to enhance decision-making processes (Boje et al., 2020). DT technology, known for its deep impact on data integration and visualization, has established itself as a fundamental aspect of decision support systems in diverse sectors (VanDerHorn & Mahadevan, 2021).

Based on Lean Construction 4.0, the collection of detailed data from the construction production environment is critical to generate DTs for decision-making (Bou Hatoum & Nassereddine, 2022). This ties in with the advancements in lean project management efficiency through the integration of IoT and Blockchain technologies, signaling a shift towards more secure, transparent, and instantaneous data management in construction projects (Martínez et al., 2022; Rane & Narvel, 2022; Wu et al., 2023). In this realm, IoT sensors act as crucial links between the physical and cyber worlds, capturing real-time data for subsequent modeling and analysis (Bou Hatoum & Nassereddine, 2022). Concurrently, Blockchain technology, known for its decentralized structure, immutability, and strong authentication processes, is vital for ensuring secure and reliable data distribution (Li et al., 2019). From the reality capture and data distribution perspectives, the integration of IoT and blockchain can address the dynamic challenges faced during infrastructure project management that often lead to delays, rework, and increased overhead costs (Amade & Nwakanma, 2021; Fobiri et al., 2022). By leveraging blockchain and IoT, the project management process can be transformed, offering real-time data insights, improved asset management, and enhanced security and transparency (Ghimire et al., 2016). This technologically advanced approach not only aligns with the principles of adaptive and intelligent IDSS, but also extends these principles by providing practical, real-time solutions for managing resources efficiently in large-scale infrastructure projects. The adoption of this Blockchain-IoT integrated architecture represents a significant leap in data collection and information distribution for digitalized, decentralized decision support systems.

Following the collection of data from construction sites through reality capture and IoT sensing, the timely generation of semantically enriched DTs remains a challenge (Boje et al., 2020). The integration of Artificial Intelligence (AI), via computer vision technology, into the real-time generation of DTs in construction and infrastructure projects is fundamental. It offers transformative possibilities in production management practices by providing real-time data modelling and analytics, which enables a dynamic and highly accurate representation of physical assets and revolutionize how projects are planned, monitored, and executed (Sami Ur Rehman et al., 2022; Shamsollahi et al., 2022; Soman & Molina-Solana, 2022; Xu et al., 2021). This integration is also one of the practical applications of SDTs within the Lean Construction 4.0 framework, enhancing production management practices(Stowe et al., 2020). Recent studies in this domain have underscored the value of computer vision and deep learning technologies in enhancing real-time monitoring and decision-making. For example, the application of Computer Vision-based Construction Progress Monitoring (CV-CPM) has demonstrated how real-time, accurate monitoring of project progress can be achieved (Bozorgzadeh & Umar, 2023). Also, reinforced learning with linked-data based constraint checking shows the potential of applying AI-based models to provide computational support for the decision-making in the LPS (Soman & Molina-Solana, 2022). Further, the development of regression-based deep neural networks for equipment monitoring and advanced 3D pose estimation techniques illustrates the capability of these technologies to provide detailed, real-time insights into construction operations (Cheng et al., 2023; Golparvar-Fard et al., 2013; T. H. Wang et al., 2023). These advancements in AI not only facilitate a more dynamic and holistic view of project environments but also align with the core principles of adaptive and intelligent IDSS. By enabling the continuous synchronization of physical and digital worlds, AI technologies contribute significantly to the creation of real-time, accurate DTs, which are crucial for the proactive management of safety, resource allocation, and overall operational efficiency.

Despite these technological advances, a gap remains in the form of an IDSS that cohesively combines these technologies within the decision-making workflow. This paper seeks to bridge this gap through the introduction of a User-Centric Digital Twin-Based Integrated Decision Support System conceptual framework, as illustrated in Figure 2. The proposed framework provides a vision to integrate the strengths of IoT and robotics for reality capture, blockchain for secure data distribution, and advanced AI-based data processing, all within a DT framework for IDSS. This user-centric approach aims to harness the full potential of these technologies, providing an innovative and robust solution for efficient and effective decision-making within the LPS.

THE DT-IDSS FRAMEWORK

This section offers a comprehensive overview of the proposed DT-IDSS Framework. The discussion is proceeded in the following order: system overview, decentralized reality capture flow, decision-making information loop, and user-centric development loop. Additionally, this section also presents the current research progress in applying the proposed framework.

USER-CENTRIC DIGITAL TWIN-BASED INTEGRATED DECISION SUPPORT SYSTEM OVERVIEW

The LPS decision-making process, as mentioned in the introduction section, can be considered to fall under the category of the gambling paradigm, characterized by decisions made under uncertainty. To mitigate this uncertainty, the decision support is anchored by four key pillars: information, visualization, computation, and service (Galjanić et al., 2022; Liu et al., 2010; Shim et al., 2002), which is shown in Figure 2. At the core of the system lies information support, providing essential data crucial to make informed decisions. This includes updates on project progress, availability of resources, and specific details about tasks. Key to this component is the integration of services, ensuring seamless access to important information for decision-makers. Service integration focuses on combining functions and services within the DT-IDSS, ensuring that different components of the system are compatible and accessible. This integration encompasses not just the harmonization of internal components but also the optimization of the user interface and external interactions, thus enhancing the overall utility of the system.

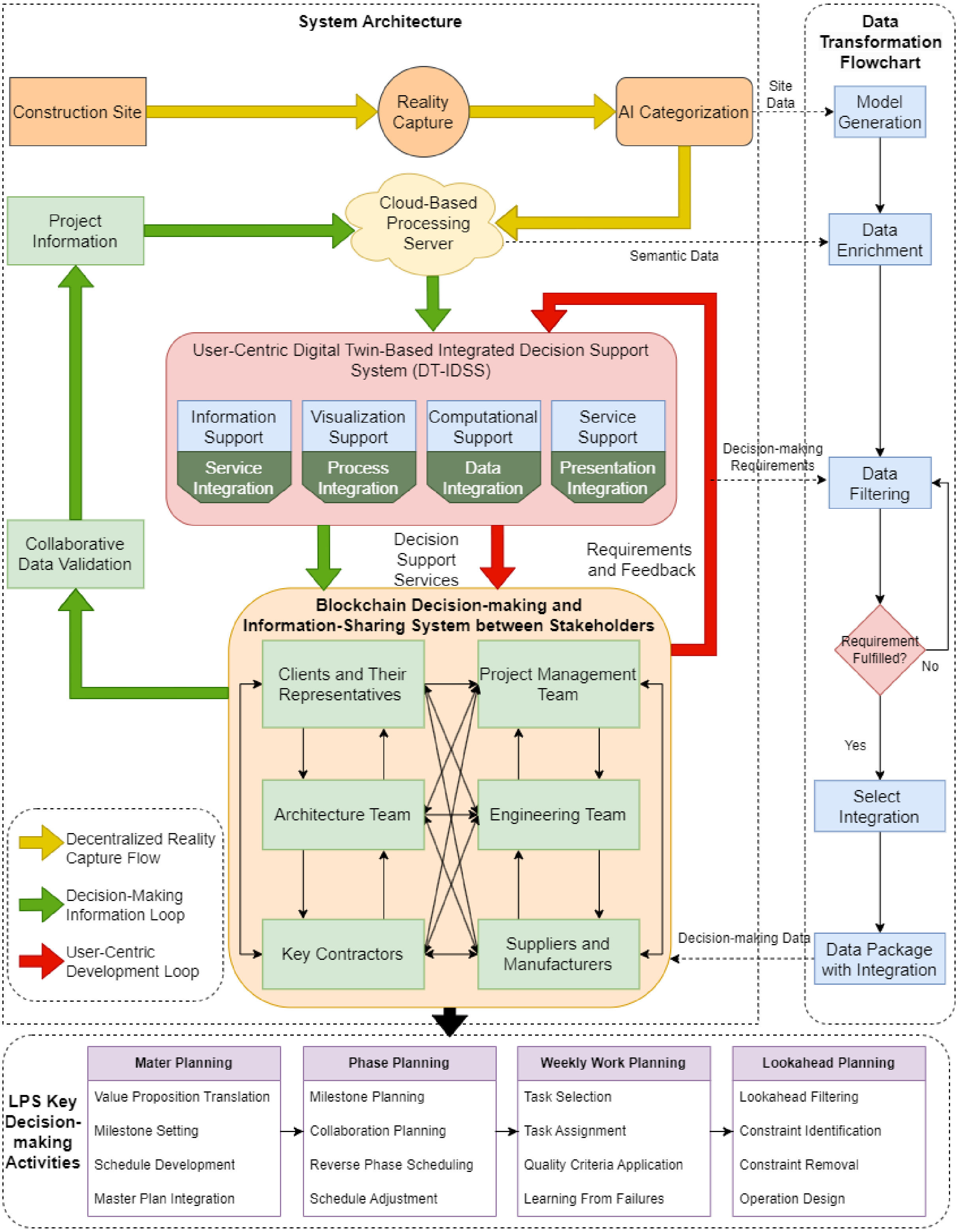

Figure 2 User-Centric Digital Twin-Based Integrated Decision Support System (DT-IDSS)

Visualization support enhances the data experience by presenting information in formats such as charts, images, videos, 2D/3D models, and Building Information Modeling (BIM) constructs. This is done in a manner that is easy to understand and user-friendly, necessitating the integration of processes to create cohesive and intuitive visual representations of data. On the other hand, computation support leverages computer systems and algorithms to streamline complex data interpretation, assisting in key areas such as planning, cost estimation, and risk analysis. This support depends on the effective integration of data, converting extensive computational outputs into practical, actionable insights.

Service support consolidates various essential tools and applications for efficient decision-making, aligned with the project's overarching objectives. This includes a range of digital planning tools, document management systems, and BIM technologies, all optimized through presentation integration for a user-centric approach. The aim here is to reduce the cognitive burden on decision-makers and make the decision-making process more efficient. Presentation integration focuses on creating a consistent user interface across the DT-IDSS, standardizing visual design and interactive elements to ease user interaction. It also involves using consistent metaphors and mental models across various components to simplify learning and minimize interference in usage.

The service support of the system offers a variety of user-focused services, like customizable interfaces for different user roles, dashboards for stakeholders. Services in presentation integration are designed to deliver a consistent and intuitive user experience across various devices and platforms, boosting stakeholder engagement and facilitating decision-making. This comprehensive approach to decision support within the DT-IDSS framework not only streamlines the management of infrastructure projects but also markedly improves the efficiency and effectiveness of the decision-making process.

DECENTRALIZED REALITY CAPTURE FLOW

As illustrated in Figure 2, the primary aim of the reality capture process is to guarantee the prompt and precise transmission of data to a cloud-based processing server, ensuring the data's integrity throughout. This workflow is designed to gather the maximum amount of information feasible, tailored to meet decision-making requirements. Consequently, it is distinct from the decision-making process, a strategic separation that ensures the data remains pure and accurately represents the original information as captured and processed. In the user-centric integration development process, the data sourced from this flow undergoes only filtration without any alteration, maintaining its authenticity.

In this setup, reality capture sensors are classified into three types: photogrammetry sensors (e.g., CCTVs and stereo cameras), sensors for geometric information (e.g., location trackers and Geofencing), and Unique Identification (UID) sensors (including RFID and Bluetooth Low Energy-based beacons). The data captured by these sensors is transmitted via Narrowband Internet of Things (NB-IoT), a specialized communication technology designed for IoT sensors. Operating on cellular telecommunication bands, NB-IoT is optimized for extending wide-area connectivity to IoT devices. It offers several advantages, including low power consumption, extensive coverage, high connectivity density, and enhanced security, making it particularly suitable for infrastructure projects (Miao et al., 2018).

AI models are employed to categorize all collected data and transfer the categorized data for the model generation. For instance, computer vision models can be applied to categorize and preprocess photogrammetry data. An example using Yolov8 developed by the IHT lab in the University of Alberta (https://www.iht-lab.com/) is shown in Figure 3. Moreover, deep learning-based models with GIS data can be applied to the 3D reconstruction process, as shown in Figure 4. Depending on the computational requirements of these tasks, the AI models may be deployed either locally at the sensor level or integrated with the cloud-based processing server.

In the proposed framework, a cloud-based server is established as an independent central unit for storing, processing, and distributing IoT data within a decentralized reality capture system. This server stores both unprocessed and processed data, ensuring its availability for the

DT-IDSS as required. Importantly, it plays a vital role in creating 3D mesh models and adding semantic attributes derived from IoT sensors and project information, aiding in the creation of real-time, semantically enriched DTs. At this stage of research, the DTs are BIM models enriched with information from reality capture, sensors, and collaborative project meetings. These DTs serve as dynamic data reservoirs, aiming to improve the efficacy of real-time decision-making processes. The server is designed to manage intricate processing tasks such as action recognition, performance evaluation, quantity calculation, and the assessment of cognitive loads on workers. Its contribution to the decision-making information cycle is essential, bringing substantial value to this integrated system.

Figure 3 Example of a Computer Vision Model Detecting Excavators and Key Points

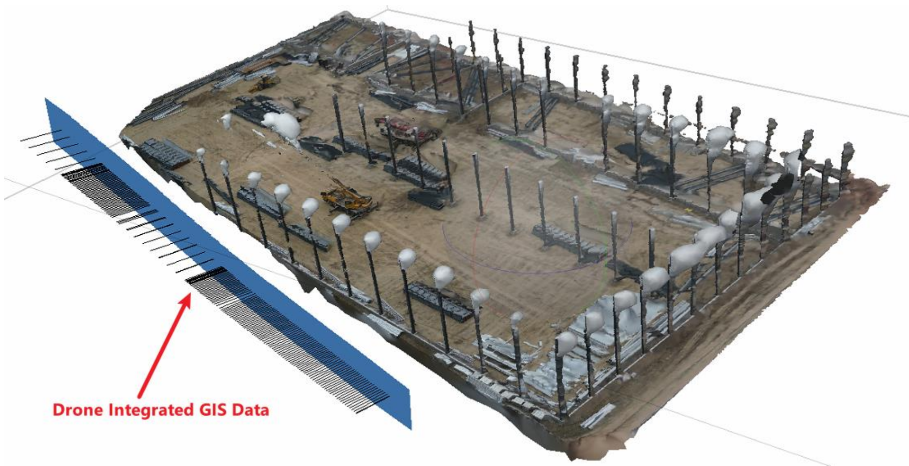

Figure 4 Example of Deep Learning Based 3D Reconstruction Using GIS Data

DECISION-MAKING INFORMATION LOOP

The decision-making information loop follows the Lean Construction 4.0 principle of *"development of human trust in the decision-making system"* (González et al., 2022). As illustrated in Figure 2, the design aims to support decentralized and collaborative interactions among stakeholders. This involves stakeholders actively participating in reviewing, validating, and updating data to ensure its accuracy and relevance to the project's needs. Stakeholders play a pivotal role in checking and refining the data within the system, while also maintaining the immutability of records, contributing their expertise, and fostering a shared understanding of project information. After the project information is validated, it is transmitted to the cloud processing server for the generation of semantically enriched DTs, which act as information conduits for the DT-IDSS. The blockchain technology here provides a decentralized approach of data management, which ensures that once data is entered, altering it requires consensus and must be transparent across all stakeholders (Wu et al., 2023). This cooperative model ensures that the system's data is current, reflective of the project status, and enriched by the varied insights and skills of all involved parties, thereby improving the quality and dependability of the decision-support framework.

Data integration within the DT-IDSS is crucial for reliable decision-making, as it ensures consistently updated and synchronized information across the system. This integration minimizes data redundancy and enables smooth data flow between system components, preserving data integrity. The establishment of clear integration standards and the maintenance of data completeness and synchronization are vital for effective decision-making. This strategy allows for quick dissemination of critical updates, such as design changes. The DT-IDSS enhances computational support by utilizing advanced techniques (e.g., data fusion, cloud computing, and blockchain) to combine and coordinate data from various sources, including architectural design software, project management tools used by the project management team, onsite reports from contractors, and inventory systems from suppliers. Leveraging decentralized blockchain technology, modifications in these data sources are instantaneously updated across all platforms accessible to stakeholders, which ensures that stakeholders receive timely, reliable, and highly integral data. As a result, they can quickly adapt their work schedules and tasks to align with evolving project requirements.

USER-CENTRIC DEVELOPMENT LOOP

The user-centric development loop in the DT-IDSS follows the Lean Construction 4.0 principle of *"consciousness about human-centered systems"* (González et al., 2022, p. 10). This method promotes an iterative and collaborative approach that is essential to agile UX design practices. It prioritizes user needs in the development of decision-making applications, ensuring that the system is not only technically proficient but also practically relevant (Wang et al., 2023). This approach is vital for successful integration of services, processes, data, and presentations, as illustrated in Figure 2, thereby improving the overall functionality and user experience within the DT-IDSS framework.

In this process, stakeholders (end-users) are actively engaged throughout the entire development cycle of DT-IDSS applications. Their crucial role involves reviewing, confirming, and enhancing system features to ensure the DT-IDSS effectively addresses practical requirements. The stakeholders' continuous involvement in validating functionalities, providing insights, and giving feedback is instrumental in the system's ongoing development. This constant loop of user engagement keeps the system in sync with the evolving needs of construction and infrastructure projects, allowing it to adapt to changes and foster a sense of ownership among all involved parties.

Agile software development principles are integrated into the design of the DT-IDSS, with a focus on sprints that address urgent needs of stakeholders. Regular meetings with interdisciplinary teams of stakeholders ensure clear communication and the swift resolution of immediate issues in the development of DT-IDSS applications. In this development cycle, backlog grooming is a continuous activity, involving regular updates to the backlog with new stakeholder requirements, feedback, and changes. At the end of each sprint, a review session is held where stakeholders can evaluate the latest version of the system and provide comprehensive feedback. Stakeholder requirements are meticulously gathered through interviews, surveys, observations, and workshops. The feasibility and impact of these requirements are analyzed, then prioritized based on the value they bring to stakeholders and the project. These consensus-based requirements are documented clearly and in detail, for instance, through user stories, to ensure they accurately reflect stakeholder needs and avoid any misunderstandings or ambiguities. An example of user-centric application designed for site surveying and progress monitoring is shown in Figure 5, applying the user-centric development framework for remote inspections adapted from Wang et al. (2023)

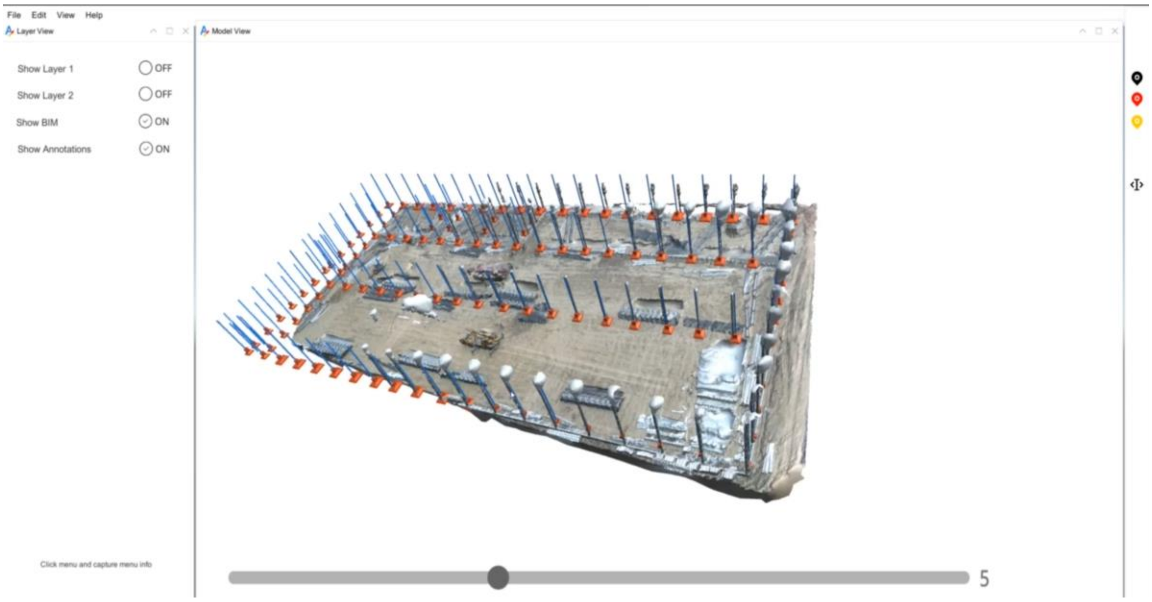

Figure 5 Application Developed for Site Surveying and Progress Monitoring

CONCLUSION AND FUTURE WORKS

This paper has highlighted the critical importance of timely and accurate decision-making in the LPS and how the digital transformation of these processes can significantly enhance project management efficacy. The proposed DT-IDSS, grounded in Lean Construction 4.0 principles, harnesses cutting-edge technologies like DT, IoT, Blockchain, and AI to tackle the complex challenges faced in LPS decision-making processes. The DT-IDSS is characterized by key elements such as a decentralized reality capture flow for accurate data processing and storage, and an information loop for decision-making that encourages collaborative involvement of stakeholders. Furthermore, the system's development loop places a strong emphasis on a user-centric, agile, and iterative approach, aligning with the dynamic needs of construction projects.

The DT-IDSS shows potential in facilitating various decision-making aspects. It assists in precise work sequencing and task allocation by utilizing real-time data on project progress and resource availability. This contributes to better forecasting, risk management, and adjustment of project schedules to accommodate changing conditions. Additionally, the DT-IDSS gives special consideration to human-centric factors, improving workforce management and safety. It offers customized work schedules to optimize team performance and well-being, while AI-driven predictive analytics help identify potential risks, creating a safer and more adaptive work environment. This comprehensive strategy is in line with Lean Construction principles, focusing on both efficiency and the human aspects of project management.

Though this framework represents an initial result of multiple ongoing research at IHT lab in the University of Alberta, it has not yet been fully developed and validated. Future research is proposed in several areas: 1) Assessing Decision-Making Effectiveness: Implement empirical studies to evaluate the impact of the DT-IDSS on decision-making and overall project results; 2) Enhancing System Scalability and Flexibility: Aim to refine the framework to cater to diverse project sizes and complexities; 3) Improving Data Management with a Focus on Security: Prioritize streamlined data management for efficient data sharing, while enhancing data security and privacy, especially regarding reality capture and data distribution in the DT-IDSS; 4) Achieving Interoperability with Existing Management Systems: Work on making the system compatible with existing project management and enterprise resource planning systems for seamless integration and data exchange.

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LEAN-BIM SYNERGY IN THE CONSTRUCTION DESIGN PHASE: AUTO-GENERATION AND EVALUATION OF THERMAL ALTERNATIVES

Karim El Mounla[1,2], Djaoued Beladjine[3] and Karim Beddiar[4]

ABSTRACT

This study explores the integration of Lean principles with Building Information Modeling (BIM) to enhance decision-making in the relatively unexplored field of thermal design for construction projects. Recognizing the limitations of current design processes, characterized by insufficient alternatives and a lack of team collaboration, we introduce a new decision-making tool. This tool centers on a breakthrough framework and algorithm that bridge BIM with Lean techniques. It facilitates the automatic generation and evaluation of insulation material alternatives for residential buildings by integrating the Pleiades software database and Industry Foundation Classes (IFC) BIM data. Our study details an automated process for selecting insulation materials through an iterative, criteria-based approach that systematically identifies the three most viable solutions using Set-Based Design methods. It then selects the optimal one by examining and evaluating their criteria according to the project's needs based on energy efficiency, profitability, and sustainability through the Choosing By Advantages method. Additionally, by incorporating Big Room and BIM, our tool promotes enhanced communication and collaboration from the outset of the design phase, underscoring the significance of this integration in automating and optimizing thermal engineering projects.

KEYWORDS

Lean Construction, Set-based Design, Choosing By Advantages, Building Information Modeling, Big Room.

INTRODUCTION

In the construction industry, the design phase is the foundational stage where a project's trajectory toward efficiency and sustainability is determined (Bello et al. 2021). This phase is more than just the inception of architectural concepts, it is the period when the crucial elements of scope, cost, and time are precisely defined. Any discrepancies at this stage can have a significant effect, causing repercussions throughout the construction lifecycle (Yusof et al. 2015). Therefore, a meticulous focus on the design phase is not just prudent, it's imperative for the successful execution of any construction project (Herrera et al. 2021a; b).

In the last decade, several studies have highlighted the pivotal role of the synergy between Lean principles and BIM in enhancing the efficiency of construction projects, particularly during the design phase (Eldeep 2022; Herrera et al. 2021b; Sajedeh et al. 2016). Initially, it is crucial to understand the individual contributions of both Lean and BIM. Lean construction

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focuses on eliminating waste and optimizing processes, while BIM provides a detailed digital representation of the project, enabling better planning and visualization (El Mounla et al. 2023; Sacks et al. 2010).

When these two methodologies converge, they create an efficient tool for improving decision-making. Decision-making is a critical aspect of the design phase, as it sets the foundation for the entire project. Decisions made during this phase have far-reaching implications on cost, duration, and overall project quality. By integrating Lean's efficiency-driven approach with BIM's comprehensive, visual, and data-rich models, stakeholders can make more informed, precise, and timely decisions (El Mounla et al. 2023; TUDublin and Sheramn 2019).

However, traditional design practices often encounter challenges due to their linear and segregated nature, leading to communication breakdowns, resistance to change, and costly design alterations down the line (Castañeda et al. 2023; El Mounla et al. 2023). These outdated methods inhibit flexibility and can be detrimental to the project's overall adaptability and success. Moreover, after conducting the literature, review we found that applying Lean/BIM synergy in the thermal field has not yet been explored. The significance of decision-making in the design phase cannot be overstated, as these early-stage decisions have lasting implications on all subsequent phases of construction. Informed, strategic choices are essential, shaping the project's aesthetics, functionality, economic feasibility, and regulatory compliance (Lee et al. 2012a; Rempling et al. 2019).

Set-Based Design (SBD) and Choosing By Advantages (CBA) are integral methodologies in construction and engineering that streamline decision-making and enhance project outcomes. SBD involves exploring a broad spectrum of design options and methodically narrowing them down to the most suitable solutions by eliminating less feasible alternatives (Castañeda et al. 2023; Sahadevan and Varghese 2018, 2019). This approach ensures comprehensive consideration of all relevant criteria from the project's inception, avoiding the premature exclusion of viable options. In addition, CBA complements SBD by offering a structured decision-making process that focuses on the comparative advantages of each option, ensuring decisions are both transparent and value-driven (Lee et al. 2012b; Mathern et al. 2018; Parrish et al. 2007). This integration is evident in complex construction projects, such as steel fabrication, where SBD's broad exploration of design alternatives including material properties and construction methods pairs with CBA's evaluative approach focusing on benefits like durability and ease of installation. This synergy optimizes decision-making, balancing feasibility with value, as exemplified in the work of (Parrish and Tommelein 2009).

In addition to these two methods, the Big Room is another Lean method that serves as a collaborative hub. It aims to bring together architects, engineers, contractors, and clients, to collectively plan, design, and manage the construction process (Fosse et al. 2017). Integrating BIM into this method significantly enhances interaction and understanding among these stakeholders. For example, a case study on a complex construction project shows how the Big Room served as the central coordination point. The project team used BIM to develop a comprehensive 3D model of the building. This model, accessible in the Big Room, allowed stakeholders to visualize the project in real-time, identify potential design conflicts early, and make informed decisions collaboratively (Fosse et al. 2017).

The research problem addressed in this study focuses on enhancing the decision-making processes for thermal engineers during the residential building design phase, particularly in selecting optimal insulation materials to achieve energy efficiency, sustainability, and high performance. The core challenges include the limited application of SBD in construction projects, which is constrained by the time and resources required for complex decision-making. This complexity arises from the need to evaluate various materials against numerous criteria and the necessity for improved collaboration among stakeholders, including architects and engineers. Additionally, integrating advanced technologies to streamline these processes is essential. To address these issues, our solution proposes a decision-making tool that integrates Lean methods with BIM. The process begins by integrating BIM within the Big Room to enhance collaboration and communication, thereby facilitating the identification of project goals and improving the flow of information for decision-making. Then this tool employs SBD to systematically explore insulation material alternatives from the Pleiades database and IFC files, facilitating the automatic generation of the top three insulation options. Subsequently, CBA is applied to evaluate these options and select the best insulation material, considering environmental standards like France's Environmental Regulations 2020 (RE2020). This innovative approach not only promotes sustainability by prioritizing materials that meet stringent environmental criteria but also broadens the thermal engineer's perspective by considering a wider range of high-performance materials. This improves the design phase's efficiency and effectiveness in construction projects, contributing to the broader goal of energy-efficient and sustainable building practices.

METHODOLOGY

In our study, we combined three distinct research methodologies to ensure a comprehensive and robust analysis: the Construction Research Approach (CRA), Systematic Literature Review (SLR), and Semi-Structured Interviews (SSI). Central to our methodology, CRA is an innovative approach aimed at creating new constructs or solutions specifically designed to address practical problems in the real world. It not only facilitates the development of tangible interventions but also enriches the theoretical framework within the field by bridging the gap between theory and practice (Piirainen and Gonzalez 2013). This approach is pivotal in guiding our research toward making significant practical and theoretical contributions. Complementing CRA, the SLR method allows us to thoroughly review and synthesize existing research, ensuring our study is deeply grounded in current academic discourse. Additionally, SSI provides nuanced insights by exploring diverse perspectives and experiences related to our research problem. Together, these integrated approaches enhance the reliability and relevance of our findings, promoting a balanced understanding that advances both practical applications and theoretical knowledge (Lukka et al. 2003).

To understand the methodology applied in our study, table 1 illustrates a structured process for integrating these methods together to construct our decision making tool. The journey begins with a SLR method where research is conducted to identify gaps and limitations in existing research (Monla et al. 2023). This step is essential for understanding the problem space and setting the foundation for application. Subsequently, SSI is conducted to provide depth and context to the research topic by gathering qualitative insights. This method helps in understanding user needs and collecting more specific requirements (Attouri et al. 2022).

Following this, the process involves discussions with experts to further understand and refine the requirements based on their expert knowledge and to validate the findings from the interviews (Attouri et al. 2022). This ensures that the frameworks created are grounded in practical realities and expert insights. With this information, the decision-making tool is developed based on the information gathered from the previous steps. Once developed, the tool is then validated by experts to ensure that it meets the intended requirements and standards before being released.

The last phase, which involves testing in real case study and then comparing the results obtained with the theoretical framework, is planned as a future step to evaluate the effectiveness of the decision-making tool in a practical and theoretical settings. This will provide an opportunity to observe how well the application performs in the real world and to identify any areas for improvement. The work completed thus far includes identifying research gaps, engaging with users and experts, as well as developing and validating the tool, setting a strong foundation for the final testing and implementation phase.

Table 1 Methodology applied in our research: A sequential process CRA to deployment of an efficient decision-making tool.

CRA Steps	Description	Action
1	Choose a practical problem with theoretical basis, focusing on under-analyzed or challenging topics.	SLR method was used to identify gaps and limitations.
2	Form a long-term collaboration with target organizations, establishing a team, funding, data access, and result dissemination agreements.	SSI was applied to provide depth and context to the research topic.
3	Gain thorough practical and theoretical understanding of the subject, analyzing the organization's current situation and theoretical research field background.	
4	Design and develop a theoretical and practical solution, emphasizing innovation and prototype development.	A framework was created, and a tool is being built based on the information gathered from the previous steps.
5	Implement and test the solution within the partner organization, typically through pilot sites.	The developed tool will be reviewed by experts to ensure it meets the intended requirements and standards. The tool is then tested in a real case study and compared with theory.
6	Reflect on the solution's scope and transferability by evaluating the success of test markets and considering broader applications. Then, identify and analyze the study's theoretical contributions and their impact on existing theories.	

To delve into details in applying SLR method, the operation starts by searching for articles related to SBD in the design phase of a construction project. A total of 31 papers between journals and conferences are obtained after filtering through the steps presented in Figure 1 (Schiavi et al. 2022; Xiao and Watson 2019). The process begins at the top with the identification of a collection of keywords, which are then used to conduct a search through Google Scholar and Scopus, resulting in the gathering of 416 papers, encompassing both articles and conference papers.

Following this initial collection, the inclusion and exclusion criteria are applied. This involves filtering the papers by reading their abstracts and titles, which helps to assess their relevance to the research topic. The process also includes eliminating duplicate papers to ensure uniqueness in the review. Additionally, the criteria specify retaining only those papers that are written in English.

After this filtration stage, a thorough reading of the full papers is conducted for the remaining ones to further evaluate their suitability for the review. This in-depth reading helps confirm that each paper contributes valuable information to the research topic. At the end of this process, 31 papers are retained for in-depth analysis and synthesis, indicating a significant reduction from the initial 416 papers, thereby focusing the review on the most relevant and high-quality research available. A deep knowledge in the domain was recognized that aids in identifying gaps and limitations within the SBD.

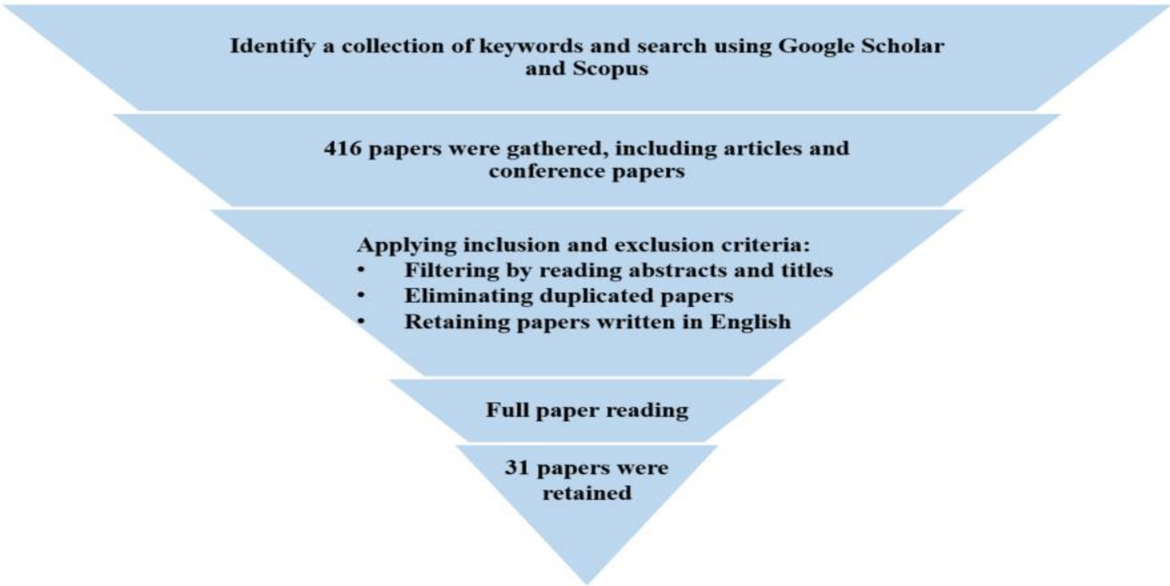

Figure 1 Systematic Literature Review procedure.

Critical limitations in applying SBD for thermal insulation selection in construction were identified: resource intensity, time-consuming analysis of all alternatives, decision complexity, information overload, integration challenges with tools like BIM, and difficulties aligning stakeholders. Therefore, our objective is to create a tool that simplifies the SBD process for thermal engineers by integrating Lean methods with BIM, thereby facilitating more efficient and effective decision-making in the design phase. Additionally, by automatically generating alternatives and selecting the best three solutions, we significantly decrease the time required for the procedure. Moreover, this approach aims to improve project outcomes by ensuring that the chosen insulation materials align with both project goals and environmental standards, such as France’s 2020 Environmental Regulations (RE2020).

Recognized for its balance of qualitative and quantitative analysis, SSI involved detailed discussions with experts in construction design from both academic and professional backgrounds (Attouri et al. 2022). The selection of the 25 experts for our project focused on their expertise in the AEC field, specifically in Lean and BIM methodologies. This process began by engaging academic researchers to validate our framework, which incorporates Lean methods like SBD, CBA, and the Big Room with BIM, tailored for applications in the thermal field. These researchers, chosen for their contributions to Construction Blogs, International Group for Lean Construction (IGLC) conferences, and other scientific publications, brought a wealth of knowledge, with experience ranging from five to twenty years. Meetings with them were conducted via Teams and face-to-face during scientific events like the IGLC 2023 conference in France and symposiums in Brest. Following this validation phase, we expanded our inquiry to include professionals such as architects and thermal engineers, conducting surveys to delve into the practical challenges and requirements of applying our framework in real-world scenarios. Specifically targeting French thermal engineers ensured the relevance of our findings to the French work environment, with selected experts also well-versed in BIM to closely align with our framework's focus. The insights obtained from these experts are pivotal, not only for completing but also for testing our decision tool in actual case studies, thereby refining our framework's accuracy, ensuring it aligns with industry best practices, and enhancing its potential to improve the design phase of construction projects. Through this rigorous validation and feedback process, our framework has gained credibility and applicability, demonstrating its effectiveness in thermal field applications. The feedback from experts was very positive, indicating that our work is essential and significant.

Table 2 Survey questions assessing the effectiveness of SBD in thermal engineering decision-making.

Number of questions	Questions
1	How effectively do you think the SBD aids decision-making for thermal engineers?
2	How would you rate the framework's ability to tackle the challenges faced in applying SBD in thermal engineering projects?
3	Do you find that the integration of CBA and the Big Room concept significantly improves SBD's application in thermal engineering?
4	How feasible do you consider the application of this framework in practical thermal engineering scenarios?

RESULTS AND DISCUSSION

LEAN METHODS COMBINATION BENEFITS

Table 3 illustrates the integration and impact of SBD, CBA, the Big Room concept, and BIM on the design process. SBD, as introduced by (Lane and Woodman 2000), focuses on delayed decision-making and considers multiple design alternatives to minimize rework and suboptimal outcomes, a concept further refined by (Ballard 2000) through positive and negative iterations. Complementing SBD, CBA, as outlined by (Arroyo and Long 2018), systematically evaluates options based on their advantages, aiding in making more informed decisions. The Big Room concept further enhances this process by fostering collaborative decision-making among all stakeholders in a shared space, ensuring a comprehensive approach to design. Additionally, the synergy of these methods optimizes efficiency, with SBD aligning production to actual demand, CBA prioritizing initiatives for discussion, and the Big Room facilitating multidisciplinary collaboration. Furthermore, BIM's role, emphasized by (Lee et al. 2012b; Lee and Cho 2012), is crucial in supporting SBD through enhanced 3D visualization and data management, enabling rapid evaluation of alternatives and maintaining accuracy throughout the design process. This synthesis is the result of a detailed analysis of the literature conducted in the state-of-the-art phase. It combines insights from various articles we have studied. The table effectively demonstrates how these methodologies, when used together, enhance the design process, making it more targeted, and effective.

Table 3 Lean methods processes and their combination benefits with BIM.

Combining CBA with SBD	Enhancing Decision-Making: Adds structure to SBD's decision-making process. Focusing on Value: Highlights the value and benefits in SBD's design choices. Facilitating Stakeholder Agreement: Helps align stakeholders during the SBD process. Aiding Iterative Refinement: Can be used at various SBD stages for refining design solutions. Resolving Conflicts: Provides clear rationale for choosing solution over another in SBD.
Combining Big Room with SBD and CBA	Fostering Collaboration: Brings stakeholders together for collective decision-making. Providing Immediate Feedback: Speeds up the SBD and CBA processes through instant input. Offering Diverse Insights: Enriches decision-making with varied expertise. Ensuring Transparency: Makes the rationale behind decisions clear to all stakeholders. Facilitating Conflict Resolution: Allows for immediate discussion and resolution of disagreements.
BIM with Lean methods	Enhanced Decision-Making: The combination of BIM, SBD, and CBA facilitates data-driven decisions, optimizing project outcomes by allowing thorough evaluation and comparison of multiple design options. Improved Collaboration: Integrating BIM with the Big Room concept promotes real-time communication and teamwork among all stakeholders, leading to a unified understanding and alignment of project goals. Increased Efficiency: This approach streamlines the design and construction process, reducing rework and modifications by ensuring well-informed, efficient decisions from the start.

OUTCOMES OF SEMI-STRUCTURED INTERVIEWS AND THE DEVELOPMENT OF A DECISION-MAKING TOOL

On the other hand, our SSI, reinforce existing literature while also uncovering new insights specific to the thermal field. These interviews highlighted key motivators for adopting SBD and CBA in thermal projects. These motivators include reducing waste, boosting productivity, shortening project durations, and enhancing decision-making processes. Additionally, the concept of the Big Room, where project stakeholders collaborate closely, emerged as a significant factor in improving project outcomes. In light of these findings, our initial step was to create a framework, which we then refined into a decision-making tool improving the thermal field. This tool, incorporating principles of SBD and CBA, along with the collaborative approach of Big Room and BIM, aims to enhance decision-making in thermal design projects. It is designed to enable better decision-making at the beginning of the design process, resulting in a more efficient assessment of thermal solutions and strategies. By integrating these methodologies, the tool specifically addresses the distinct challenges and demands of thermal engineering. This enables professionals to make well-informed, effective decisions that are align with project objectives and sustainability criteria, while also featuring automated processes to further streamline its use.

Figure 2 demonstrates a comparison between the traditional thermal engineering process and our improved method, which applies our framework. Initially, thermal engineers would manually define parameters, select two solutions, simulate them using thermal software, and then choose the best option.

Our framework applies the Big Room concept, where, using BIM, the thermal engineer, architect, client, and other engineers can identify the project's goals and make suitable decisions. For example, they use the 3D visualization provided by BIM to identify solutions and solve problems. This approach improves communication and collaboration, enabling the team to make the right decisions necessary for advancing the design phase. Then, through coding, SBD is applied to explore all possible alternatives from the Pleiades database and information obtained from IFC files to automatically generating the top three insulation materials that meet the project's objectives and have the best performance. These three solutions are then integrated directly into three different IFC files and connected to Pleiades software for thermal simulation of the building. Subsequently, CBA is used to evaluate and select the best insulation material from these options after analyzing the results from Pleiades. This tool enhances sustainability by selecting insulation materials that meet environmental standards, such as RE2020. Additionally, by testing all possible alternatives, it provides a broader vision for the thermal engineer, aiding in the selection of better insulation materials that may offer superior performance. By applying Lean methods in conjunction with BIM, we create more innovative and efficient thermal design solutions, thus elevating the overall effectiveness of the design phase in construction projects, a key factor in achieving energy efficiency and sustainability in buildings.

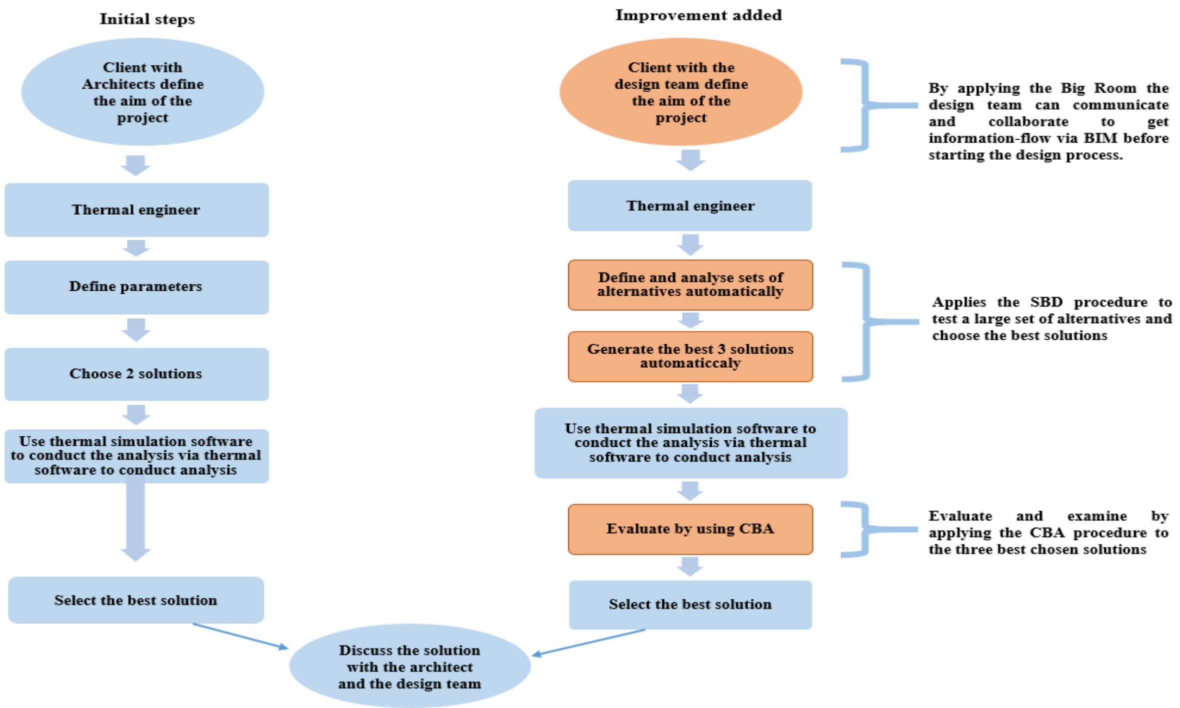

Figure 2 Traditional framework (left) versus Proposed framework (right) (with the orange rectangle indicating the additional value our framework provides).

AUTOMATING PROCESSES USING THE R STUDIO PROGRAM

To delve into the specifics of our work and the creation of the automation process, figure 3 illustrates a flowchart that outlines the procedural code for a thermal engineering application. The process initiates with the crucial step of "Identifying parameters", involving a strategic combination of data from both the Pleiades software and IFC BIM models. This integration of two distinct data sources is essential for accurately identifying relevant attributes and uncovering potential correlations. By leveraging the strengths of Pleiades and IFC BIM, we aim to develop a comprehensive understanding of the parameters that will guide the "Generation of sets of alternatives" for insulation materials. This approach ensures a thorough and nuanced analysis, setting a strong foundation for the subsequent stages of the process. Once these sets are created, the "Start the process" step initiates, where insulation material is selected based on the engineer's criteria.

If the chosen material "Complies with the requirements" such as thermic conductivity, CO2 emission, density… the process returns to generating alternatives, indicating an iterative approach to find the optimal solution. In case of non-compliance, the alternative is discarded, and the results are stored in a database. This phase includes a crucial decision point, "Last alternative?" If the answer is "Yes" the process progresses to "calculating scores for each alternative based on their criteria" followed by a generating of "top 3 solutions".

The flowchart also illustrates a client-server model through the App block, featuring a User Interface (UI) component that interacts with the server to process 'Input' and deliver 'Output'. This suggests that user inputs through the UI initiate server-side processes, which in turn provide outputs back to the client. The "request-response" mechanism between the client and server indicates that the decision-making tool, facilitating dynamic interaction as the server processes data and returns results for display or further analysis. Integrating a decision-making tool is a key part of automating the workflow, thus enhancing the decision-making process in thermal engineering projects.

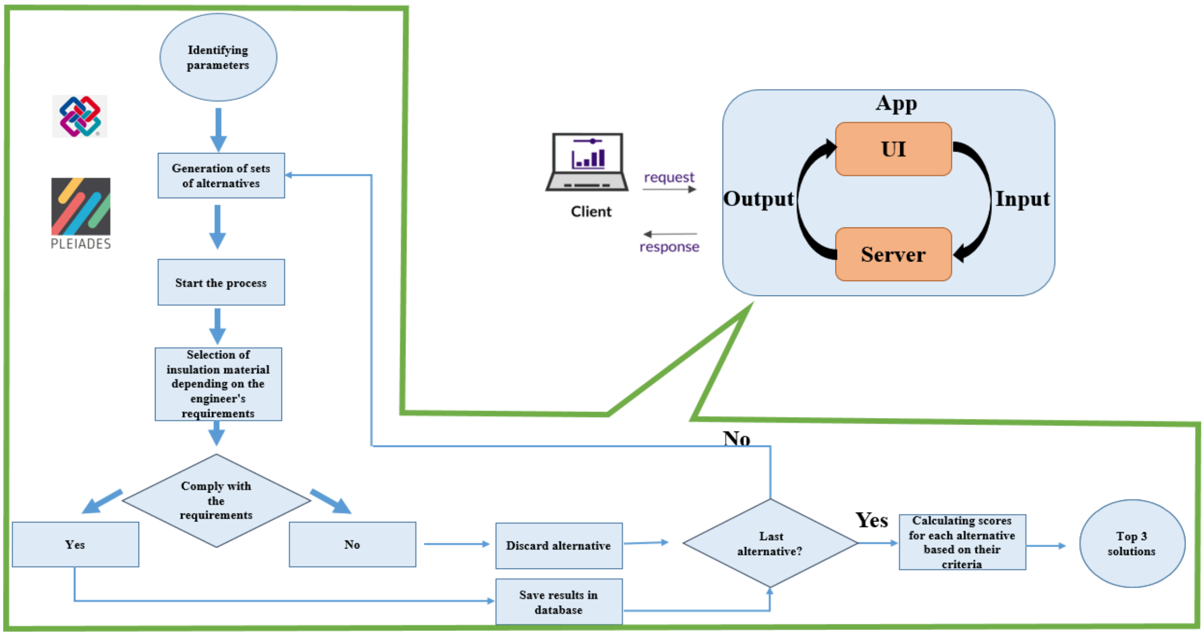

Figure 3 Architecture of decision-making tool for Lean-integrated thermal design process.

In our study, we have demonstrated the feasibility of enhancing the design phase by applying Lean principles with BIM, leading to significant improvements in the thermal engineering process for building design. The results, as illustrated in the figures above, show a clear distinction between the traditional approach and our research framework. Our method leverages automated parameter definition and a comprehensive evaluation of insulation material alternatives, leading to a more effective selection process. This approach, enhanced by the use of a decision-making tool, aligns with digital construction methodologies and provides a structured, streamlined method for thermal engineering. The key improvement is in the decision-making process, where thermal engineers can now evaluate a broader range of options using SBD and CBA techniques, ensuring the selection of the most optimal solution based on multi-criteria analysis. This not only improves the accuracy and consistency of the design process but also significantly reduces manual efforts and time spent on repetitive tasks. The integration of Lean principles with BIM technology in our framework represents a forward step in addressing the challenges of energy efficiency and sustainability in building design, show casing the potential for innovative solutions in the field of thermal engineering.

CONCLUSION AND FURTHER WORKS

In conclusion, this research has established a novel framework that synergizes Lean principles with BIM to optimize the design phase in construction, with a specific focus on thermal engineering. Grounded in comprehensive literature reviews and validated through surveys and semi-structured interviews with industry experts, the framework introduces automation in the generation and evaluation of design alternatives and then choosing the best 3 solutions automatically. This automation, facilitated through a decision-making tool, has demonstrated its effectiveness through its constituent elements in enhancing decision-making, reducing costs, and increasing the value of construction projects. Future work for this article involves completing the coding of the decision-making tool and then testing it in real-case studies. Additionally, applying this tool to other aspects of thermal design will add significant value, especially for HVAC systems, which present challenges in decision-making. This process will ultimately ensure the tool's effectiveness in practical applications.

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BIM AND IOT INTEGRATION FOR CONSTRUCTION AND LOGISTICS MANAGEMENT: A STATE-OF-THE-ART REVIEW

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ABSTRACT

Considered a promising avenue for achieving improvements in construction and logistics management, the integration of Building Information Modelling (BIM) and the Internet of Things (IoT) has proposed the ability to revolutionize the Architectural, Engineering, Construction, and Facility Management (AECFM) industry. Many studies have been examining different applications of BIM and IOT integration, specifically within the context of industry 4.0 through recent years. However, the existing literature appears to be fragmented due to the absence of review and categorization, leading to difficulties for practitioners and researchers in identifying trends and gaps. This paper delves into the convergence of BIM and IoT within the field of construction and logistics management by reviewing and categorizing the current cited literature derived from various journals using OpenAlex. On the one hand, the results suggest the utilization of RFID and LoRa for logistics, tracking, and inventory management with BIM and IoT as the most frequent topic. On the other hand, the implementation of BIM and IoT for simulating emergency evacuation scenarios is the least mentioned topic. The main foci within each topic-subcategory are also highlighted and described respectively.

KEYWORDS

Building Information Modeling, Internet of Things, Construction Management, Logistics Management

INTRODUCTION

Nowadays, we are witnessing a significant improvement in the productivity of several industrial sectors as the outcome of digitization. As a result of this promising outcome, the utilization of digital tools to design, build, and operate buildings and infrastructure assets is also becoming a common practice in the Architecture, Engineering, Construction, and Facility Management (AECFM) industry (Borrmann et al., 2018). To address the new challenges originated by the change of practice as an outcome of digitalization, Building information modeling (BIM) offers a model-centric information storage and distribution approach for construction projects, similar to other model-based product development approaches in many other industries (Kagermann, 2015). Additionally, the Internet of Things (IoT) is another industry 4.0 concept gaining more

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attention from practitioners by the day, based on the Global Standards Initiative (GSI) recommendation for the Internet of Things, IoT has been defined as the global infrastructure for the information exchange network that can facilitate the interconnecting physical and virtual assets (things) based on communication protocols such as the Radio-Frequency Identification RFID, Wireless Sensor Network technologies, Low Energy Bluetooth, and other developing protocols (Bayani et al., 2017). In other words, IOT provides a standard platform and a unified language for IOT-enabled devices to exchange information and communicate with each other and with external networks. IoT contributes to a variety of aspects within the AEC industry with instances such as smart user-centric environmental quality adjustment or energy consumption optimization using IoT-enabled components for building systems. Utilization of IoT for tracking products, assets, and materials in various stages of procurement for construction projects would have considerable effects on efficient delivery and waste reduction through improved management and coordination of construction projects consequently, the use of IoT and BIM for tracking and logistics optimization is an instance of lean construction approach in practice (Dave et al., 2016). The utilization of BIM and IoT for procurement and progress tracking is an example of how integrating product-centric information models and IoT technology can address the challenges with supply chain automation and logistics optimization in lean construction (Araújo et al., 2021).

The convergence of BIM and the Internet of Things (IoT) holds a huge potential to revolutionize construction and logistics management (Dilakshan et al., 2021; Khurshid et al., 2023). Numerous studies have highlighted the significant achievements in the integration of IoT with BIM or other centralized information management approaches. For instance, Chow et al. (2006) introduced a resource management system for warehouse operations using RFID technology, emphasizing efficient resource allocation and real-time management. Adiono et al. (2017) introduced a rapid Warehouse Management System (WMS) utilizing Radio-Frequency Identification (RFID) as a means of information exchange for inventory reporting management, demonstrating the efficiency-enhancing capabilities of IoT in inventory management. Biswal et al. (2018) extended this concept to consumables supply chains in India, emphasizing the potential of IoT in enhancing distribution logistics. Given the diverse aspects by which BIM and IOT integration contribute to construction management and logistics optimization, a growing interest in research in this field can be observed (see Figure 3). Despite this trend, the existing literature related to BIM and IoT integration is fragmented leading to difficulties for practitioners and researchers in identifying research trends and potential gaps. Additionally, few papers have focused on providing specific focal categories towards BIM and IoT integration for construction and logistics management context. Therefore, in terms of research goals, this research aims to identify potential research gaps by systematic categorization and review of the state-of-the-art research foci on BIM and IoT integration in the context of construction and logistics management. The contribution for this research is providing a valuable resource for practitioners and researchers interested in this field.

RESEARCH METHODOLOGY

The methodology selected for this research is literature review, which involves systematic examination and synthesis of existing literature on a specific topic. The initial inspiration for the research methodology comes from the scoping review framework (Arksey & O'Malley, 2005). Unlike the expansive nature of scoping reviews, the state-of-the-art review in this study reflects a deliberate focus on providing the latest and comprehensive understanding of BIM and IoT in construction and logistics management. This research prioritizes a more detailed exploration of recent literature, aiming to capture the dynamic trends, challenges, and opportunities in this evolving field.

By applying the state-of-the-art review methodology, detailed procedures conducted in this study are displayed (see **Error! Reference source not found.**).

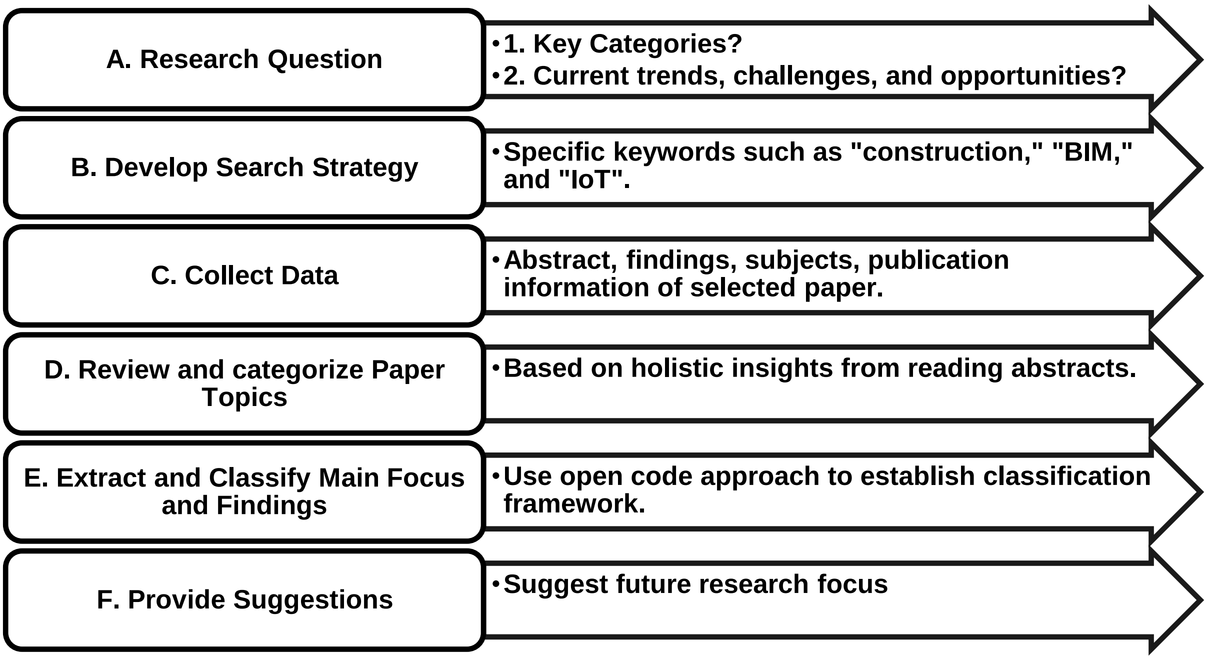

Figure 1: Process Flow Demonstrating Research Methodology

The research goals for this paper are (1) to systematically categorize and review the existing literature on the combined use of BIM and IoT in construction management logistics, (2) to identify research gaps and areas where further improvements and innovation are needed, and (3) to provide a valuable resource for practitioners and researchers interested in this field. Considering these goals, this paper is going to find answers to the following questions: What are the key categories of research for BIM and IoT implementations in construction and logistics management? What are the current trends, challenges, and opportunities for future research in this field?

After research goals and questions are determined, comes the selection of the reference database. Considered a user-friendly interface with various functions for researchers, OpenAlex is one of the free research databases that enable interactive filtering with organized and structured data, allowing researchers to identify and export query results for research.

As for the inclusion and exclusion criteria, all indexed papers in the Open Alex database are tagged with multiple concepts, based on the title, abstract, and available text. An automated classifier algorithm trained on the Microsoft Academic Graph (MAG) database serves as the tagging tool for the articles. The tags provided by Open Alex, which are named "concepts," in this paper are listed as "Building information modeling," "Internet of Things," "Scheduling (production processes)", "Engineering management", and "Operations management". (see Figure 2). Considering that the scope of research is limited by BIM, IOT, and Management adding the term "Logistics" to the inclusion criteria resulted in the removal of a sizable portion of citations from the literature. The research team decided not to include this term because adding it to the filters would have resulted in the omission of many studies with relation to construction logistics that didn't necessarily use the term logistics in their subjects and abstracts. Consequently, a wider range of subjects was evaluated, and the additional unrelated works were filtered out of the literature during the abstract review based on the qualitative judgment of the researchers.

Figure 2 Inclusion and Exclusion Criteria for OpenAlex

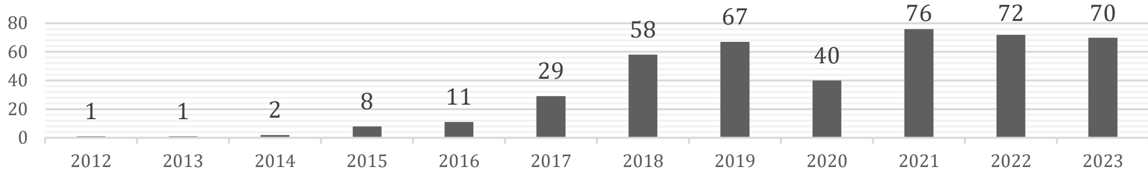

Figure 3: Publications by year including all English-published articles with BIM & IOT & Construction in the title, abstract, text, or concept (report from Open Alex)

Using the inclusion and exclusion criteria mentioned above, here are the search results demonstrating the number of publications (see Figure 3). As shown in the diagram, a significant increase in terms of the publication numbers occurred in 2015. Consequently, the publication time duration is limited from 2015 to 2023. Also, considering citation counts as a quality assessment of peer-reviewed publications, articles without citations were removed from the dataset.

While creating the categories for the articles, a rigorous method is employed to systematically organize and categorize the diverse information. The initial step involves assembling a spreadsheet dataset that encompasses articles associated with specific article IDs and corresponding bibliographical data including topics, summary of focus, and findings. After removing out-of-scope search results, reports, and duplicate items from the data, which consists of 404 papers, seventy-six articles with citations are chosen for full-text review. In the next stage, similarities among different topics and focus points of the articles are identified and the foundation for summarizing the common subject is established. Each article is assigned to only one category and subcategory.

Finally, an iterative categorization approach is implemented, where articles are initially grouped based on shared characteristics and subsequently refined to eliminate redundancies and ensure coherence. Using the open coding method (Cho & Lee, 2014), the categories are named thematically to encapsulate the subjects they represent, and the entire process is thoroughly documented for transparency and reproducibility. The results capture the diverse facets of the BIM and IoT implementations in construction and logistics management within the context of the Architectural, Engineering, Construction, and facility management (AECFM) industry.

LITERATURE REVIEW

As a result of the full-text review and open coding, this section discusses the categorization of literature based on areas of focus that emerge from the exploration of research papers with combined implementations of BIM and IoT in construction logistics and management (see **Error! Reference source not found.** and Figure 4). Categories and subcategories are proposed, based on specific applications and multifaceted ways in which BIM and IoT integration interact with various aspects of the construction and logistics management areas. In the following paragraphs, the logic behind categories and subcategories are explained respectively with additional examples provided from the literature. At this point, it is necessary to clarify that the categorization is merely the result of an open coding process and qualitative thematic analysis of studies by the authors. Furthermore, to provide future researchers with additional dimensions for potential gap spotting, The research topics were also categorized based on thematic connections with established classifications such as project management body of knowledge PMBOK (Project Management Institute, 2017) knowledge areas Each knowledge area represents a distinct domain of knowledge and practice within the broader discipline of project management. By breaking down project management into these specific areas, the PMBOK Guide facilitates a structured approach to understanding and managing projects. This approach allows project managers to focus on key aspects such as scope, time, cost, quality, human resources, communication, risk, procurement, and stakeholder engagement, ensuring comprehensive coverage and effective management throughout the project lifecycle. Additionally, the studies within each subcategory were also tagged based on topic relationships with common building lifecycle phases. The primary phases utilized for categorization purposes are Pre-construction (I), Construction (II), and Operation/Maintenance (III), Additionally, it is necessary to consider that in some cases the integrated implementation of BIM and IoT addresses the Entire building Lifecycle (IV) of buildings.

Table 1 Classification of Literature for BIM and IoT Implementations

Category	Sub-Category	Area of Focus	Phase	PMBOK Knowledge Area	References
Implementation and examination of New Technologies with the help of BIM and IoT	Cognitive Technologies	Operation and Maintenace Monitoring	III	Quality	(Santarelli et al., 2019; J. Xu, Lu, & Li, 2019; J. Xu, Lu, Xue, et al., 2019)
	Prefab and Manufacturing	Prefabrication, Supply Chain	I	Resource	(Wang, Altaf, et al., 2020; Wang, Wang, et al., 2020)
	Big Data	Estimation and Predictive maintenance	III	Cost	(Chu et al., 2021; Halmetoja, 2019)
	Distributed construction	Novel Offsite Construction Approaches	II	Time	(Dallasega et al., 2018; Pang et al., 2019)
	Digital Twin Applications in construction and maintenance	Procurement & Interactive Coordination of resources in Construction and Operation	III	Procurement	(Esmaeili & Simeone, 2023; Liu et al., 2023; Peladarinos et al., 2023; Rezaei et al., 2023; Rossi et al., 2019; Sepasgozar, 2021)
	Smart Building Systems	System Monitoring & Inspection	III	Integration	(Afzaal & Shoaib, 2021; Cantarero et al., 2018; Rahman et al., 2020; Vivi et al., 2019)
Integration/Optimization of information with the help of BIM and IoT	Blockchain & BIM Integration	Model-Based Traceability of Changes	IV	Scope	(Chung et al., 2022; De La Pena & Papadonikolaki, 2019; Fitriawijaya et al., 2019; Lu et al., 2021)
	Digital Twins & IoT Integration	Model-Based Real-Time Tracking and Procurement	IV	Procurement	(Chang et al., 2018; Esmaeili & Simeone, 2023; Nath, 2022; Tang et al., 2019)
	BIM Adoption Challenges Within Industry 4.0	Seamless Flow of Information	IV	Integration	(Al-Sinan et al., 2023; Begić et al., 2022; Mahajan, 2022; Yilmaz et al., 2023)
	BIM Adoption in Developing Countries	Process Implementation	IV	Integration	(Dosumu et al., 2023; Maqbool et al., 2023)
	BIM for Facility Management	Model-Based System Monitoring & Inspection	III	Integration	(Kameli et al., 2020; Lauria & Azzalin, 2023; Moreno et al., 2022)

Table 2 (continued) Classification of Literature for BIM and IoT Implementations

Category	Sub-Category	Area of Focus	Phase	PMBOK Knowledge Area	References
Construction Safety With BIM and IoT	Safety & Emergency Management	Safety For Workers and Equipment	II	Risk	(Park et al., 2018; Ribeiro et al., 2022; Sassi et al., 2022)
	Emergency Evacuation	Simulation Of Disaster Response	III	Risk	(Birajdar et al., 2020)
Construction Logistics and Transportation Optimization With BIM and IoT	IoT in Parts Transportation	Procurement Tracking	II	Resources	(Ben Neila et al., 2021; Sepasgozar et al., 2019; Tazikova & Struková, 2021; Treiblmaier et al., 2020; G. Xu et al., 2019)
	RFID and LoRa (long-range, low-power data transmission)	Procurement Tracking	II	Procurement	(Dervishaj et al., 2023; Gaba et al., 2018; Juraboev & Díaz, 2024; Kameli et al., 2020; Ragnoli et al., 2022; Teizer et al., 2018)
	Information and Communication Technologies (ICT)	Management Information System	IV	Communications	(Hammad et al., 2021; Li et al., 2022)
	AI & Supply Chain Innovations	Coordination In Distributed Construction	III	Resource	(Orooje & Latifi, 2021; Tien et al., 2022; Villa et al., 2022)
Facilitating User Comfort	Occupant Feedback & Digital Twins	Improve Occupants' Satisfaction	III	Stakeholder	(Dave et al., 2018; Donkers et al., 2022; Mao et al., 2018; Stojanovic et al., 2019; Su & Kensek, 2021)
Sustainability With BIM and IOT	Circular Economy in Construction	Sustainable Waste Management Solutions	III	Integration	(Batista et al., 2022; Sassanelli et al., 2021; Tao et al., 2018)
	Sustainable Construction Practices	Sustainable Construction Solutions	II	Integration	(Ben Neila et al., 2021; Klymenko et al., 2021; Mao et al., 2018; Petschen et al., 2023; You et al., 2020)

Within the category of "New Technologies", the sub-category of Cognitive Technologies (J. Xu, Lu, & Li, 2019; J. Xu, Lu, Xue, et al., 2019), is about the utilization of cognitive IoT and digital twins for efficient facilities management. Prefabrication and Manufacturing Technologies, (Wang, Altaf, et al., 2020; Wang, Wang, et al., 2020), is about BIM and IoT for real-time data synthesis, optimizing off-site construction processes. Other subcategories include the integration of Big Data with BIM and IoT for improved facility management (Chu et al., 2021; Halmetoja, 2019). Distributed Construction (Dallasega et al., 2018; Pang et al., 2019), which holds the studies on BIM and IoT for real-time logistics planning and monitoring, contributes to distributed construction. Digital Twin Applications (Esmaeili & Simeone, 2023; Peladarinos et al., 2023; Rossi et al., 2019), showcases reduced costs and improved efficiency of construction management through BIM and IoT integration. Finally, Smart Building Systems, presented in articles (Cantarero et al., 2018; Rahman et al., 2020), propose building system architectures with IoT, utilizing BIM.

The category of "Integration/Optimization," is about the utilization of BIM and IoT to facilitate collaboration and integration, especially within the context of construction management. Blockchain & BIM Integration sub-category (Chung et al., 2022; Fitriawijaya et al., 2019; Lu et al., 2021), contains references proposing transparency and traceability in supply chain management, ensuring accurate digital representation and enhancing trust with information exchange platforms. Digital Twins & IoT Integration (Chang et al., 2018; Esmaeili & Simeone, 2023; Tang et al., 2019), focuses on real-time data gathering, reducing costs and enhancing decision-making through the integration of BIM and IoT with digital twins.

The sub-category of BIM Adoption Challenges Within Industry 4.0, (Begić et al., 2022; Mahajan, 2022; Yilmaz et al., 2023), assesses digitalization and automation across construction project life-cycle phases, emphasizing the impact of technologies like BIM and IoT on the future of construction and the adoption challenges within the context industries already embracing initial BIM adoption stages. On the other hand, the subcategories of BIM Adoption in Developing Countries, (Dosumu et al., 2023; Maqbool et al., 2023), delves into challenges such as network infrastructure, standardization, and interoperability with implementing BIM in developing countries, recommending awareness and policy enactment. BIM for Facility Management sub-category, (Kameli et al., 2020; Lauria & Azzalin, 2023), contains various integrations of BIM and IOT specifically with RFID as a means of tracking and information exchange, for optimizing building maintenance.

Moreover, the category of safety is divided into two main sub-categories “Emergency management” and “Emergency evacuation,” where BIM and IoT are employed for simulation and management of user safety or critical circumstances. Safety & Emergency Management (Park et al., 2018; Ribeiro et al., 2022; Sassi et al., 2022), introduces BIM-based systems for disaster management, explores immersive visual technologies for safety training, and reviews emerging technologies for health and safety standards. Emergency Evacuation (Birajdar et al., 2020), reviews recent advancements in building fire detection and evacuation systems, emphasizing the role of BIM and IOT in enhancing safety protocols and simulation of immediate disaster response.

The category of “Logistics” explores the potential of BIM and IoT in Parts and Transportation management for construction. With parts transportation sub-category proposing cloud-based fleet management platforms and investigating the potentials of the Physical Internet for sustainable logistics networks (Ben Neila et al., 2021; G. Xu et al., 2019); RFID and LoRa technologies integrated with BIM models for efficient asset tracking, real-time monitoring, and location sensing in construction logistics (Gaba et al., 2018; Idrissi Gartoumi & Koumetio Tékouabou, 2023; Juraboev & Díaz, 2024; Kameli et al., 2020; Ragnoli et al., 2022); Information and Communication Technology (ICT), including studies defining BIM-based and IoT enabled information exchange platforms in the construction industry(Hammad et al., 2021; Li et al., 2022); And artificial intelligence Supply Chain Innovations category, (Orooje & Latifi, 2021), which reviews the integration of AI in BIM-IoT for healthcare facility maintenance management, emphasizing the transformative impact of technology on supply chain operations.

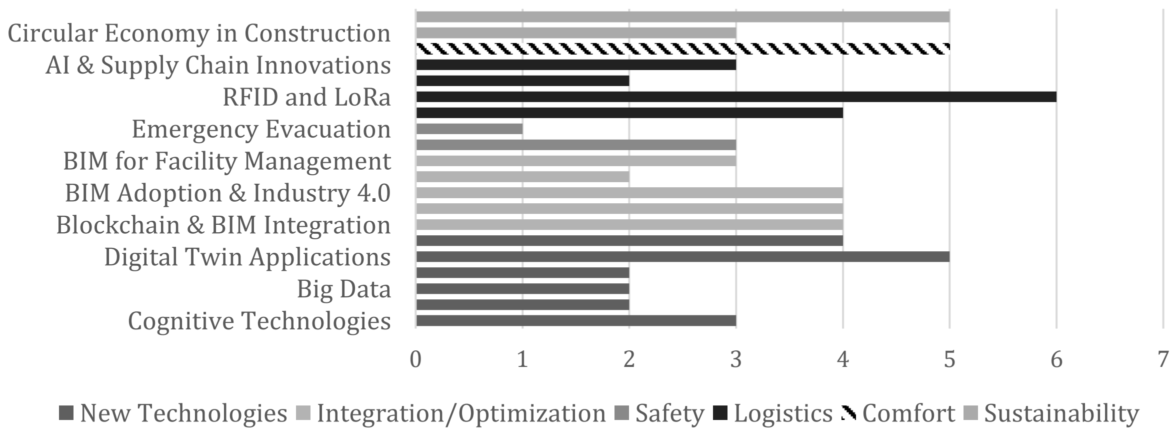

Figure 4: Categorization of Research Focus

The "Comfort" category is addressed through the interaction of IoT-enabled Occupant Feedback & Digital Twins, focusing on comprehensive building lifecycle management. Through the integration of real-world data, IoT sensors, and predictive models using BIM and BIM-Asset Management (BIM-AM) systems papers within this subcategory have implemented BIM and IOT to optimize air quality, enhance energy efficiency, improve building performance, and occupant comfort. (Dave et al., 2018; Donkers et al., 2022; Mao et al., 2018; Stojanovic et al., 2019; Su & Kensek, 2021)

"Sustainability" in construction is explored through two sub-categories of Circular Economy in Construction/Facility Management and Sustainable Construction Practices. Circular Economy in the built environment sub-category (Batista et al., 2022; Sassanelli et al., 2021; Tao et al., 2018), is more inclined toward the operation and maintenance phase, encompasses studies utilizing BIM-enabled simulation approaches for demolishing and disassembly processes, proposing real-time greenhouse gas emission monitoring systems using BIM and IOT, and integrating BIM-IoT-FM for sustainable water consumption. Sustainable Construction Practices, however, are about sustainability concerns in the earlier procurement and construction phases of buildings. This subcategory is also examined by studies investigating the potentials of the Physical Internet (PI) for sustainable logistics networks (Ben Neila et al., 2021); By proposing an informatization scheme for real-time monitoring of illegal behaviors in Construction and Demolition (C&D) waste disposal (You et al., 2020); and finally through the examination of the role of digitalization in manufacturing companies' sustainability-accounting framework, promoting sustainability in the corporate strategic decision making (Klymenko et al., 2021).

Figure 5 demonstrates the categorization of the article focus areas based on project management body of knowledge (PMBOK) knowledge areas, and their relationship with the provided themes of BIM and IoT applications in construction (see **Error! Reference source not found.**).

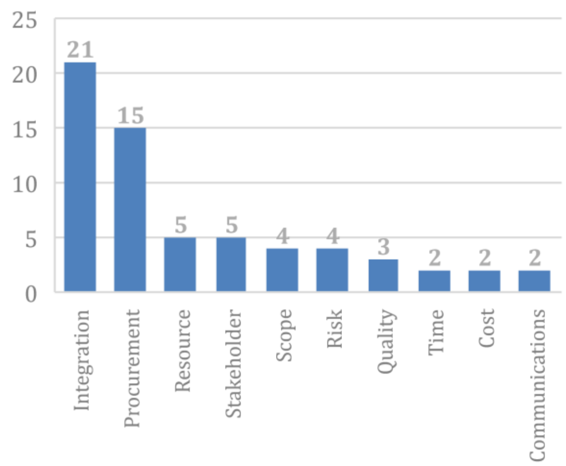

Figure 5: Number of references related to project management knowledge areas

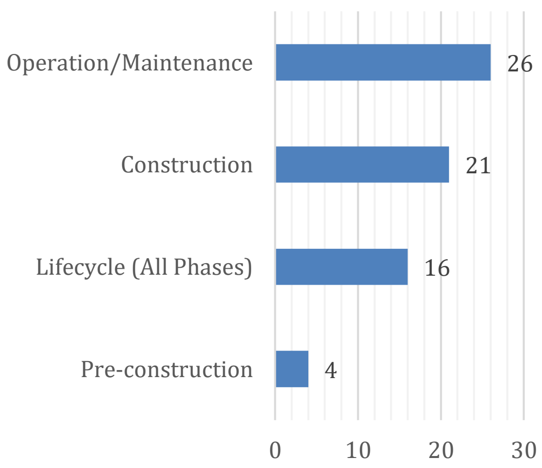

Figure 6: Analysing the number of references based on relation to construction phases

The distribution of articles across different phases of the project lifecycle (see Figure 6) reveals a comprehensive exploration of the synergies between Building Information Modeling (BIM) and the Internet of Things (IoT). The emphasis on the Operation/Maintenance phase, with the most articles, underscores a keen interest in leveraging BIM and IoT for sustained facility performance and efficiency. This phase represents a recognition of the long-term transformative impact of these technologies in ensuring optimal operational conditions and streamlined maintenance practices.

CONCLUSION

The examination of literature across various categories and subcategories within the scope of this research sheds light on key areas where the integration of BIM and IoT has been extensively explored. Notably, the utilization of “RFID and LoRa” for procurement tracking and construction logistics emerges as a well-explored area with a total of six references. These articles delve into the integration of BIM and IoT for real-time tracking and procurement, emphasizing its potential to enhance procurement and inventory tracking processes. Conversely, the “Emergency Evacuation” subcategory stands out as the least explored, with only one reference addressing the simulation of disaster response. This gap highlights a potential need for more research into innovative strategies leveraging BIM and IoT to improve emergency evacuation plans, ensuring the safety of users and equipment during unforeseen catastrophic events. Additionally, the “Distributed Construction” subcategory, within novel construction techniques, is also among the topics with few references highlighting the need for further exploration. Future researchers are encouraged to delve into these less-explored domains to contribute nuanced insights and innovative solutions, fostering a more comprehensive understanding of the challenges and opportunities in the integration of BIM and IoT in the construction and logistics industry.

The distribution of articles within project management knowledge areas suggests a substantial interest in understanding and enhancing project integration, with emphasis on Procurement, Stakeholder, and Resource aspects. The prevalence of articles in these subcategories indicates a recognition of their critical role in the successful implementation of BIM and IOT. Future research in this field could further explore innovative integration strategies, while paying more attention to less-represented areas such as Time, Cost, Communications, and Risk. Additionally, exploring the interplay between different knowledge areas while considering the effects of BIM and IoT integration would be valuable for advancing project management practices in the construction industry.

Additionally, the substantial focus on the Operation/Maintenance phase highlights the long-term benefits of BIM and IoT integration in the entire lifecycle efficiency of construction projects. While the Pre-construction phase features the least number of articles, its inclusion underscores the acknowledgment of early-stage planning and conceptualization as foundational to successful BIM and IoT integration. This holistic approach reinforces the transformative potential of BIM and IoT throughout every stage of construction, from project inception to ongoing facility management.

LIMITATIONS AND SUGGESTIONS FOR FUTURE RESEARCH

It is necessary to consider that the lack of research on BIM and IoT integration within any of the mentioned research areas in the conclusion section might be affected by other factors such as lack of potential for improvements or technical barriers however these factors are not examined and are excluded from the scope of this research.

Another limitation of this research originates from the limitations of scope. Although the provided categorization may be subject to updates and improvement in future studies, the intention here is to create a foundation for future reviews to build upon.

The aim of this study is merely to reflect and compare the literature within the context of proposed categories that are coming from open coding and exploration of the main focus for each reference to identify and suggest the potential gaps based on the provided results.

Considering the limitations of the number of articles included in this review, changing the initial search keywords and concepts might result in a more generalized categorization. Additionally, future researchers can include other factors such as research methodology and sample and demography information along with limitations suggestions, and implementations of each reference during the initial data collection phase to improve the generalizability of the results.

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AN ONTOLOGY FOR REPRESENTING CRAWLER CRANE OPERATIONAL SPACE REQUIREMENT ON SEMANTIC WEB

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ABSTRACT

Lookahead planning incorporates checking and removing operational constraints to develop achievable plans. The manual constraint-checking process is arduous because (1) Construction constraints are dynamic due to constantly changing project conditions, and (2) The information concerning constraints, e.g., attributes and status, are dispersed across heterogeneous databases. While semantic web technology has been used to automate constraint-checking and address these issues, space constraints, e.g., space needed for resource operation, have often been ignored. Cranes are crucial construction resources, necessitating checking of associated space constraints for developing constraint-free lookahead plans. Representing crane operational space requirements on the semantic web should be the first step for such checking. However, existing ontologies cannot do so.

This study aims to develop a Crane Space Representation Ontology (CSRO) to represent different components of the operational space of a crawler crane with a lattice boom. Built using Ontology Development 101 methodology, CSRO includes four classes, 19 subclasses, nine object properties, and seven datatype properties, representing crane operational space with diverse geometries like bounding box, cylinder, and cone. Automated consistency checking and task-based evaluation confirm the CSRO's consistency and effectiveness in addressing the competency questions regarding various aspects of space requirements for crane operation.

KEYWORDS

Last Planner® System, Lookahead Planning, Constraint Analysis, Semantic Web, Crawler Crane.

INTRODUCTION

Lookahead Planning (LAP) is a key stage in the Last Planner® System (LPS) (Ballard, 2000). It consists of three steps, i.e., task breakdown (breaking down the work processes into operations), constraint management (identification, checking, and removal of constraints associated with the operations), and design of operations (scheduling the operations according

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to constraint status) (Hamzeh et al., 2012). Effective constraint management is crucial for continuous workflow, improved task preparation, and schedule adherence on construction projects (Lagos & Alarcón, 2021). However, constraint management lacks appropriate implementation (Dave et al., 2015) due to the complexity and dynamic nature of construction projects (Soman et al., 2020). To this end, attempts have been made to utilize automated data-driven approaches to support constraint management, such as semi-automated constraint identification (Zaeri et al., 2017), tracking the status of constraints (Xiao et al., 2021), and constraint checking in the schedules (Soman et al., 2020).

Constraint checking is the process of checking if the prerequisites for the scheduled activities are complete, which is critical to ensure that only achievable activities are committed (Soman et al., 2020). Most existing automated constraint-checking approaches related to schedules do not apply to the LAP process. These studies usually utilize Building Information Models (BIM) and construction schedules as the main sources of information for rule checking (Ji & Leite, 2018). However, the situations in construction projects are everchanging, and such dynamically changing constraint information is distributed in heterogeneous databases with different stakeholders (Soman et al., 2020), resulting in BIM being an insufficient source of information for constraint checking. To this end, Soman et al. (2020) developed a linked data based constraint checking system. Linked data offers an opportunity to connect cross-domain data in a machine-readable manner and make logical inferences from it (Pauwels, Zhang, et al., 2017). However, they fell short in checking space-related constraints, such as safety and site layout, which are essential in lean construction (Ballard, 2000).

Checking and removing space constraints in LAP is crucial for the seamless execution of construction projects to eliminate or minimize the waste of resources (Akinci et al., 2002). Different types of space-related constraints can be found on construction projects, including space requirements for working of resources, storing materials, and installing temporary facilities on site. Cranes are crucial for space constraint checking perspective in construction, as many activities rely on them for material lifting and transfer. Further, cranes have very high monetary implications on the overall project cost, necessitating their efficient use (Aghajamali et al., 2023). Thus, checking space constraints related to operations involving cranes is essential for generating reliable lookahead schedules. Similar to other constraints, the existing efforts towards checking such space constraints related to cranes mainly utilized 3D models and centralized databases as primary sources of information (Aghajamali et al., 2023). Further, such approaches failed to incorporate the dynamics of construction sites quickly (Hussein & Zayed, 2021), restricting their applicability in LAP.

Linked data facilitates addressing this gap by semantically interlinking heterogeneous datasets such as-built data collected using automated data collection technologies, BIM models, constraint information, and construction schedules to perform constraint checking. Performing such constraint checking requires all the information to be represented on the semantic web (Soman et al., 2020) with the help of ontologies. According to Gruber (1995), an ontology is *"an explicit specification of a conceptualization"*. It provides a way to formally describe the knowledge in a domain using concepts and their relationships. Several ontologies exist in the construction domain that can represent information, such as schedules (Farghaly et al., 2024), building topology (Rasmussen et al., 2021), and product-related information (Wagner et al., 2022). However, existing ontologies cannot represent the information related to the detailed operational space requirements of the cranes. This creates a bottleneck in performing linked data based space constraint-checking of crane-dependent operations in lookahead schedules.

To address this gap, this study aims to develop a Crane Space Representation Ontology (CSRO) to represent the space required by a crane to perform its lifting operation in a construction project. The scope of this study is limited to mobile crawler cranes with lattice booms, as they are commonly used in construction projects (Aghajamali et al., 2023).

LITERATURE REVIEW

SEMANTIC WEB AND LINKED DATA IN CONSTRUCTION

The semantic web is a transformation from the web of documents to the web of data, where the data is represented in a semantically interlinked and machine-readable manner (Berners-Lee et al., 2001). Linked data is a set of principles for representing the data on the semantic web in the form of subject-predicate-object triples.

Owing to the potential of semantic web technology to improve data interoperability, it has been extensively adopted in requirement checking from heterogeneous data. Pauwels, Van Deursen, et al. (2011) used the semantic web to check the acoustic performance regulations on building data. Fitkau & Hartmann (2024) checked safety regulations using the semantic web. However, limited attention has been given to checking the constraints that can prevent construction activities from being executed. Cao et al. (2022) developed an approach to check constraints related to the manufacturability of prefabricated components, such as resource availability, space availability, and lead time. However, they did not consider constraints related to space requirements for the operations of construction equipment. Soman et al. (2020) utilized linked data to check various constraints in lookahead schedules, such as cardinality, resource availability, and precedence. However, they used ifcOWL ontology (an ontology to represent Industry Foundation Class (IFC) data schema in Web Ontology Language (OWL)) to represent site and schedule data, which, is not well suited for performing reasoning on geometric data (Pauwels, Krijnen, et al., 2017).

ONTOLOGIES FOR REPRESENTING CONSTRUCTION SITE ELEMENTS

Ontologies act as the foundation over which the semantic web technology is built. They provide a common understanding of a domain, supporting interoperability between different applications (Farghaly et al., 2024). Ontologies are built using components such as classes, subclasses, and properties. Classes represent a collection of entities having common characteristics. Classes may contain subclasses, which represent more specific entities than classes and inherit the characteristics from classes. Properties provide additional information about the classes to furnish a complete description of intended knowledge (Noy & McGuinness, 2001). Several ontologies have been proposed to represent construction site-related data on the semantic web.

Being fundamentally based on IFC, ifcOWL is limited to the constructs defined in IFC. The Building Topology Ontology (BOT) is a domain ontology used to represent the topological relationships between building components (Rasmussen et al., 2021). The BIM Shared Ontology (BIMSO) represents BIM data related to buildings, which can be used for developing domain-specific ontologies such as design and scheduling (Niknam & Karshenas, 2017). The Building Product Ontology (BPO) focuses on describing singular instances of products that can be part of the building (Wagner et al., 2022). The Digital Construction Ontologies (DiCon) support formally representing and integrating the information related to construction workflow (Zheng et al., 2021). DiCon comprises an 'entity' module related to construction site elements such as equipment. Several ontologies facilitate safety regulation checking in construction, by representing site elements like equipment, materials, and personnel (Li et al., 2022).

The utility of the above-mentioned ontologies for performing space constraint checking related to cranes is limited for two reasons: (1) Only a few of the above-mentioned ontologies have classes, like construction equipment, that can be instantiated with construction cranes. (2) These studies addressed construction equipment at a general level, where the representation of the space occupied by construction equipment on a site was limited to a bounding box covering the entire equipment in a fixed orientation. However, the operations of crawler cranes on construction sites are complex. They involve changing boom length, rotation of boom, rotation of mast, rotation of the main body, rotation of counterweights, possible rotation of the lifted object, and space required for outriggers, among others (Aghajamali et al., 2023; Olearczyk et al., 2014). Therefore, a new ontology is needed to perform accurate linked data based space constraint checking of operations involving cranes, which should consider different components of the space required by cranes to operate. To this end, this study develops CSRO to represent the space requirement of mobile crawler crane operations.

ONTOLOGY DEVELOPMENT METHODOLOGY

Ontology Development 101 (Noy & McGuinness, 2001) was utilized to guide the development of CSRO ontology. This methodology was selected because of its simplicity and feasibility to be used by inexperienced ontology designers (Noy & McGuinness, 2001), and its widespread use in the construction sector (Wu et al., 2021). This study utilizes the Protégé system, a widely used open-source environment for developing, storing, and maintaining the CSRO ontology. The ontology development was done by following the below-mentioned seven steps as described in Ontology Development 101. These steps include determining the domain and scope of the ontology, exploring the reusing existing ontologies, identifying important terms in the ontology, determining classes and class hierarchy, defining the properties associated with the classes, defining the facets of the properties, and creating instances.

CRANE SPACE REPRESENTATION ONTOLOGY

This section discusses the development of CSRO through the seven steps of Ontology Development 101.

STEP 1: DETERMINE THE DOMAIN AND SCOPE OF THE ONTOLOGY

Firstly, the ontology's scope, intended uses, end-users, and domain were determined. It was performed by answering the following fundamental questions within the context of this research (Noy & McGuinness, 2001):

1. What is the domain that ontology will cover?
   In this research, the representation of a mobile crawler crane's operational space requirement on a construction site is the domain of the CSRO ontology.

2. What is the purpose of the ontology?
   The CSRO ontology will be used to represent a crawler crane's space requirements in the context of a semantic web representation of a construction site, thus supporting space constraint checking for operations involving cranes on construction sites.

3. Who are the intended users and maintainers of the ontology?
   The end users of the CSRO ontology are construction planners involved in the lookahead scheduling of operations on construction projects.

4. What are the competency questions for the ontology?
   The competency questions are a set of questions that the knowledge base based on the ontology should be able to answer (Noy & McGuinness, 2001). To develop the competency questions for CSRO ontology, literature related to mobile crawler crane planning was reviewed. The literature included academic publications, textbooks, and practitioners' guides related to mobile crawler cranes. The objective of the review was to identify the different components of the space requirement for the operation of the mobile crawler crane. The following competency questions were formulated for the development of CSRO ontology:

CQ1: What is the space required to place the crane at a particular location?
CQ2: What is the space required for the rotation of crane components such as the main body, boom, and counterweights of the crane?
CQ3: What is the space required for crane outriggers to be extended?
CQ4: What is the space required for the object to be lifted and its rotation while lifting?

STEP 2: CONSIDER REUSING EXISTING ONTOLOGIES

PURPOSE AND USE

Reusing existing ontologies can save time and effort in the ontology development process (Noy & McGuinness, 2001). To identify existing ontologies that can be reused to represent the knowledge related to crane space requirements, ontology libraries such as Ontobee, DARPA Agent Markup Language (DAML), and Linked Open Vocabularies (LOV) were searched. A literature search using Scopus was conducted to explore any research studies on crane ontology, as it is one of the most prominent literature databases (Hussein & Zayed, 2021). No specific ontology was found for the representation of the space requirement of the crawler cranes. However, some existing ontologies can generally represent construction equipment, which can be partially reused for crane representation. For instance, ifcOWL ontology has *IfcConstructionEquipmentResource* as a class, which can indicate construction equipment such as cranes. To represent spatial aspects of cranes, existing ontologies such as GeoSPARQL (*OGC GeoSPARQL – A Geographic Query Language for RDF Data*, 2011) and approaches such as Well Known Text (WKT) (Pauwels, Krijnen, et al., 2017) expressions were utilized in CSRO.

STEP 3: ENUMERATE IMPORTANT TERMS IN THE ONTOLOGY

Enumerating all the necessary terms is essential to ensure a complete representation of the intended knowledge. These terms make the foundation of class and class hierarchy development. To identify important terms for CSRO, this study utilized knowledge sources such as textbooks related to construction equipment (Peurifoy et al., 2018; Shapiro & Shapiro, 2010), literature concerned with crane space planning (Lei et al., 2013; Olearczyk et al., 2014) and web pages related to crawler crane components. The important terms identified for building CSRO consisted of two main aspects: (1) the terms related to crane components such as boom, boom mast, outriggers, and hoist rope, among others, and (2) the terms related to types of geometries used for representing crane space requirements, such as cylinder, cone, polyhedral surfaces, etc. Instead of considering each small component of the crane, only the prominent space-consuming components, whose bounding boxes incorporate the smaller crane components, were considered. For instance, elements like counterweights, the operator's cab, the winding drum (if present), the primary body of the crane, the engine unit (for crawler cranes), the access points, and walkways are considered together in a single component called 'Lower rotating body.' The meaning of each term was described in the ontology to ensure clarity during usage.

STEP 4: DEFINE CLASSES AND CLASS HIERARCHY

The classes and class hierarchy were defined from the identified key terms. A middle-out/combination development approach was used to this end. In this approach, a few of the most general and most specific concepts were defined first. They were then linked with some middle-level concepts. For instance, the ‘crane’ can be a general concept, and the specific geometry of space requirement for a crane operation can be a specific concept. They can be connected using intermediate classes, such as ‘geometry.’ This process is repeated multiple times till all the terms are designated in an adequate class hierarchy (Noy & McGuinness, 2001).

Figure 1 shows the class hierarchy of CSRO as shown in the Protégé interface. It consists of four classes, i.e., *Crane*, *CraneComponent*, *Geometry*, and *Solid*. The *Crane* class has *CrawlerCrane* as a subclass, which can be extended to other types of cranes. The *CraneComponent* class has different significant components of the crane as subclasses. The *Geometry* and *Solid* classes are not explicitly created in CSRO. The *Geometry* class is imported from Simple Features ontology (https://opengeospatial.github.io/ogc-geosparql/geosparql11/sf_geometries.ttl), and the *Solid* class is imported from Geometry (http://rdf.bg/geometry.ttl#) ontology for specific purposes.

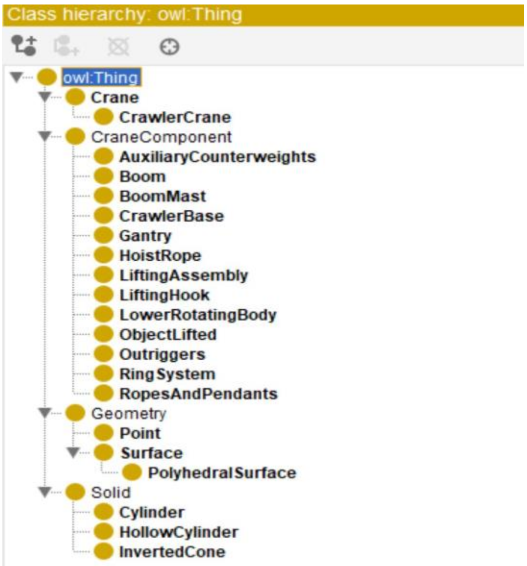

Figure 1:Class hierarchy of CSRO

The space occupied by the crane to be placed at a particular location was represented in CSRO using 3D bounding boxes covering its components. Despite not capturing accurate geometry, bounding boxes offer an approximate representation that can be used for space constraint checking (Chen et al., 2017). To represent such bounding boxes on the semantic web, the *PolyhedralSurface* sub-subclass, which is a subclass of the *Surface* class, was used.

The crane operation also involves the rotation of its components. For instance, The lower rotating body of the crane can rotate around the center of rotation while lifting the load (Lei et al., 2013). The Point subclass was imported from the simple features ontology to consider such a center of rotation. The space required for such rotation was represented in CSRO in the form of a cylinder with its radius and height depending upon the dimensions of the crane component. To consider this, the *Cylinder* subclass of the *Solid* class was imported from the Geometry ontology. Similarly, the crane boom also rotates while transferring the lifted object. The space required for such boom rotation is governed by the maximum and minimum possible radius of operation of the crane (Aghajamali et al., 2023; Lei et al., 2013). As the crane boom is inclined and rotates about a center point, the space required for such rotation can be roughly considered as a cone, as shown in Figure 2a. Therefore, the *InvertedCone* subclass was created as the subclass of the *Solid* class. As the boom rotates, the attached lifting assembly and the lifted load also rotate. The space required for such rotation takes the form of a hollow cylinder, as shown in Figure 2b. Therefore, the *HollowCylinder* subclass was introduced in the *Solid* class.

STEP 5: DEFINE THE PROPERTIES OF CLASSES – SLOTS

Object properties connect the classes, and datatype properties relate classes to specific values. (Noy & McGuinness, 2001). The object and datatype properties in this study were defined based on the different types of class-to-class and class-to-datatype relationships needed to represent the space requirement of the crane. A brief description of the object and datatype properties used in CSRO is given in Table 1 and Table 2.

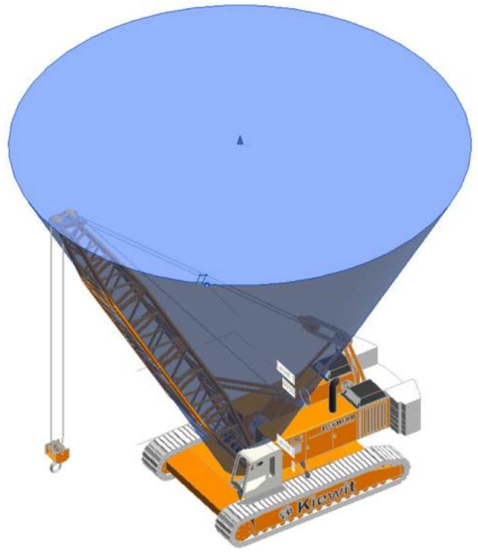

Figure 2a: Space requirement for the boom rotation

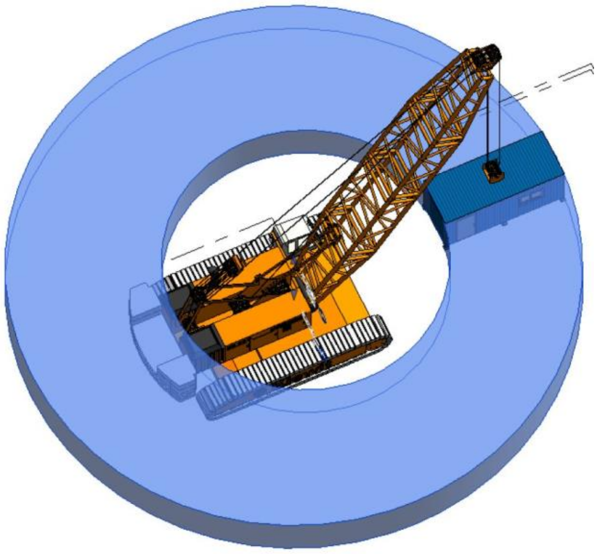

Figure 2b: Space requirement for rotation of the lifted object

Table 1: Object properties used in CSRO

Property names	**Purpose**	**Domain**	**Range**
hasComponent	Connecting a crawler crane class to its components	CrawlerCrane	Crane- -Component
hasBoundingBox	Connecting crane components to their bounding box representations in the form of polyhedral surfaces	Crane- -Component	Polyhedral- -Surface
hasCylindricalRotation- -Space	Connecting relevant crane components to the cylinder geometry representing their rotational space requirement	AuxiliaryCounter- -weights, LowerRotating- -Body	Cylinder
hasMaximumConical- -Space, hasMinimumConical- -Space	Connecting the crane boom to the inverted cone geometry representing its rotational space requirement at the maximum and minimum boom radius	Boom	Inverted- -Cone
hasMaximumHollow- -CylindricalSpace, hasMinimumHollow- -CylindricalSpace	Connecting relevant crane components to the hollow cylinder geometry representing their rotational space requirement at the maximum and minimum boom radius	LiftingAssembly, HoistRope, LiftingHook, ObjectLifted	Hollow- -Cylinder
hasVerticalMotion- -Space	Connecting relevant crane components to the cylinder geometry representing their vertical motion space requirement	LiftingAssembly, LiftingHook, ObjectLifted	Cylinder
hasCenterofRotation	Connecting geometries such as Cylinder and InvertedCone to their center of rotation.	Cylinder, HollowCylinder, InvertedCone	Point

Table 2: Datatype properties used in CSRO

Property names	Purpose	Domain	Range
hasModelNumber	Mentioning crane's model name and number using string datatype	CrawlerCrane	xsd:string
asWKT	Describing the geometries such as polyhedral surfaces and points using WKT literals	Geometry	WKT Literal
Innerradius, outerradius	Providing the float values of the inner and outer radius of the hollow cylinder	HollowCylinder	xsd:float
height	Providing the float values of the height of the hollow inverted cone	InvertedCone	xsd:float
length	Providing the float values of the length of the cylinder and hollow cylinder	Cylinder, HollowCylinder	xsd:float
radius	Providing the float values of the radius of the cylinder and inverted cone	Cylinder, InvertedCone	xsd:float

STEP 6: DEFINE THE FACETS OF THE SLOTS

The defined properties were connected to their domain and range. Domain and range are the classes/datatypes to which a property's subject and object belong in a linked data representation. Table 1 and Table 2 provide concise details about the domain and range of the properties in CSRO. Figure 3 depicts CSRO, including all its classes and properties.

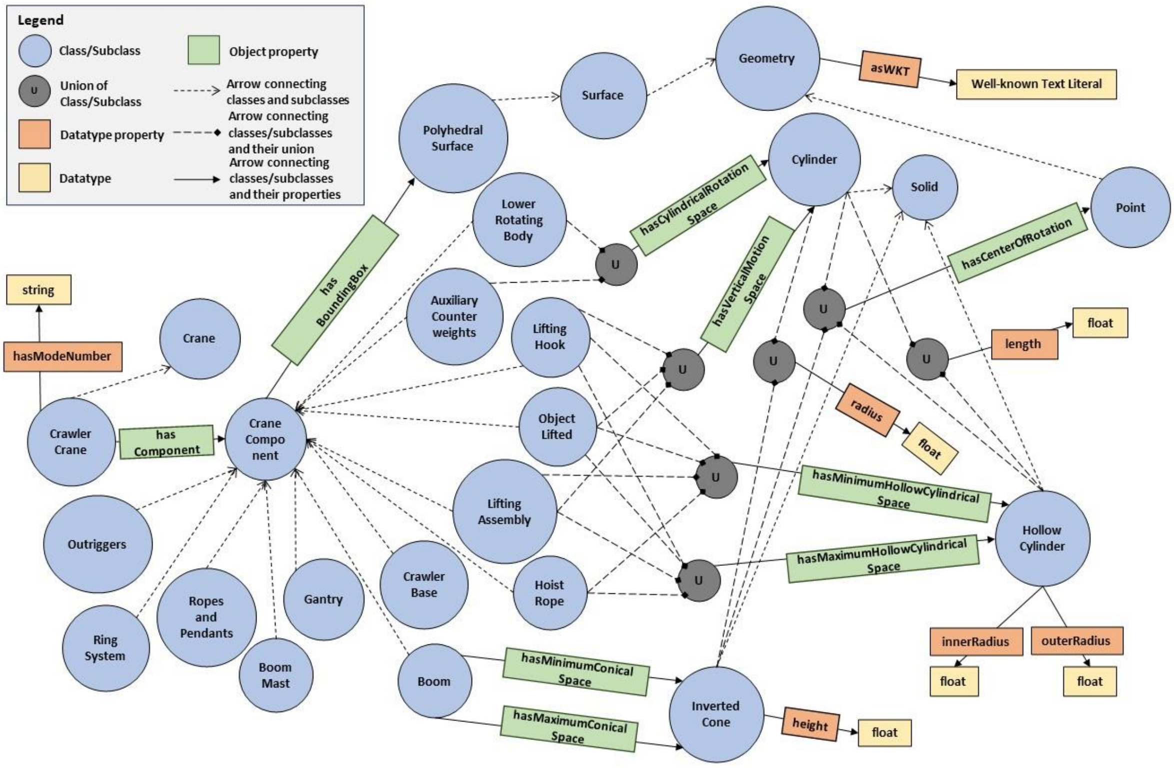

Figure 3: Crane Space Representation Ontology

STEP 7: CREATE INSTANCES

At this stage, individual instances corresponding to the classes and properties are defined, and the associated properties are assigned the values according to the instance. For demonstration, a Revit family of a crawler crane was imported into a Revit model, and the values of the properties were assigned accordingly. Figure 4a shows the crane with a bounding box around its boom. The coordinates of the corner of the bounding box are identified using the spot coordinates feature of Revit. The representation of this bounding box based on CSRO ontology is depicted in Figure 4b. Similarly, other space requirements can be instantiated.

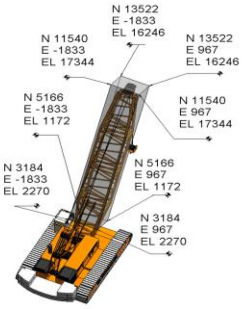

Figure 4a: Crane boom with bounding box

```
@prefix : <http://www.semanticweb.org/aagr657/ontologies/2023/9/CraneSpaceRepresentationOntology#> .
@prefix sf: <http://www.opengis.net/ont/sf#> .
@prefix owl: <http://www.w3.org/2002/07/owl#> .
@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix CSRO: <http://www.semanticweb.org/aagr657/ontologies/2023/9/CraneSpaceRepresentationOntology/> .
@prefix geom: <http://rdf.bg/geometry.ttl#> .
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#> .
@prefix geo: <http://www.opengis.net/ont/geosparql#> .
@base <http://www.semanticweb.org/aagr657/ontologies/2023/9/CraneSpaceRepresentationOntology#> .
CSRO:BoomInstance1 a CSRO:Boom;
        CSRO:hasBoundingBox sf:PolyhedralSurface1.
sf:PolyhedralSurface1 a sf:PolyhedralSurface;
        geo:asWKT "POLYHEDRALSURFACE Z(
            ((-1833 13522 16246, 967 13522 16246, 967 11540 17344, -1833 11540 17344, -1833 13522 16246)),
            ((-1833 13522 16246, -1833 11540 17344, -1833 5166 1172, -1833 3184 2270, -1833 13522 16246)),
            ((967 13522 16246, 967 11540 17344, 967 5166 1172, 967 2184 2270, 967 13522 16246)),
            ((-1833 3184 2270, 967 2184 2270, 967 5166 1172, -1833 5166 1172, -1833 3184 2270)),
            ((-1833 11540 17344, 967 11540 17344, 967 2184 2270, -1833 3184 2270, -1833 11540 17344)),
            ((-1833 5166 1172, 967 5166 1172, 967 2184 2270, -1833 3184 2270, -1833 5166 1172)))
"^^geo:wktLiteral.
```

Figure 4b: Polyhedral surface representation of the bounding box

ONTOLOGY EVALUATION

The ontology evaluation ensures clarity, completeness, consistency, and fitness for the purpose of the developed ontology (Zheng et al., 2020). Several methods for ontology evaluation are available, including task-based evaluation, gold standard evaluation, and automated consistency checking, among others (Zheng et al., 2021). As CSRO was developed for the specific task of representing the space requirement of crane operation, automated consistency checking and task-based evaluation were used for its evaluation. These methods have also been used to evaluate other task-specific ontologies (Zheng et al., 2020). To check the consistency, this study utilizes Protégé's HermiT reasoner due to its faster speed and memory efficiency compared to other reasoners such as Pellet (Glimm et al., 2014). On running the reasoner, it showed no error, ensuring the consistency of the ontology. SPARQL queries were developed for task-based evaluation to check if the ontology-based knowledge base can answer the developed competency questions. The knowledge base was developed based on the crane family imported in Revit. An open-source tool named GraphDB was used to run the queries. The total space required to position a crane at a particular location can be expressed as the bounding boxes covering its components. Figure 5 shows the SPARQL query for extracting the bounding box of the crane boom. The query successfully fetched the bounding box in the form of the polyhedral surface, as shown in Figure 5. Similarly, the queries to address other competency questions were written. The queries could successfully extract the required information from the knowledge base and answer all the competency questions.

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX : <http://www.semanticweb.org/aagr657/ontologies/2023/9/CraneSpaceRepresentationOntology#>
PREFIX sf: <http://www.opengis.net/ont/sf#>
PREFIX CSRO: <http://www.semanticweb.org/aagr657/ontologies/2023/9/CraneSpaceRepresentationOntology/>
base <http://www.semanticweb.org/aagr657/ontologies/2023/9/CraneSpaceRepresentationOntology#>
SELECT ?boundingBoxCoordinates
WHERE {
  :Boom1 rdf:type CSRO:Boom ; :hasBoundingBox ?polyhedralSurface .
  ?polyhedralSurface rdf:type sf:PolyhedralSurface ; <http://www.opengis.net/ont/geosparql#asWKT> ?boundingBoxCoordinates. }
```

	boundingBoxCoordinates
1	"POLYHEDRALSURFACE Z (((-1833 13522 16246, 967 13522 16246, 967 11540 17344, -1833 11540 17344, -1833 13522 16246)), ((-1833 13522 16246, -1833 11540 17344, -1833 5166 1172, -1833 3184 2270, -1833 13522 16246)), ((967 13522 16246, 967 11540 17344, 967 5166 1172, 967 2184 2270, 967 13522 16246)), ((-1833 3184 2270, 967 2184 2270, 967 5166 1172, -1833 5166 1172, -1833 3184 2270)), ((-1833 11540 17344, 967 11540 17344, 967 2184 2270, -1833 3184 2270, -1833 11540 17344)), ((-1833 5166 1172, 967 5166 1172, 967 2184 2270, -1833 3184 2270, -1833 5166 1172)))"^^<http://www.opengis.net/ont/geosparql#wktLiteral>

Figure 5:SPARQL query and results related to CQ1

CONCLUSION AND FUTURE RESEARCH

In LAP, checking space constraints related to crane usage for crane-dependent operations is critical for developing quality assignments for trade crews and ensuring a reliable workflow. Given the complexity and dynamicity of construction projects, frequent constraint checks and adjustments to lookahead schedules are necessary. Further, the information required for constraint-checking remains in disparate, often non-interoperable databases. Therefore, conventionally used manual constraint-checking is tedious and error-prone, and most existing automated constraint-checking methods are not applicable in LAP. Consequently, LAP suffers from poor constraint-checking. Linked data based constraint-checking provides an opportunity to address these gaps. However, adequate space constraint-checking for crane-dependent operations using linked data is still lacking due to the unavailability of an ontology that can represent the space required for crane operation on the semantic web. Improper space constraint checking can result in time-space conflicts and unsafe conditions on the site, contributing to non-value-adding activities such as resource wastage. To address this gap, this paper developed Crane Space Representation Ontology (CSRO) for mobile crawler cranes with a lattice boom. CSRO considers the different elements of the space required for crane operation, such as the space needed to place the crane at a particular location and to rotate the crane's various components. The representation of such space requirements is done through different geometries such as cylinder, cone, and bounding box. The ontology is evaluated using automated consistency checking and a task-based evaluation approach. The evaluation results confirm the consistency of the ontology and its ability to answer intended competency questions.

This study contributes to research on leveraging technology for lean construction implementation by introducing a novel ontology to facilitate automated constraint checking in LAP. The CSRO can be semantically linked with the crane-dependent operations in lookahead schedules, as-built data, and other relevant information containers to perform automated linked data based checking of space constraints associated with operations involving crane usage. This provides two-fold benefits from a lean perspective. First, such space constraint checking can be used to develop constraint-free lookahead schedules based on the latest information from heterogeneous databases, improving workflow reliability and reducing non-value-adding activities on the site. Second, automation can reduce time, human effort, and error likelihood in the space constraint checking process, contributing toward minimizing rework and resource wastage in LAP and reducing potential non-value-adding activities on site due to errors in LAP.

In the future, CSRO should be extended to represent space required for other types of cranes as well, such as crawler cranes with luffing jib, cranes with telescopic boom, and tower cranes, among others. Future studies should extend CSRO to consider such additional operations such as walking, simultaneous slewing and lifting. Currently, significant manual effort is needed to process the heterogeneous information containers and ensure that the right information is expressed by the concepts of CSRO. Similar concepts might be represented by different terms in different databases, which might create ambiguities during representing data using CSRO. Future research should aim to develop automated tools for semantically annotating information containers to extract relevant data needed for crane space representation using CSRO. In addition, efforts should be made toward unification of semantic standards and development of equivalent relationships between the concepts. Finally, in the future, the authors will focus on utilizing CSRO to perform space constraint checking in lookahead schedules.

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AUTOMATED DATA CAPTURE AND ANALYSIS TO DETECT PROCESS WASTE IN INTERIOR FINISHING WORK

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ABSTRACT

Detecting process waste in complex production systems is still a challenge in construction projects. The integration of lean construction with automated data capturing technologies presents an opportunity to timely detect process waste and steer projects towards targets. By using vision-based technology for automated progress monitoring in a residential building, this study examines interior finishing work activities through the lenses of process/location flow and operations/trade flow. Location-based management tools (flowlines and line-of-balance) were used to visualise the data. Results showed that planned production deviated from actuals in all activities. Significant variability was observed within the completion of each activity at each location. The ratio between average production rate and exemplar performance indicated a missed opportunity to improve project performance. Resultantly, several waste types were identified including inefficient work, space not being worked in, unnecessary movement of people and unnecessary transportation of materials. The ability to actively pinpoint process waste provides managers with a granular understanding of inefficiencies, enabling targeted interventions to enhance productivity and reduce waste. The findings support that automated data capturing and analytics through the lenses of lean construction is a useful strategy to inform construction programmes to be more realistic, improving upon efficiency and waste reduction.

KEYWORDS

Flow, process, waste, location-based management (LBM), work in progress/process (WIP).

BACKGROUND

Waste is defined as the use of more resources than needed to generate an output, or the production of an unwanted output (Bølviken et al., 2014). According to Bølviken and Koskela (2016), the industry's significant waste is primarily attributed to the management approach in construction, which often prioritises contract management over production management. Additionally, this issue is exacerbated by the complexity of construction with multiple tiers of subcontractors and low-price procurement strategies. Bølviken et al., (2014) defined flow waste in construction as 1) unnecessary movement (of people); 2) unnecessary work; 3) inefficient

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work; 4) workers waiting for work to be done; 5) space not being worked in; 6) materials not being processed; 7) unnecessary transportation (of materials).

Interior finishing work package is challenging due to the presence of multiple subcontractors, lack of detailed planning and control, and the complex linkages between tasks. Previous research has found high levels of work-in-progress (WIP), long cycle times, and significant process waste during this work package. Brodetskaia et al. (2011) found that subcontractor capacity unpredictability causes turbulent workflow, and re-entrant workflow patterns, in which crews return to the locations multiple times affecting performance. Murguia et al. (2016) applied the Value Stream Mapping (VSM) tool to detect process waste in interior finishing work and implemented a new work structuring, collaborative planning, and the flowline method to reduce cycle times. Due to the inherent complexity of this work package, it is difficult to determine which areas are performing optimally and which areas need improving.

To make visible and eliminate waste, a constant stream of production data generated in the field needs to be observed and analysed. However, project teams do not have the ability nor the bandwidth to collect this data whilst managing other aspects of construction. Therefore, a focus on production management along with automated data capture and analysis becomes a real need in order to identify areas where project teams should direct their efforts to avoid cascading delays. Technologies such as laser scanning (Wei et al., 2018), video data, computer vision, (Khosrowpour et al., 2014; Roberts et al., 2020; Görsch et al., 2022), and sensors (Akhavian & Behzadan, 2016; Barbosa & Costa, 2021) are used for this. Automated progress monitoring in construction involves capturing as-built data from sites and estimating progress by comparison with plans. One commonly used method for data collection is handheld 360-degree cameras (Ekanayake et al., 2021; Sami Ur Rehman et al., 2022).

By analysing internal processes and performance on the ground, it can be used to detect waste and see where efficiency optimisation is possible. To that end, the objectives of this paper are 1) to detect process waste in interior finishing work using vision-based automated data capture and 2) to describe the current challenges of vision-based data capture technology.

RESEARCH METHOD

A case study approach was used in this research to observe interior finishing work activities at a residential building development in London. Data collected included the construction programme and progress data. The construction programme was used to create the baseline to compare plans and actuals. The progress data were collected at weekly intervals using a 360^0 camera. A construction technology company provided services for this project to automatically analyse visual data using advanced computer vision techniques and record progress. The research team had access to the data via an online system including date of capture, 360^0 images, location (i.e., apartment), trade, activity, and percentage of cumulative progress.

However, our approach relied on investigating progress between two consecutive measurements (i.e., quantity of work carried out at a certain time interval) to better understand the flow of activities at each location. As such, flowline charts and line-of-balance (LoB) diagrams were used to visualise operation/trade flows and process/location flows. LoB diagrams have two visual representations, with some authors using dual parallel lines to represent activities, whereas others use boxes (Tzortzopoulos et al., 2020). In this paper, the second method was used. A data-to-dashboard approach (Murguia et al., 2022) was used to generate LoB visualisations automatically using Python codes purposively created for this research. With the data, the following metrics were calculated: 1) actual duration, 2) average cycle time, 3) average days worked, 4) number of visits to location, 5) production rate, and 6) observed exemplar and worst performance. These metrics have been proposed in previous studies (Rathnayake et al, 2023). We used these diagrams and metrics to visualise and quantify different types of waste at each unit location (i.e., apartment).

RESULTS

The case study was a residential building project constructed on a design and build contract. The internal fit-out activities were sub-contracted. Five fit-out activities in the critical path of the construction programme were observed, viz. erecting demising walls, internal wall closure, ceiling closure, painting, and flooring. For this study, observations and analysis were limited to a single level (level 4) which included ten apartments in total. A 360^0 camera was used to capture the weekly progress of interior finishing work. Cumulative progress was determined using a computer vision-based algorithm. The deployment of this technology was a pilot project within the business. Planners and site managers were unfamiliar with the potential to use the data to inform decisions. Traditional Gantt charts and activity counts were used as control metrics in measuring progress. Progress data were unused in production management.

PLAN AND ACTUALS

Data drawn from the online system were used to generate flowlines for the fit-out activities in level 4 (Figure 1). The horizontal axis shows calendar dates whilst the vertical axis shows the locations (apartments 401 through 410). An examination of the flowlines provides some understanding of actual performance. First, the flowlines indicated a clear mismatch between planned and actual progress. About 1/4th of the activities finished before their planned completion, while the rest of the activities were delayed, averaging a fourfold delay over their planned durations. Second, sequence deviations were observed between activities. For instance, flooring activities commenced in apartment 7 before painting even though the plan indicated a finish-to-start relationship between the two activities. This attests to the complexity of the interior finishing work package in managing several activities among several trades. Third, plans were made with the "level" (e.g., level 4) as the smallest unit as opposed to the "apartment". For instance, all the demising walls and internal wall closures were planned simultaneously across the ten apartments. However, granular data at the apartment level were available from the online system. Notwithstanding the above, the time lag between data collection made it impossible to differentiate the exact installation dates at each location. For instance, all demising walls for apartments 403 to 406 were installed between January 15th and January 29th. Therefore, the flowlines (in red) for these were identical across locations. Finally, the flowlines' slopes vary significantly between different locations suggesting different production rates. For instance, the production rates for internal wall closures (in blue) for apartments 401 to 404 were significantly different to those of apartments 405 to 410. Therefore, further analysis is needed to understand the differences and LoB diagrams were used to explore how much work was accomplished over time at each location (see Figure 2).

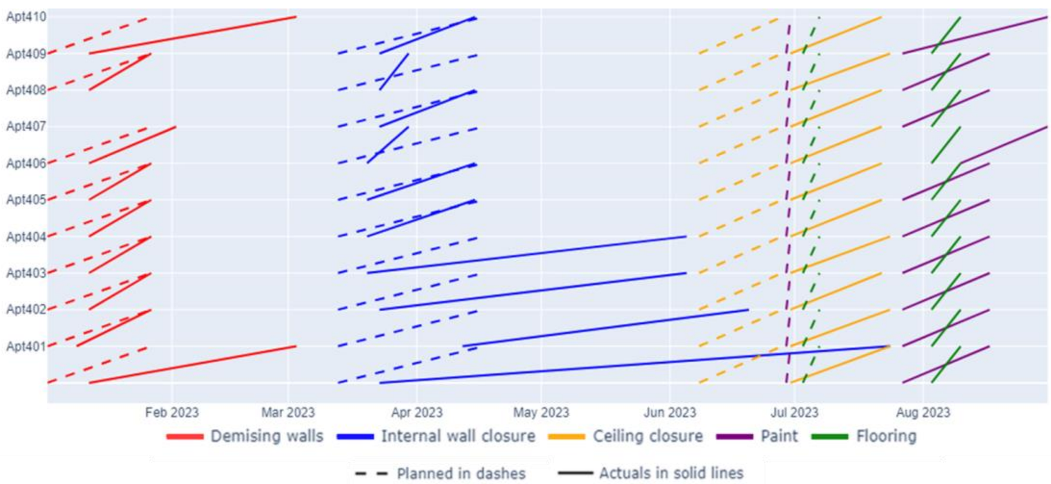

Figure 1: Flowlines – planned v actual

OPERATION/TRADE FLOW

In construction, products are stationary, and workers and equipment move across locations. Therefore, the two types of flow can be redefined as follows: 1) process/location flow, where different trades flow through a single location, and operations/trade flow, where a single trade flows through different locations (Sacks, 2016; Tommelein et al., 2022). Figure 2 shows the LoB diagrams for the five activities under examination across the ten locations. The horizontal axis indicates calendar dates, and the vertical axis indicates each location. The faint vertical bars in the background indicate weekends and public holidays. Each LoB illustrates one or more segments along the activity duration. Each segment is defined by two consecutive data capture events. The colour of each segment indicates the percentage of average daily work done during that period (i.e., % of progress/number of days, the corresponding colours can be found in the legend). Segments with no colour mean no work done.

Figure 2: Line-of-balance – operation/trade analysis

Each LoB diagram illustrates when work started, % of average daily progress between observations, revisits to the same location, and notably, when the locations were left idle with no area utilisation. However, a manual cross-check with site images showed that in many apartments the work was completed without any idle time as suggested by the data. In the case of painting, further investigations showed the separate work done earlier couldn't have been avoided due to the interdependencies of different activities. Managing this has to do not only the trade delivery monitoring but also with better planning the sub-activities. LoB diagrams are a handy way to visualise not only the progress of each activity over time but also the different types of process waste occurring at each location. As mentioned, area utilisation is clearly observed in the LoB diagrams, and so are sequence deviations from plans, as well as the distribution of a single trade over different areas of a level. An additional layer of information provided in these diagrams is the colour intensity indicating the rate of work done. This illustrates a variance between work done over different observed periods. For example, for apartment 1 ceiling closure, 47% of the work was done in 1 day and the rest over 16 days.

However, the LoB diagrams in Figure 2 only show one part of the story. As in the fit-out phase multiple trades are operating in close proximity to one another within a short period of time it is equally important to see how the different activities progress over time at a single location. Hence, LoB diagrams were drawn illustrating each apartment (see Figure 3).

PROCESS/LOCATION FLOW

Figure 3 shows a location analysis of a sample of three apartments. The LoB diagrams visually depict a number of process waste occurring at each location, viz. idle time, revisits, sequence deviations, and output inconsistencies (indicated by the varying colours of the boxes). Moreover, this visual prompt allows digging deeper into area utilisation at each apartment. The results show that apartment 401 took 156 net working days to complete the observed interior finishing work package activities from the first start to the last finish of an activity. However, it was only on 59 working days that an actual activity was carried out by at least one trade at this location, indicating an area utilization of 38%. This example indicates a common theme of wanton waste occurring during this construction phase, waste that can be easily identified using the right analytical tools to be dealt with by project teams to optimise their performance. However, it also is indicative of an underlying limitation of automated data capturing, where other uncaptured activities may be happening in these locations.

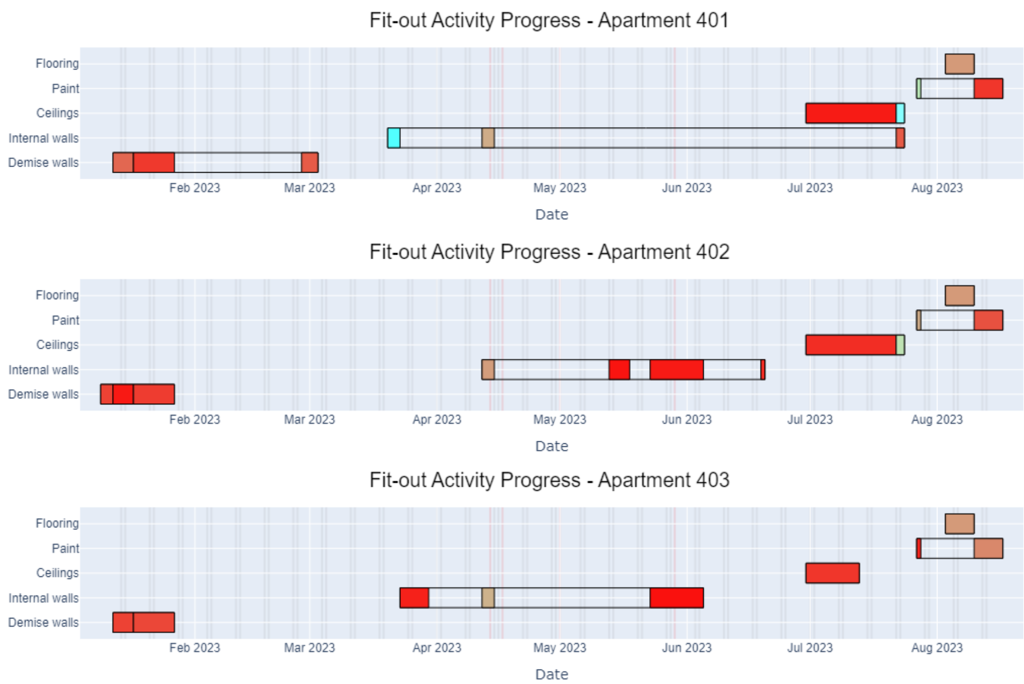

Figure 3: Line-of-balance – process/location analysis

To further explore process flow within locations, the research team analysed image data to obtain the actual start and end dates for all activities at a given location, as depicted in Figure 4. This figure introduces a novel flowline visualisation, showcasing activities on the Y-axis rather than locations, beginning from "demise walls" to "carpentry & joinery." The sequence of activities and their planned dates were extracted from the project Gantt charts and are depicted in blue. The actual data (in red) were derived from visual examination of the image data. Focusing on a specific location, level 4 – apartment 5, a notable gap between plans and actuals was observed in most activities. Notably, despite the first activity commencing earlier than planned, a substantial gap between the completion of demising walls and the initiation of MEP

1st fix was evident, indicating considerable work in progress (i.e. space not being worked in). Similarly, a gap exceeding one month was identified between the completion of internal walls and the start of MEP 2nd fix. Moreover, the production rate of MEP 2nd fix was significantly lower than the plan, as evidenced by the extended duration of the activity. The visual comparison between planned and actual start and end dates provide a clearer picture of progress. Whilst these analysis was conducted retrospectively, the tool and visualisation technique can be applied on future projects to monitor progress across locations (apartments, levels, buildings), enhance situational awareness, improve decision-making, and generate data for future projects.

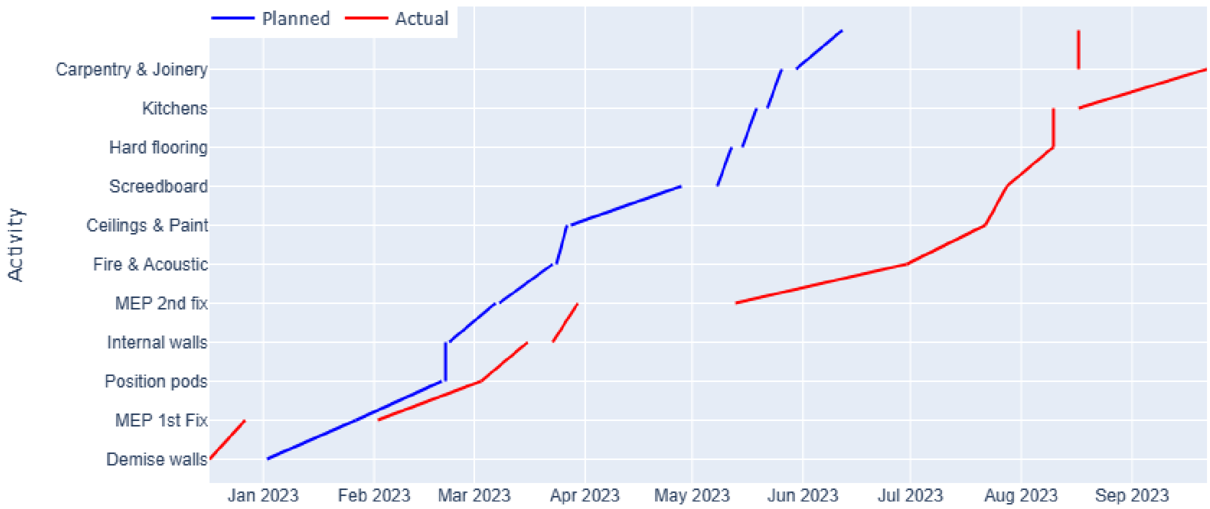

Figure 4: Process flow – example of level 4 apartment 5

METRICS

Table 1 provides some metrics on activity durations at the smallest location unit considered in this study, the apartments. As mentioned earlier, the Gantt Charts plans dictate fit-out activities at each apartment to be carried out simultaneously, yet evidence shows that there is significant variability between the time taken to complete activities in each apartment. For example, considering the activity of internal wall closure, that activity has a large variability in its overall completion times. However, looking closely at why that is the case it was observed that this activity has some sub-activities (e.g., drywall lining, single and double-sided partitioning) that were dependent on work completion by various other trades (e.g., demise wall, pipework, bathrooms, kitchen). Therefore, this trade could not complete their work at certain locations as per their schedule. The quantities of work conducted do vary between the different apartments, although that difference is not significant. These results are indicative of output inconsistencies.

The metrics of average cycle time and average days worked at an apartment are useful in terms of understanding process waste observed at the site. Both are measures of waste and are indicative of the mismatch between planned and actual realisation of plans, thus leading to waste. Apart from flooring activity, all other activities have varying average cycle times and days worked. With a variability of over 5 times with the planned duration in the case of painting. This type of metrics can be fed back to the planning process to make plans more realistic.

Table 1 further shows the number of visits from each trade to a single apartment to complete the activities during this duration. This was also observed in Figure 3. It is observed that while some activities are carried out from start to finish during one visit to the location, in many cases multiple visits are made to the same location over time to complete the same. Indicating idle time at these locations. Among the insights this shows, the distribution of a single trade over different areas of a level can be important information to the construction managers on site. Output inconsistencies at each location within level 4 are further collated in Table 2.

A summary of production rates for each activity is given for each location (i.e., apartment) and time interval (i.e., between two observations). In this study production rate is defined as the ratio of output to time. The output inconsistencies are observed to a greater degree when considering the varying production rates for both categories, location-wise and time interval-wise. In the example of ceiling works, the production rate ranges from 2.2 m/day to 16.4 m/day at different apartments. At the same time, in between the different observations made over the weeks when work is carried out an exemplar rate of production can be established at 6.43 m/day. On the other hand, the worst performance for this trade indicated a measly 0.01 m/day during a separate time. Interestingly, when analysing the complete results over time at each location, no inferences can be made from this data only to explain this behaviour of varying production rates. From the current observations, it is seen that high production rates are achieved at one location at the beginning of the work, and they fall off over time, yet the opposite happens at a different location. The only conclusion that can be made from the present data is that there is no consistency in the production rates. There may be several contributing factors explaining this variability. Further contextual data must be provided to determine these factors.

Table 1: Descriptions for observed fit-out activities (Level 4)

Activity (Trade)	**Planned duration (days)**	**Actual duration (days)**	**Duration per location (apartment) (days)**				**Visits to location (apartment)**	
			Minimum	**Maximum**	**Average cycle time**	**Average days worked**	**Minimum visits**	**Maximum visits**
Demise walls	20	53	17	34	21.3	16.4	1	3
Internal walls	26	126	8	30	17.3	13.1	1	2
Ceilings	15	24	23	24	24.2	16.4	1	1
Paint	2	35	10	35	12.8	10	1	1
Flooring	5	7	7	7	7	6	1	1

Table 2: Production rate metrics for observed fit-out activities (Level 4)

Activity	**Production rate (m2/day)**			**Per time interval**	
	Overall average per location	**Minimum per location**	**Maximum per location**	**Observed exemplar**	**Observed worst**
Demise walls	2.5	0.5	6.2	15.9	0.07
Internal walls	1.9	0.5	6.4	13.8	0.04
Ceilings	5.4	2.2	16.4	9.6	0.03
Paint	10.0	1.8	22.9	29.8	0.29
Flooring	21.9	21.9	21.9	5.52	5.52

The statistical inferences supplement the visual diagrams developed when informing the project teams of the interior finishing work packages. They are used to provide additional clarity, offering a comprehensive view of the sequence and interdependencies of various tasks within the interior finishing work packages. In tandem, these provide a more intuitive and accessible means for project teams to understand the temporal relationships between tasks, identify potential bottlenecks, and process waste to prompt optimised resource allocation.

DISCUSSION

This paper aimed to detect process waste in interior finishing work using automated data capture and analysis. The findings presented above show several inconsistencies between planned and actual work. This section discusses how the observed findings relate to the different types of process waste established in the lean construction literature.

According to Navon and Sacks (2007), project teams waste considerable time due to poor coordination, inaccurate and late information. If the work at a location is completed earlier than scheduled it results in early completion of activities, with waste of work efforts resulting in WIP at said location until the next trade moves following the schedule. This waste was observed in the data due to high variability in actual production duration in locations by many different trades. Relatedly, WIP (i.e., space not being worked in) as waste is noted throughout the observed period as locations are kept idle for long stretches of days in certain instances. For example, Table 1 shows the duration per location for each activity, indicating variations in the time taken to complete tasks in different apartments. Idle time in this case can be attributed to the coordination between trades in the critical path as well as the speed of their production during active installation. The varying production rates for each activity are presented in Table 2. The observed fluctuations in production rates suggest inefficient work at certain locations, which is yet another process waste. The delays and discrepancies between planned and actual durations may indicate potential issues with delivering the final specified results at each location. This is considered an indication of production defects. However, further contextual data such as quality reports must be used to substantiate this, which was not part of the scope of this paper. However, this work supports to overcome the manual observation of construction activities to measure performance, which has clear merits (Roberts et al., 2020).

Other types of waste identified are related to the unnecessary transportation of material and unnecessary movement of people arising from multiple visits to the same location to complete an activity. With multiple visits to a single location, further transportation-related issues can occur such as poor logistic conditions due to material and equipment left behind by different trades at locations where they intend to return. The waste types relating to inventories were not explicitly observed from the data. However, an additional waste discussed in lean management literature, underutilisation of talent, can be inferred by looking at the present data. This is suggested by the varying production rates for different trades. Some locations exhibit high productivity initially but experience a decline over time, indicating the potential underutilisation of talent. The trades could have potentially achieved more productive work in locations, given any contributing blockers to productivity were identified and managed within a timely manner. Therein lies an opportunity for improvement (Gondo & Miura, 2020).

In this research, several metrics were used to identify construction process waste, as discussed above. These metrics themselves provide a foundational framework for automated data capture and analysis for project teams. Thus, aiding them to identify and address shortcomings within their projects in a timelier manner. The results provide evidence to support the practical implications of such metrics, particularly in identifying and addressing sequence deviations to avoid cascading effects on project schedules. This in turn would help optimise area utilization for faster turnaround times and maintain trade output consistency for more accurate timeline predictions whilst reducing return visits to locations. When integrated into construction project planning and management, the study results help close the empirical data loop between planners and the site conditions during interior finishing works. This provides a comprehensive understanding of project performance when combined with existing benchmarks such as schedule performance and other similar frameworks (Marcy et al., 2021).

Due to the inherent complexity of the industry, it is difficult to determine which areas of the project are performing optimally and which areas are improving. Location-based management is useful in navigating through various project information and identifying where efforts should be concentrated. By analysing internal processes and performance on the ground during interior finishing work, this study provides the framework to address coordination issues, improve planning, and enhance the flow of activities.

Automated data capture and analysis, therefore, provides a very clear opportunity to improve site activity level performance and productivity by removing each of the identified waste streams incrementally. More realistically this sort of analysis can be used to identify and empirically explain the notion that actual performance happens not along the best case as assumed by the plan. The planning fallacy, a bias marked by the underestimation of time, costs, and risks in future actions despite historical evidence, is at times used to explain these challenges (Love et al., 2019). This work provides a basis on which dynamic assessment of progress against initial plans can be facilitated automatically, which can potentially provide insights to combat the planning fallacy. Visual tools enhance comprehension, aiding project teams in identifying bottlenecks and adjusting plans (Arditi et al., 2022). Moreover, instant issue recognition and agile decision-making enable prompt responses to challenges, mitigating the rigid adherence to optimistic planning assumptions. This study proposes a data capture and analysis framework for optimising project resource allocation (see Figure 5), offering a data-driven approach to address inefficiencies and process waste. Therefore, this study helps identify the intersection between the gathered data and useful insights to update planning practices in interior finishing work. Practices which can be expanded throughout the construction industry with further work.

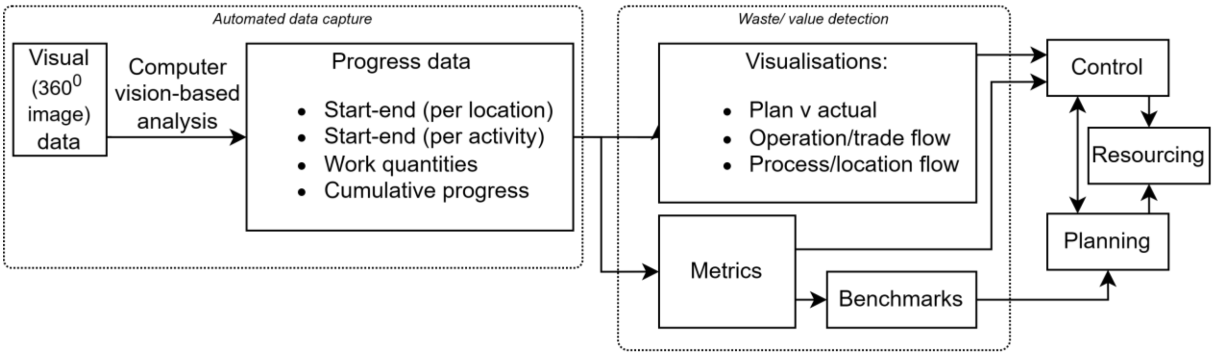

Figure 5: Automated data capture and analysis framework

CHALLENGES OF AUTOMATED DATA COLLECTION

Image data were captured on site at regular intervals and subsequently analysed using computer vision algorithms. However, upon analysing the resultant raw progress data, certain limitations were noted that need to be addressed to further advance the field. First, there were some discrepancies in the terminology and grouping of activities between the plans (Gantt Chart) and the actuals reported by the system. For instance, the plan had an activity named "Second drylining visit" whilst the system identified more granular activities such as "Frame", "Closure", and "Skim". Whilst having this granularity is a strength of the system, it was unclear how to match the planned activities and the corresponding actuals for flowline creation.

Second, the system does not support the analysis of re-entrant workflows (Brodetskaia et al., 2011). For instance, the activity "Plumbing" groups several elements that were installed at different times. However, they were all consolidated into a single activity within the system. From a workflow perspective, it is essential to disaggregate these elements to understand the interactions with other activities.

The third limitation was due to some instances of errors in the start-end dates and progress calculation presented by the system. A manual quality check was carried out when durations were too long, and we found some differences between the images and the progress data generated. During the data processing and verification stages, these were corrected for the analysis to the best of the authors' ability. Although this research cannot report the rate of detection error, further work is needed to ensure more quality in the data.

The fourth shortcoming was due to the data collection intervals. In many cases, most activities within several apartments were completed between two consecutive observations. Consequently, all the flowlines are the same, despite trades potentially moving daily between apartments. Thus, production rates at the apartment level are meaningless unless they are aggregated at the floor level. In other instances, some activities in the critical path are not properly reported due to activities happening within the time elapsed between two consecutive observations (e.g., the placement of prefabricated bathroom pods in each apartment). Therefore, the weekly data collection frequency does not cater for measuring production at the operational level. A trade-off is needed between more frequent data collection and the level of analysis required. However, presenting the available data with a flow point of view as opposed to cumulative progress is a valuable contribution of this study.

Automated data capture provides an opportunity for planners to quickly capture an approximate measure of work done. It is envisaged that further advances in this technology would make the accuracy and reliability of data improve over time. Even so, in its current form, this technology along with a construction flow point of view can help planners close the loop between actual site performance with their plans for interior finishing work. It can show where deficiencies of plans may occur, or where additional time, resources, and methods are needed.

CONCLUSIONS

Underpinned by operations and process flow, this research investigates process waste by leveraging progress data extracted from image data collected during the interior finishing work of a residential building. Flowlines and line-of-balance were produced to enable improved situational awareness. Awareness that leads to targeted interventions. A key contribution of this research is the data capture and analysis framework that supports the identification and visualisation of various types of process waste, such as inefficient work, space not being worked in, unnecessary movement of people and unnecessary transportation of materials. Overall, the study explores the intersection between process waste and advances in automated site data generation, integrating Lean Construction with advanced digital technologies. The current work is limited in its use of a single case study. Albeit the research methodology presented in this study can be utilised for other construction work packages with identifying relevant metrics for each work package. Another limitation is the lack of qualitative data to contextualise and draw the causes for the observations. This form of data capture in its current form should not be used in isolation. This data should be used in conjunction with other site data streams such as quality reports, site diary entries, and planners' reports. Data captured automatically need contextual information to allow for understanding variations. The data collection is also limited to the level of granularity the work package plans are made. With more granular plans, the data could further be delved into sub-activities. To that end, this work succeeds in detecting process waste in interior finishing work using vision-based automated data capture and identifies the current challenges of vision-based data capture technology.

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EXPLORING USER EXPERIENCE AND EFFECTIVENESS OF AN INNOVATIVE LEANBUILD UK PROJECT MANAGEMENT SOFTWARE: USABILITY STUDY POST DEVELOPMENT STAGE

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ABSTRACT

This paper explores the usability and efficiency of the LeanBuild project management software; an innovative solution rooted in Lean Construction 4.0 principles. Through collaboration with the University of Wolverhampton UK, Kingston University UK, and London South Bank University UK, the LeanBuild Limited project presents a promising innovation in the construction industry.

The integration of usability evaluations and user recommendations in software development is limited, despite the importance of usability testing. Even with limited adoption of construction project management software, Target Value Delivery principles are often overlooked. The study employs a mixed-methods approach, incorporating focus groups, questionnaires, and interviews to assess the software's usability. Recommendations gathered from industry practitioners, academics, and IT professionals emphasize the need for improvements such as financial reporting, critical path display, resource assignment features, simultaneous file uploads, BIM integration, enhanced security, and E-Tendering and Marketplace integration.

The paper concludes that despite requiring further enhancements from its minimum viable product, LeanBuild is an effective solution, endorsed by users as a viable and scalable innovation with global applicability for efficient project delivery. This study highlights the importance of post-development usability checks and positions LeanBuild as a significant breakthrough in the construction software landscape.

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KEYWORDS

Lean construction, Digital Innovation, Project management, Software Usability test, Target Value Delivery

INTRODUCTION

Lean construction (LC) researchers actively advocate the integration of both old and modern technologies within the framework of Lean Construction 4.0 (LC 4.0) (Musa et. al., 2023). In light of the revolutionary changes occurring in the construction sector due to creative digitalization, automation, and artificial intelligence, Lean Construction (LC) has embraced digitalization by utilising both conventional and innovative technology through the use of Lean Construction 4.0 principles.

Recognizing the potential for significant service and delivery benefits, Architecture, Engineering, and Construction (AEC) firms are increasingly embracing emerging construction technologies (McCoy & Yeganeh 2021a). This trend stands in contrast to the historical perception within the AEC sector that innovation disrupts established workflows and leads to inefficiencies (Love et al. 2014). Studies now show that strategic implementation of technologies can enhance collaboration, improve project predictability, and ultimately reduce costs (Azhar et al. 2017). However, challenges remain. McCoy and Yeganeh (2021b) highlight the need for upskilling the workforce and ensuring interoperability between different technologies for successful innovation uptake.. Therefore, there is a strong push for advocating the adoption of these technologies to maximise their potential in the construction industry (Momoh et. al., 2016, Musa et. al., 2023). The concept of LC 4.0 involves the seamless integration of digital technologies into the construction process (Hamzeh et al., 2021). As a result, the adoption of project management software becomes an essential tool to ensure the overall delivery of projects.

Currently, web app development has become a matter of paramount significance for firms as the global economy is experiencing an exponential rise in commercial digitalization. The increasing number of businesses choosing web applications as a means to address societal problems and facilitate service delivery further accentuates the significance of web applications (Agarwal & Venkatesh 2002). This has led to the development of LeanBuild project management innovation; a construction technology software in the UK that aims to optimise user experience and efficiency in the evolving demands of digitised project management. The software is efficient in managing diverse project types. It is leveraging on digitalizing an innovative framework called the Framework for Implementing Target Value Delivery (FFITVD) that aligns with the principles and values of TVD (Target Value Delivery) (Musa et. al., 2023). This is an approach for the automated management of large construction projects to secure cost savings and minimise waste. The digitalization of an innovative framework enhances technological fluidity, and user engagement, and fortifies the framework's intellectual property policies.

TVD is an innovative management approach that applies target cost, quality, and schedule to design to generate value for stakeholders by minimising waste and ensuring that every facet of the construction process aligns with the agreed-upon targets, encompassing cost, quality, standards, time, and stakeholder value (Musa, 2019, Orihuela et. al., 2015, Zimina et. al., 2012). The LeanBuild web app encompasses all essential software requirements for each phase of project management, starting from initiation to closure. It successfully integrates both TVD and the traditional construction approach into the user interface designs. The software is offered on a subscription basis to clients who will be able to manage their construction projects ‘end-to-end’ using an applied software package which, by its nature, is accessible on any enabled device. As a result, it becomes imperative to evaluate the effectiveness and acceptance of the software provision and properties (Musa et. al., 2023).

To develop a functional technological system for global utility, it is crucial to consider the influence of user experience (UX) within the context of technological innovation (Hassenzahl, 2001). Usability studies, a key component of UX design, aim to identify usability issues, improve the user interface (UI), and ultimately enhance the overall user experience, leading to increased user satisfaction, system adoption, and potentially, even greater innovation (Nielsen, 1993; Rogers, 2020, Desideria & Bandung 2020).

Conducting a usability check on the software has resulted in a significant enhancement by the implementation of the recommendations from participants. It underscores the importance for any developed software to undergo usability testing before launch and implement key recommendations to improve functionality and versatility. This approach ensures the software becomes a viable and scalable innovation for global utility.

RESEARCH GAPS

There is limited integration of usability evaluations of user recommendations before the official launch of the software (Shneiderman et al., 2009). Although there is widespread adoption of various construction innovations, most of the adoptions give little or no attention to the integration of Target Value Delivery (TVD) principles into the construction digitization process. Current literature indicates that the implementation of TVD remains inadequately realized in the construction space, with both organisations and project teams falling short of fully embracing its transformative potential (Musa, 2019, Musa et. al., 2023). While there is an innovative framework for implementing Target Value Delivery (FFITVD), the digitalization of the framework becomes a necessity to enhance the understanding of the framework, digital integration, user validation, and protection of the framework's intellectual property rights. The lack of digitalization of the framework is a shortfall, prompting further innovation to digitize the framework to system that facilitates seamless progression of construction activities, efficient resource allocation, timely production and delivery of project outcomes. Conclusively, there are numerous construction project management software in circulation; several of them lack full coverage of the entire lifecycle of a typical construction project.

AIM AND OBJECTIVES

This paper aims to evaluate and enhance the usability of the LeanBuild software for improved user experience.

a) To explore the overall user experience of the LeanBuild software, including ease of use, user-friendliness, and satisfaction.
b) To identify any usability issues that may hinder users from effectively utilising the software.
c) To gather feedback and suggestions from users for further improvements and enhancements.

LITERATURE REVIEW

EVOLUTION OF LEANBUILD FROM LEAN CONSTRUCTION TO LEAN CONSTRUCTION 4.0

Lean Construction (LC) takes its origin from the practice of the manufacturing industry that has gained adoption in the construction industry (Koskela, 2000; Musa, 2019, Demirkesen, 2021, Daniel, 2017). The target of LC is the full optimization of resources, adequate reduction of waste, and improvement of the entire performance of construction activities (Ahmed et. al., 2018, Nikakhtar et. al., 2015, Musa 2019; Daniel 2017, Francis & Thomas 2019). The procession in lean thinking forms the basis of LC, which harmonizes design and product delivery for both small and capital projects.

The construction industry's successful integration of Lean practices across a wide range of activities, from design and planning to execution and handover, has laid a strong foundation for further innovation (Babalola et al., 2019; Hamzeh et al., 2021). This evolution is driven by the emergence of modern digital solutions and the increasing utilization of the Internet of Things (IoT) dubbed Lean construction 4.0 (Hamzeh et al., 2021; Ramadan & Salah, 2019). LC 4.0 builds upon Lean principles by leveraging enhanced connectivity through digital technologies for improved construction management throughout the project lifecycle (Hamzeh et al., 2021; Oguntona et al., 2018; Al-Aomar, 2012). A key distinction between LC and LC 4.0 lies in its emphasis on data-driven decision-making and the utilization of advanced technological solutions. While the potential of LC 4.0 is significant, challenges such as a lack of industry-wide standards, workforce upskilling needs, and initial investment costs may hinder its widespread adoption.

PROJECT MANAGEMENT AND SOFTWARE SOLUTIONS IN CONSTRUCTION

Effective project management (PM) ensures construction projects are completed on time, within budget, and meet quality standards (Akintola & Goulding, 2006). It involves strategic planning, resource allocation, task management, and risk mitigation (Project Management Institute, 2017).

Traditional PM methods are giving way to Project Management Software (PMS) due to its advantages. PMS offers features for task & schedule tracking, resource allocation, team collaboration, project planning and progress reporting (Akintola & Goulding, 2006). However, choosing the right PMS can be challenging due to software complexity, limited scope, customization issues, integration problems, access restrictions, and security concerns (Musa et al., 2023; Goncalves, 2018)

Organizations should assess their needs before adopting new technology (Talukder, 2012). Tools like LeanBuild address challenges by offering comprehensive project management functionalities and user-friendly interfaces. Despite advancements in software development, the construction industry faces slow technology adoption (McKinsey & Company, 2020) as a result of the beliefs within the AEC sector and this have impeded the full realization of benefits offered by established and emerging technologies.

SOFTWARE USABILITY TESTING

The efficacy of any software depends on rigorous usability testing, a pivotal phase in software development. Usability evaluations assess user-friendly interactions and evaluate software's effectiveness before deployment (Sadowska & Piętak, 2015, Bandi & Heeler, 2013, Lárusdóttir, 2011, Dillon, 2015, Bruun & Stage, 2015). Thorough usability testing is an essential part of software development that determines how effective any software will be. Software usability assessments determine how user-friendly the interface is and how effective the programme is. Various methods exist for conducting usability tests, including:

a. Usability testing: In this approach, users are tasked with completing specific assignments using the software, their actions are observed, and the outcomes of their performances are systematically collected. This method identifies the challenge of a user trying the software and suggests an improvement scheme for the enhancement of the software's efficiency. (Moran, 2019, Hasan, 2014).
b. Heuristic evaluation: This approach involves gathering feedback from a group of experts on the software and identifying challenges through the practice of usability evaluation. The limitation of this approach lies in its inability to capture the comprehensive picture and overall user experience. (Ssemugabi & Villiers, 2010).

c. Expert review: This method entails obtaining feedback and insights from a single subject expert who reviews and identifies issues related to the software under evaluation. This method proves most beneficial when there is a need to pinpoint a specific issue; however, it falls short of providing a comprehensive overview of the user experience with the software (Privitera, 2019, Harley, 2018).
d. Evaluation of User Experience (UX): Among all the methods, the UX approach stands out for its holistic nature, encompassing fundamental aspects of user experience such as functionality, efficiency, effectiveness, and overall user satisfaction.(Musa et. al., 2023, Kaisa and Virpi, 2008).

Researchers have established that carrying out usability on time is a key factor in determining whether the software was developed in consideration of the intended users (Lárusdóttir 2011). User experience testing helps in revealing if the software would be adopted by the users based on their reviews, results, and recommendations. From the result of carrying out user experience testing, the user experience (UX) will undergo continuous improvement until the best of the software becomes globally utilizable.

METHODOLOGY

This section details the methodology employed to evaluate the usability of LeanBuild software, focusing on a user-centered design (UCD) approach (Morris et al., 1995). UCD prioritizes understanding user needs and incorporating their feedback throughout the design process to ensure the software aligns with established usability principles. These principles, as outlined by Krug (2000), encompass aspects like learnability (ease of initial use), efficiency (effectiveness in accomplishing tasks), memorability (recalling features after a period of non-use), error tolerance (forgiving user mistakes), and user satisfaction.

The researchers adopted a mixed-method approach, combining qualitative and quantitative data collection techniques to gain a comprehensive understanding of user experiences. This approach goes beyond surface-level data, capturing not only user behavior but also their perceptions, attitudes, and thought processes (Tashakkori & Teddlie, 2010). The study utilized a blend of established usability testing methods: focus groups, interviews, and questionnaires (Musa et al., 2023; Kontio, 2001; Lehtola et al., 2004; Sunikka, 2004).

Usability testing for this research involved participants from the UK (mainly from the University of Wolverhampton’s Construction Futures Research Centre UK, the School of Architecture and Built Environment at Kingston University UK, and the School of Engineering and Architecture of London South Bank University UK) and from Nigeria, (predominantly from Brains and Hammers Limited, IBTank Limited, Canon Projects, and Design and Shelters Limited).This research included participants from the UK and Nigeria to capture diverse user perspectives and potential market variations in construction practices. However, to mitigate bias, the study acknowledges potential limitations arising from sample size, cultural differences, and pre-development evaluation involvement of some participants. Focus group discussions: Five sets of focus groups discussions (including two face-to-face sessions and three online/virtual sessions) were held with a total of 25 participants to gather both qualitative and quantitative data on software usability. This group setting allows participants to bounce ideas off each other, potentially revealing learnability issues and areas for improvement in the software's initial user experience (Kontio et al., 2004; Beyea & Nicoll, 2000).

Questionnaire survey: The questionnaire survey was used to gather feedback aspects like ease of use, functionality, and overall satisfaction in a structured and standardized format. 21 out of the 25 focus group participants filled out the online questionnaire survey. The questionnaire survey was conducted using SurveyMonkey, a widely used online survey tool.

This method incorporated elements from frameworks like the User Experience Questionnaire (UEQ) (Sauro, 2011), ensured efficient data collection and facilitated comparison across participants, contributing to an understanding of user efficiency and overall satisfaction with LeanBuild.

Interviews: Interviews were conducted with about 14 out of the 25 participants in the focus groups to gather personalized insights into their experiences with the software application and specific areas of interest raised during focus groups. Prior consent was obtained from the interviewees, and the sessions were recorded to facilitate accurate transcription

The respondents in the study were industry practitioners, academics, and software/Information Technology (IT) professionals. With the combination of these different perspectives, the researchers hope to collect a holistic view of the usability of the LeanBuild software application and initiate paths for continuous improvement of the software. Given the relatively small number of participants (25 in focus groups, 14 in interviews), a descriptive analysis approach was deemed most appropriate. Descriptive analysis focuses on summarizing and describing the collected data, providing valuable insights into user experiences without relying on complex statistical inferences (Creswell & Creswell, 2018). This approach is particularly suitable for smaller sample sizes where statistical tests might lack power or generalizability (Maxwell & Reed, 2004).

RESULTS AND DISCUSSION

This section provides an analysis and discussion of the results derived from the study.

LEANBUILD SOFTWARE PRESENTED

The LeanBuild project management software is a construction technology software that aims to optimise user experience and efficiency in the evolving demands of digitised project management. The software is efficient in managing diverse project types. It is leveraging on digitalizing an innovative framework called the Framework for Implementing Target Value Delivery (FFITVD) that aligns with the principles and values of TVD (Musa et. al., 2023).

The LeanBuild web app encompasses all essential software requirements for each phase of project management, starting from project initiation, planning and design, execution, monitoring and evaluation and to closing. It successfully integrates both TVD and the traditional construction approach into the user interface designs. The software is offered on a subscription basis to clients who will be able to manage their construction projects ‘end-to-end’. Screenshots and demo of the LeanBuild application can be found on https://leanbuild.co.uk/

DEMOGRAPHY OF RESPONDENTS

Relevant information was gathered from the administered questionnaire regarding respondents' background, expertise, and familiarity with the use of the Internet and other software tools, particularly project management software.

The professional backgrounds and years of experience of the respondents are detailed in Table 1.

Table 1: Respondents' Professional backgrounds and years of experience

Professional background	% of Participants	Years of Experience	% of Respondent
Industry Practitioners	71%	Not more than 5 years	5%
Academics	14%	5 to 10 years	24%
Software/IT Professional	15%	10 to 15 years	38%
Others	10%	More than 15 years	33%

The analysis shows a varied distribution of experience levels among respondents, representing diverse professional backgrounds. Results indicate 96% possess internet familiarity, and 72% have used project management software, suggesting a majority are acquainted, potentially needing minimal training.

USABILITY CHALLENGES ENCOUNTERED IN PROJECT MANAGEMENT USAGE

The results of interviews and surveys highlighted key challenges in project management software utilisation. About 33% cited restrictions on file uploads, 22% mentioned software complexity and internet dependency. The development team addressed these concerns, streamlining the user interface for ease of use and allowing multiple file uploads, enhancing the overall efficiency of the software.

The study findings highlighted an essential suggestion that, the software's limitations are primarily geared towards the construction industry, leading to one-sided consideration. Addressing this feedback, the software's research and development team, equipped with substantial expertise, skills, and market awareness in the digital construction industry, is aligning lean principles and practices to shape the innovation for a more extensive range of sectors, encompassing construction, manufacturing, and other service-intensive industries.

EFFICIENCY AND INCLUSIVENESS OF LEANBUILD SOFTWARE

The software comprehensively covers the entire project lifecycle, with 100% of respondents attesting to this. While 76% found the project initiation clear, 24% expressed concerns about its focus on construction, limited financial reporting, and lack of quick signposts for estimates. For the planning phase, 90% found it adequate, but 10% raised unspecified potential issues. Additionally, 95% were satisfied with the execution stage, acknowledging it as a representative interface for project implementation. These results indicate the participants' recognition of the software's Minimum Viable Product (MVP) comprehensiveness, incorporating best practices at the execution phase.

The procurement interface received approval from 81% of respondents, while 14% were undecided, and 5% strongly disagreed. Concerns centred around the need for an easy search tool and a notification trigger for material requests. For the schedule interface, 90% agreed it encompassed all necessary elements, with 10% undecided. Suggestions included features on the Gantt chart for resource assignment and highlighting the critical path in red for better visibility. The development team valued these recommendations, enhancing the software to include resource assignment options and highlighting essential paths.

The cost interface received recognition from 95% of respondents for its adequacy, while 5% neither agreed nor disagreed. Suggestions included enabling direct uploads of BIM-enabled drawings and files for better transparency. For the closing interface, 90% acknowledged its efficiency, but 10% strongly disagreed, emphasising the need for a snag list and defective liability period. The development team carefully considered these suggestions, integrating them into the software before its official launch.

The project feed integration is a strategic innovation to enhance project team efficiency. 95% of respondents affirmed its benefits in interactive communication, collaboration, and coordination, while 5% did not disclose sentiments. Other suggestions for improvement included generating comprehensive downloadable reports, compatibility with files from other software, and a feature for efficient resource allocation management..

USABILITY AND EFFECTIVENESS ASSESSMENT OF LEANBUILD SOFTWARE

The questionnaire results indicate that most respondents find the project management software easy to use beginning from the signup interface. The software's label, instructions, and functionality were distinct with simple applicability as 100% of the respondents admitted to the clarity of the software's navigation and functionality.

Concerning the suitability of the software interface's visual appearance, 90% of respondents concurred that the visual representations employed for all project phases are visually appealing. Additionally, 100% acknowledged the clarity and lack of ambiguity in the tooltips and instructions for utilising the software. Extensive research contributed to the current visual presentation of the software, and the development team remains committed to making continuous improvements to enhance the visual aspects of the software.

The software's project dashboard serves as a comprehensive summary of any project, with 81% of respondents affirming that it encompasses all essential features of a typical project dashboard. However, 14% remained undecided, and 5% strongly disagreed with the suitability of the project dashboard interface. Some respondents suggested the addition of TVD and traditional methods to the software project dashboard. The dissatisfied respondents expressed reservations, noting that the dashboard seemed limited to construction activities and suggested adding features for accounting, procurement, and other reporting summaries.

INNOVATIVENESS OF LEANBUILD SOFTWARE

94% acknowledged LeanBuild's groundbreaking advancement compared to traditional project management software, with 6% not expressing their views. 78% find Target Value Delivery (TVD) Path the most innovative, 11% prefer project feeds, and another 11% highlight control procurement. Overall, 100% of the respondents agreed that the innovation covered the full cycle of a project from initiation to closing. These results align with the software's integration of lean construction practices, making TVD the most perceived innovative feature. What makes this software innovative is that the norm of large construction projects in the UK for 'packaged' management has primarily been a process known as the traditional method. The inclusion of TVD in the software has substantial advantages over traditional approaches and has identified no current directly competing offerings available in the UK.

The findings highlight the effectiveness of the UX in facilitating construction project execution, aligning with (Bruun and Stage 2015). Ongoing enhancements are necessary for comprehensive software development, including aspects like the financial interface, plugins, multiple security factors, and integration of BIM, E-Tendering, and Market Place Integration. As there is a need to meet the fast-growing market for improved management of ever more complex construction projects requiring sophisticated applications to support delivery, The software is unique in its ability to cover all stages of construction projects, ranging from initiation to planning, execution, monitoring & control, through to hand over and operation.

VIABILITY AND SCALABILITY OF LEANBUILD SOFTWARE

The research and development team of LeanBuild Limited UK, working alongside the University of Wolverhampton's Construction Futures Research Centre UK, the School of Architecture and Built Environment at Kingston University UK, and the School of Engineering and Architecture of London South Bank University UK, showcases a data-driven approach to construction software development. This collaboration allows LeanBuild to leverage the academic expertise of these institutions to conduct thorough market research and gain a profound understanding of current trends and demands within the construction software industry. The technical expertise and experience of the director of LeanBuild Limited, alongside the supporting team, have effectively validated the software's viability and strategically positioned it for continuous improvement. This iterative enhancement process ensures the software remains in alignment with lean principles. The team is dedicated to addressing user recommendations through collaboration with proficient and experienced professionals. This collective approach seeks further to augment the functionality and adaptability of the LeanBuild software, ensuring its continual evolution in consonance with industry requirements and user preferences.

The survey result shows that most participants (90%) score 7 or higher on the recommendation scale, indicating the software's readiness for widespread use. Although 10% provided a lower score, this positive majority highlights the software's scalability as an innovative tool. Additionally, the gradual adoption of Target Value Delivery (TVD) in the UK industry is acknowledged, recognizing that it takes time for new ideas to get fully integrated into any industry.

The software's structured planning is evident as a contemporary innovation that not only supports job creation but also stimulates growth in both national and international construction markets. Leveraging a broad construction client base in the UK, Nigeria, and worldwide, it advocates for the adoption of construction technology software to enhance business operations. This positions LeanBuild software solution as highly scalable.

INTERVIEWS FINDINGS AND RECOMMENDATIONS

The interview outcomes offer valuable insights and recommendations for enhancing the LeanBuild software. Figure 1 displays the diverse suggestions along with the corresponding number of interviewees who provided these recommendations.

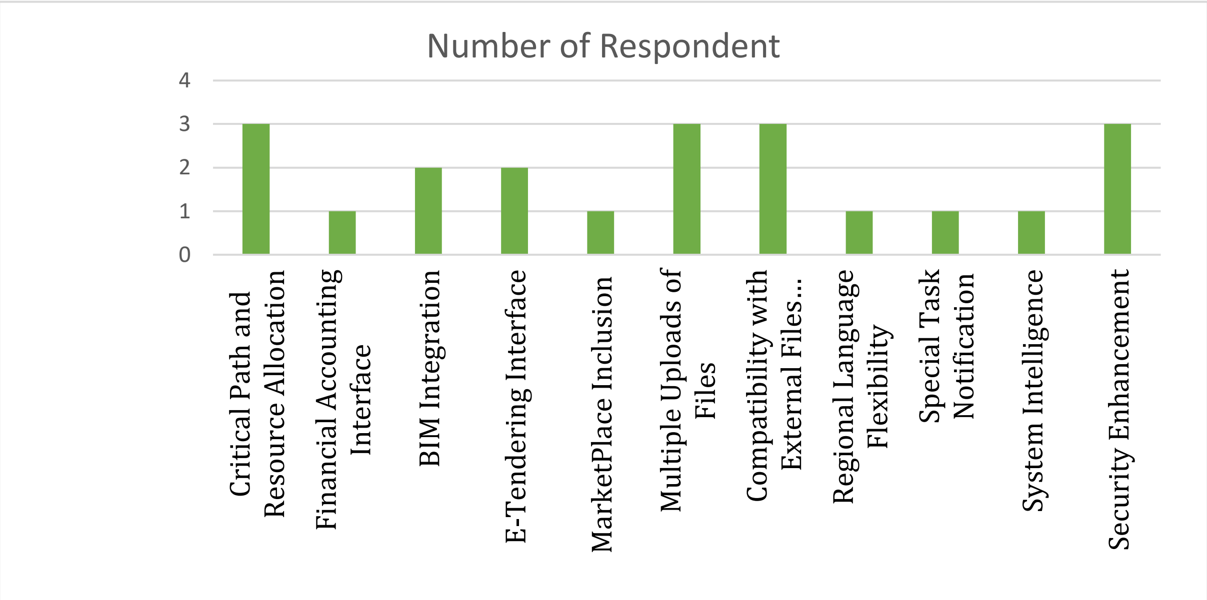

Figure 1: Suggestions and number of respondents that made the recommendation

Figure 1 outlines recommendations to enhance LeanBuild software, including a financial accounting interface and comprehensive critical path display on the Gantt chart for identifying delays. Respondents suggested features like simultaneous multiple file uploads, drag-and-drop functionality, critical paths integration for schedule monitoring, and direct resource assignment.

Stakeholders recommended an instructional guide for estimating activities or materials, BIM integration, compatibility with external files, and interfaces for snag lists and defective liability periods. Users emphasised simplicity, intelligence, multilingual support, and mobile accessibility. These suggestions align with ongoing efforts to refine LeanBuild's functionality and accessibility.

CONCLUSIONS

This study investigated the user experience and efficiency of the LeanBuild software post-development. Employing a mixed-methods approach involving focus groups, questionnaires, and interviews, the research gathered diverse perspectives from industry practitioners, academics, and IT professionals. The research and development team of LeanBuild UK collaborated with esteemed institutions in the UK.

The findings yielded key recommendations for software improvements, including financial reporting, critical path display, and resource assignment features. Stakeholder suggestions encompassed simultaneous file uploads, critical path integration, and direct resource assignment. Ongoing enhancements were proposed in financial interface, plugins, security, and integration of E-Tendering and Market Place. Users emphasised simplicity, intelligence, multilingual support, and mobile accessibility.

Despite limitations such as a small sample size and limited generalizability, the study's significance lies in highlighting the necessity of conducting usability checks after the development stage but before the software launch. The study introduces a digital innovation advocated by lean construction experts, addressing the entire project lifecycle by incorporating Target Value Delivery (TVD) and traditional construction approaches. Additionally, it underscores the benefits of conducting usability tests post-development and before the software launch, emphasizing the positive endorsement of LeanBuild as a scalable and globally applicable innovation for efficient project delivery.

This study recommends conducing user experience studies with construction professionals from other countries to understand cultural variations in software interaction and preferences.

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A BIM-LEAN APPROACH TO IMPLEMENT LEAN PRINCIPLES IN OFFSITE CONSTRUCTION PROJECTS: A CABLE-STAYED BRIDGE CASE STUDY

Mohamed Assaf[1], Otto Hedges[2], Zeyu Mao[3], Hamidreza Golabchi[4], Xinming Li[5], Vicente A. Gonzalez[6] and Farook Hamzeh[7]

ABSTRACT

Recently, the attention to offsite construction (OSC) has grown due to its potential for waste minimization, higher quality, and speedy construction. However, OSC projects are sometimes adopted at a slow pace due to inefficient workflow. Further, OSC adoption requires a high level of information sharing to integrate the manufacturing of components, onsite assembly, and logistics processes. Previous research on the integration of Lean principles with advanced technologies, i.e., BIM and blockchain, in OSC was limited to improving the onsite operations only. To this end, this research aims to bridge this gap by providing a BIM-blockchain system to apply lean principles in enhancing the workflow of the OSC projects considering offsite, onsite, and logistics operations. Lean principles, namely Kaizen, Heijunka, Just-in-Time, One-piece flow, and Poke a yoke, form the focus of this study. Further, the study presents a secure information-sharing system based on blockchain technology to update the status of the process, i.e., pulling material from the inventory. A case study is introduced to validate the developed system. The proposed system is expected to improve the efficiency of the OSC operations and enhance the integration of stakeholders.

KEYWORDS

Lean Construction, Offsite construction, BIM, Smart contract, Blockchain.

INTRODUCTION

Cable bridges are some of the most complex infrastructure projects that require careful planning, design, and construction (Souza et al. 2022). These bridges typically have long spans, high loads, and complex geometries, making them challenging to build. Additionally, these

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bridges are usually constructed using offsite construction techniques, as they include several prefabricated components and volumetric modules (Yu & Chen 2020). Furthermore, cable bridges often must be constructed over water bodies, deep gorges, or other challenging terrains, which adds another layer of complexity to the project. As a result, cable bridge construction projects can be expensive, time-consuming, and prone to errors (Kim et al. 2011).

To solve this problem, a plausible solution would be adopting lean construction in the cable bridge projects. Lean construction has proven to be an effective methodology for reducing waste, improving productivity, and enhancing quality in construction projects. By adopting a lean approach, project teams can streamline their processes, eliminate non-value-added activities, and focus on delivering value to the customer (Bajjou et al. 2017). Similarly, advanced technologies such as Building Information Modeling (BIM), blockchain, and extended reality technologies can also be utilized to optimize cable bridge construction. For example, Using BIM enables project teams to simulate different scenarios, collaborate efficiently, and reduce rework. Extended reality technologies provide comprehensive visualization and a better understanding of the process, leading to improved project outcomes (Goh et al. 2014). Moreover, Although several scholars have recently proposed integrating lean principles and advanced technologies to solve complex project implementations, such as offsite construction projects (Hadi et al., 2023), this approach has yet to be fully explored in the literature. To this end, this study aims to improve the implementation of cable-stayed bridges by answering the following two research questions (RQs): RQ 1: What are the current drawbacks of bridge construction supply chain, and the role of lean principles in addressing them? RQ 2: How can lean principles be implemented in bridge construction using BIM and blockchain technologies?

Hence, the study objectives can be summarized as follows: 1) Discover the difficulties in the bridge construction supply chain, the role of lean principles in addressing them, and how advanced technologies can promote the use of lean principles; 2) Analyze the current state of cable-stayed bridge construction and identify the possible drawbacks using value stream mapping method; 3) Provide improvements to the discovered drawbacks and implement these improvements with the aid of BIM and blockchain technologies.

LITERATURE REVIEW

BIM AND LEAN CONSTRUCTION

There are challenges in implementing offsite construction (OSC) due to issues with design errors and level of completeness (Hussein et al, 2021). Site restrictions must be carefully considered during the design to limit redesign and other negative outcomes, including loss of productivity and a decrease in quality and onsite safety (Jung and Yu, 2022). To address the aforementioned problem, previous researchers have adopted BIM technology in offsite construction projects. For example, Park et al (2009) concluded that the use of 3D CAD (computer-aided drafting) in cable-stayed bridge construction greatly improved the constructability of the bridge. Nevertheless, BIM research for offsite construction has mainly focused on methods and tools on the practical level but not the organizational level (Santos et al., 2017). Al Hattab and Hamzeh (2018) pointed out that even though BIM is being utilized in many companies as a tool, it is mainly used to supplement traditional management strategies and achieve short-term goals, while comprehensive and detailed implementation procedures and guidance tend to be missing.

To systematically use BIM technology and make organizational-level improvements, it is suggested that the combination of BIM and lean construction can be a plausible solution (Rafael et al., 2010). Howell (1999) describes Lean Construction as “the application of a new form of production management to construction” in reference to the Toyota Production System developed by Taiichi Ohno beginning in the 1950s (Liker, 2021). Some key lean ideas have shown their efficiency in construction include (Hei et al., 2024; Kifokeris & Tezel, n.d.; Zeng et al., 2023): Value Stream Mapping (VSM), which assists practitioners in identifying the point of deficiencies in the process; Kanban, which is a visual scheduling system used to manage and control the material and task flows in a production system; Just-in-Time, which is an inventory control strategy aimed at producing goods or delivering services only as they are needed; Heijunka, which is a method used to reduce unevenness in production and minimizing overburden for different stations; One-Piece flow, which is a production method where items are processed one at a time without batches, and Poke a yoke, which refers to techniques implemented to prevent defects from occurring during the production process.

The combination of BIM and lean construction in offsite construction has also been reported in several studies. Moghadam (2014) proposed a systematic approach to offsite manufacturing management by integrating lean principles, BIM, and simulation. The proposed approach can identify the current building practice challenges and propose improvements through simulation. Gbadamosi et al. (2019) developed a design assessment and optimization system for offsite construction building assembly by combining lean construction and BIM technologies. The framework enhanced the constructability of offsite construction projects and can reduce the inefficiencies in resource use.

BLOCK CHAIN AND SMART CONTRACT

Even though the combination of BIM and lean shows a promising research trend in optimizing offsite construction processes, there are still major challenges that need to be addressed in cable-stayed bridge construction projects. Barkokebas et al. (2021) pointed out that digital strategies (like BIM) in offsite construction have not been fully implemented and have even been misused. For example, previous research was mainly focused on using lean and BIM to improve on-site operations only. To this end, a few studies tried to consider off-site operations in bridge construction projects. For example, Celik, Petri, & Rezgui, (2023) invesigated the collaboration between BIM and blockchain throughout life cycles and supply chains. They aimed to enhance the streamlined processes and improve resource traceability in projects. Elghaish et al., (2023) initiated the research effort to focus on addressing the disconnection nature of blockchain and smart contracts adoption across construction procedures. Celik et al., (2023) proposed a Blockchain-based BIM data provenance model to support information exchange in a real-world bridge construction project, where blockchain has been used to record metadata of BIM objects. These proposed approaches provide stakeholders with the availability of upstream information and enable construction practitioners to share their building components' information.

The theoretical implications of integrating lean construction and blockchain have been studied recently by scholars. For instance, Kifokeris et al., (2023) have shown the positive impact of integrating lean with blockchain and smart contracts in facilitating lean construction through building mutual trust and recording all of the data. Similar results were also discovered by Hadi et al., (2023). However, the need to implement these theoretical benefits still persists. Hence, this paper presents a BIM-Lean-supported smart contract system to comprehensively enhance the workflow of OSC projects and foster lean implementation in cable-stayed bridge construction projects by considering both offsite, onsite, and logistics operations.

RESEARCH METHOD

This section illustrates the research method that is adopted in this study. Figure 1 shows the proposed system and the overall methodological approach. Four main parts are included in this study: Literature review, process understanding and analysis, process improvement, and process implementation and validation. The literature review, as discussed in the previous section, seeks to demonstrate the association between lean construction and new technologies, i.e., building information modeling (BIM) and blockchain. In the second part, the main activities and processes in cable-stayed bridges are identified through reviewing past studies. Moreover, discovering the deficiencies and drawbacks is performed using the VSM. In order to do so, all the resources and stations (manufacturing stations) are identified. This information is used to develop the current state VSM. The current state of VSM assists practitioners in identifying the points of deficiencies in the process. These deficiencies can include the following: 1) waiting time for each process and 2) work-in-progress (WIP) items that can disrupt the workflow and create variations among stations.

To improve the process, the deficiencies identified in the previous part are studied, and ideas for improvements are proposed. To come up with improvement ideas, the authors of the current study carried out brainstorming sessions. After evaluating these improvements, they are visualized with the future state map of the VSM. A simulation model is developed to quantify the improvements achieved in the future state map. It is worth mentioning that this simulation model is detailed in another study carried out by Assaf et al., (2023). However, this study mainly focuses on the digital system that integrates lean construction with BIM and smart contracts.

In the process of implementation and validation of this study, the proposed improvements are implemented in virtual environments (BIM models). In this section, a 3D BIM model is developed to visualize the discussed improvements. This is also followed by developing a 4D BIM model to simulate the implementation of the bridge after employing the improvements. The study also goes beyond static visualization to actual digital implementation. The developed BIM models are then integrated with blockchain and smart contract technologies to serve as a digital system that keeps up-to-date tracking data and visualizes lean concepts, such as Kanban and just-in-time. The digital system will allow the user to submit a request for products (modules) when their inventory is low, without relying on fixed schedules.

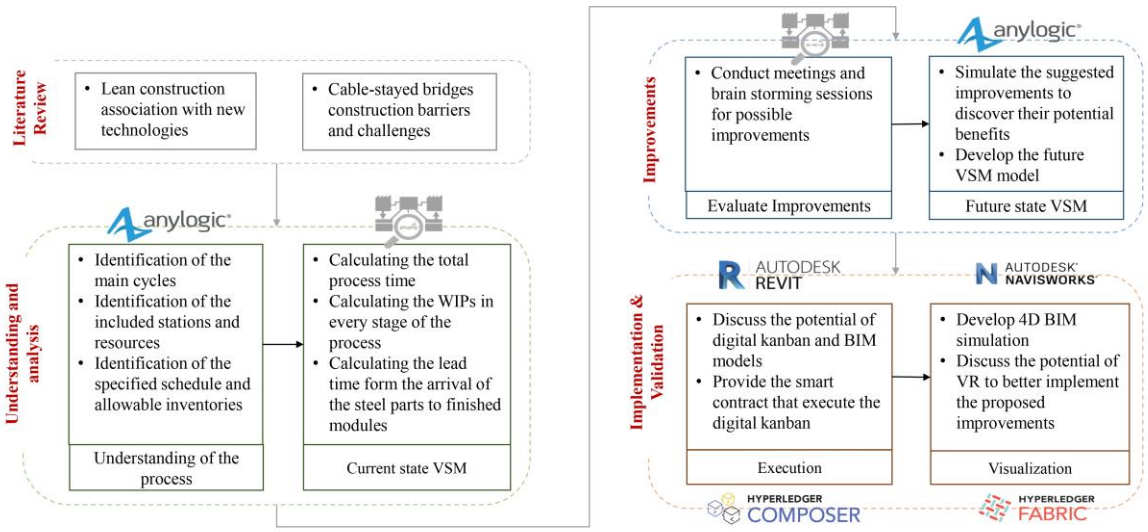

Figure 1: The proposed system in the current study

RESULTS AND IMPLEMENTATION

The proposed system is validated through a case study. The case study represents the construction of a cable-stayed bridge that was presented by Yu & Chen (2020). The bridge comprises both onsite and offsite construction techniques. The onsite technique includes the following tasks: footings construction works, columns construction works, pylons construction, tie beams construction, cables (strands) installation, and concrete works of the stitches (joints). In addition, the bridge also comprises a wide range of offsite processes, including the following:

1) the fabrication of the main and cross girders; 2) the assembly of steel modules on the yard; 3) the fabrication of precast slabs to be placed on top of the steel modules.

CURRENT STATE MAPPING

The production process of the cable-stayed bridge is hampered by several deficiencies. Hence, the lean transformation practice is discussed below. This paper uses VSM to reveal the value stream of the project and determine problem areas. The simulation results shed light on the inventory amount between each station. Based on the simulation, the current state mapping of this girder bridge project is drawn sequentially using VSM notation, as shown in Figure 2. By walking through the whole value mapping, the calculation shows that the actual value-added time for the current process is 34 days. However, the production lead time will be 110.7 working days. This indicates that the process efficiency ratio has just reached 31%, while 69% of the time will be wasted or non-value-adding.

The Takt time (5 days/module) has also been calculated by dividing the total operating time by the total daily customer demands. The analysis revealed that the cycle time of some workstations, such as cable tensioning, installing slabs, and reinforcing joints stations, is less than the takt time. However, the cycle time of the main girder station and build module station are higher than the takt time.

FUTURE STATE MAPPING

Future state mapping implements lean principles to reduce waste and improve flow. The ability to achieve a piece flow for this project is difficult due to the nature of the construction process. Each module must be fully installed, aligned, joined, and cured before the next module can be placed. This is due to the tight working space and connection requirements between modules. Each module connects to the previously installed module in the current state. As shown in Figure 3, using BIM, the construction manager can modify the installation process to install multiple modules at the same time to better achieve a one-piece flow. This is identified in the future state map as kaizen burst immediately below the construction manager to signify that the BIM Manager and construction manager work together with the information provided to and from the workstations to determine modules that can be installed independently of one another.

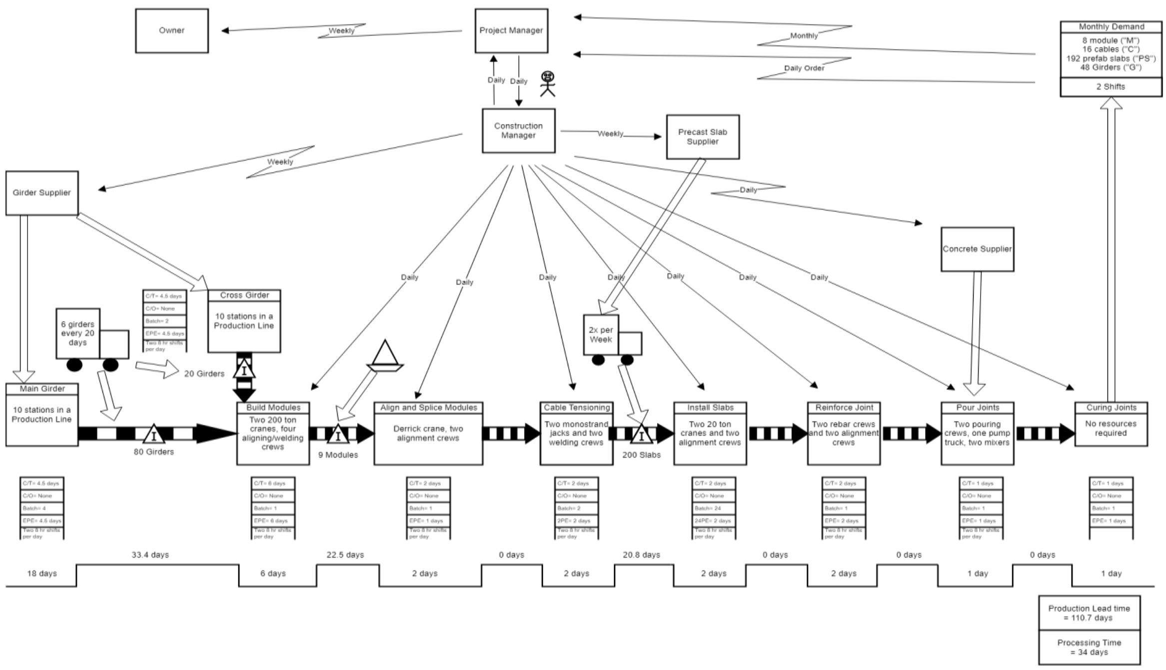

Figure 2: Current State Mapping

The inventory associated with the precast slabs can be eliminated by delivering slabs "just in time". A safety stock of 24 slabs is provided, which is enough to complete one module, and is available in the event there are supply issues with the slab provider.

The girder supplier can build a girder every 4.5 days. Their process allows them to create a cross girder and main girder at the same time, without changeover. Since we require four main girders and two cross girders per module, the total time for girders per module is 18 days. Due to the duration of the girder construction compared to the downstream module construction (6 days), the girders were pre-ordered and are required to be stored on-site, creating waste. The future state map indicates the need to go and see the girder production to better understand and reduce the timing of the girder supply. Options include introducing a changeover for the cross-girder assembly line to also create main girders or finding an additional girder supplier.

The girder inventory is waste in that it must be managed, moved, and takes up valuable working space on site, and in the event that there is an issue with the girders, the amount of inventory accumulated will exacerbate the level of waste. The upstream girder supplier requires significant lead time, so there is a need to create a supermarket, sized appropriately, with attention given to the kanban so that the girder supplier has ample time to create the necessary girders while limiting the amount of storage required. This is identified on the future state map with the supermarket pull system. Moreover, kanban helps ensure that inventory levels are optimized and that materials are available when needed. A kanban system is developed through BIM to signal when more materials are needed for the construction process. By doing so, it is expected to minimize waste by reducing excess inventory and preventing stockouts.

The align and splice module activities and the cable tensioning must be completed at a minimum before starting a new alignment and splicing of a module. This means that the duration of the activities, starting from aligning and splicing modules to the curing, could vary between 6 and 10 days. As such, a pull process between the Align and Splice Modules activity and the Build Modules Activity was appropriate, as the beginning of the construction of a new module was dependent on the availability of the downstream processes to accept it. This is identified on the future state map as a pull process.

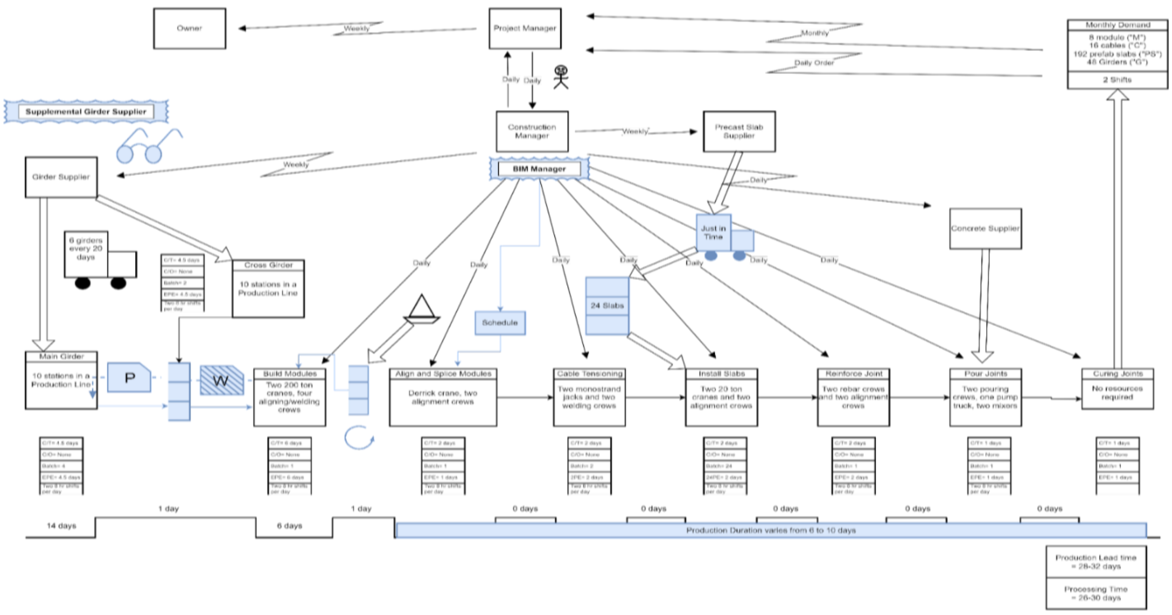

Figure 3: Future State Mapping

IMPROVEMENT IMPLEMENTATION

Knowing we can improve the process, we still lack a system that can implement these improvements. To address this, we applied a BIM-based smart contract approach to implement these improvements on a digital system that allows the user to perform the following tasks: 1) submit a request for specific elements when needed; 2) submit any document any defects at any point of the project; 3) inquiry of any past resolved issues.

BIM-Based Smart Contracts

This subsection discusses the development of the BIM-based smart contract model that helps implement lean improvements (González et al. 2022). Figure 4 shows the developed BIM model and details the included prefabricated components. The model comprises three main prefabricated components: precast slabs, manufactured steel modules, and steel girders. Every component in the model is marked with an ID that will be used in the smart contract system. The component ID specifies the component type and installation location. The processes of installing the prefabricated components, along with the onsite works, form the primary operations of this case study. The following section shows the development of a smart contract that facilitates the implementation of the discussed lean principles.

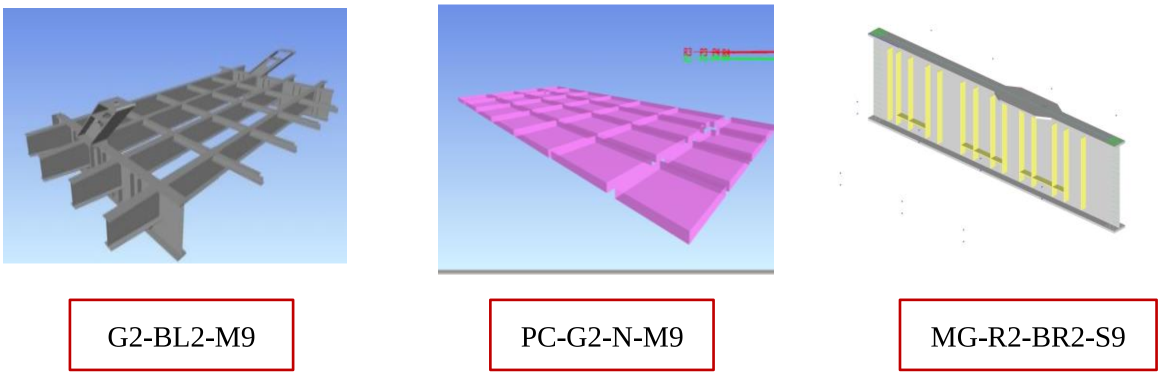

Figure 4: the developed BIM model showing the prefabricated components

Developed Smart Contract

This section shows the development of the smart contract that is associated with the BIM model. The system functions according to lean principles. These included lean principles can be summarized as follows: 1) *One-piece flow*, the developed system facilitates the operator of each station to request products when needed, without relying on a fixed schedule; 2) *Heijunka*, the system levels out the process by mitigating the inventory between stations by implementing the Just-in-time approach; 3) *Quality at bay*, the system allows the participant to submit a notification when a defect is discovered to the other operators. This notification is attached with the element ID, location, description, and deficiency degree. 4) *Poke a yoke*, any submitted quality issue and how it was solved is stored in the system transaction part.

The developed smart contract comprises many operators. Figure 5 illustrates the operators included in the network. Operator one is responsible for the fabrication of the steel girders, and Operator two is responsible for assembling these steel girders into modules. Operator three is responsible for the onsite works, and Operator four is in charge of the fabrication of precast slabs. Three main transportation routings are included in the system: transporting the steel girders from the factory to the yard by truck, shipping modules from the yard to the bridge by ships, and trucking the precast slab to the bridge deck from the offsite slab construction facility.

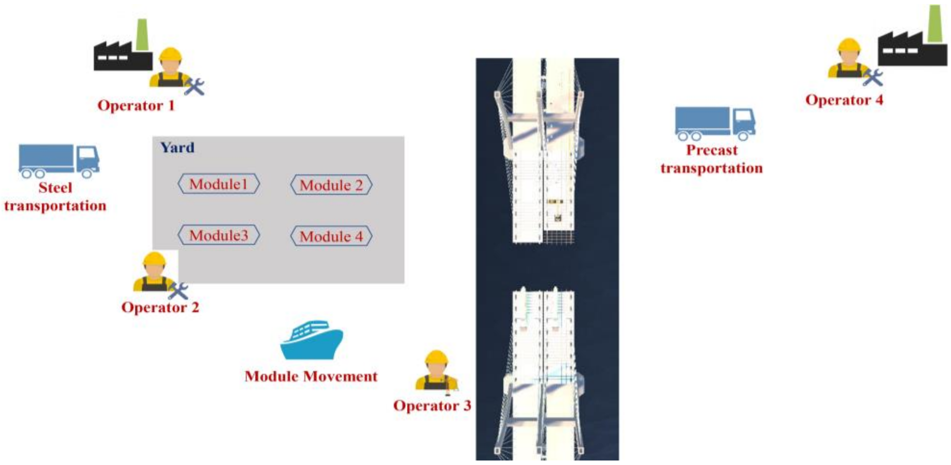

Figure 5: The included operators in the systems

The structure of the developed system uses two main systems: Hyperledger Fabric and Hyperledger Composer. The Hyperledger Fabric is an open permissioned blockchain framework that was developed by the Linux Foundation (Eltoukhy et al., 2022). The system comprised four main elements: participants, assets, transactions, and access control. Figure 6 shows these components in accordance with the proposed system. The participants in the network are all the operators identified above. The assets include the data of the inventory in each inventory. For example, in the operator1-operator2 inventory, the information of the two operators, the current available inventory, and the maximum allowable inventory are defined.

The transactions part includes the following elements: 1) submission of a request for more elements, specifying the quantity and elements IDs; 2) submission of the needed elements by the corresponding operator and update of the ledgers on the system; 3) notify any quality issue (Andon) by an operator; and 4) query of any submitted defect resolution (mistake proofing).

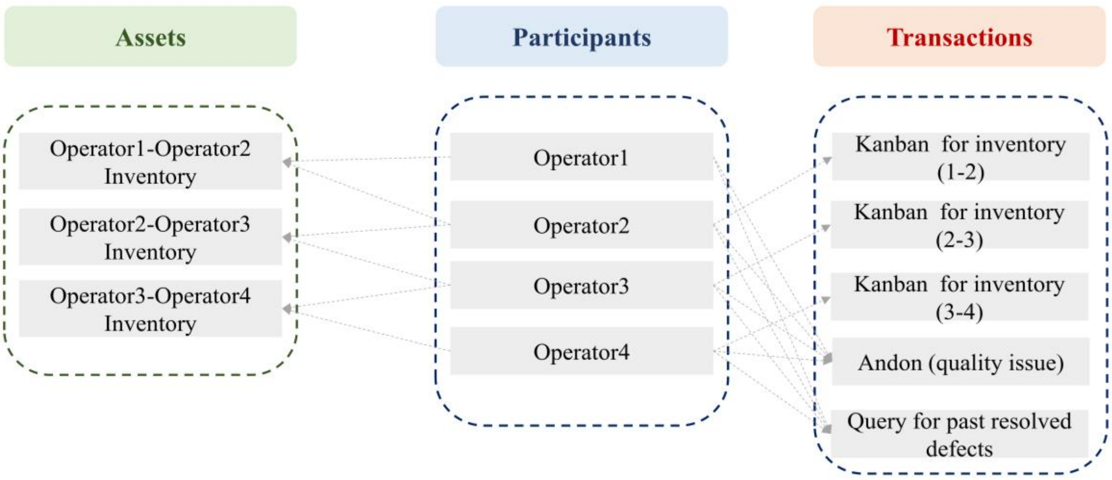

Figure 6: the components of the blockchain system

To implement the above transaction components, a smart contract was developed and deployed in the model script of the Hyperledger Composer tool. JavaScript is the language supported by the tool and was used to write the smart contract. All of the functions of the smart contract, as discussed above, are related to element ID. When participants submit a request to supply or inspect a particular element, they must specify the element ID. Figure 7 shows an ID of a steel module and what it represents.

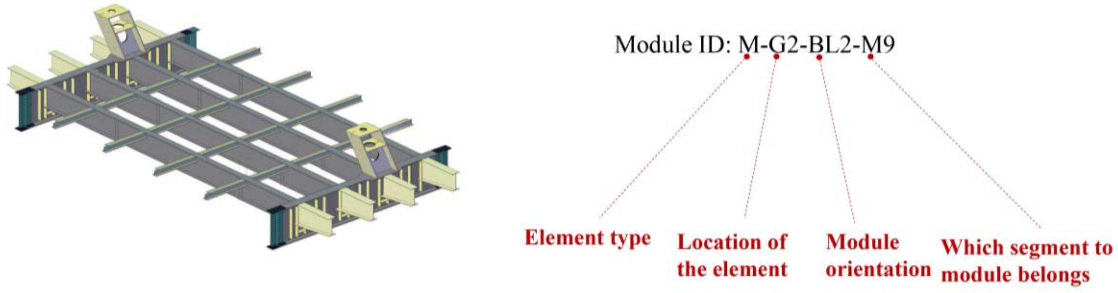

Figure 7: the representation of an element ID

Any transaction made by any participant is timestamped and saved in the transaction with a hash value that is immutable through time. This ensures the security of the network and promotes trustworthiness between participants (Assaf et al., 2022). The transactions available in the system focus on the digital kanbans to request more materials, notification of a quality issue at any time, and a request for a historical record of any issue and its solution method. Figure 8 visualizes how the transactions work in the system.

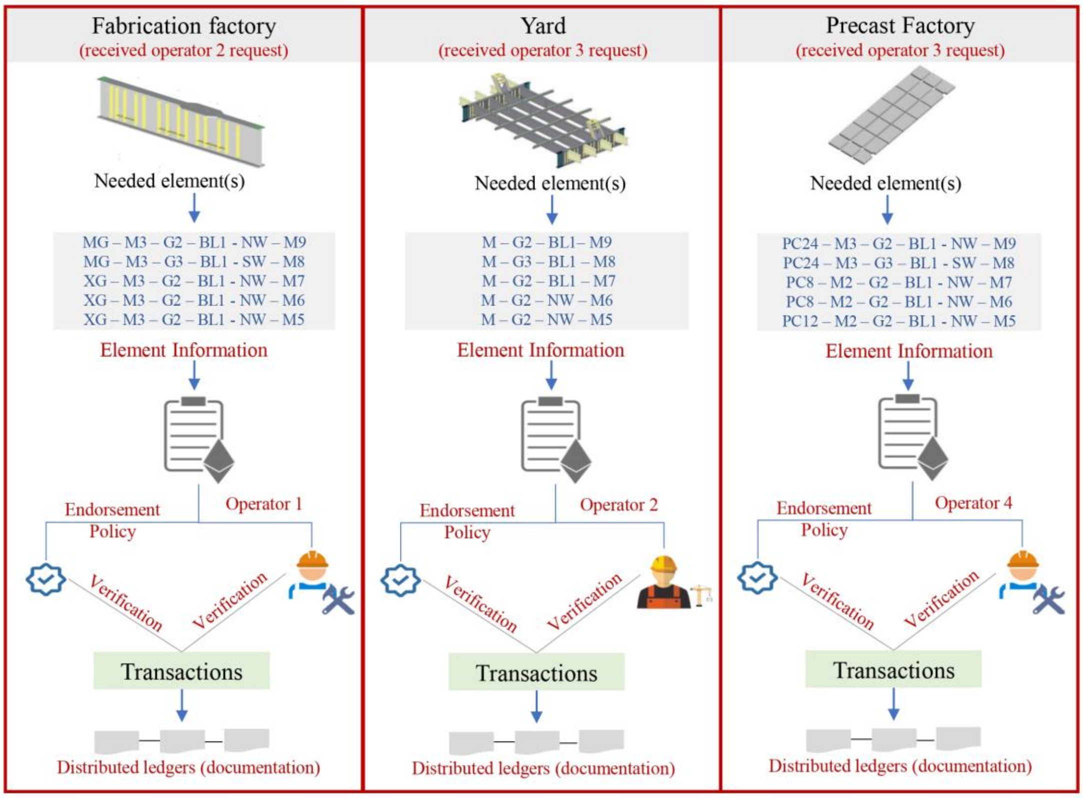

Figure 8: visualization of the functions of the smart contracts

Functionality of the Smart Contract

In this subsection, several scenarios were identified to prove the functionality of the model. First, the model is tested when a material (steel girders) is needed by Operator 2 (the yard) from Operator 1 (the steel factory). Firstly, Operator 1 logs into the system by their digital identity. This operator would have certain access to the system defined by the access control feature (ACL) of the system. Figure 9 shows the network cards that are issued to the participants and allow them to access the system. Operator 2 then selects the transactions section and submits to Operator 1 a digital kanban specifying the following: elements' IDs, quantities, and location. Operator one then receives a notification on the system of the needed items. The smart contract verifies the request first based on an endorsement policy, and then Operator 1 verifies this transaction based on the available data.

Table 1 shows the inventory assets after accepting the submitted request by operator 2 along with the submitted request. The available inventory for Operator 1 will go down by the submitted needed items, and the available inventory for the supermarket between the two stations (factory and yard) will increase by the same amount. In a scenario where the steel factory does not have enough steel girders to cover the operator 2 request, the system itself will notify the operator about the unavailability of the materials. The eligible participant can then view any of the submitted requests at any moment to keep track of the available inventory, as will be shown in the second section.

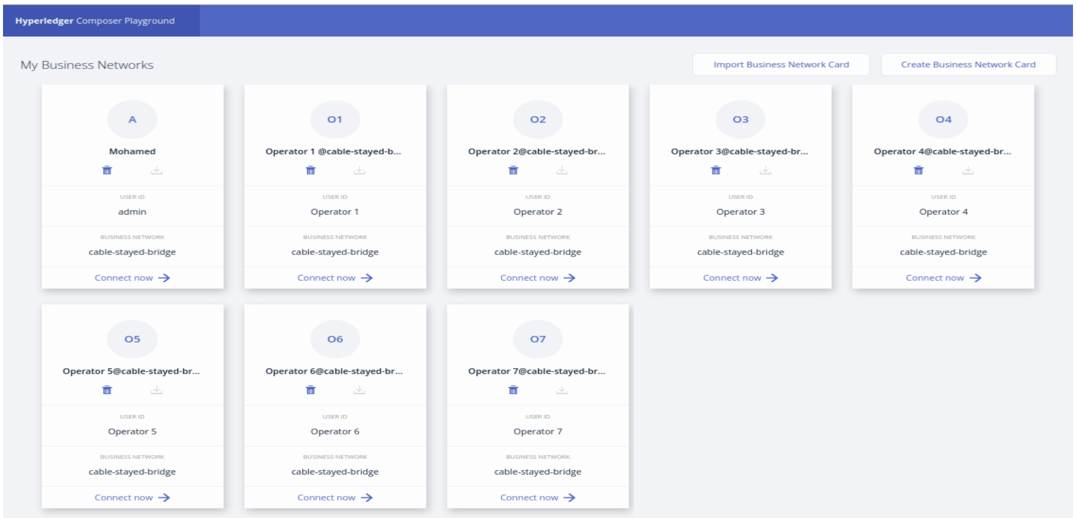

Figure 9: Network cards given to each operator

Table 1: Details of the test scenario

Step	Details
The submitted request by operator one	
The supermarket update after accepting the request	

Besides digital kanbans, the system provides operators with a *Pulling Andon* feature. In a scenario where an operator discovers a quality issue in one or more of the elements, he/she can submit an Andon on the system. The Andon specifies the following data: the element ID, the name of the station, a description of the issue, the Andon pulling time, and the degree of the quality issue (red or yellow). The transaction is visible to all operators in the system. If the issue is not resolved, the operator then submits another Andon with a red deficiency degree, and all operators in the system will stop the work. Further, all of these submitted Andon are documented in the system with its resolving strategies (Poke a yoke). Figure 10 shows a historical submission of an Andon, showing every detail of the quality issue.

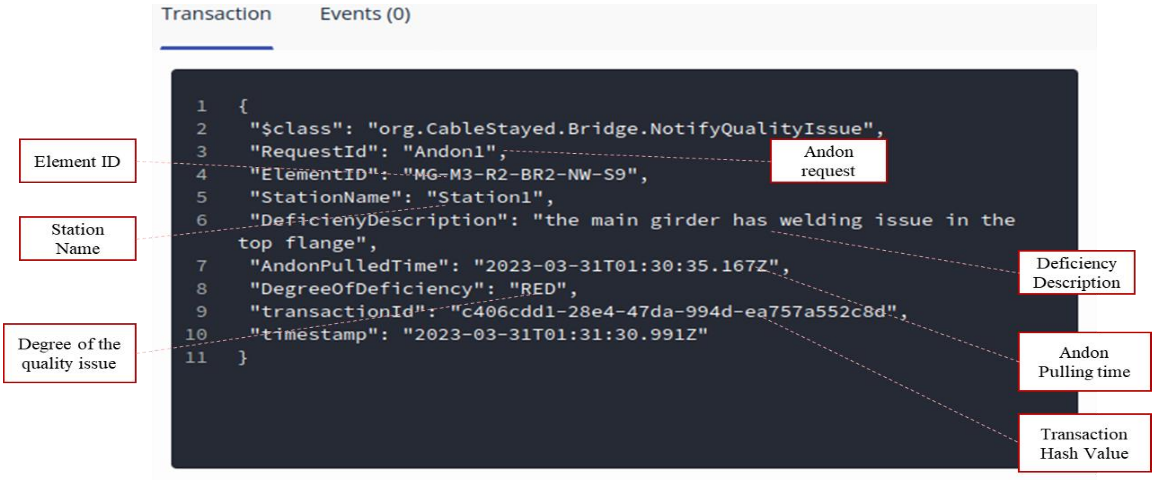

Figure 10: A historical record of a submitted Andon on the system

CONCLUSIONS

This study tackles the challenges in implementing OSC projects through the combination of advanced technologies, such as BIM, blockchain, and smart contracts, with lean principles. The study was motivated by the need to have a holistic framework that addresses the OSC challenges in onsite, offsite, and logistics operations. *Kaizen*, *Heijunka*, *Just-in-Time*, *One-piece flow*, and *Poke a yoke* are the main lean principles that were considered in this study and implemented through the mentioned technologies. Four main areas were addressed in this study. These include an extensive literature review, understanding of cable-stayed processes, providing of improvements, and implementation of the proposed improvements. The application of Value Stream Mapping (VSM) through the current state and future state mapping outlined areas of improvement that the application of BIM was able to exploit. Discrete event simulation was used to observe the impacts of providing these improvements. Further, the study provides a secure information-sharing system based on blockchain technology to fully exploit the benefits of the BIM-Lean approach. The potential incorporation of virtual reality (VR) into this process also is expected to provide an efficient training ability for the operator to be familiar with and train on lean principles.Besides the contribution provided by the current study, it also includes a number of limitations. The developed model future and current VSM do not consider the processes included in the manufacturing factories. Future research may explore the possibility of extending the scope of the presented study. Also, the smart contract system needs the participant to manually specify the element tag number. Future research may explore the full automation of the system.

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AN INTEGRATED FACILITY MANAGEMENT SYSTEM SUPPORTED IN VDC AND LEAN

Alvaro Daniel Bazán Montalto [1], Jose Francisco Vidal Quincot [2] and Alexandre Almeida Del Savio [3]

ABSTRACT

The operational costs during the maintenance phase can account for 15% to 70% of a facility's total life cycle expenses, depending upon the type and size of the project. This paper explores the integration of Virtual Design and Construction (VDC) and Lean methodologies, offering practical solutions to optimize the maintenance operations of an engineering laboratory. A comprehensive literature review was conducted to identify common challenges in facility management and assess existing methods and technologies to address these issues. This research introduces the concepts of VDC and Lean within maintenance management, proposing an Integrated Facility Management System (IFMS) that applies these frameworks to the operations and maintenance (O&M) processes. The IFMS aims to harmonize the facility's physical structure, organizational dynamics, and procedural workflows, providing a practical roadmap for facility managers and maintenance professionals. Implemented in an engineering laboratory in Lima, Peru, the IFMS has significantly improved maintenance efficiency. The results include a fivefold reduction in the average time required for corrective maintenance and a 50% decrease in the incidence of such maintenance tasks. Finally, applying VDC and Lean principles to the maintenance phase can yield substantial operational benefits, as evidenced by the data from the implemented IFMS.

KEYWORDS

Facility Management, VDC, Lean, Value stream, Integrated Project Delivery (IPD), BIM.

INTRODUCTION

Despite their innovation, flexibility, and cost limitations, construction products are inherently complex (Nam & Tatum, 1988). This complexity manifests in the organization, the product, and the process. Construction projects involve numerous stakeholders with diverse objectives and interests, leading to fragmentation issues among professionals and organizations (Esa et al., 2014). Moreover, construction products are characterized by many interdependent elements, equipment, and intricate systems that constitute a building (Nam & Tatum, 1988). They are part of a challenging, lengthy supply chain involving numerous internal and external suppliers (Ashworth & Perera, 2015). Some authors correlate this complexity to the construction's heterogeneity and project-based nature (Gálvez-Martos et al., 2018). As a result, construction is ranked the second-lowest sector in adopting information technology (Agarwal et al., 2016).

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On the other hand, the project maintenance phase represents 15% to 70% of a facility's life cost cycle, depending upon the type and size of the project. Furthermore, corrective maintenance corresponds to this cost more significantly (65% to 85%)(Janjalkar et al., 2023). The consequences of deficient building maintenance entail risks to its users' safety and maintenance cost uncertainty (Shou et al., 2020). These maintenance costs are proportional to the downtime (DT) of the system or an asset. The DT is when equipment/system is down until it returns to normal working conditions. The increase in DT is due to non-value-added (NVA) activities or wastes in maintenance operations (Mostafa et al., 2015).

This research presents a background study on the challenges and problems faced by maintenance management and the methods and technologies proposed for their solution. Moreover, Virtual Design and Construction, Integrated Project Delivery, and Lean concepts are introduced. The hypothesis is that implementing these concepts in the maintenance stage generates substantial operation benefits. Finally, an Integrated Facility Management System (IFMS) is proposed based on VDC and Lean.

BACKGROUND

FACILITY MANAGEMENT

The concept of Facility Management (or Facilities Management) has been around for more than 50 years. According to the International Facility Management Association and ISO 41011:2017, it is "an organizational function that integrates people, places, and processes within the built environment to improve people's quality of life and productivity of the core business" (ISO, 2017). Facility management began as a simple sanitary and cleaning service during the 1970s. Since then, it has constantly been evolving into what is known today as the occupational profession, with millions worldwide involved in managing organizations, their facilities, and services (Drion et al., 2012).

LEAN

Lean management principles are a philosophy that draws on the lessons learned from how Toyota does things. This principle helps an organization manage its operations more efficiently (Liker, 2004). The lean philosophy provides waste minimization methods while creating value for the stakeholders (Denzer et al., 2015). Several studies focus on the effect of lean techniques on maintenance efficiency. These tools are 5S; 5Whys, Total Production Management (TPM), Kaizen, Poka-Yoke, Kanban, Process Mapping (PM), Computerized Maintenance Management System (CMMS)/Computer-Aided Maintenance Management (CAMM), Just In Time, Failure Mode and Effect Analysis (FMEA), standardization of procedures, Value Stream Mapping (VSM) (Dragone et al., 2021). However, VSM is the most frequently applied lean technique for understanding the maintenance process by representing material and information flows (Shou et al., 2020).

VIRTUAL DESIGN AND CONSTRUCTION (VDC)

Virtual Design and Construction is a management methodology that integrates product, process, and organization models (Kunz & Fischer, 2004). The latter is one of his most significant contributions since his approach focuses on integrating a specific work team to achieve the proposed and, ultimately, the client's objectives. Since then, it has evolved into what is known today, with its main components: Client Objective, Project Objective, Integrated Concurrent Engineering (ICE), Building Information Modeling (BIM), and Project Production Management (PPM). The VDC literature shows various implementations in the design and construction phases, with outstanding results in achieving the client's objectives (Balcazar et al., 2023; Barcena et al., 2023; Bustamante et al., 2023; Del Savio et al., 2022; Majumdar et al., 2022; Palpan et al., 2022; Quinteros et al., 2023; Salazar et al., 2023; Tuesta et al., 2022). These results were obtained for projects in the design and construction phase. However, applying the same rationale for maintenance management implies measuring the production objective with some recurrence and not necessarily fixing it in a project timeframe.

INTEGRATED PROJECT DELIVERY (IPD)

Integrated Project Delivery (IPD) is a delivery model based on the collaboration between the project stakeholders in the construction industry (Aslesem et al., 2018). IPD was initially developed to confront the challenges of increased project complexity, high fragmentation levels in the construction industry, and inadequate communication among stakeholders (Ahmed et al., 2021). A multiparty agreement and the involvement of key stakeholders at an early design stage characterize this delivery system. The emphasis is on relationships, collaboration, and pursuing mutual goals. This implies sharing the risks and rewards of the project as an incentive to achieve this mutual goal (Teng et al., 2017; Durdyev et al., 2019).

METHODOLOGY

This paper aims to conduct an explanatory investigation into implementing an integrated facility management system supported by Virtual Design and Construction (VDC) methodology and Lean concepts.

It is hypothesized that integrating VDC and Lean concepts could help fulfill the client's objectives during the building maintenance phase. Based on this premise, a bibliographic review was carried out in indexed databases, such as Scopus, Mendeley, and Web of Science, as well as regulations and standards of good practice, using the following keywords: "Facility Management," "Virtual Design and Construction," “Lean Maintenance” and "Information System."

The methodology follows the Value Stream Mapping method. First, it identifies the target process to improve. Then, the baseline or current state of the value stream map is constructed based on semi-structured interviews with laboratory personnel in charge (identifying the waste). Next, a future value stream map for maintenance supported by the VDC, IPD and Lean is proposed. Finally, a working plan is developed based on that optimized process (Martonen & Baglee, 2019).

RESULTS AND DISCUSSIONS

PROJECT INTRODUCTION

The facility studied in this article is the Laboratories of the Civil Engineering Department (Figure 1) at the Universidad de Lima, located in Lima, Perú (Figure 1). When the Civil Engineering Program began in 2017, the need arose to implement laboratories to provide (i.) technical and academic support to the subjects taught, (ii.) research support, and (iii.) support for the construction industry. In this sense, the direction of the Civil Engineering Department defined a gradual procedure for implementing the laboratories to meet those goals. The following laboratories were identified and implemented: Laboratory of Materials, Soils, Rocks, Topography, Geomatics, Structures, Environmental Engineering, Pavements, Sanitary Engineering, Hydraulics, and Hydrology. The results obtained in this chapter reflect the method proposed to implement the IFMS under a VDC and Lean approaches applied to the Operation and Maintenance stage.

Figure 1: Overall view of the Laboratories of the Civil Engineering Department of Universidad de Lima.

PROBLEMATIC ANALYSIS BASED ON PRIMARY INFORMATION

It was employed semi-structured interviews with stakeholders responsible for equipment maintenance in the laboratory. These interviews facilitated the definition of objectives, identification of critical equipment, mapping of the equipment maintenance process, identification of problems or sources of variability, and proposal of improvements in the maintenance process. The results of these interviews are presented below.

One hundred percent (100%) of the interviewed managers agreed that the value of the investment made in implementing the laboratories is measured in the degree of use of the equipment in academic courses, research, and industry support.

The laboratory managers pointed out 11 critical pieces of equipment, presented in Table 1, organized by the laboratory disciplines. A piece of equipment is considered vital when it meets the following requirements: (1) its operation is essential due to its high demand, (2) its maintenance is complex and laborious or with much variability in the correction period, or (3) that it does not have a replacement available in the local market.

Table 1. Key equipment.

Laboratory	Key Equipment Name
Materials	Uniaxial Compression Machine (Automax) and Multi-testing Machine (600 KN)
Geotechnics	Triaxial Soil System and Direct Cutting Equipment
Pavements	Hamburg Wheel and Servo-Hydraulic Universal Testing Equipment
Structures	Single-ended Hydraulic Actuator
	Uniaxial Compression Machine (3000 KN)
Sanitary, Hydraulic, and Hydrology Engineering	Compact Fluid Mechanics Basic module (HM250) and Flow and Sediment Transport Channel
Environmental	Spectrophotometer Infrared (FTIR)

Based on the interviews, it was mapped the current maintenance process for the laboratories using the Business Process Model and Notation (BPMN) standard. This process is shown in Figure 2. The stakeholders are the laboratory team, civil engineer career team, maintenance team, buy area, and maintenance suppliers.

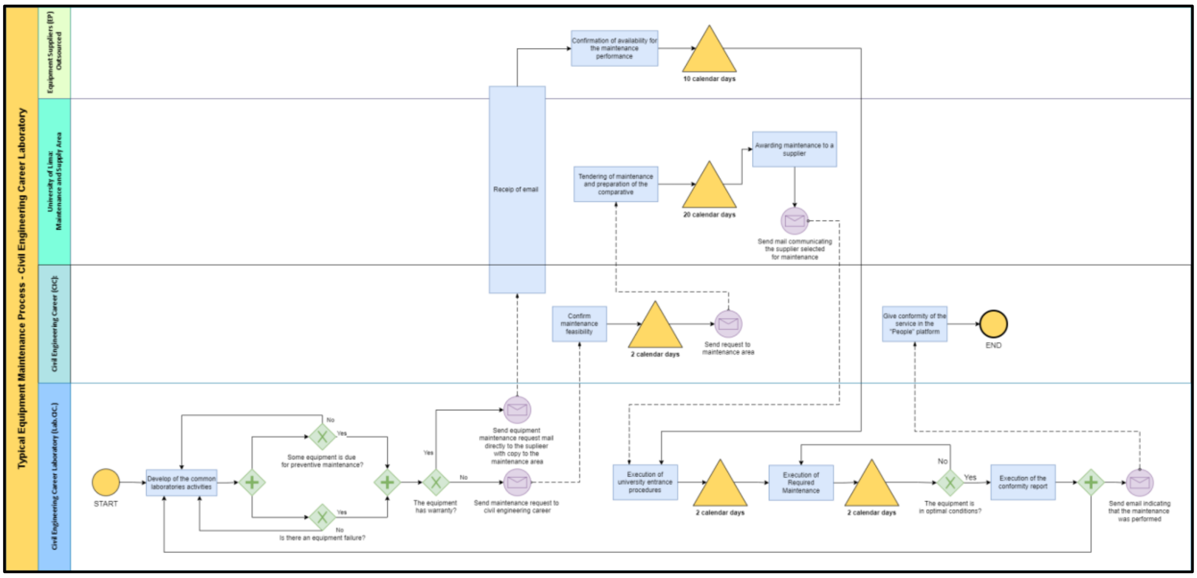

Figure 2 - Current maintenance flow.

The maintenance process is sequential and fragmented. Most communications are made by email. The average duration of the equipment maintenance process depends on two variables: the type of maintenance (corrective or preventive) and an equipment warranty. The equipment inoperability days were increased from 2 days (duration with preventative maintenance and warranty) to 26 days for equipment that did not have a warranty (Table 2). In this sense, strategies are needed to include a more extended warranty.

Table 2. Current maintenance process analysis.

Type of Maintenance	Warranty	Total Process Duration (Days)	Duration of Inoperability (Days)
Preventive Maintenance	Yes	14	2
	No	26	2
Corrective Maintenance	Yes	14	14
	No	26	26

The interviewees identified the main issues with the maintenance process as follows: (1) Latency in communications and deficiencies in following up maintenance requests, (2) variability in the duration of provider selection, (3) the absence of extended warranties, and (4) maintenance information management. Additionally, the laboratory team does not participate in provider procurement. Hence, the duration of the award process and the reliability of the chosen supplier emerge as the primary sources of variability within this process.

The waste analysis and classification were based on the current maintenance flow. In this context, the most impactful wastes are the waiting times and ineffective data management in the entire process. A fragmented approach to maintenance management generates those wastes. The sequential and fragmented process increases communications latency and increments the total cycle time.

As a result, 60% of the interviewed managers reported that some equipment in their laboratory was inoperative due to maintenance, with an average repair time of 130 calendar days for critical equipment (corrective maintenance).

VDC FRAMEWORK ELABORATION

The VDC framework includes explicit specification of client and project objectives and measured performance for the project. This includes specifying a performance objective and a desired performance measured with a specific frequency (Kunz & Fischer, 2020). The proposed VDC framework, presented in Table 3, was based on the stakeholders' interview information and the systematic bibliographic review. Subsequently, the stakeholders validated this framework, and the impact of applying it on the maintenance process was measured. The VDC outputs and production metrics allowed the maintenance process production to be evaluated and compared with a target value.

The client's objective is to guarantee the critical equipment operability in the laboratory. The goal, 95% of operability, was defined considering only one day stop for preventive maintenance per month. It is desired to avoid any equipment inoperability due to corrective maintenance. The project team's (the maintenance process stakeholders) objective is to develop an integrated facility management system to manage the 11 critical equipment and supply the client maintenance needs.

The operability percentage is the core metric of the maintenance process. Two identified problems were the absence of extended warranties and delays in provider selection. As controllable factors, the IFMS includes process mapping and uses collaborative contracts with an IPD scope for maintenance suppliers. This IPD contract implementation has improved the willingness to collaborate and create an open communication culture, integrated information, collaborative goal definition and decision-making, and early involvement of the key participants (Kahvandi et al., 2017; Aslesem et al., 2018). In this sense, the IFMS aims to consider IPD contracts to create long-term collaborative contracts with the maintenance providers and guarantee preventive maintenance and availability for corrective maintenance. This IFMS/IPD contract shall consider sharing the risks and rewards of the year maintenance budget as an incentive. However, this contract should be considered in the early phases of the design process to align better the process needs.

Weekly meetings with the maintenance stakeholders were considered for the ICE component. The communication latency was one of the main problems identified in the interviews. The ICE sessions generated response latency reductions. Hence, the IFMS proposal shall include ICE sessions weekly to keep updated on the maintenance status of the 11 critical equipment. Some important issues were the maintenance provider selection, the information needed to include on the BIM, and a collaborative contract with the selected supplier with an IPD scope.

Another issue was managing maintenance information. The BIM component allows maintenance information to be managed following the COBie standard. As a controllable factor, the IFMS proposes creating a required information checklist for each project. The information needed for the maintenance team may vary per project and organization. The goal for this component is to include all the required information for maintenance in the BIM with the COBie Standard.

Table 3. Proposed VDC Framework.

VDC Framework				
Client Objectives	Guarantee a 95% operability of the critical equipment. (This means only one day stop for preventive maintenance per month)			
Project Objectives	Develop and implement an Integrated Facility Management System (IFMS), which manages the 11 critical equipment of the laboratories.			
Components	**Item**	**Description**	**Metric**	**Goal**
ICE	Production Metrics	Have 100% compliance with the agenda in the sessions (% Agenda Compliance).	$\%Agenda\ Compliance = \frac{\#Items\ Completed}{\#Items\ Scheduled}\ x\ 100$	100%
	Controllable Factors	Send the Meeting Agenda in advance.	Number of days in advance to send the agenda	2
BIM	Production Metrics	Have 100% equipment operation and maintenance information included in the BIM model (With COBie Standard)	$\%\ \text{O\&M}\ Information\ in\ BIM = \frac{\#Inf.\ Included}{\#Inf.Required}\ x\ 100$	100%
	Controllable Factors	Define the information needed for the maintenance checklist for critical equipment.	Required Information Checklist per essential equipment	1
PPM	Production Metrics	Have 95% monthly operability for the 11 critical equipment	$\%\ \text{Operability} = \frac{\#Operating\ Hours}{\#Total\ Hours}\ x\ 100$	95%
	Controllable Factors	Create the VSM for the current maintenance process and optimize it with IFMS.	# of Process Map developed	1
		Create collaborative contracts with the maintenance suppliers with an IPD scope	$\%\ Critical\ Equipment\ with\ a\ colaborative\ contract\ scope = \frac{\#Equip.with\ Contract}{\#Total\ Critical\ Equip.} x\ 100$	100%

IFMS IMPLEMENTATION AND VALIDATION

The maintenance stakeholders validated the IFMS methodological approach. The approach received a satisfaction level of 73% and suggestions for improvement related to developing specific strategies for each piece of equipment and laboratory. Table 4 shows the results of the three-month early adoptions of the IFMS. It can be observed how the average duration for the corrective maintenance was reduced by five times, and the number of corrective maintenance incidents was reduced by half, validating the IFMS implementation.

Table 4. IFMS implementation results.

Process	Baseline Measurement	Maintenance Process with IFMS	Delta	Target
Average Duration of the Corrective Maintenance Process (Calendar Days)	130	22	108 (5 times less time)	2
Number of Corrective Maintenance Incidents	5	2	3 (Reduced by Half)	0

CONCLUSIONS

The main objective of this research was to propose an Integrated Facility Management System (IFMS) based on the concepts and practices given by the VDC and Lean. The IFMS was built based on information from the maintenance process problem identified through semi-structured interviews. This allowed for understanding, validating, and precisely defining the client and project objectives. Also, the systematic review helped to suggest production metrics and controllable factors that support the implementation of IFMS based on the VDC and Lean principles.

With the early implementation of IFMS, the average duration for corrective maintenance was reduced by fivefold, and the number of corrective maintenance incidents was reduced by half. Moreover, this methodology received the acceptance of 73% of the stakeholders. The next step is developing a relational contract with the maintenance suppliers. This will allow us to improve the operability performance of the critical equipment based on collaborative relations.

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CAN CHATGPT HELP WITH THE LAST PLANNER® SYSTEM IMPLEMENTATION? AN EXPERT OVERVIEW

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ABSTRACT

In recent years, the construction sector has been influenced by different technologies, which has given way to construction 4.0. One of the elements of Construction 4.0 is the use of artificial intelligence, and in recent years, chatbots have become popular in different industries, including construction. However, the literature on how chatbots can help in construction projects is limited. In this sense, the following article aims to study the degree of reliability presented by a chatbot (ChatGPT) to improve the implementation of the Last Planner® System (LPS). This article begins with a literary review of LPS barriers. From this, 13 main barriers are validated with the help of 10 expert judgments. After that, ChatGPT 3.5 is interacted with to provide possible solutions to the barriers found, which are validated again with eight expert judgments. The results show that 68.27% of ChatGPT responses are “Totally agree” and “Somewhat agree.” The following article will contribute to professionals in the construction sector so that they can evaluate the reliability of chatbots and explore their applications to solve LPS implementation problems and other problems in construction projects.

KEYWORDS

Last Planner, Artificial Intelligence, ChatGPT, construction 4.0, lean construction.

INTRODUCTION

The construction industry faces cost overruns, changes in execution, delays, and low productivity, and one of the main factors for these is the slow technological adoption of the construction industry (Hui et al., 2019). In this sense, Industry 4.0 can transform construction into a technological industry (Kozlovska et al., 2021). Given this, there are efforts to combine Industry 4.0 technologies in construction, which has given rise to Construction 4.0, where technologies such as BIM, virtual reality, mixed reality (Hossain & Nadeem, 2019) and artificial intelligence (AI) are used (Forcael et al., 2020).

One of the elements of Construction 4.0, AI, which is defined as a powerful management tool that provides superior analysis operated by humans, allows time savings in automating

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processes and forecasting results (Ayoubi et al., 2023). Its applications occur in intelligent manufacturing and predicting phenomena related to building design, construction, and operation, identification of elements on a construction site, and developing patterns to follow workers' performance (Forcael et al., 2020). The use of artificial intelligence in construction is increasing due to the large amount of data produced by digital transformation, the capacity for data management, and the improvement in computational quality (Baduge et al., 2022).

AI has been explored to generate synergies with the lean philosophy. For instance, Cisterna et al. (2022) explain how AI can leverage the data generated by Lean. In addition to this, in recent years, AI chatbots such as ChatGPT have been developed, which, due to an immense amount of data, training models, adaptability, and learning, are capable of maintaining conversations, understanding the context, and presenting solutions (Yan et al., 2023). This is how its implementation has expanded in different areas, and lean construction has not been the exception. Therefore, interactions between Lean Construction and Chat GPT have a promising future (Hatoum & Nassereddine, 2023). For example, Etges and Fireman (2023) generated a conversation with ChatGPT about the dimensions of lean construction concepts, tools and people and validated them with 14 experts, finding that 77% of ChatGPT responses are "good" or "very good".

In this way, construction 4.0 could support several Lean Construction objectives, such as LPS, Jidoka, and VSM. That is why Hamzeh (2021) mentions that together, these elements could give rise to what is known as Lean Construction 4.0, a new philosophy that uses emerging technologies to streamline processes and promote a culture of continuous improvement, elimination of waste, and respect for people. This new philosophy prioritizes the harmonious integration of people, processes, and technologies.

While there are studies on ChatGPT and lean construction, research on adopting Chatbots within Lean Construction still needs to be explored. Dumrak and Zarghami (2023) highlight that one of the most important gaps is understanding AI's potential in the Lean field and how it can aid in the application and concept practice. Schia et al. (2019) note that one of the benefits of using AI is its ability to automate repetitive processes, thereby reducing human errors and allowing people to focus on value-added tasks. This benefit aligns with the Lean principles of waste reduction and value generation. Despite this, as Cisterna et al. (2022) point out, there needs to be more research that analyzes the synergy between the fields of Lean construction and AI, indicating a significant untapped potential. This untapped potential underscores the importance and urgency of our research in this area.

For this reason, the following article delves into how ChatGPT can help establish practical strategies to mitigate the barriers to Last Planner System implementation. To achieve this, the researchers collect and validate barriers associated with LPS through expert judgment. Then, using the categorized barriers, they ask ChatGPT for strategies to mitigate their impact. Finally, they validate the certainty of the obtained answers with expert judgment, thereby providing concrete insights and strategies for leveraging ChatGPT in Lean Construction, specifically in the context of Last Planner System implementation.

BACKGROUND

ARTIFICIAL INTELLIGENCE AND LEAN

Lean Construction is a construction management philosophy implemented on different continents (Engebo et al., 2017). Thus, in recent years, due to the technological revolution, various technological advances have been generating synergy with construction 4.0, giving rise to the concept of lean construction 4.0, which seeks to combine the technology of industry 4.0 with the people-process-technology lean triad (Hamzeh et al., 2021). Thus, one of the key elements of this synergy is the interaction of Lean Construction with artificial intelligence.

In that sense, Cisterna et al. (2022) mention that implementing AI and Lean together generates synergies that add value to what they would have when applied separately. Likewise, other authors have explored these synergies in different fields. Prieto et al. (2023) study the use of artificial intelligence for decision-making, thus avoiding people's subjective judgment that can lead to waste, such as unproductive actions that do not add value. Dumrak and Zarghami (2023) conducted a classification study on the different categories and AI tools to make an application in lean construction management (LCM) to support its principles.

Likewise, this synergy has extended to the interaction of chatbots such as ChatGPT with Lean Construction. Etges and Fireman (2023) conducted a conversation to obtain the definitions that ChatGPT can provide about the concepts, tools and behavior of people related to lean construction and then be evaluated by experts on the subject. Hatoum and Nassereddine (2023) focused on collecting and summarizing IGLC articles and identifying their trend in research that relates to lean construction and ChatGPT and their ability to educate and train on both theoretical and practical aspects of the application of lean construction.

CHAT GPT AND CONSTRUCTION INDUSTRY

ChatGPT is used in different industries, and the construction industry is no exception. Thus, ChatGPT promises to transform not only the way we build but also the way we imagine the infrastructure of tomorrow (Rane, 2023). ChatGPT can help carry out preliminary designs, structural analyses, and simulations, in addition to facilitating the optimization process and evaluation of the feasibility of each alternative (Aluga, 2023). In addition, it has been used in risk management (Aladağ, 2023) and in project planning, where it has promising results, especially for simple cases, but since it is not a tool designed for planning, it has limitations in the programming of real projects. (Prieto et al., 2023). ChatGPT also helps in the development of intelligent, sustainable, automated cities, BIM models, and choice of materials and technologies, showing that even with the challenges it presents, such as the need for specialized training and possible job changes, it seems clear that ChatGPT will have a central role in the development of the construction industry (Rane, 2023).

PROBLEMS IMPLEMENTING THE LAST PLANNER SYSTEM

The Last Planner System (LPS) tool, a Lean Construction tool, is used for production planning and monitoring to increase reliability and performance while establishing a predictable workflow (Hamzeh et al., 2009). It has been shown that its implementation brings benefits such as improved organizational control (Cerveró et al., 2013), a decrease in variability that translates into greater productivity, and a reduction in costs (Koskela et al., 2010), simplifying thus the production control and planning process (Aziz & Hafez, 2013). Despite these benefits, its successful implementation faces several barriers.

Liu et al. (2020) described the barrier of lack of knowledge about LPS, mentioning that one of the causes is the low effectiveness through which social dynamics are managed in construction organizations, which reduces both absorption and diffusion of LPS. These can be without a solution for a long time.

On the other hand, Venkatesh and Venkatesan (2021) explained that the barriers of "resistance to change" and "Lack of collaboration between project team members" have a relationship between the two because, in the construction industry, there is a late acceptance of the change and one of the main reasons for this is the low participation of various segments deployed in the project.

Lindhard and Wandahl (2015) focus mainly on two barriers: "Partial Implementation" and "Lack of Knowledge of the LPS execution process." In their research, they mentioned that a theoretical and practical study revealed that only parts of the LPS are implemented, and this directly influences the process's reliability. In addition, a lack of knowledge of the implementation can cause reliability problems to go unnoticed.

Based on the literature review, 15 barriers to implementing the Last Planner system were detected, which are presented in Table 1.

Table 1: Barriers associated with the implementation of the last planner system.

Barriers	References*
Lack of leadership and management commitment for the implementation of the Last Planner System (LPS).	1
Lack of Last Planner training to managers to manage the project.	2, 3
Management has a short-term vision in the implementation of LPS in their organization.	4
Lack of knowledge about the LPS System	1, 2, 5, 6, 7, 9
Lack of role definition in LPS implementation	3, 5
Lack of commitment of the team in the LPS implementation	2, 4
Lack of involvement of the last planners	5, 6
Lack of involvement of the members of the production chain (customer, suppliers, subcontractors)	2, 3, 5, 7
Resistance to change	1, 2, 3, 6
Lack of transparency and weak communication in the exchange of information in the weekly meetings	2, 3, 5, 7
Lack of commitment of the whole team in the implementation of LPS	6, 7
Failure to use a gradual process of LPS implementation	9
Lack of self-criticism to take improvement actions during LPS implementation	3, 7
Incorrect use of the information gathered during implementation to create a learning loop	1, 3, 5, 7
Lack of management support for LPS implementation	1

Note: *1. Murugaiyan et al. (2022), 2. Venkatesh and Venkatesan (2021), 3. Murguia (2019), 4. AlSehaimi et al., (2009), 5. Brady et al. (2011), 6. Liu et al. (2020), 7. Tayeh et al. (2018), 8. Lindhard and Wandahl (2015), 9. Perez and Ghosh (2018).

RESEARCH METHOD

Figure 1 shows the phases of the methodology of this research. In the first phase, a literary review of the barriers to the implementation of the last planner system is carried out by searching with the keywords "Last planner" and "barriers" in the IGLC and Scopus databases because IGLC contains the most significant amount of Lean Construction publications (Daniel et al., 2015) and Scopus has a greater range of construction publications than other databases (Mongeon & Paul, 2016). In the second phase, a survey was developed that allowed the main barriers of LPS to be categorized, and the survey was sent to 10 experts using the Likert scale. The surveys were used because they have been used in other lean construction studies, such as those of Murguia (2019).

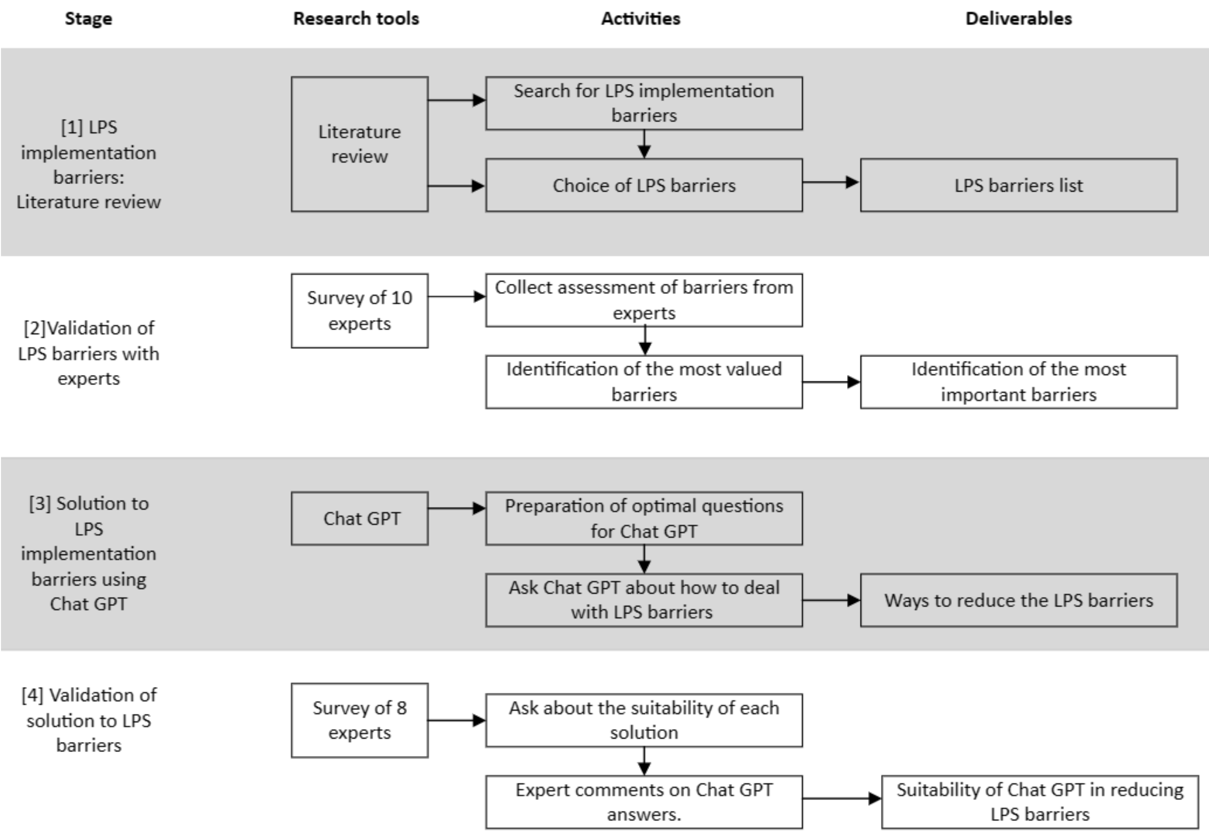

Figure 1: Structure of the Paper.

The selected experts had to be civil engineers with more than five years of experience in lean construction. Table 2 shows their profiles.

Table 2: Profile of the experts who validated the LPS barriers.

Number	Experience	Experience in Lean Construction	Industry/Academic	Business /Interest Area
Expert 1	10-20 years	10-20 years	Industry Participant	Project management
Expert 2	5-10 years	5-10 years	Industry Participant	Construction
Expert 3	>20 years	>20 years	Academic	Research, development and innovation
Expert 4	10-20 years	10-20 years	Industry Participant	Construction
Expert 5	5-10 years	5-10 years	Industry Participant	Construcción
Expert 6	10-20 years	10-20 years	Industry Participant	Project management
Expert 7	10-20 years	10-20 years	Industry Participant	Construction
Expert 8	5-10 years	5-10 years	Industry Participant	Project management
Expert 9	5-10 years	5-10 years	Industry Participant	Construction
Expert 10	10-20 years	10-20 years	Industry Participant	Project management

In the third phase, ChatGPT was used to ask how it would resolve the barriers with an average greater than 4, of which there were 13 and were considered the most important. In the last phase, the answers were sent in a new questionnaire to experts, with the same requirements as the previous validation. They were evaluated using a Likert scale to evaluate how much they agreed with the content and quality of the answers and to write a comment with their opinion. Table 3 presents the characteristics of the experts.

Table 3: Profile of the experts who validated the set of CHAT GPT's answers.

Number	Experience	Experience in Lean Construction	Industry/Academic	Business /Interest Area
Expert 1	10-20 years	<5 years	Industry Participant	Construction
Expert 2	10-20 years	10-20 years	Industry Participant	Construction
Expert 3	5-10 years	<5 years	Industry Participant	Project management
Expert 4	5-10 years	5-10 years	Industry Participant	Construction
Expert 5	10-20 years	10-20 years	Industry Participant	Construction
Expert 6	10-20 years	10-20 years	Industry Participant	Research, development and innovation
Expert 7	10-20 years	10-20 years	Industry Participant	Project management
Expert 8	5-10 years	5-10 years	Industry Participant	Construction

RESULTS AND DISCUSSION

LAST PLANNER BARRIERS

From the surveys with the experts, 13 barriers were obtained, shown in Table 4.

The most important barrier is barrier B1, with an average of 4.6. This shows that a key factor in the successful implementation of LPS is management's support and commitment to it. For this same reason, the B3 barrier does not allow us to achieve the expected results.

It is argued that barriers B2, B4, and B5 exist because the LPS is a tool that requires a good understanding of the principles and their composition to put them into practice and obtain results. Furthermore, barriers B6, B7, B8, B10, and B11 exist because the LPS is a tool that requires collaboration from the entire team (Daniel et al., 2015), so if it is not available, it can lead to problems in implementing this tool. On the other hand, barrier B9 is typical of lean approaches such as LPS despite the benefits it may bring (Pedrosa et al., 2023).

Table 4: Most important Barriers of LPS.

Code	BARRIERS	s.d.	Mean	Rank
B1	Lack of leadership and management commitment for the implementation of the Last Planner System (LPS).	0,70	4,6	1
B2	Lack of Last Planner training for managers to manage the project.	0,71	4,5	2
B3	Management has a short term vision in the implementation of LPS in their organization.	0,88	4,5	3
B4	Lack of knowledge about the LPS System	0,70	4,4	4
B5	Lack of role definition in LPS implementation	0,70	4,4	5
B6	Lack of commitment of the team in the LPS implementation	0,82	4,3	6
B7	Lack of involvement of the last planners	0,79	4,2	7
B8	Lack of involvement of the members of the production chain (customer, suppliers, subcontractors)	0,63	4,2	8
B9	Resistance to change	0,79	4,2	9
B10	Lack of transparency and weak communication in the exchange of information in the weekly meetings	0,67	4,1	10
B11	Lack of commitment of the whole team in the implementation of LPS	0,74	4,1	11
B12	Failure to use a gradual process of LPS implementation	0,67	4	12
B13	Lack of self-criticism to take improvement actions during LPS implementation	0,82	4	13

For reasons of space limitations, the responses provided by ChatGPT are not presented in this research, as this conversation occupied 31 pages of results. However, of the barriers identified in the previous stage, the questions asked to ChatGPT are presented in Table 5. The "act" prompt was used since this instruction guides the artificial intelligence to execute or reproduce a specific set of skills from a group of experts. This research scenario allowed the AI to provide us with solutions based on the answers previously uploaded by lean construction experts to its database. It is observed that the most critical barrier turns out to be barrier B1, with an average of 4.6, which shows that for a successful implementation of LPS, a key factor is the support of management and their commitment to the implementation. For this same reason, the B3 barrier does not allow us to achieve the expected results.

Furthermore, it is important to highlight that at the beginning of the conversation with ChatGPT, the pre-set question "What is lean construction?" was asked because it was observed that ChatGPT provided higher-quality answers by building connections with past answers (Etges and Fireman, 2023).

Table 5: Most important Barriers of LPS solved by ChatGPT.

Code	Questions to ChatGPT	Number of words
B1	Act as a professional in lean construction, how would you solve this barrier to implementing last planner system: Lack of leadership and management commitment for the implementation of the Last Planner System (LPS)?	396
B2	Act as a professional in lean construction, how would you solve this barrier to implementing last planner system: Lack of Last Planner training to managers to manage the project?	449
B3	Act as a professional in lean construction, how would you solve this barrier to implementing last planner system: Management has a short term vision in the implementation of LPS in their organization?	473
B4	Act as a professional in lean construction, how would you solve this barrier to implementing last planner system: Lack of knowledge about the LPS System?	449
B5	Act as a professional in lean construction, how would you solve this barrier to implementing last planner system: Lack of role definition in LPS implementation?	460
B6	Act as a professional in lean construction, how would you solve this barrier to implementing last planner system: Lack of commitment of the team in the LPS implementation?	472
B7	Act as a professional in lean construction, how would you solve this barrier to implementing last planner system: Lack of involvement of the last planners?	485
B8	Act as a professional in lean construction, how would you solve this barrier to implementing last planner system: Lack of involvement of the members of the production chain (customer, suppliers, subcontractors)?	495
B9	Act as a professional in lean construction, how would you solve this barrier to implementing last planner system: Resistance to change?	504
B10	Act as a professional in lean construction, how would you solve this barrier to implementing last planner system: lack of transparency and weak communication in the exchange of information in the weekly meetings?	504
B11	Act as a professional in lean construction, how would you solve this barrier to implementing last planner system: Lack of commitment of the whole team in the implementation of LPS?	504
B12	Act as a professional in lean construction, how would you solve this barrier to implementing last planner system: Failure to use a gradual process of LPS implementation?	515
B13	Act as a professional in lean construction, how would you solve this barrier to implementing last planner system: Lack of self-criticism to take improvement actions during LPS implementation?	509

The experts' answers are in Figure 2. On average, 68.27% of the responses are in the range of "Totally agree" and "Somewhat agree," which is" close to the 77% obtained in the ChatGPT and lean construction study by Etges and Fireman (2023).

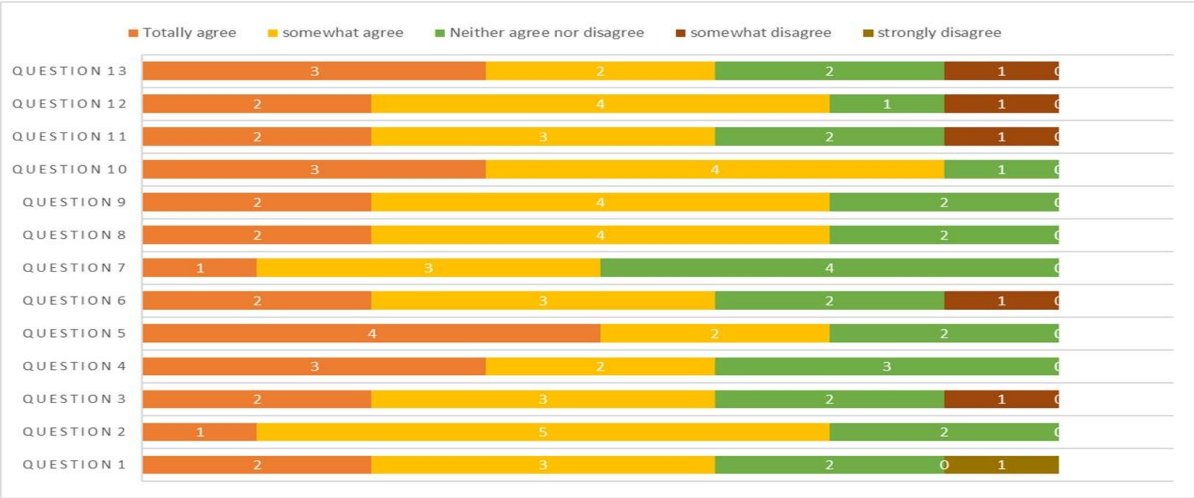

Figure 2: Chart of expert evaluation results on Chatgpt.

Question 10 is where the experts agreed the most, where no expert answered, "somewhat agree" or "strongly disagree." However, they would also propose an appropriate selection of the implementation team, making a better evaluation of the profile and performance of the participants.

Question 7 has the least approval, with 50% answering "Totally agree" and "Somewhat agree." Half of the respondents mentioned that more information was needed from Chat GPT and that, from the experts' experience in practice, they mention that this barrier is also influenced by factors external to those raised in the answer.

The only question with a "strongly disagree" answer was question 1. The expert who gave that rating commented that Chat GPT's answer fits the adoption of a general tool and not a tool with a philosophy of continuous improvement and lean transcendence, such as the LPS, which is consistent with what was mentioned by Etges and Fireman (2023). However, there were also responses in "Totally agree," arguing that good responses were given, such as highlighting the economic benefits to the company, as this will ensure a successful start to implementation and with high involvement of senior management.

In question 2, the experts mention the relevance of training operational managers and project supervisors but not so much that of "managers," pointing out that raising their awareness is enough to improve management with LPS. On the other hand, some criticisms were that knowledge management is more than the application of learning tools; rather, it is a process to ensure the learning achievements that are to be transmitted.

The experts highlight that question 4 is developed using the approach of barrier 2. However, both the question and the answers are more specific. It is also differentiated by the inclusion of "internal champions," who will be the defenders and mentors in the integration of LPS. There are unaware of LPS due to a generational issue, but not because they do not know of its existence.

In question 3, the experts mention that ChatGPT's answers were predictable in the sense of prioritizing that the LPS is oriented with the strategic plans and demonstrating the business benefit of implementing LPS.

Question 5 has the most answers in "Totally agree," and the experts mention that they provide accurate recommendations on role recognition in the implementation of the LPS, but they also mention that there should be more emphasis on the communications management part.

Most experts gave their opinions with a "Totally agree" rating for question 6, showing their interest in a relationship with communications management within the workplace.

In the comments on question 8, they mention that Chat GPT provides general answers to multiple factors, so it would be better to identify the flaws in a project personally and then ask Chat GPT what it would do to solve them.

Question 9 has a generally accepted answer. However, the experts mention that one must look beyond providing training and incentives and worry, for example, about generational change and how to generate change for senior professionals.

For question 11, it was recommended that this barrier can be avoided with better personnel selection and evaluation of profiles and performance of participants so that they are aligned with the work's objectives.

In question 12, the experts mention that adequate points were given in the answer but that the implementation process depends on each problem, so the answers are very general. In addition, they recommend getting more information to ask about a particular case.

Experts mostly agree with the answers provided by Chat GPT. However, some recommend that each problem for LPS adoption be first identified in addition to collecting data. So that Chat GPT has a greater context of the situation and generates better, more precise, and more understandable solutions. Results are consistent with the results found by Etges and Fireman (2023).

CONCLUSIONS

From this research, Chat GPT can be a good tool for providing responses related to mitigating the impact of the barriers associated with the Last Planner System since the specialists agreed with the different measures proposed by ChatGPT in 68.27% of cases.

The authors propose that future research try more interactions between lean construction and ChatGPT, increase the quality of the questions in the present study, and follow the recommendations of the experts to solve LPS implementation problems in a particular case study with ChatGPT so the answers can be more accurate.

The strong approval in question 10 indicates that experts recognize the importance of carefully choosing the implementation team. This finding suggests they value the need for trained and committed personnel to ensure success in applying the LPS. Furthermore, no expert selected "somewhat agree" or "strongly disagree" highlights a consensus on this topic.

The lower approval recorded for question 7 highlights a concern about the need for more information provided by Chat GPT in certain aspects. Experts suggest that a lack of clarity or detail in some areas could be an obstacle to the effective implementation of the LPS. This finding underscores that communication and the availability of complete information are critical elements for project success.

The experts' analysis shows that "Lack of leadership and management commitment for the implementation of the Last Planner System (LPS)" is the main barrier, which indicates the importance of management support and commitment.

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DIGITAL MONITORING FOR LEAN CONSTRUCTION: EFFICIENCY IN MAJOR INDONESIAN TOLL ROAD PROJECT

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ABSTRACT

The Karangjoang-Kariangau Section 3A Toll Road Project in East Kalimantan, Indonesia, aims to connect Balikpapan City with Nusantara, the New Capital City. This 13.4 km project, primarily involving intensive earthwork, utilizes heavy equipment whose efficiency is crucial for enhancing productivity and reducing costs. Our study examines inefficiencies such as unnecessary equipment motion, transportation delays, and extended waiting times—common challenges in lean construction. We implemented a digital monitoring system to compare its effectiveness against traditional manual methods in improving resource utilization and minimizing waste. Findings indicate that digital monitoring, despite the higher initial costs, significantly helps to boost operational efficiency by providing detailed data, then the data can be used to analyze the core of the problem so that a solution is found that successfully reduces idle time by 37% and increasing equipment utilization by 39%. These results demonstrate the substantial benefits of integrating digital technologies into construction management, suggesting a crucial shift towards digital methods to meet the demands of modern infrastructure development effectively. This study underlines the alignment of digital monitoring with lean construction principles, advocating for its adoption to optimize productivity and cost-efficiency in large-scale projects.

KEYWORDS

Lean construction, waste, digital monitoring, continuous improvement

INTRODUCTION

The Karangjoang-Kariangau Section 3A Toll Road Project, referred to as the "New Capital City Nusantara" called Ibu (IKN), spans 13.4 kilometers and plays a crucial role in connecting Balikpapan City to the New Capital City, Nusantara, in East Kalimantan, Indonesia. Ensuring

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efficient and controlled use of heavy equipment is vital due to the project's extensive scope, where precision in monitoring and control are essential to adhere to the project schedule and prevent delays and cost overruns. Challenges such as equipment location monitoring and productivity rate assessments have been identified as key factors contributing to these delays and additional costs. These challenges are often exacerbated by traditional management methods, which typically involve low-frequency monitoring that does not provide real-time data, thus failing to allow timely corrective actions (Nasr E., 2013).

In response to these issues, this study aims to evaluate the impact of implementing a digital monitoring system on the operational efficiency of heavy equipment in the section 3A Toll Road Project. Our objectives include assessing how digital monitoring can enhance real-time tracking, reduce equipment idle times, and support lean construction principles by improving resource utilization and reducing waste. By transitioning from traditional to digital monitoring methods, this research seeks to provide empirical evidence on the improvements in project management that can lead to significant cost savings and efficiency gains. The adoption of a stricter and more sophisticated monitoring system is not just a requirement but a strategic enhancement in line with national strategic project goals.

LITELATURE REVIEW

This literature underscores the evolving landscape of construction technology and sets a foundation for this study's exploration of digital monitoring's impact on lean construction practices in the context of Indonesia's significant infrastructure projects.

LEAN CONSTRUCTION CYCLE PROCESS

Lean Construction is grounded in the philosophy of continuous improvement, influenced significantly by Kaizen, which promotes incremental enhancements to boost efficiency and foster collaborative innovation. The Plan-Do-Check-Act (PDCA) cycle and Lean Six Sigma's DMAIC framework are pivotal methodologies within this realm, enhancing workflow, reducing waste, and improving quality by utilizing structured, data-driven problem-solving techniques (Lean Construction Institute, 2023; IdeaScale, 2023). In line with the Toyota Way's principles, the adoption of new technologies in construction must be reliable and tested extensively to ensure they support continuous operations and enhance worker productivity.

IDENTIFICATION OF WASTE IN CONSTRUCTION

Waste in construction encompasses more than just material waste; it includes inefficiencies in time, labor, and processes that can lead to increased costs and project delays. Classic waste types identified in lean construction include defects, overproduction, waiting, non-utilized talent, unnecessary transportation, excess inventory, and excess motion (Ohno, 1988). Techniques such as Value Stream Mapping (VSM) and the Last Planner System (LPS) are employed to identify and mitigate these wastes by visualizing workflows and enhancing planning reliability (Koskela, 1992; Ballard, 2000). Emerging technologies like Building Information Modeling (BIM) and automated monitoring with drones and sensors have further advanced the capability to identify and reduce waste, particularly in large-scale projects (Smith & Doe, 2020).

DIGITAL MONITORING

Advancements in digital monitoring technologies, such as Global Positioning Systems (GPS) and On-Board Instrumentation Systems (OBIS), represent significant strides in construction management. GPS technology, known for its autonomous operation and real-time data provision, is crucial for monitoring equipment effectively on large-scale construction sites, facilitating better resource management and operational efficiency (Pradhananga & Teizer, 2013). OBIS complements GPS by monitoring mechanical conditions and operational parameters to optimize the productivity of heavy equipment, addressing issues such as equipment idle times and inefficient resource use, critical in projects like the IKN 3A Toll Road (Alshibani, 2015).

METHODOLOGY

The methodology of this study systematically investigates the impact of digital monitoring on enhancing lean construction practices within the Section 3A Toll Road project in the middle of the project (August - October). Our approach combines qualitative and quantitative data to provide a comprehensive understanding of the role digital monitoring plays in waste reduction and process optimization. The research commences with identifying waste through both conventional and digital monitoring techniques to provide continuous improvement. Conventional monitoring serves as a baseline for comparison, while digital monitoring, enabled by a real-time dashboard, allows for a more detailed performance analysis and recognition of dominant waste streams. A comparative analysis between traditional and digital monitoring methods is conducted to evaluate their efficacy in waste identification and reduction. The digital monitoring system, featuring a dynamic dashboard, offers real-time insights and performance metrics that facilitate a continuous improvement cycle. Lean construction tools such as current state value stream mapping (VSM) and Fishbone Diagrams are employed to map out existing workflows and diagnose inefficiencies. This analysis is enhanced through root cause analysis, allowing us to develop targeted countermeasures. A future state VSM then helps to envision improved processes with higher cycle efficiency. The research aims to yield actionable outcomes, including a comprehensive guideline tested and refined through the research process to assist in the implementation of digital monitoring in lean construction & identification of digital monitoring features that contribute to lean construction waste reduction, substantiating the system's effectiveness in improving operational efficiency.

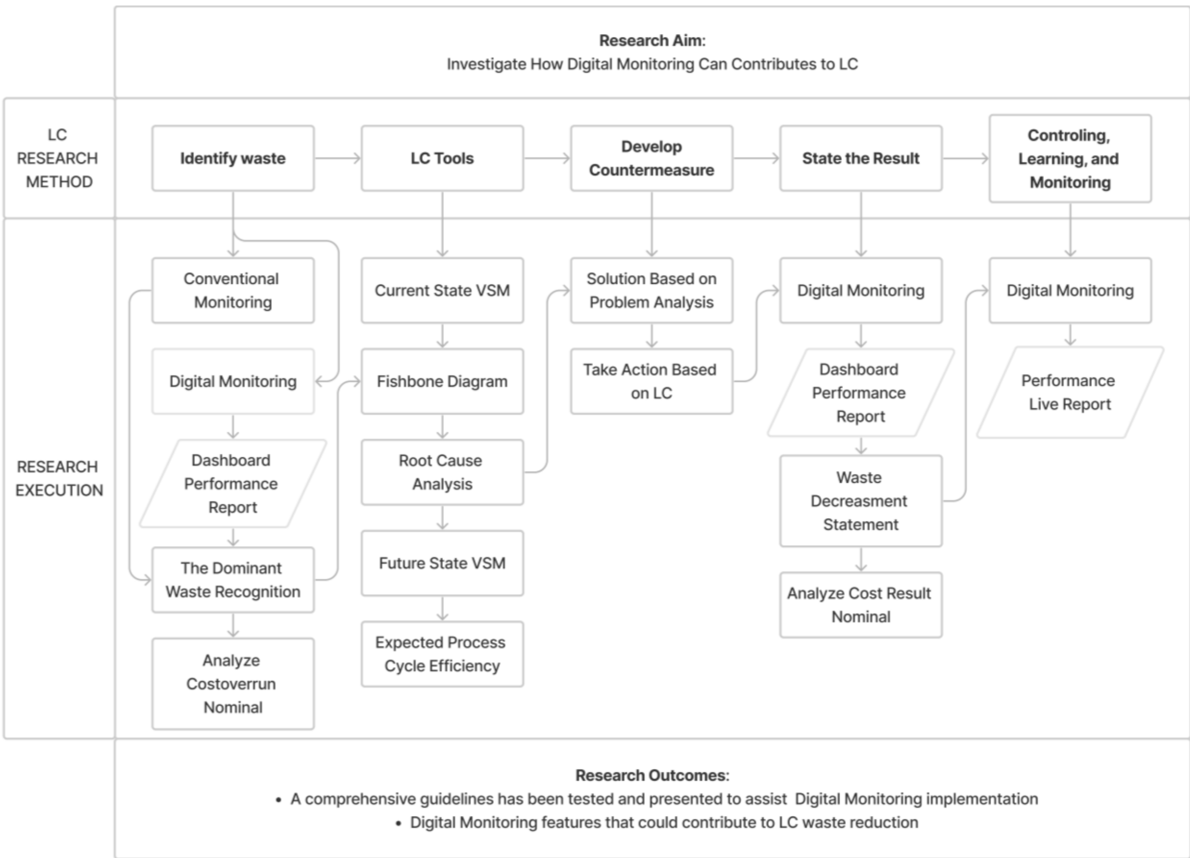

Figure 1: Research Methodology

INITIAL DATA REPORTS COMPARATION

Table 1: Report of Heavy Equipment Timesheet from Conventional Monitoring & Digital Monitoring

Criteria	Month	Idle Time (Monthly)		Driving Times (Monthly)		Total Timesheet (Hour)	Total Cost
		Hour	%	Hour	%		
Conventional Monitoring	Aug	Undetectable		Undetectable		5,880.00	3,80 Bio
Digital Monitoring	Sept	3,134.77	*55.28%*	2,267.12	44.72%	5,401.88	3,48 Bio

The comparative analysis depicted in Table 1 substantiates the advantages of digital over conventional monitoring in evaluating operational activities. In August, conventional methods failed to capture idle and driving times, which stands in sharp contrast to the following month, September, where the digital monitoring system was able to precisely quantify idle time at 3,134.77 hours. This accounted for 55.28% of the total timesheet, surpassing the driving times, which were 44.72% or 2,267.12 hours. The significant proportion of idle time, outstripping active operation, signals a pressing concern for resource wastage, potentially caused by extensive queuing during excavation tasks. Corroborating field observations confirmed these inefficiencies, particularly the protracted waiting periods of machinery, which not only diminish productivity but also elevate operational costs, as indicated by the total cost of IDR 3,487,472,454.74. Of this amount, approximately IDR 1,927,874,772 is attributed to waste. The implementation of digital monitoring thus emerges as a pivotal tool for operational management and cost reduction, providing a clear path to mitigate inefficiencies and optimize resource allocation.

LEAN CONSTRUCTION TOOLS IMPLEMENTATION

CURRENT STATE MAPPING

Advancing from the initial data capture through digital monitoring, applying the Lean Construction methodology to dissect and understand inefficiencies. The deployment of Value Stream Mapping (VSM) is pivotal in this phase, as it provides a visual representation of the current state of operations, laying bare the flow and accumulation of waste. By charting each step in the excavation and construction process, VSM helps us pinpoint where delays occur, where resources lie idle, and where processes diverge from the ideal lean workflow. The Value Stream Mapping (VSM) applied to the Section 3A Toll Road project’s earthwork stages has offered us a granular view of the project's current workflow and efficiency. Based on Figure 2, That illustrates the sequence of earthwork activities for every 100 meters of the construction project, encapsulating the flow of operations from excavation to compaction. The process commences with mobilization of heavy equipment, taking half a day, leading to the excavation phase, which has a value-adding duration of 4 days and a cycle time of 7 days. Subsequent dumping activities contribute 3 days of value-adding and a cycle time of 4 days, followed by grading with 3 days of value-adding and a 5-day cycle time. The final compaction step culminates the sequence with a value-adding time of 5 days and the longest cycle time of 8 days. This VSM, part of a broader project spanning 13.4 km and scheduled for 365 days, is overseen by a project manager conducting daily follow-ups and weekly progress updates. The visualization indicates a total lead time of 28 days for the earthwork process, distinguishing between 15.5 days of value-adding work and 12.5 days potentially available for lean improvement, underscoring the significant opportunity for enhancing operational efficiency and reducing waste.

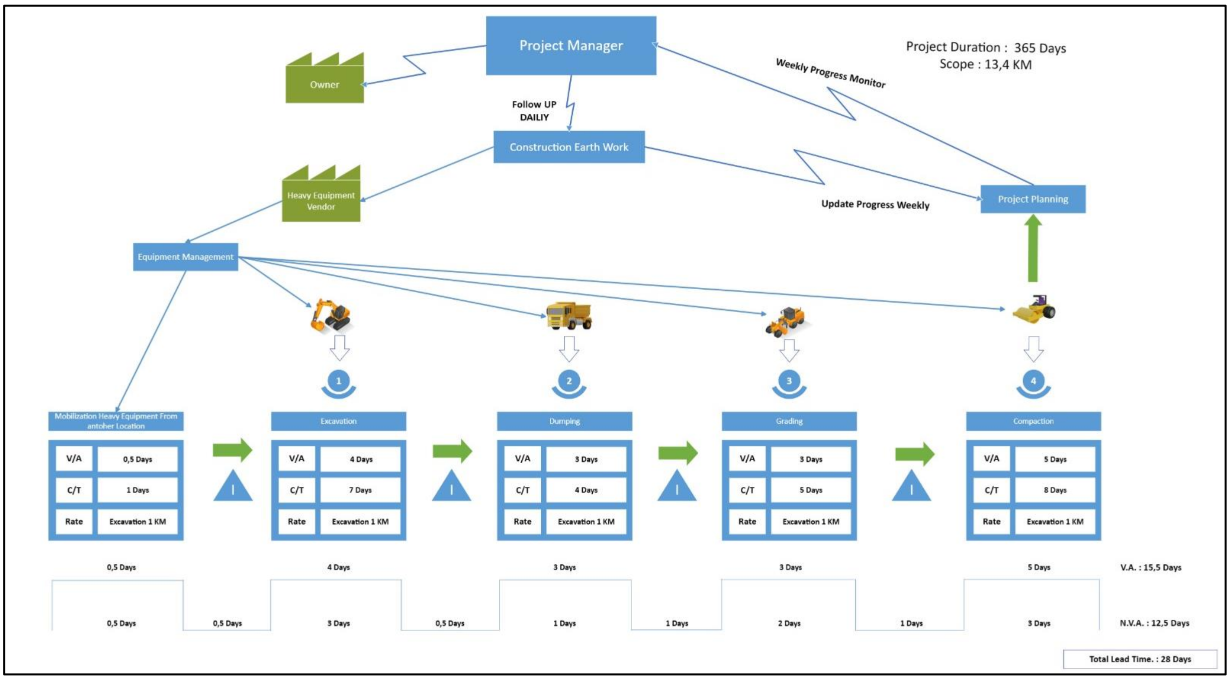

Figure 2: Current State VSM Diagram

With the current state now analyzed through VSM, we shift our attention to the causes of the identified waste. This sets the stage for the Fishbone diagram analysis, which will explore the systemic reasons behind the inefficiencies and pave the way for developing actionable strategies for waste reduction

Fishbone Diagram and Root Cause Analysis

The Fishbone analysis is expected to provide a structured investigation into the complexities of project delays and inefficiency, offering the next critical layer of understanding necessary for implementing Lean Construction principles effectively. In the comprehensive Fishbone analysis conducted for the Section 3A Toll Road project based on Figure 3, systematic exploration of root causes across categories methods, materials, machine, manpower, measurement, and environment has revealed key inefficiencies impacting the project.

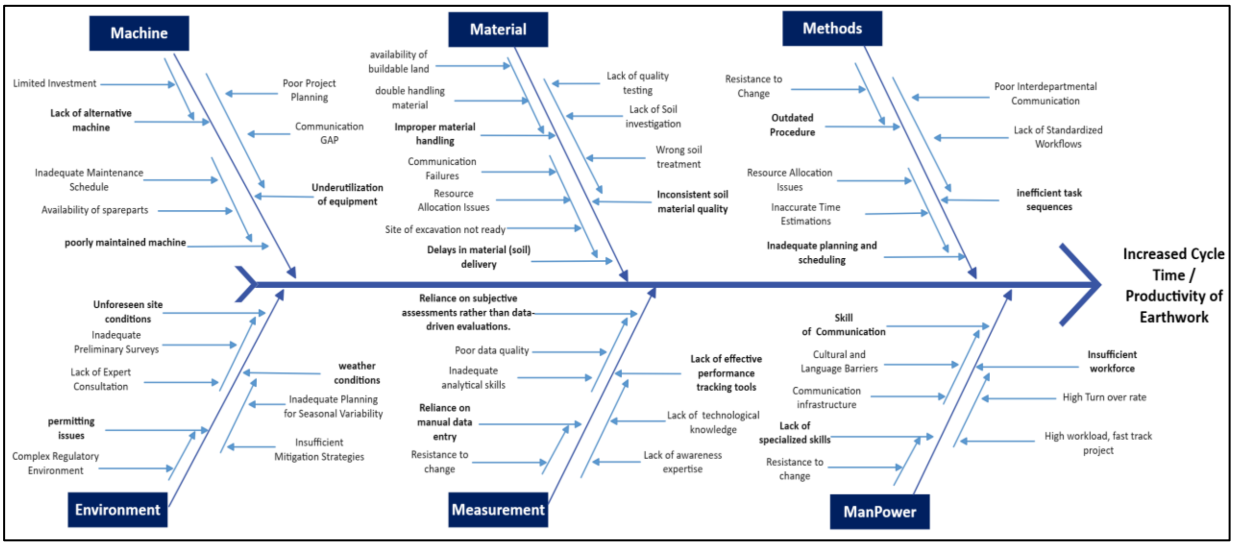

Figure 3: Fishbone Diagram

Based on the Fishbone analysis derived from field reports, several significant issues frequently arise across different categories. Within Methods, the main problems identified include planning and scheduling processes that are inadequate, lacking in detail, and not applicable as field references. For Materials, the soil often used cannot be utilized for earth filling because it does not meet the required criteria. In terms of Machinery, there is a lack of maintenance planning and coordination, leading to significant downtime with many machines remaining idle. Regarding Manpower, there is a substantial communication gap between field staff and management office personnel. Measurement issues persist due to reliance on manual measurement and monitoring systems, resulting in inaccurate data. In the Environment category, the complexity of obtaining excavation permits at the project's commencement poses challenges. Based on the results presented in Table 2, root causes have been categorized and ranked according to the frequency of occurrences over the past two months and the extent of their impact, as discussed in weekly meetings. This was done during periods of both conventional monitoring and digital monitoring. Subsequently, these root causes have been prioritized to determine which issues are most urgent and need to be addressed immediately.

Table 2: Top Root Causes by Frequency and Impact to Productivity

Category	Root Cause	Waste Category	frequence (2 month)	Impact
Methods	Resources Allocation Issue	Waiting, Motion	35 cases	Major
	Schedule not suitable with real condition on site	Waiting, Motion	40 cases	Major
Material	Wrong soil treatment	Defect	12 cases	Major
	lack of soil investigation	Defect, Motion	15 cases	Major
	Double handling material	Transportation, Motion	18 cases	Major
Machine	Availability of spareparts	Waiting	9 cases	Major
	inadequate maintenance schedule	Defect	28 cases	Major
Man Power	Miss coordination between field coordinator	Waiting, Motion	48 cases	*Severe*
Measurement	lack of tecnological knowledge	Non – Utilized Talent	8 cases	Major
	lack of awareness expertise	Non – Utilized Talent	8 cases	Major
Environment	Insufficent mitigation strategies for weather condition	Waiting, Defect	10 cases	Major
	Inadequate planning for seasonal variability	Waiting, Defect	10 cases	Major

COUNTERMEASURE DEVELOPMENT

To effectively address the major root causes identified in our analysis, we have developed and evaluated targeted solutions aimed at preventing ongoing issues and mitigating cost escalations. Table 3 outlines how these challenges were addressed using Lean Construction concepts. By implementing strategic actions grounded in Lean Construction methodologies, we aim to enhance operational efficiency and control project costs more effectively.

Table 3: Solution Based on Lean Approach

Root Cause	Solution
Resources Allocation Issue	Collaborate with the scheduling, procurement, and equipment departments to ensure that resources are prepared in accordance with the planned requirements. This preparation should be informed by the outcomes of previous productivity evaluations. Additionally, involving field coordinators in discussions about heavy equipment needs is essential. Together, develop a more comprehensive pull planning schedule that incorporates insights from all levels of the project team.
Schedule not suitable with real condition on site	Engage with key stakeholders including schedulers, procurement staff, equipment managers, field coordinators, foremen, and vendors. By facilitating a comprehensive discussion among these parties, we aim to develop a new, more dependable Last Planner System. This revised planning approach will serve as a fresh benchmark for ongoing schedule monitoring and evaluation, ensuring that all project activities are aligned and optimized for maximum efficiency.
Wrong soil treatment	Initiate further discussions with planning and design consultants to resolve the issues arising from differences between actual soil conditions and initial design specifications. It's imperative to quickly determine suitable soil treatment solutions to prevent heavy equipment from remaining idle while waiting for decisions.
Lack of soil investigation	Undertake a comprehensive reassessment of the soil conditions and quickly communicate the results to the planning consultants. This will ascertain whether the excavated soil meets the requirements for reuse as fill material or if there is a need to import soil from an external source.
Double handling material	Develop a detailed work plan for excavation and backfill activities, ensuring that every excavation task has a predefined disposal area to prevent inefficient practices such as double handling. Utilize weekly Last Planner System (LPS) planning to strategically sequence the excavation activities, coordinating which sections are to be excavated first and confirming the availability of designated backfill locations.
Availability of spareparts	Develop a procurement strategy for frequently replaced spare parts informed by the Last Planner System (LPS) and pull planning analyses. Should spare parts be unavailable, formulate a contingency plan to borrow heavy machinery from other sites temporarily. This plan requires a reassessment of the project timeline to accommodate machinery availability and prioritizes critical areas to prevent project delays.
Inadequate maintenance schedule	Begin scheduling routine inspections for heavy machinery, particularly during holidays, to ensure that the equipment operates at its maximum efficiency during working periods. This strategy minimizes technical issues with each piece of heavy machinery during operations and mitigates the cost of repairs by addressing potential problems early. Regular maintenance checks can prevent significant downtime and expensive fixes.
Miss coordination between field coordinator	Implement daily coordination meetings between on-site workers and field managers to effectively manage and optimize the utilization of available resources. Use these sessions to track the status of equipment and identify any operational constraints, ensuring that any deficiencies or challenges are immediately reported to the engineering and procurement teams.
Lack of tecnological knowledge	Deploy programs to rapidly and effectively upskill workers on new technologies, enhancing their proficiency and adoption.
Lack of awareness expertise	Develop a skills matrix to identify expertise gaps and implement cross-training programs to broaden the skill sets of the workforce

Table 3 (continued): Solution Based on Lean Approach

Root Cause	Solution
Insufficent mitigation strategies for weather condition	Develop comprehensive risk management plans that include specific mitigation strategies for adverse weather, integrating contingency plans into the project schedule.
Inadequate planning for seasonal variability	Create a construction schedule by integrating historical weather data provided by the local meteorological agency. This data should be carefully analyzed to anticipate potential weather disruptions over the upcoming month. By aligning this information with the project timelines, you can adjust the work schedule proactively to factor in likely weather conditions.

The solutions derived from the Lean approach analysis have been integrated into the current state map to develop a comprehensive future state map. This map projects substantial enhancements in the productivity of earthwork operations and aims to significantly reduce waste. A key focus is on minimizing idle time for equipment, thereby streamlining operations, and improving overall project efficiency. This strategic integration highlights the potential for tangible improvements in project execution and cost-effectiveness.

FUTURE STATE MAP

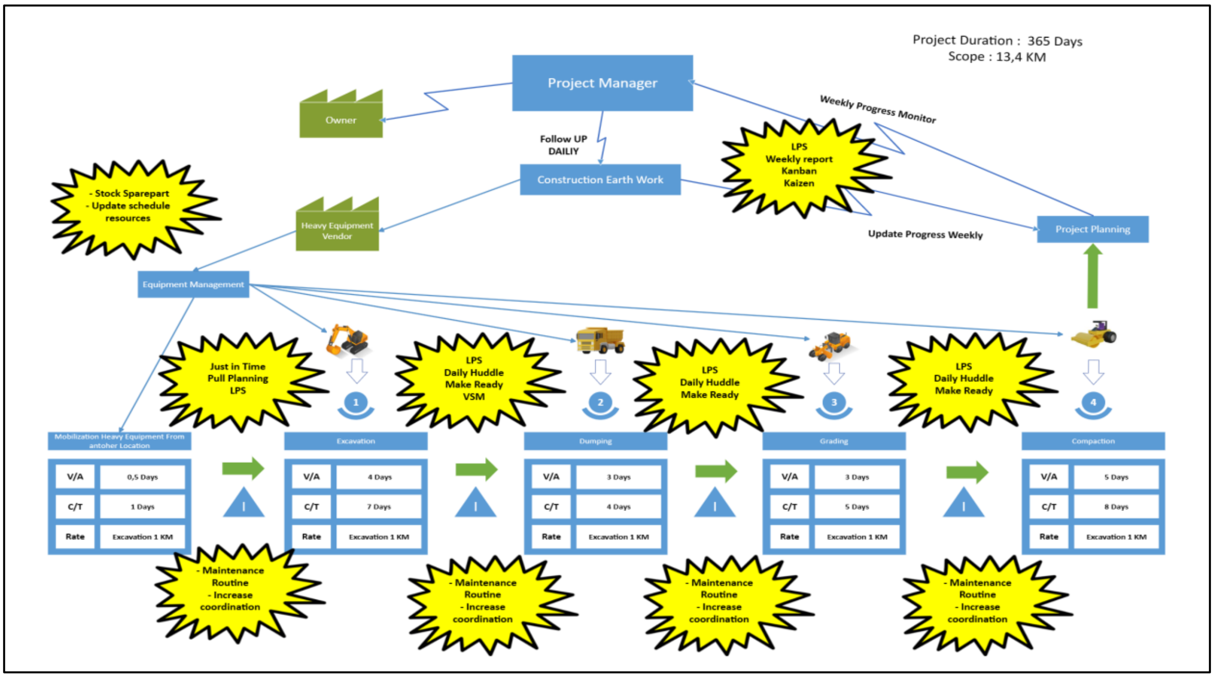

Figure 4: Future State Map

The Future State Map for the Section 3A Toll Road project based on Figure 4 reflects an adoption of Lean practices, integrating lean tools to align resource allocation and task execution with real-time needs. Maintenance is scheduled more effectively with improved coordination to minimize equipment downtime. Weekly reviews incorporate continuous improvement through Kaizen, allowing the project to adapt quickly to changes. A focus on increasing coordination between key person, also maintaining an updated inventory for spare parts and adjusting resource schedules is essential to prevent equipment idleness and boost productivity. This map sets a new standard for operational efficiency by embedding Lean methodologies into the project's processes. This streamlined approach is anticipated to increase non-value-added activities and diminish waste time, setting a new benchmark for operational efficiency and project performance.

DATA REPORT AND RESULTS

After thorough evaluations, the following month saw the deployment of the designed solutions and the Future State Map that had been previously analyzed. Discussions on root cause analyses and corresponding solutions took place in weekly meetings, with updates being made to the Last Planner System. These meetings, attended by representatives across all levels, especially the last planners on-site, were crucial for unifying the understanding and ensuring a coordinated approach to field operations for the next month. Table 4 in the subsequent section will detail the outcomes of applying the Lean tools to the digital monitoring system, showcasing the tangible improvements, notably in increased driving time, indicating a stride toward enhanced operational efficiency.

Table 4: Data Report Recap

Criteria	Month	Idle Time (Monthly)		Driving Times (Monthly)		Total Timesheet (Hour)	Total Cost
		Hour	%	Hour	%		
Manual	Aug	Undetectable		Undetectable		5,880.00	3,800,428,500.00
Digital Monitoring Without Lean Improvements	Sept	3,134,77	55.28	2,267.12	44.72	5,401.88	3,487,472,454.74
Digital Monitoring After Lean Improvements	Oct	1,237.78	18.26	5,589.81	81.74	6,827.59	4,450,175,157.25

Efforts to optimize the capability of heavy equipment by allocating it led to a total timesheet (hours) increase of about one thousand hours, resulting in a total cost increase to Rp. 4,450,175,157.25. Table 5 shows that the driving times before the implementation of lean construction were only at a percentage of 44.72%, unlike after the implementation of lean construction, which reached a percentage of 81.74% driving times. Additionally, from the recap table above, a comparison of idle time percentage between Digital Monitoring After Lean Improvements and Digital Monitoring Without Lean Improvements reveals a percentage decrease from 55.28% to only 18.26%.

Table 5: Waste Improvements

Criteria	Without Lean Improvements	After Lean Improvements	Deviation (Waste Improvements)	Info
Idle Time (Hour)	3,134.77	1,237.78	*-1,896.98*	Idle Time Decrease, Driving Time and Productivity Increase
Waste (%)	58.03%	18.13%	*-39.90%*	Waste % Decrease, Efficiency Increase 39%
Waste Cost / Idle Cost (Rp)	$ 124,787.00	$ 49,745.00	*-$ 75,041.00*	Waste Cost Decrease, Turn into Cost Productivity

The implementation of lean construction based in Table 5 on reducing waste and increasing value, is proven by the impact of corrective actions that have been conducted. There is a decrease in idle time, coupled with an increase in driving time. In other words, there has been a 39% increase in efficiency due to the decrease in waste. This change transforms costs that were previously used for waste into costs that are now used for productivity.

CONTROL AND MONITORING

Following the successful implementation of Lean tools and digital monitoring in October, it is imperative to ensure the continued application of these strategies to sustain the improvements achieved. A critical component of this ongoing effort is the deployment of a real-time monitoring dashboard for heavy equipment, utilizing integrated OBS (On-Board Systems) according to Figure 5. This system allows for the continuous measurement of each piece of heavy machinery's performance. The dashboard not only monitors productivity levels of individual equipment but also quickly identifies issues such as equipment breakdowns or idle times. Immediate identification enables a rapid response to apply Lean principles to diagnose and address the root causes of any discrepancies. This proactive approach fosters a culture of continuous improvement, or Kaizen, ensuring that the project continually adapts and evolves to improve efficiency and effectiveness.

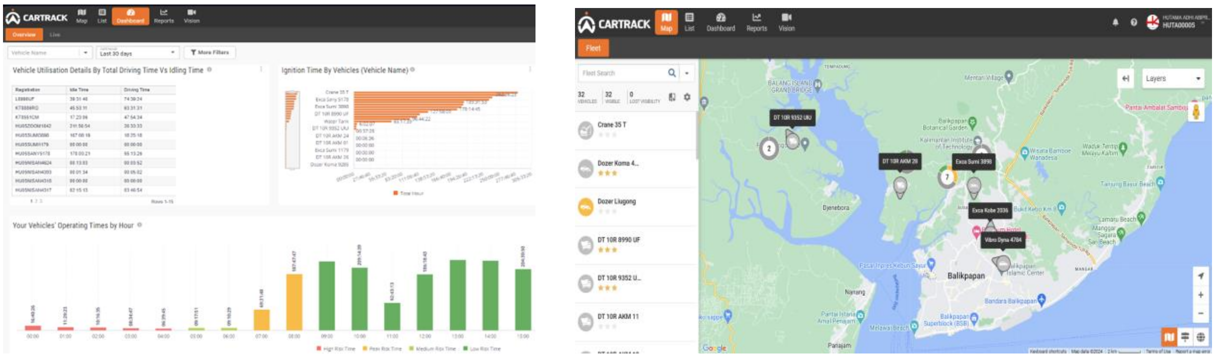

Figure 5: Dashboard in the Digital Monitoring by Cartrack

DISCUSSION

Following the significant improvements detailed in Tables 4 and 5—where driving times increased from 44.72% to 81.74% and idle times decreased from 55.28% to 18.26%—it is evident that Lean construction tools can illuminate hidden operational issues that regular meetings might miss. These tools, integrating with digital technologies, provide the project team with enhanced capabilities to identify and address inefficiencies promptly. future research could focus on several impactful areas. Quantitative assessments could explore the environmental impacts, particularly in terms of reduced fuel consumption and carbon emissions due to enhanced equipment efficiency. A cost-benefit analysis would be valuable, especially considering the reported increase in total project costs to USD 274,393.00 alongside a 1000-hour increase in total timesheet hours. Further studies might include longitudinal tracking to evaluate the long-term sustainability of these improvements, the integration of predictive analytics to optimize efficiency further, and an investigation into workforce adaptation to these changes.

CONCLUSIONS

The primary objective of this paper was to investigate the impact of digital monitoring on waste identification and management in Lean Construction (LC). The findings indicate that digital monitoring is instrumental in detecting and reducing waste, providing teams with the instant data necessary to implement rapid changes for waste minimization. Furthermore, it facilitates effective control measures to sustain improvement efforts and promotes continuous enhancement of processes. The application of digital monitoring in LC delivers a significant advantage by allowing for the prompt identification of inefficiencies that manual methods may overlook. By integrating Lean principles, the approach systematically highlights waste and its root causes, and pinpoints specific equipment that adds to inefficiencies. The analysis demonstrates that digital monitoring enables a structured and precise evaluation process, enhancing the capability to identify underperformance that is not readily apparent through conventional Lean practices. The research has successfully shown that with the aid of digital monitoring, underutilized heavy equipment can be quickly identified, leading to the reallocation of value-added time previously lost to idle periods. It quantifies waste accurately and in real-time, substantially improving the effectiveness and productivity of construction work, as well as facilitating a more informed performance evaluation of individual machinery. The results of this study confirm that the integration of digital monitoring into LC practices fulfills the research aim by substantiating its role in improving the efficiency and reducing the waste of construction projects.

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A REVIEW OF THE ROLE OF DIGITAL TWIN APPLICATIONS FOR WATER SUSTAINABILITY

Mehwish Qureshi[1], Zhenan Feng[2], Vishal Kumar[3], Ruggiero Lovreglio[4] and Mohammed Abdelmegid[5]

ABSTRACT

This paper investigates the convergence of Digital Twin (DT) applications, Lean Construction (LC) principles, and water sustainability. The DT concept, which originated in the 2000s, has gained momentum across various industries. Yet, integrating DT into the construction industry, particularly in water systems, is at an early stage. A comprehensive literature review is conducted to explore the potential benefits of DT in water management, aligning with the principles of LC.

The exploration reveals the integration of DT into diverse water systems, encompassing distribution networks, sewage systems, river and lake management, dam systems, and wastewater treatment plants. The identified benefits extend beyond operational efficiency to water sustainability, addressing climate change adaptation, disaster risk reduction, and resource optimization. The study also explores the tools and technologies employed in DT applications, emphasizing their alignment with LC principles of reducing waste and fostering collaboration.

Nevertheless, limitations exist in the identified tools and technologies, such as data interoperability, computational complexities, and data reliability, underscoring areas for future research to enhance DT application effectiveness. Despite these limitations, the synthesis of DT, LC, and water sustainability holds promise for transforming water resource management.

This study offers guidance on achieving efficient, sustainable, and collaborative water management across various contexts. It provides essential insights for scholars, practitioners, and policymakers, emphasizing the importance of policy support and technological innovation to overcome current challenges. Furthermore, it suggests avenues for future research to evaluate the long-term effects and enhance the effectiveness of DT systems.

KEYWORDS

Digital Twin, Water Management, Water Sustainability, Lean Construction

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INTRODUCTION

The inception of the Digital twin (DT) concept dates back to early 2000 when Professor Michael Grieves introduced it during a Product Life cycle Management Course at the University of Michigan (Grieves, 2005). Since its introduction, DT has gained substantial traction, becoming a cornerstone in various industries. According to Kritzinger et al. (2018), the core of DT lies in the cyber-physical connection, termed the Digital Thread, enabling bidirectional communication between physical and digital spaces.

DT adoption in the construction industry is at a nascent stage; however, it is highly regarded for its significant benefits. It holds the potential to diminish waste through effective decision-making and analysis facilitated by real-time monitoring and control. DT also offers a comprehensive solution that harmonises lean thinking, computing, and monitoring technologies within the construction sector (Altan & Işık, 2023). This technological advancement is in line with the principles of LC, an approach that underscores efficiency, collaboration, and waste reduction throughout the construction process. The integration of DT technology into LC practices can significantly amplify operational efficiency by fostering collaboration among stakeholders and streamlining processes.

Indeed, while lean construction principles may not directly connect to water sustainability projects, their integration into water systems can bring notable benefits. By applying LC principles to water management, efficiency can be heightened, waste reduced, and overall sustainability in water usage improved. Yang et al. (2021) emphasised the need for innovative measures within a diverse social framework, especially those integral to water. Achieving water sustainability entails efficient use of clean water and judicious reuse and treatment of rainwater and sewage water for various purposes. In recent years, water utility planning, operation, and management have seen rapid digitalization and the use of various digital tools to achieve water sustainability. DT, as a transformative tool, is gaining prominence in water infrastructure, water treatment, and networking processes (Matheri et al., 2022).

Notably, prior scholarly works predominantly discuss DT applications in the context of management and operational functions rather than explicitly addressing their relevance to water sustainability. Nonetheless, it is imperative to acknowledge that efficient and intelligent operational and managerial practices significantly contribute to the broader goal of achieving water sustainability. This study endeavours to bridge this scholarly gap by conducting a comprehensive literature review encompassing water systems and their associated DT applications using lean principles.

To guide this exploration, specific research questions were formulated:

1. What water systems have been studied, tested, or evaluated with DT applications?
2. What are the benefits of those DT applications to water sustainability?
3. What are the tools and technologies applied in those DT applications?
4. What are the challenges and barriers of applying these DT applications to water systems?

METHODOLOGY

Research methodology forms the backbone of any study, providing a structured plan that guides the investigation from start to finish. Conducting a literature review is a crucial approach for acquiring insights into the research topic and grasping the current state of knowledge in the field.

This study employs a systematic literature review approach using the PRISMA framework as outlined by Khan et al. (2003), and utilizes the Scopus database as the primary research platform. The literature review encompassed both journal articles and conference papers. The search keywords were “digital twin” OR “building information modelling” OR BIM AND water. We included building information modelling and BIM because these terms are often used interchangeably with DT, ensuring a comprehensive search for relevant literature and studies on the topic.

The second part of the search keywords is: “water”. This search strategy encompassed a broad scope by including "water" rather than "water sustainability". This deliberate choice aimed to capture a wide array of literature concerning water management and its relevance to DT. The keywords were applied to search for titles, abstracts, and keywords.

The search was executed in September 2023, resulting in 1142 initial findings retrieved from Scopus. Using the Preferred Reporting Items for Systematic Literature Reviews and Meta-Analyses (PRISMA) approach (Page et al., 2021), the results were refined as illustrated in Figure 1. Firstly, 33 duplicates (e.g., the same DT application was published in different sources) were removed. Secondly, articles were excluded based on the following criteria: (1) The article has no relation to water and DT. (2) The proposed application in the article was not designed for the water sector. (3) The article proposed theoretical frameworks without practical applications. (4) The article was not in English.

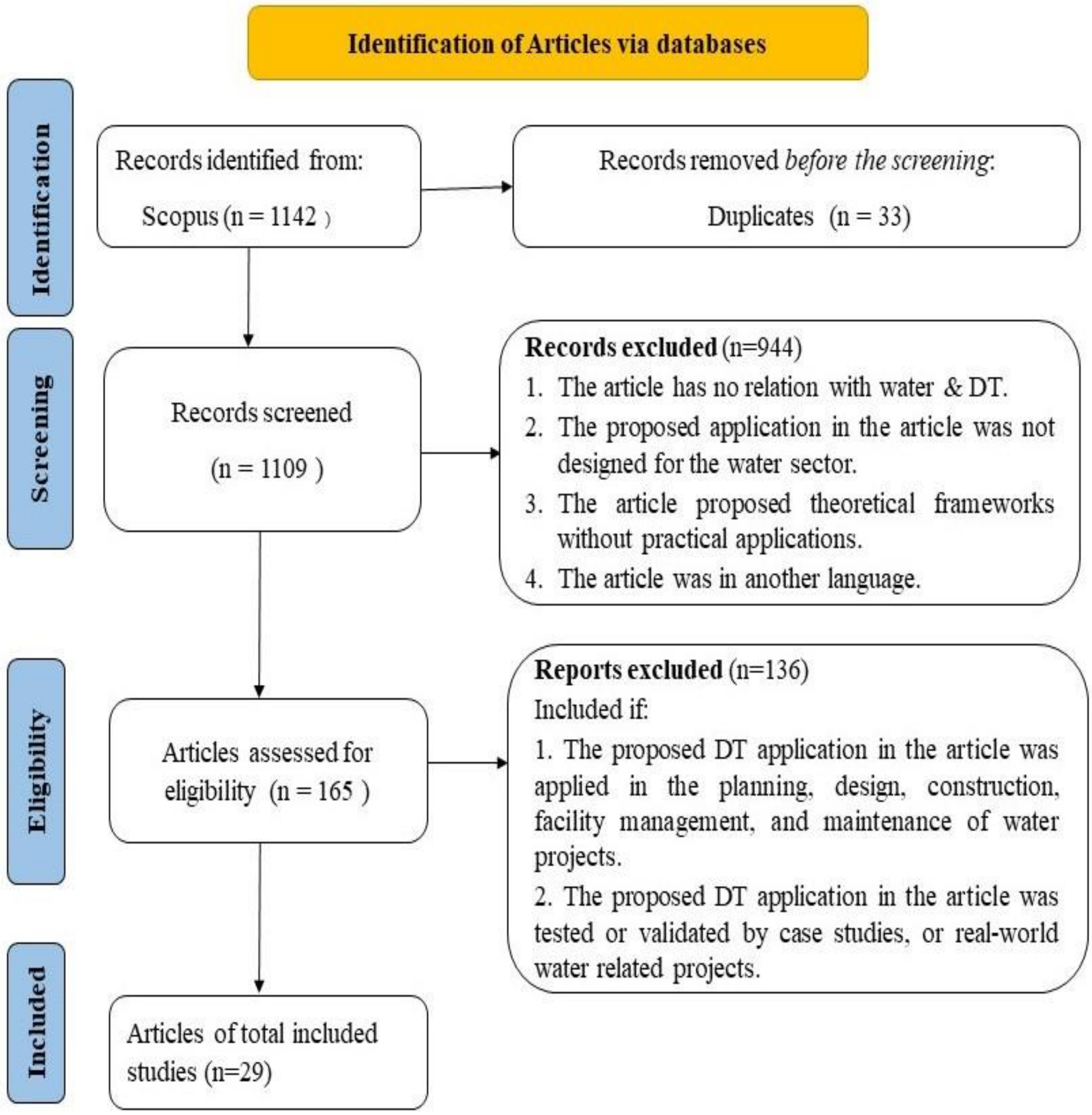

Figure 1 The PRISMA Workflow

During this step, 944 articles were excluded, leaving 165 articles for further analysis. Finally, we scrutinized the full text of these remaining articles, applying the subsequent inclusion criteria: (1) The proposed DT application in the article was applied in the planning, design, construction, facility management and maintenance of water related projects. (2) The proposed DT application in the article was tested or validated by case studies, or real-world water related projects.

This process resulted in 29 articles meeting the eligibility criteria for inclusion in this literature review. Among them, there were 18 journal and eleven conference papers, all published between 2017 and 2023 (Figure 2).

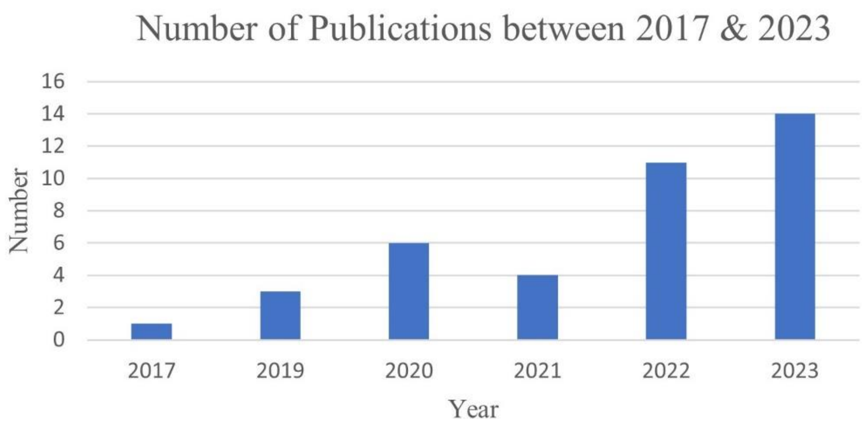

Figure 2 Number of Publications

RESULTS

This study examines the eligible articles to discover the water systems that have been equipped with DT, the benefits to water sustainability, the tools and technologies employed in DT applications, and the challenges and barriers of applying DT.

WATER SYSTEMS

The integration of DT technology into various water systems aligns with the principles of LC, emphasizing efficiency, sustainability, and continuous improvement. These systems encompass water distribution networks, river and lake management systems, dam management systems, sanitary sewage systems, water resource recovery facilities (WRRFs), wastewater treatment plants (WWTP), groundwater management systems, drainage systems, and wetlands (Figure 3).

Conejos Fuertes et al. (2020) explored DT for city management in Valencia, Spain, demonstrating a commitment to lean principles by enhancing daily operations, strategic planning, and responses to unplanned events. Ramos et al. (2023) suggested a DT application for a pumping system in Sta Cruz, targeting a decrease in water demand volume and an increase in renewable energy generation, aligned with sustainable development goals (SDGs). This reflects a lean approach towards resource efficiency.

Fargas and Cornellà (2023) addressed a DT application in managing water distribution pipes for asset management purposes, highlighting the challenge faced by the Tarragona Water Consortium (Consorci d'Aigües de Tarragona - CAT). This application aligns with lean principles, addressing specific challenges and streamlining asset management processes.

Another application of DT towards river, lake, and dam management, presented by Wang et al. (2022), emphasizes lean principles by upgrading conventional water systems to enhance efficiency and reduce energy consumption in the Weihe River Basin (WRB) in Shaanxi province, China. Additionally, Park and You (2023) introduced an innovative DT platform for dam and watershed management, enabling real-time data utilization for flood response and water resource management for Sumjin Dam and its river water system in Korea. This proactive approach embodies one of the principles of LC, which leverages efficient response to environmental challenges.

Moreover, the DT concept was employed to mitigate the impacts of climate change on groundwater levels in distinct water systems. Henriksen et al. (2023) presented a Danish case study introducing the Hydrological Information and Prediction Digital Twin (HIP DT) for Denmark, reflecting a lean focus on climate change adaptation, water security management, and disaster risk reduction.

Three papers specifically focused on wastewater treatment plants and water resource recovery facilities. Bellandi et al. (2022) investigated the DT of an advanced wastewater treatment plant in the Netherlands, aimed at improved performance and water safety. In the context of lean management, this approach enhances operational effectiveness.

Melo et al. (2019) studied the Sanitary Sewage System of Piumhi, a city in Brazil. They applied the framework of City Information Modelling (CIM), a management model leaning on preventive actions and a decision-making process based on accurate information. Payne et al. (2023) used Machine Learning (ML) for surrogate groundwater modeling in Barbados (Caribbean region), showcasing a lean use of technology for efficient groundwater management.

Moving towards natural systems, Ruangpan et al. (2023) explored smart solutions and DT to manage flooding and irrigation systems in the Rangsit Area, Thailand, to enhance urban resilience. Similarly, the environmental improvement project in the Green Water Wetland in the Yangtze River, China, by Huang et al. (2023), integrates technology for lean water system management, emphasizing connectivity, hydrodynamics, and modeling for analysis and verification.

The exploration of DT water management extends to buildings, with Batista et al. (2023) designing a specialized framework for optimizing water efficiency in the Central Market of Belo Horizonte, Brazil. Yang et al. (2021) devised a framework employing advanced technology and algorithms for maintaining water dispensers within campus settings. These frameworks showcase the potential for enhanced water conservation and management, which is a lean approach contributing to sustainable water practices in constructed spaces.

By aligning with lean principles and focusing on continuous improvement, DT technology not only addresses current water management challenges but also paves the way for innovative solutions that could significantly impact resource efficiency and sustainability in both natural and constructed environments.

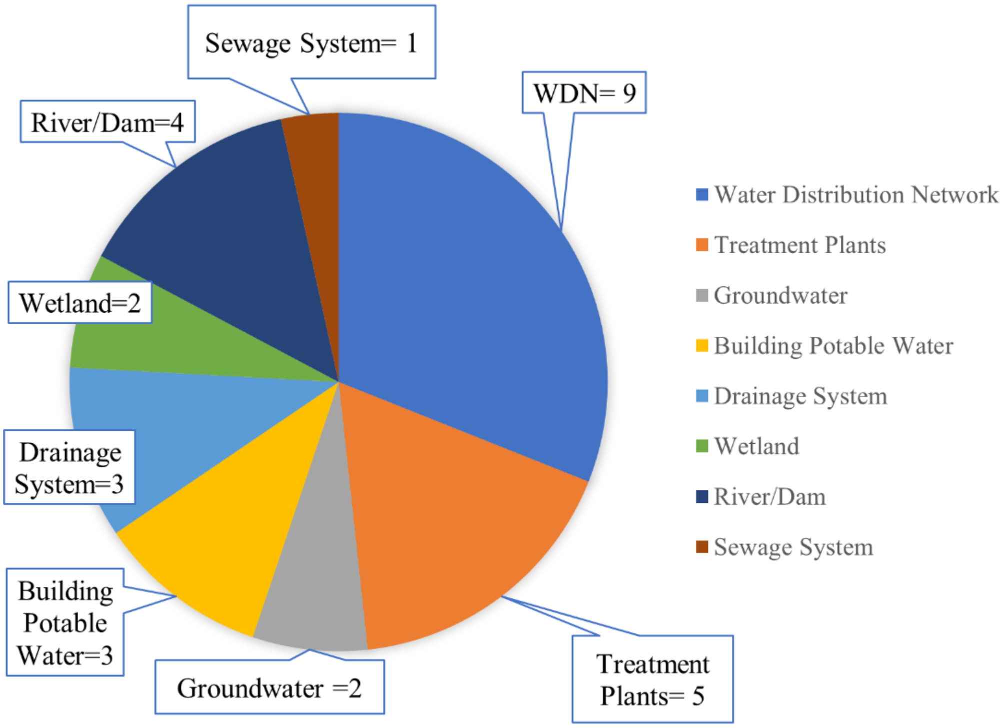

Figure 3 Digital Twin Publications: Water Systems Classification

BENEFITS TO WATER SUSTAINABILITY

The exploration of DTs across diverse water systems presents a multitude of benefits that align with water sustainability and resonate with LC principles. They enhance resilience through proactive monitoring, anticipating, and mitigating challenges. DTs also contribute to sustainability, preserving water quality and promoting long-term sustainable development objectives. For instance, Conejos Fuertes et al. (2020) showcased how DTs contributed to efficient water resource management in city operations, daily activities, and strategic planning. These applications embody LC's emphasis on minimizing waste and optimizing processes.

Similarly, Fargas and Cornellà (2023) highlight the role of DTs in asset management that exemplifies LC commitment to effective asset utilization for streamlined project delivery. DT applications in preserving water quality, flood prevention, and mitigation align with sustainable water practices and LC principles of minimizing inefficiencies (Park & You, 2023; Wang et al., 2022). Moreover, DTs play a pivotal role in adapting to climate change and reducing the risks associated with disasters, as demonstrated by Henriksen et al. (2023). The application of DTs in this context reflects both LC's focus on adaptability and the broader goal of sustainable water resource management.

Treatment plants optimization presented by Bellandi et al. (2022); Remigi et al. (2022) showcase the DT's capacity to enhance overall performance, aligning with LC's principles of continuous improvement. City-specific water solutions proposed by Ramos et al. (2023 a); Ramos et al. (2023 b) reflect a focus on sustainability, renewable energy, and system efficiency. These applications correspond with LC's goal of optimizing resources and improving overall system efficiency.

The use of DTs in groundwater management under changing climates (Payne et al., 2023) aligns with LC's adaptive project management approach. Additionally, the optimization of urban water cycles using Cyber-Physical Systems mirrors LC's emphasis on efficiency (Sun et al., 2020). Smart solutions for flooding and irrigation proposed by Huang et al. (2023); Ruangpan et al. (2023) emphasize resilience and integration of nature-based solutions, aligning with LC's focus on adaptability and resilience in the face of challenges.

Finally, the applications of DTs in buildings by Batista et al. (2023); Yang et al. (2021) optimize water efficiency within commercial structures and campus settings, aligning with LC's principles of efficiency and resource optimization. In summary, the highlighted benefits emphasize the versatility of DT applications, making substantial contributions to both LC practices and sustainable water management. DT technologies significantly contribute to water sustainability, closely aligning with LC principles by optimizing resource use, enhancing resilience, and supporting sustainable development through a wide range of applications across water systems management and infrastructure efficiency.

TOOLS AND TECHNOLOGIES

The eligible articles introduced various tools and technologies employed for developing and implementing DT applications in water management (Table 1). Many of these tools, readily available in the market, have been integrated into new platforms or adapted for use in existing systems to facilitate integration and management.

Conejos Fuertes et al. (2020) extensively detailed the tools and technologies applied in managing the drinking water management system of Valencia, Spain, with the GO2HydNet serving as a foundational platform. The system seamlessly integrated the hydraulic model with various information sources, like Geographical Information System (GIS), Automated Meter Reading (AMR), Computerized Maintenance Management Systems (CMMS), and field data stored by the Supervisory Control and Data Acquisition (SCADA) system. Specialized algorithms facilitated high-efficiency model construction, exemplified by the creation of a comprehensive model with 32,000 nodes in about a minute.

Ramos et al. (2023) employed similar tools but integrated them into the hydraulic model via Artificial Intelligence (AI) algorithms and Information and Communication Technology (ICT). Conversely, Bonilla et al. (2022) utilized Python libraries to estimate pump speed and derive pressure and flow rate information for non-monitored pipes using EPANET 2.2. Fargas and Cornellà (2023) explored the integration of online monitoring technologies such as Acoustics Fiber Optics (AFO) and electromagnetic pipe inspection in the implementation of DT for the Tarragona Water Consortium (Consorci d'Aigües de Tarragona - CAT).

Distinct tools were utilized for managing rivers, lakes, and dams compared to water distribution networks. For instance, Park and You (2023) utilized the K-Twin SJ platform for dam and watershed management, integrating 3D Geospatial Reality Modelling with Aerial LiDAR Survey & Drone, hydraulic and hydrological simulation models. Qiu et al. (2022) developed a web-based interactive twin platform for watershed management using Virtual Geographic Environment, integrating geospatial data with terrain visualization, unmanned aerial vehicle (UAV) tilt photography, and 3D modeling. Furthermore, real-time video monitoring and water quality data were integrated into a 3D scene, enabling a detailed representation of the area and aiding in precise watershed management.

Henriksen et al. (2023) developed a DK-model employing the MIKE SHE-MIKE Hydro software, simulating various hydrological processes, and supplementing it with machine learning (ML) algorithms for enhanced accuracy. The DT for Water Resource Recovery Facility developed by Remigi et al. (2022) comprised components such as MIKE OPERATION for real-time data, WEST model for simulation, and a user-friendly dashboard for operator control. Melo et al. (2019) proposed a combination of technologies for the operation and maintenance of the sanitary sewage system of Piumhi. He utilized GPS GNSS RTK L1/L2 for high-precision positioning survey and designed the sewage network on AutoCAD Civil 3D and QGis.

Various articles explored groundwater sustainability, irrigation and drainage system behavior, wastewater management, and wetland simulations, utilizing software tools such as FEFLOW, MIKE 11, GAMS with CPLEX solver, and Unreal Engine. Huang et al. (2023)

recommended using BIM & GIS as a communication platform during the construction period, while Batista et al. (2023) proposed AquaBIM, a web-based application integrating BIM-IOT-FM for water sustainability within buildings.

This review highlights the diverse tools and technologies employed across various projects, showcasing the versatility of DT applications in the realm of water resource management. Furthermore, the utilization of AI, ML, and streamlined data integration contributes to the lean principles of reducing waste, enhancing productivity, and fostering collaborative decision-making processes. Notably, Geographical Information System (GIS) emerges as the most prevalent technology across these water management systems, employed for managing, analyzing, and visualizing geographic data. Similarly, Supervisory Control and Data Acquisition (SCADA) systems are widely used for control, monitoring, and analysis purposes.

Table 1 Tools and Technologies

Water System	Platform	Tools and Technologies
Drinking Water Management System Valencia (Spain)	GO2HydNet	Hydraulic Model on EPANET, Geographical Information System (GIS), Automated Meter Reading (AMR), Computerized Maintenance Management System (CMMS)
Dam and Watershed Management-Korea	K-Twin SJ Platform	3D Geospatial Reality Modelling, Aerial LiDAR Survey & Drone, Hydraulic and Hydrological simulation Model
Water Resource Recovery facility (WRRF)-Italy	MIKE OPERATION	SCADA, WEST model
Water Distribution Network Madeira Portugal	Big Data Platform	GIS, Sensors, SCADA, Smart Metring, CMMS integrated in EPANET via AI algorithms
Watershed Environment of Chaohu Lake	Web-based platform using Virtual Geographic Environment	geospatial system, unmanned aerial vehicle UAV tilt photography, 3D modelling, video monitor
Hydrological Information and Prediction (HIP) Model Denmark	SHE-MIKE	Supplemented with Machine Learning (ML) algorithm
Water Management systems Belo Horizonte, Brazil.	AquaBIM	Revit Model, Smart Meters

CHALLENGES AND BARRIERS

he authors of the eligible articles have demonstrated various challenges faced by researchers and practitioners in implementing DT within water systems. These challenges span technical, data-related, organizational, and practical aspects.

Conejos Fuertes et al. (2020) addressed challenges related to GIS data integration and model requirements by developing algorithms, ensuring a seamless blend between spatial data and modeling needs. Notably, their proactive approach involved creating supplementary systems to store crucial data, rectifying errors, and modifying EPANET software. This reflects a sophisticated strategy to overcome technical obstacles and enhance the robustness of DT applications.

Tomic et al. (2022) focused on challenges encountered in city implementation, emphasizing the critical role of accurate data. The authors recognized the importance of addressing data challenges for effective DT application, showcasing a meticulous approach to city-level water system management.

In a distinct scenario, Qiu et al. (2022) identified challenges associated with prolonged computational durations in 3D modeling. Their response involved advocating for accelerated approaches in model computation, demonstrating an understanding of the need for agility and efficiency.

Henriksen et al. (2023) viewed establishing explicit project goals, objectives, and comprehensive plans as prerequisites for implementing DT at a national level, emphasizing the importance of clear objectives and efficient resource utilization. The authors recognized the substantial investment in resources and expertise required for national-level DT implementation, showcasing a holistic and strategic mindset.

Similarly, Melo et al. (2019) encountered challenges in surveying the sanitary sewage system and explored alternative surveying methods. Some studies posed challenges and barriers in applying DT in real-world scenarios. Ramos et al. (2023) faced challenges related to the reliability of data used to develop the DT model. They emphasized the need for accurate data related to system configuration. The authors recognized the crucial role of accurate data in the success of DT applications, highlighting the importance of close collaboration between researchers, designers, and municipal management.

Bonilla et al. (2022) rendered challenges in obtaining monitored data on the relative operating speed of pumps. Payne et al. (2023) addressed calibration limitations in spatial coverage of data and challenges in predicting transient groundwater response. Their approach involved advanced calibration technologies, emphasizing accuracy and efficiency in spatial coverage.

Sun et al. (2020) highlighted the challenge of ensuring effective management of routine interactions among subsystems within efficient computational timeframes. Lu et al. (2023) recognized the challenge of collecting data from the extensive Poyang Lake wetland and focused on optimizing data collection strategies.

In the building context, Yang et al. (2021) emphasized challenges in proposing BIM applications for water dispensers' maintenance. Their acknowledgment of interoperability and staff unfamiliarity showcases an understanding of the importance of improved computerization.

Despite these challenges and barriers, innovative solutions and strategic approaches showcased by researchers underline the critical importance of accurate data, streamlined computations, and clear objectives in advancing DT applications for more effective water systems management.

CONCLUSION

This literature review explores the synergy between DT applications, LC principles, and water sustainability. The analysis of diverse water systems demonstrates that integrating DT with LC fosters efficiency and sustainability. The identified benefits, spanning optimized operations and resource management, resonate with LC principles, showcasing a commitment to waste reduction and collaborative decision-making.

Despite challenges in technical, data-related, organizational, and practical realms, the authors exhibit resilience and innovative problem-solving, aligning with the ethos of LC. This synthesis of DT, LC, and water sustainability holds promise for transformative advancements in water resource management. As the confluence of DT and LC principles evolves, this study provides foundational insights for scholars, practitioners, and policymakers navigating the complex landscape of water systems.

The review underscores the importance of incorporating advanced technologies such as AI, ML, and GIS into DT applications, indicating a move towards more nuanced and interdisciplinary approaches. It suggests the necessity for policy development that encourages sustainable practices and allocates resources to surmount technical hurdles, thereby guiding investments in water management technologies.

Additionally, the review points out existing gaps in DT application, such as data integration and model accuracy, suggesting a direction for future research that focuses on closing these gaps to boost DT system efficiency and reliability. The call for longitudinal studies to evaluate the long-term impacts of DT on water sustainability, system efficiency, and environmental outcomes suggests an avenue for future research that could shape the continuous improvement and scaling of DT applications.

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ENHANCING LEAN CONSTRUCTION THROUGH INNOVATIVE TECHNOLOGY: A FOCUS ON VIRTUAL REALITY IN CONSTRUCTION

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ABSTRACT

This study delineates the integration of Virtual Reality (VR) within Lean Construction, emphasising its application across the philosophy, principles, methods, and tools of Lean Construction. By conducting a systematic literature review, this research considers the utilisation of VR to enhance construction processes, specifically focusing on its role in mitigating waste, maximising value, continuous improvement, and respect for people. The investigation reveals VR's capacity to bridge the theoretical and practical aspects of Lean Construction, offering a novel perspective on its implementation. The results demonstrate VR's potential in advancing Lean Construction practices through its philosophy, principles, methods, and tools. Also, the utilisation of VR, particularly in SCRUM, Set Based Design and Visual Management, underlines a transformative potential for enhancing construction project efficiency and value. The paper concludes by highlighting the contributions of VR to Lean Construction, proposing actionable insights for practitioners and suggesting avenues for future research. This approach provides a comprehensive review for integrating VR in construction projects, aligning with Lean Construction for enhanced project outcomes.

KEYWORDS

Lean Construction, Set Based Design (SBD), VDC, Virtual Reality (VR), Smart Construction.

INTRODUCTION

Numerous essential technologies support intelligent building practices, including big data analysis, robotics, laser scanning, 3D printing, and virtual reality (VR) (Wang et al., 2023). Among these, VR emerges as a notable advancement in the field of smart construction. Smart construction is closely associated with the concept of "Lean Construction," which was

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introduced by Koskela, (1992) as a novel production philosophy emphasising principles, concepts, and methodologies within the construction industry. that no longer regard construction as a mere process of converting materials into buildings but rather as a sequence of activities that add value (flow process). This perspective entails identifying problems within the flow and implementing solutions and improvements to address these issues (Wang et al., 2023). VR is one of the promising technologies that can improve the process of design, construction, application, and maintenance in many AEC projects (Safikhani et al., 2022). VR has garnered recognition for its ability to enhance customer satisfaction (Noghabaei et al., 2020), reduce project duration by minimising conflicts, serve as a cost-effective alternative to physical mock-up installations and savings of 15% of capital delivery (Haahr et al., 2019). Moreover, Building Information Modelling (BIM) is one of the VR tools that refers to the creation and utilisation of a computer-based information model that encompasses multiple dimensions. This model is not limited to structural documentation but also includes simulations of the construction and operation of capital facilities (Bidhendi et al., 2023). Increased penetration of BIM, as a manifestation of modern technology in construction, specifically VR, positively impacts resilience and waste reduction in construction (Saeedi et al., 2022). These outcomes stem from VR's ability to mitigate a major factor contributing to waste: deficiencies in communication, collaboration, clarification, and understanding, thereby enhancing the confidence required to accomplish the designated tasks (Getuli et al., 2020; Safikhani et al., 2022; Seyman Guray & Kismet, 2023; Zhang, 2021).

Jacobsen et al. (2021) emphasised the use of a VR-based serious gaming environment to teach Lean Construction concepts, underscoring the potential for collaborative and interactive learning. Liu et al. (2022) explored the socio-technical aspects of Lean Construction, particularly examining the Last Planner System (LPS) and its implementation challenges within an Immersive Virtual-Reality (IVR) setting. Trivedi et al. (2022) discussed the integration of VR simulations with Lean Construction principles to enhance project delivery and achieve high-performance in infrastructure projects. In a slightly different approach, Spisakova et al., (2020) focused on the use of virtual reality in designing safe construction sites, without specifically incorporating Lean Construction principles. Also, Brioso et al. (2019) presented a preliminary methodology for integrating Lean Construction and VR in the planning phase of structural interventions in heritage structures. Lastly, Rischmoller et al. (2018) discussed the use of Virtual Design and Construction (VDC) as a lean strategy for integration in construction projects, without mentioning VR in the context of Lean Construction. While several studies have investigated various aspects of VR applications in Lean Construction, including enhancing learning and training (Jacobsen et al., 2021; Liu et al., 2022), project planning and design (Brioso et al., 2019, Spisakova et al. 2020), and project integration and delivery (Rischmoller et al., 2018; Trivedi et al., 2022), there appears to be a lack of comprehensive research that holistically links the use of VR to the overarching philosophy, principles, and methods of Lean Construction. This indicates a research gap where a structured study could provide a more integrated perspective on how VR can be systematically aligned with and support the broader objectives of Lean Construction.

Our discussions are structured to explore the influence of VR on Lean Construction within projects of varying scales and environments, involving a variety of stakeholders. Accordingly, the research questions are set as follows:

1. How can VR support the Lean Construction Philosophy?
2. How can VR support the Lean Construction principles?
3. How can VR support Lean Construction methods?
4. What tools are offered to implement VR in Lean Construction?

In this paper, a systematic review and integration of literature across various sections are conducted to identify the intersection of VR and Lean Construction. Following this introduction, the paper is structured as follows: first, the research method section details our systematic literature review process and the criteria for selecting relevant studies. This is followed by the results section, where we present findings from the reviewed literature, categorising them into Lean Construction philosophy, principles, and methods enhanced by VR. In our analysis, we provide commentary on all four pillars of Lean Construction: value generation, waste minimisation, continuous improvement, and respect for people (Abdelhamid et al., 2008). Furthermore, we explore value identification, value stream mapping, workflow optimisation, demand-driven execution, and continuous improvement, as guiding Lean Construction principles (Karmaoui et al., 2023). We also have selected SCRUM, Set Based Design, and visual Management as our preferred methods to examine. In our analysis, we specifically examine how VR as an innovative technology can be integrated within the pillars, principles, and methods of Lean Construction to enhance construction project outcomes. The Discussion section then synthesises these findings, examining the implications for current and future Lean Construction practices. Finally, the Conclusions section summarises the key insights, discusses the limitations of our study, and suggests directions for future research.

RESEARCH METHOD

This study utilises a bibliometric approach via a universal library portal that incorporates EBSCO, a prominent supplier of research databases, e-journal and e-package subscription services, book collection planning and procurement management, as well as a significant provider of library technology solutions. This strategy was preferred over direct engagement with databases like Scopus for its broad access to diverse materials, including academic journals, books, and other varied databases. This allows for a more extensive review and analysis of literature across different fields and subjects.

The literature search aimed to systematically identify and select publications that contribute to the understanding of integrating VR into the Lean Construction methodologies. The search strategy was carefully designed to encompass a broad spectrum of databases and sources, leveraging keywords such as "Lean Construction", "Lean Construction Philosophy", "Lean Construction Principles", "Lean Construction methods and tools”, “Virtual Reality (VR)", "Smart Construction", "SCRUM", " Set Based Design", and "Visual Management". These keywords were used in various combinations to ensure a comprehensive retrieval of relevant literature. In identification process, 18 books and 13,662 articles were founded.

The selection process commenced with an initial screening based on the relevance of titles, abstracts, and keywords to the research topic. This preliminary filter aimed to capture studies that directly address the use of VR in enhancing construction processes, aligning with Lean Construction methodologies which 13 books and 152 articles were chosen. Following this, a more detailed assessment was conducted, examining the conclusions, discussions, and methodological approaches of the papers to ensure they provided substantive insights into the research questions where we could select 3 books and 42 articles.

Given the innovative nature of VR applications in construction and the evolving landscape of Lean Construction practices, the study extended its inclusion criteria beyond peer-reviewed journals to encompass conference papers, industry reports, and unpublished studies. This was predicated on the condition that these additional sources were recent, maintained academic validity, and offered substantial contributions to the field.

The selection process culminated in the identification and detailed examination of 23 articles and 3 books that provide a comprehensive overview of the current state and potential of VR in the Lean Construction. The process can be seen in Figure 1. Notably, the selection favoured qualitative insights due to the exploratory nature of the topic, although quantitative studies were also considered to ensure a balanced view. However, it was observed that quantitative research in this specific area remains limited.

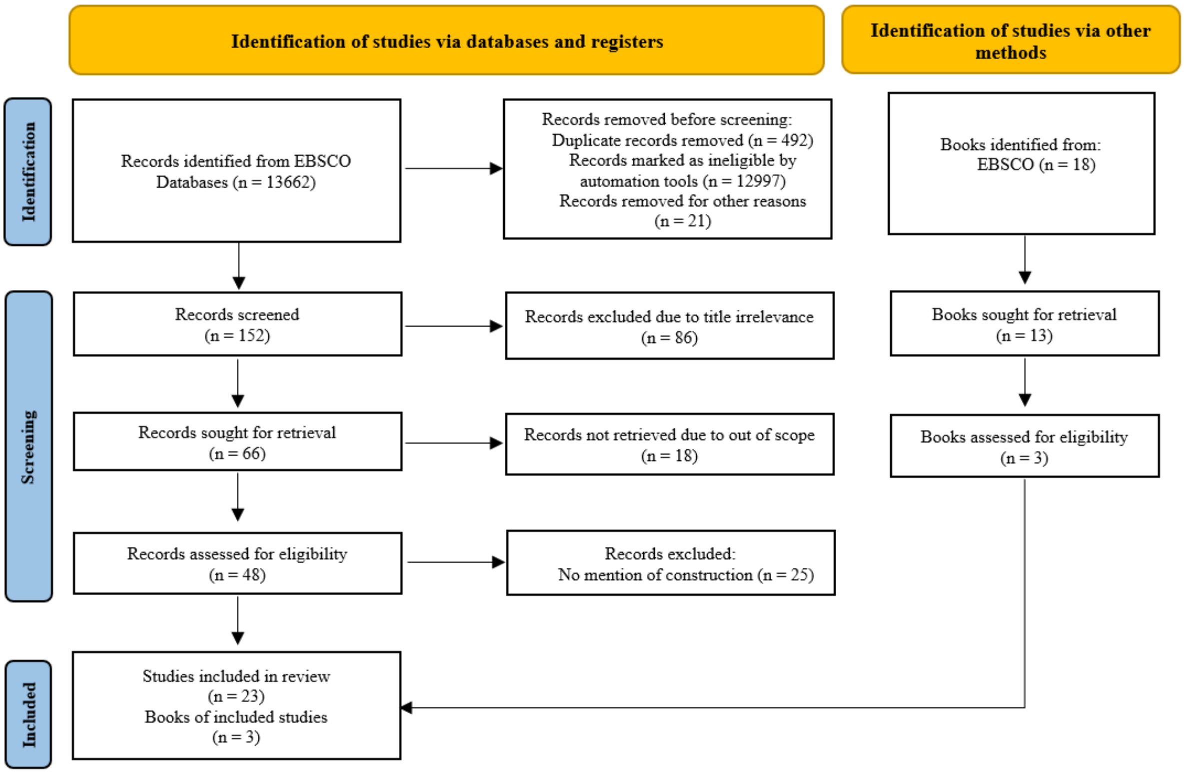

Figure 1. Identification, Screening and Selection process of the systematic literature review

LEAN CONSTRUCTION PHILOSOPHY AND VR

Lean Construction philosophy is based on the principles of lean manufacturing, which originated from the Toyota Production System. This approach focuses on eliminating waste, improving efficiency, and delivering value to customers. Glenn Ballard and Lauri Koskela have conducted extensive research on Lean Construction philosophy. They argue that lean construction is not limited to standardised products or high-volume construction projects. Instead, they believe that Lean Construction can be applied to dynamic projects, promoting innovation and value generation (Ballard & Koskela, 1998). According to Ballard and Howell, Lean Construction philosophy is not about cost-cutting or cheapness. It is about focusing on producing value for customers and eliminating everything else (Ballard & Howell, 2003).

The four pillars of Lean Construction are: Waste Minimisation which focuses on reducing non-value-adding activities and materials in construction processes; Value Maximisation that Emphasises creating maximum value for clients through efficient and effective construction practices; Continuous Improvement which Involves the constant evaluation and enhancement of construction processes to achieve better outcomes; and Respect for People Prioritising the welfare and development of all individuals involved in the construction process (Abdelhamid et al., 2008).

To establish a linkage between the Lean philosophy and VR predicated upon its four pillars, the following connections can be drawn:

WASTE MINIMISATION

VR has a transformative impact on minimising waste in construction, addressing the eight types of waste identified in Lean Construction. Defects are reduced through detailed simulations, allowing for early identification of design flaws (Trivedi et al., 2022). VR aids in accurate demand assessment, which helps prevent overproduction (Jacobsen et al., 2021), and streamlines project timelines to reduce waiting times (Rischmoller et al., 2018). It also promotes the utilisation of talent by visualising every team member's contribution, and assists in reducing unnecessary transportation and motion by enabling precise planning (Noghabaei et al., 2020). Furthermore, VR contributes to maintaining optimal inventory levels and prevents over-processing by allowing teams to finalise designs virtually (Zhao, 2022).

VALUE MAXIMIZATION

As highlighted by Nasirzadeh & Nojedehi, (2013), VR enhances value in construction projects through improved visualisation, aiding in better decision-making and client satisfaction, which are core aspects of value maximisation in Lean Construction. It enables clients to experience and interact with the project before construction, ensuring their needs are accurately met (Trivedi et al., 2022). Furthermore, enhanced communication facilitated by VR leads to a clearer understanding among stakeholders, while also allowing for detailed inspection and quality control (William & Jose, 2023).

CONTINUOUS IMPROVEMENT

VR's ability to simulate various construction scenarios supports the Lean principle of continuous improvement. It allows for iterative testing and refinement of project designs before actual construction, aligning with the ideas presented by Muya et al., (2013). This approach allows for the rapid incorporation of feedback into project plans and aids in performance tracking and analysis for ongoing improvement (Hatoum & Nassereddine, 2023).

RESPECT FOR PEOPLE

Incorporating VR in construction respects and enhances the workforce's capabilities. It offers safer, more efficient, and ergonomically beneficial ways for workers to engage with construction projects, thus respecting and enhancing the workforce's capabilities (McHugh et al., 2023).

Moreover, accidents on construction sites often result from a deficiency in proactive safety measures (Bidhendi et al., 2022). Proactivity, in this context, involves training for safety awareness and the identification of potential risks. To address this, many organisations are increasingly emphasising 'cultural intervention, enacted policies, communication, and induction' (Li et al., 2018). Figure 2 illustrates the efficacy of VR in on-site risk mitigation, as tested and demonstrated.

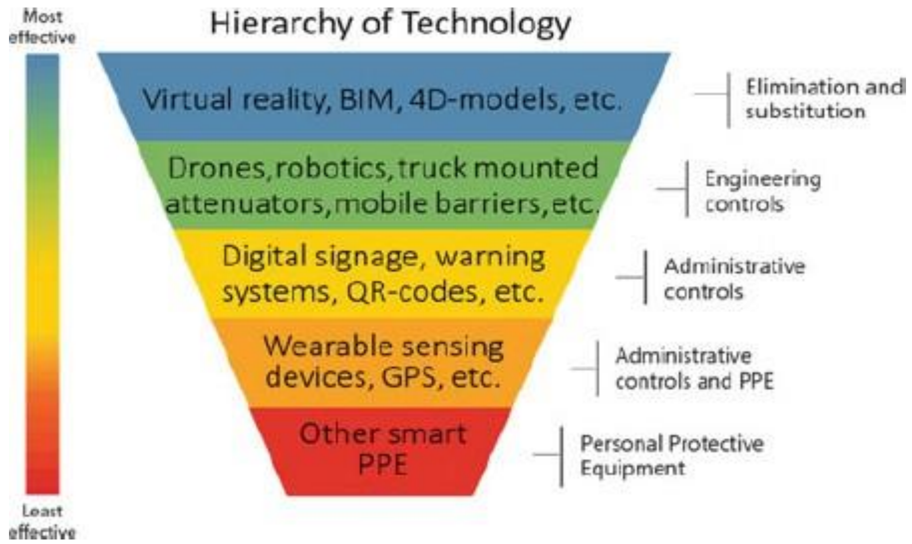

Figure 2: "Technology alternative organised in a hierarchy based on level of risk mitigation effectiveness" (Karakhan et al., 2019)

In the context of Lean Construction, VR aids in the identification and elimination of potential on-site hazards such as spatial collisions. Through VR-enacted site walkthroughs, construction personnel can practice emergency response protocols, bolstering their instinctive reactions to critical incidents (González et al., 2022). Moreover, VR enables the safe visualisation of demolition processes, highlighting potential risks without actual exposure (Seyman Guray & Kismet, 2023).

LEAN CONSTRUCTION PRINCIPLES AND VR

VR is increasingly recognised as a catalyst for enhancing the Lean Construction framework. This section aims to explore the integration of VR with the Lean principles of value identification, value stream mapping, workflow optimisation, and continuous improvement, as these are crucial for advancing construction practices. These principles were selected due to their direct impact on operational efficiency and their ability to be significantly enhanced through technological integration (Karmaoui et al., 2023).

IDENTIFYING VALUE

At the forefront of Lean Construction is the principle of delivering value as envisioned by the client. VR technology serves as a conduit for this vision, providing clients and stakeholders with a tangible representation of project outcomes. Through VR, clients can virtually walk through the construction project, offering feedback that can be incorporated instantly, ensuring that the end result aligns with their expectations (Trivedi et al., 2022). This interactive approach helps in defining the scope more accurately and avoiding costly changes during later stages of construction.

MAPPING THE VALUE STREAM

Value Stream Mapping in Lean Construction is integral to visualising the entire project from inception to completion, pinpointing inefficiencies, and minimising waste. VR can significantly enhance this process by creating a virtual model of the construction value stream, allowing for a comprehensive analysis and optimisation of each step. This digital twin approach not only helps in identifying current waste but also in predicting and preventing future inefficiencies (Sacks et al., 2009).

CREATING FLOW

Creating a consistent and uninterrupted flow of work is crucial to maintaining efficiency on construction sites. VR technology aids this Lean principle by simulating the construction process and identifying potential workflow interruptions. This preemptive analysis allows teams to reorganise tasks and resources to prevent bottlenecks and ensure a smoother flow of operations (Liu et al., 2022).

PURSUING PERFECTION

Pursuing perfection through continuous improvement is a key tenet of Lean Construction. VR allows for an iterative design process where construction scenarios can be tested and optimised in a virtual environment. This virtual prototyping not only enhances the quality and performance of the construction process but also fosters a culture of continuous learning and improvement within the team (Li et al., 2018).

The integration of VR with Lean Construction principles provides a robust framework for enhancing construction project outcomes. By leveraging the immersive and interactive capabilities of VR, stakeholders can achieve a deeper alignment with Lean Construction principles, leading to reduced waste, improved efficiency, and enhanced client satisfaction (Noghabaei et al., 2020).

LEAN CONSTRUCTION METHODS AND VR

This section aims to explore the integration of VR with Lean methodologies like SCRUM and Set-Based Design (SBD). These methods were selected for their potential to significantly benefit from VR's capabilities in enhancing collaborative and iterative processes. Given the scarcity of direct references connecting VR with SCRUM and SBD in existing literature, this document interprets supportive evidence and discusses its potential application to these frameworks.

SCRUM

Recent advancements in project management have seen the integration of SCRUM, an Agile method, into Lean Construction practices to address the dynamic and uncertain environments of construction projects. This integration, conceptualised as 'AgiLean PM', enhances Lean Construction by incorporating SCRUM's agility and iterative feedback processes, proving effective especially in the design phases of construction projects (Bryde et al., 2014).

SCRUM, akin to a relay race featuring brief pauses between each participant, is a highly collaborative method that emphasises continuous review, feedback, progress, and repetition for incremental advancements and superlative quality, all while striving to deliver the highest value swiftly (Arroyo, 2022).

VR facilitates a more profound and qualitative design review throughout the entire project lifecycle by inviting end-users to navigate freely in a virtual environment and provide candid opinions (Spisakova et al., 2020). This heightened engagement enhances productivity by securing each decision-making process, ultimately reducing the need for rework. Given SCRUM's rapid and confident approach, feedback from end-users becomes a crucial resource. For instance, clients evaluating alternative design options can virtually experience the scale of rooms affordably. In another context, researchers found that VR, without additional cost, significantly reduced lighting electricity consumption in commercial buildings by providing options for lighting conditions (Noghabaei et al., 2020). This underscores how VR-enabled design reviews not only add enduring value for end-users but also contribute to ongoing cost reductions.

Moreover, for projects requiring simulations, VR can realize real-time occupancy flow, making it less cognitively demanding for clients (Safikhani et al., 2022). However, if VR settings reveal excessive detail too early in the process, they can become distracting and create false expectations, potentially obscuring the overall project scope (Ventura et al., 2019). With these possibilities in mind, it becomes evident that in the context of VR and SCRUM, effective management necessitates a directive approach to adopting VR and avoiding incremental deviations from the principal task.

SET BASE DESIGN

The foundational design method, Set Base Design (SBD), is characterised by its open-minded approach, keeping design options open until the final stages to better address unpredictable elements through continuous inquiry, analysis, clarification, and selection. SBD relies on a competent and dependable team that can undergo training and eventually operate autonomously toward achieving the project's end goal (Oliveira et al., 2024). This section explores the role of Virtual Reality (VR) in enhancing SBD practices.

In an experiment involving riggers, signal person, and operators, it was found that VR enabled participants to visualise the impact of their decisions on project cost and schedule. It also provided a platform for practicing tasks, boosting confidence, and reducing human error (Safikhani et al., 2022). This led to a significant reduction in decision-making time and the elimination of timidity (Paes & Irizarry, 2018). Additionally, VR proved beneficial in identifying potential clashes in building services (Haahr et al., 2019). A proposed method for on-site training involved setting up a trailer with full equipment capable of hosting virtual meetings, which was found to enhance satisfaction and communication richness compared to non-VR alternatives (Getuli et al., 2020).

While the research acknowledges that the accuracy and appropriateness of meetings were better in a non-VR face-to-face setting, the overall effectiveness of VR in SBD lies in its ability to empower individuals in decision-making. This worker-centered approach, although not necessarily reducing project timelines, influences the occurrence of rework or defects, thus aiding in budget control.

VISUAL MANAGEMENT

Visual Management (VM), defined as 'visual and definitive verification' (Hatoum & Nassereddine, 2023), is a Lean principle adopted in methodologies such as Last Planner System (LPS), SCRUM, Kanban, and others. Research indicates that visual platforms like VM can forecast design conflicts and deficiencies, thereby minimising rework in construction projects (Noghabaei et al., 2020). VM enables the calculation of metrics such as Percent Plan Complete (PPC) by breaking down and making tasks measurable through visual representation.

In the research conducted by Liu et al., (2022), VR was utilised in an LPS setting, incorporating VM elements within their hypothetical project. While VM was not the primary focus of their study, it contained pertinent elements of VM. The Figures below illustrate key aspects of their research.

In Figures 3 and 4, one can observe tables listing tasks alongside adjacent images. The VM environment depicted is reminiscent of actual scenarios, albeit possibly more simplified. Consequently, the study indicates that participants engaged in more negotiations and achieved a higher Percent Plan Complete (PPC) compared to projects managed using conventional methods, even though negotiations in both instances took place within a VR context. The author further suggests that VR contributed to reducing mental stress, fostering clear communication, and enhancing commitment among participants (Liu et al., 2022). This effect may stem from the necessity for discussions to be straightforward or focused, as the visuals in VR are self-explanatory, eliminating the need for complex language usage by those negotiating.

Figure 3: “ In the construction phase, the sub-scene manager on the construction site oversees the work and updates the progress.” (Liu et al., 2022)

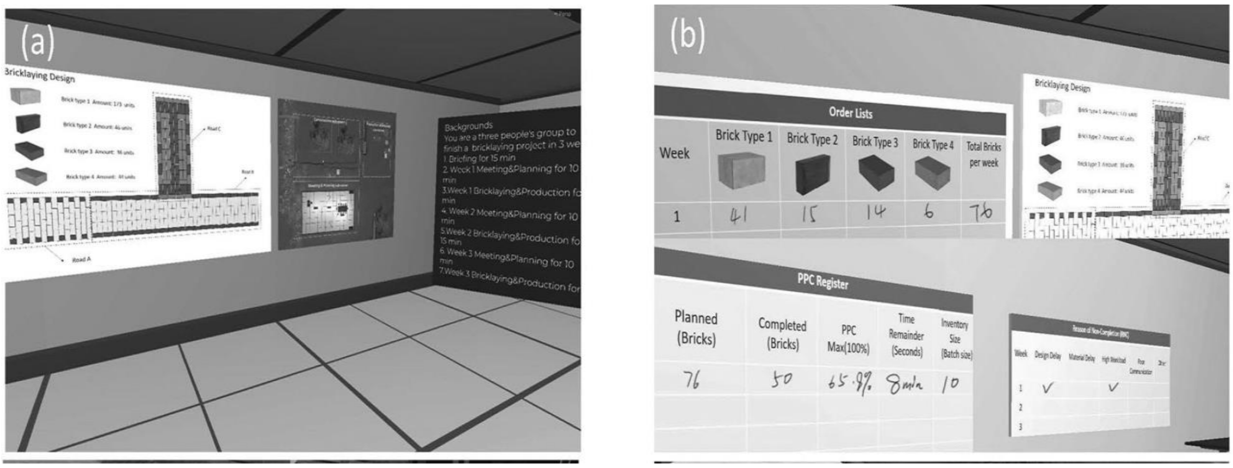

Figure 4: Presenting their VM (Virtual Model) within a VR (Virtual Reality) environment offers a level of detail far surpassing that of conventional methods used in meetings (Liu et al., 2022)

FINDINGS AND DISCUSSIONS

This research comprehensively examines how Virtual Reality (VR) can enhance Lean Construction practices. Our findings suggest that the utilisation of VR, particularly in SCRUM, Set Based Design, and Visual Management, underlines a transformative potential for enhancing construction project efficiency and value. Notably, VR's impact on reducing rework and defects while fostering an environment conducive to innovation and continuous improvement aligns with Lean Construction philosophy pillars. The study further emphasises VR's capacity to enhance Lean Construction's principles: value maximisation, waste minimisation, and continuous improvement. Studies by Jacobsen et al., (2021) and Trivedi et al., (2022) have similarly highlighted VR's role in improving project delivery and training effectiveness. The discussion points to VR as not just a technological tool, but a paradigm shift in construction management, fostering a more collaborative, efficient, and safety-conscious project environment. The integration of VR into Lean Construction not only streamlines project management and design processes but also enhances safety and worker engagement, aligning with the Lean principle of Respect for People. For practitioners, adopting VR could lead to more efficient project outcomes and improved stakeholder satisfaction.

The research identifies a crucial need for quantitative analysis to measure VR's impact, suggesting future studies focus on empirical data to solidify VR's role in Lean Construction. This exploration opens avenues for innovative project management strategies, advocating for VR's broader adoption in the industry.

Despite the qualitative nature of this research analysis, the evidence suggests VR as a pivotal tool in bridging communication gaps. However, the research underscores a critical gap in quantitative studies, pointing to an emergent need for empirical evidence to validate VR's operational benefits comprehensively.

One of the main limitations of our study is its reliance on secondary data, which might not capture the nuanced experiences of implementing VR on construction sites. Future research should focus on primary data collection, including case studies and experimental designs, to validate and extend our findings. Future explorations should aim at quantifying VR's effectiveness in Lean Construction, offering a clearer picture of its return on investment. This study serves as a steppingstone for deeper inquiries into VR's role in smart construction, encouraging stakeholders to consider its strategic implementation for Lean-aligned project outcomes.

Our discussion underscores the transformative potential of VR in Lean Construction but also acknowledges the complexity of its implementation in real-world settings. By addressing these challenges and focusing on empirical studies, future research can pave the way for more effective and widespread use of VR in Lean Construction.

CONCLUSIONS

In conclusion, this study has demonstrated the transformative potential of VR in enhancing Lean Construction practices. Our research systematically investigates how VR supports the four pillars of Lean Construction—value maximisation, waste minimisation, continuous improvement, and respect for people—as well as principles and methods, thereby contributing significantly to smarter construction practices.

Our findings illustrate that VR can act as a powerful enabler of Lean Construction by providing immersive and interactive environments that improve understanding and collaboration among project stakeholders. Through detailed VR simulations, construction projects can reduce waste and enhance efficiency, aligning closely with the principles of Lean Construction. Specifically, methods such as SCRUM, Set-Based Design and Visual Management have shown great potential for integration with VR, offering new ways to manage and execute construction projects that promote both efficiency and precision.

While our study primarily utilised secondary data, the potential for VR in qualitative research remains substantial. Future research could focus on case studies that examine the real-time application of VR in construction sites to provide deeper insights into its operational benefits and challenges. This will be particularly impactful in exploring how VR can further streamline Lean Construction in practice.

The ongoing development in VR technology promises further innovations that could be harnessed to support Lean Construction philosophy principles and methods more robustly. It is imperative for future research to continue exploring these technologies in diverse construction environments to solidify VR's role and optimise its benefits in Lean Construction.

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BIM AS AN ENABLER OF LEAN CONSTRUCTION IN THE PUBLIC SECTOR

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ABSTRACT

Several governments are mandating Building Information Modeling (BIM) for public construction worldwide. While this top-down approach can be effective in some contexts, the lack of a lean construction perspective within BIM project delivery might hinder the expected outcomes. This paper aims to unpack the interplay between lean principles and BIM adoption that support formal and informal lean construction implementation in the design phase of public construction projects. The study focuses on a Latin American country subject to a current BIM mandate. Qualitative data was collected through semi-structured interviews with senior public sector practitioners. The findings reveal that the BIM practices *informally* align with lean principles, as there is no explicit emphasis on lean implementation within the BIM mandate framework. Drawing on these insights, the discussion compares these results with previous studies and suggests the inclusion of BIM as a facilitator of lean practices in the Lean in Public Sector (LIPS) agenda. The conclusion highlights the current opportunities for leveraging the BIM public policy trend towards lean implementation in public construction projects.

KEYWORDS

Lean construction, BIM, lean-BIM synergy, lean in the public sector (LIPS), public policy.

INTRODUCTION

Lean construction and building information modeling (BIM) have positively impacted the construction industry, and their interaction has been a major topic of discussion in both research and practice. Koskela (1992) defined lean construction as the application and adaptation of the underlying concepts and principles of the Toyota Production System (TPS) to construction. On the other hand, BIM is "a verb or adjective phrase to describe tools, processes, and technologies *facilitated by digital machine-readable documentation about a building, its performance, its planning, its construction, and later its operation."* (Eastman et al., 2011).

Despite being independent efforts to transform and enhance construction as an industry, lean construction and BIM share similarities and differences in adoption and potential outcomes once implementation occurs (Sacks et al., 2010). Bhargav et al. (2013) argued that lean and BIM have four significant mechanisms of interaction: BIM contributes directly to lean goals; BIM enables lean processes and contributes indirectly to lean goals; auxiliary information systems, enabled by BIM, contribute directly and indirectly to lean goals; and lean processes facilitate the introduction of BIM. Andujar-Montoya et al. (2019) found that BIM considerably reduces construction waste in the form of lack of information exchange, poor communication, poor decision-making, and frequent design changes. Moreover, Eastman et al. (2011) stated

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that some of the principles of lean construction can be fulfilled by using BIM, and it will also enable the achievement of other principles.

Considering the interaction between lean and BIM, several studies have proposed frameworks to understand their relationship and guide their adoption. The interaction matrix of lean principles and BIM functionality presented by Sacks et al. (2010) provided examples based on published research on how lean and BIM align. Bayhan et al. (2023) also developed a framework that shows how lean and BIM interact and then validated the more relevant topics of these interactions through five case studies. Similarly, Karatas and Budak (2023) proposed a lean and BIM framework for the construction phase only, which was then validated through a statistical approach. On the other hand, other papers have presented case studies of the lean construction-BIM synergy, such as the ones presented by Khanzode et al. (2006) with Virtual Design and Construction (VDC), Rischmoller et al. (2006) with lean principles in the design stage, and Sacks et al. (2009) with the use of BIM to enhance product and process design. More recently, Eldeep et al. (2022) demonstrated using BIM as a lean tool to minimize construction waste and reduce the number of change orders in an educational project. Similarly, McHugh et al. (2019) combined the use of production planning software to implement lean tools and BIM models to improve visualization and enhance the project delivery phase of a data center. In sum, previous research has investigated BIM and lean interactions, but there seems to be a gap in how these interactions work in public construction.

Several countries have implemented BIM as a public policy to enhance public construction in their regions. Given the interaction of lean and BIM, these public policy efforts represent an opportunity to ask whether *formal* or *informal* lean construction applications can also be implemented. Unfortunately, several BIM implementation policies focus primarily on the administrative aspects of BIM project delivery (e.g. plans and documentation) without consideration of BIM-enabled production management. Consequently, this paper aims to understand the opportunities for lean implementation using BIM policies as an enabler in the public sector. To achieve this objective, this research focuses on the design stage of public projects in the Peruvian public sector, which served as the case study.

This paper is structured as follows. First, a literature review exploring the interactions of lean construction and BIM in public construction is introduced. Subsequently, the research methodology is presented, culminating in the presentation of results, including the alignment of lean principles with BIM use in the design stage. Following this, the discussion section will contrast the findings with prior research and current trends of lean construction. Finally, the conclusion section summarizes the results and proposes avenues for future research work.

LITERATURE REVIEW

LEAN CONSTRUCTION AND BIM

Sacks et al. (2010) presented one of the most acknowledged lean and BIM interaction matrices in the construction management literature. They found 56 interactions between lean and BIM, and 48 of the 56 were supported by practical evidence from industry case studies showing how BIM functionalities (or BIM uses) positively enable the achievement of lean principles. This matrix suggests that an incremental and integrated adoption of lean and BIM can enhance project and organizational results rather than their adoption separately. Oskoui et al. (2012) extended Sacks et al. (2010) interaction matrix by adding more BIM functionalities and lean principles enabled by this new set of BIM uses. These new interactions were found primarily in the operations & maintenance phase of projects.

Bayhan et al. (2023) proposed a lean and BIM framework using an analytical network process to find the most predominant factors contributing to the lean and BIM synergy. The study results showed that production, standardization, and information accuracy are the most critical factors, and they are mainly used to control production during the delivery phase of projects. Similarly, Karatas and Budak (2023) developed a framework to understand the impact of lean and BIM synergy in labor productivity during the construction phase. That study argued that the BIM uses of 4D planning and coordination support achieving lean principles. Furthermore, using 4D models alongside visual management tools such as dashboards significantly impacts construction labor productivity.

The literature also shows many lean and BIM case studies that provide practical evidence of these synergies in various contexts. Vestermo et al. (2016) developed a project on-site hardware called "BIM station," which facilitates the integration of lean construction and BIM, considering the application of BIM solutions to satisfy lean principles, such as visual management. Gerber et al. (2010) presented three case studies on the integration of lean and BIM. All three case studies showed advancements in delivering increased value to clients while significantly reducing waste in time and material. Gomez Sanchez et al. (2019) presented the use of BIM models with lean tools and methods (i.e., lines of balance, visual management, the Last Planner System) as good practices in the Colombian construction industry. In this case, conducting a BIM implementation seems to allow for a "leaner" project as it facilitates a better communication flow to obtain more reliable production plans.

Mollasalehi et al. (2018) developed a lean BIM maturity model to assess the joint implementation of both innovations in construction. That study proposed an integrated BIM and lean maturity model called IDEAL, which adopted the initial concepts of previous BIM and lean construction maturity models. Previous research have provided an extended understanding of the lean and BIM synergy, the frameworks developed to explain it, examples of their implementation, and how to assess their joint implementation. However, most examples are from the private sector. Understanding the challenges of conducting this effort in public projects is a significant gap that this study intends to address.

LEAN CONSTRUCTION AND BIM IN THE PUBLIC SECTOR

Considering the systemic and wide approach of lean construction and its foundation in lean production, the implementation of lean construction comes along with instrumental changes in how public organizations are managed. Several authors have found significant challenges and barriers for implementing "lean" as a way of thinking and as a foundational aspect of the practices in the public sector. Bathia & Drew (2006) conducted a study to implement lean manufacturing techniques in the United Kingdom (UK) public sector, concluding that "*Applying lean is difficult in the private sector, and more so in the public sector. Therefore, successful lean transformations must close the capability gap early in the process so managers and staff can make the transition to a new way of working*."

Andersson et al. (2023) conducted quantitative research that showed some challenges in understanding what "lean" means in several Norwegian public sector workers. Based on that study, lean is perceived mostly as a set of tools instead of a way of thinking or as a mindset that can be beneficial for delivering more value to the end users of public services. This study also showed several misconceptions about lean and the lack of focus on production and flow management, which is inherent to the concept of lean as it was conceived in the 1950s. Having said that, more specific studies use public projects as case studies to showcase lean construction-related concepts, techniques, or principles (e.g. Kuprenas, 1998; Prado, 2021).

Kuprenas (1998) presented the implementation of lean thinking concepts, tools, and processes in the City of Los Angeles Bureau of Engineering due to poor project delivery performance. Kuprenas (1998) explained a holistic perspective of their lean journey, which contains organizational changes, systems optimization training, and implementation of performance metrics that combine production-related metrics and cost and time metrics. Recently, LIPS emerged as an international forum where practitioners share lessons learned during lean transformation in the public sector and non-profit organizations (LIPS, 2024). Currently, based on the LIPS website, their research areas are Lean in Healthcare, Transformation in Transportation, Empowering people in Utilities, Lean Thinking in Education, Future of Infrastructure, and Principles of Lean Services. The specific topic of lean construction implementation in the public sector enabled by technologies such as BIM is not explicitly stated as part of the agenda items of this organization. However, one of the objectives of the 2022 LIPS conference (LIPS, 2022), which was held in Chile, was to inspire Lean initiatives in public programs, including digital technologies/BIM. Therefore, there seems to be a current discussion on integrating lean and BIM in specific projects and several public sector programs to enhance the delivery of public infrastructure.

The current implementation of BIM as a public policy in several countries (particularly in Latin America) could be used as an enabler to implement not only lean in public projects but also change the way of working in public organizations towards delivering more value to the end-users (i.e. the beneficiaries of the infrastructure delivered). Based on the BIM Network of Latin American Governments, the Latin American region intends to pursue a collaborative effort to implement BIM towards accelerating national digital transformation processes (Red BIM Gob Latam, 2024). Considering that this paper uses Peru as a case study, it is important to mention the current state of the BIM public policy in this country. The BIM adoption policies are led by Plan BIM Peru of the Ministry of Economy and Finance as the regulatory public body in charge of disseminating and overseeing this public effort (Plan BIM Peru, 2024). Several pieces of policy documentation have been published, and the ultimate goal is to use BIM for all public projects by 2030 (Ministry of Economy and Finance, 2023).

Despite the apparent positive interactions between lean and BIM, it seems that no piece of policy addresses these two innovations. However, the literature shows that some public organizations have used lean and BIM collaboratively through case studies. For instance, Umstot et al. (2014) presented a public sector case study in which BIM enabled lean construction. This case study was developed thanks to the combination of two factors: (a) the 2008 Californian law, which granted authority to community colleges to use design-build contracting to deliver capital projects exceeding $2.5M, and (b) the decision of the San Diego Community College District (SDCCD) to require all new projects to be designed and constructed using BIM. Umstot et al. (2014) demonstrated how the combination of lean construction significantly impacted change order reduction, schedule reliability, and the completion of sustainability certification. In the case study of that research, the use of BIM allowed the project to achieve several lean principles.

Monyane et al. (2018) included BIM as a lean construction tool to enhance the cost management framework in South African public sector projects. In that study, Monyane et al. (2018) conducted interviews and found that many respondents agreed on the use of BIM to enhance design and construction workflow and the application of BIM uses (i.e., clash detection) to improve design documents. Similarly, Prado (2021) discussed the use of BIM and lean in combination with the Virtual Design and Construction (VDC) implementation process (and its challenges) in Peruvian public projects. Moreover, Prado (2021) stated that the need for a lean approach is instrumental to overcoming several challenges in implementing these innovations.

Given the influential role of the government in the industry, its ability to encourage and empower public organizations is crucial for delivering value throughout the project lifecycle. These studies indicate that integrating lean construction tools, methods, and innovative technologies can enhance performance in public construction projects. Therefore, the application of a framework that integrates these two concepts, such as the lean and BIM framework presented by Sacks et al. (2010), could be used as the theoretical artifact to understand the opportunities for joint implementation of lean construction and BIM.

RESEARCH METHOD

Given the background of the authors of this paper with the Peruvian public construction sector, and the similar approach in BIM implementation in the Latin American region, Peru was selected as the case study. The first step is to develop a version of the lean and BIM interactions framework. Considering the context of the BIM implementation policies in Latin American countries and the lean and BIM interaction matrix presented by Sacks et al. (2010), this study proposes a more specific version of this framework addressing the design phase. The second step is to develop a qualitative analysis process based on semi-structured interviews with public managers. These public managers are required to have experience in managing public projects implementing BIM and have knowledge of lean construction, so the interactions between these two innovations can be found through the interviews. The interviewees were asked questions about the interaction of lean and BIM in the projects they manage and how lean principles are enabled using BIM. The questions were:

- How many projects have you developed with BIM?
- What do you understand as lean construction and lean overall?
- Based on the list of lean principles, which lean principles are enabled by each BIM use implemented in your projects? Could you elaborate on the evidence?

The demographics of the managers are shown in Table 1.

Table 1: Demographics of public managers interviewed

N°	Public organization	# of years of experience	# of projects using BIM
1	Ministry of Housing	20	10
2	Ministry of Education	15	8
3	Ministry of Education	5	5
4	Ministry of Housing	23	20
5	Regional Government of Callao	30	4
6	Ministry of Education	16	9
7	Ministry of Economy	30	25

The third step is to find the similarities and differences in the lean principles (including lean tools and methods) that BIM enables based on the experiences shared by the interviewees. Using the answers of all the interviewees facilitates the construction of a more robust understanding of the perception of public managers regarding how BIM (uses) supports the satisfaction of lean principles and the evidence related to it. This step will lead to obtaining an explanation of how lean principles are enabled by BIM in the public sector.

RESULTS

CASE STUDY CONTEXT

Projects developed under the Peruvian public construction legislation follow a typical design-bid-build (DBB) as the delivery method of choice (Ministry of Economy and Finance, 2018), which mainly focuses on financial accountability, and generates fragmentation among project stages. Additionally, public projects usually involve many actors throughout their phases, and the regulatory body auditing public procurement constrains public managers from innovating if there is no specific piece of legislation that supports that innovation. Consequently, managing public projects is considered a heavily bureaucratic process, and innovation is usually triggered after a policy is released to "shield" public managers who decide to implement it. In this regard, a new BIM policy now allows public institutions to implement BIM uses and conduct BIM implementation (at organizational and project levels). This policy is also included in different types of delivery methods not commonly used in this sector, such as design-build, and legal frameworks that differ from the standard used in the case study, such as the New Engineering Contract (NEC). Considering the interrelated relationship between lean and BIM and the current BIM policy, the case study context has many variables to study that might or might not affect the opportunities for lean principles to be included in the current BIM mandate.

LEAN CONSTRUCTION & BIM INTERACTIONS IN THE DESIGN STAGE

Table 2 shows the outcome of the lean and BIM interactions in the case study. This is shown by aligning lean principles to BIM functionality based on the case study.

Table 2: Lean construction & BIM framework in the design stage of public projects

BIM functionalities (BIM uses)	Lean Principles (validated by the case study)
Visualization of form (Existing conditions records, 3D visualization)	Reduce variability Verify and validate Go and see for yourself Use visual management Ensure requirements flow down
Rapid generation of multiple design alternatives (Design authoring, Design review, 3D Model coordination)	Reduce variability Reduce cycle times Use visual management
Automated generation of drawings and documents (Documentation production, Quantity take-off)	Reduce variability Reduce batch sizes
Collaboration in design and construction (3D Model coordination, 4D Model simulation, Data coordination, 3D Visualization)	Reduce variability Reduce cycle times Increase flexibility Ensure comprehensive requirements capture Verify and validate Decide by consensus considering all options

In the first column of Table 2, the BIM functionalities are drawn from the initial lean construction and BIM interaction matrix, and the associated BIM uses (in parenthesis) are drawn from Plan BIM Peru. This portion of Table 2 shows the “correlation” between the BIM functionality and BIM uses extracted from the two pieces of literature used in this study. This alignment was necessary to ensure a good understanding of terminology during the interviews with the public managers. Moreover, Plan BIM Peru is working on having the same language within the public sector in terms of the terminology used for BIM-related concepts. The lean principles are presented with the same terms as the original interaction matrix. The explanation of these terms was also part of some interviews with the public managers who participated in this research.

The results of Table 2 show that the BIM functionality of Collaboration in design and construction (the combination of the following BIM uses: 3D Model coordination, 4D Model simulation, Data coordination, and 3D visualization) enables more lean principles than the other

BIM functionality for the design phase of projects. This BIM functionality enables six lean principles based on the interviewees' responses. These lean principles are: reduce variability, reduce cycle times, increase flexibility, ensure comprehensive requirements capture, verify and validate, and decide by consensus considering all options. The BIM functionality of visualization of form (the combination of the following BIM uses: Existing conditions records and 3D visualization) enables five lean principles: reduce variability, verify and validate, go and see for yourself, use visual management, and ensure requirements flow down.

The BIM functionality of Rapid generation of multiple design alternatives (combining the following BIM uses: Design authoring, Design review, and 3D Model coordination) enables four lean principles: reduce variability, reduce cycle times, and use visual management. Lastly, the BIM functionality of Automated generation of drawings and documents (combining the following BIM uses: Documentation production and Quantity take-off) enables two lean principles: reduce variability and batch sizes. From a BIM perspective, there are overlaps in the BIM functionality's impact on lean principles (several BIM functionalities impact several lean principles), which shows the complex and multilayered interaction between lean and BIM. Additionally, it seems that the BIM uses combined could also provide more robust support to a combination of lean principles.

LEAN PRINCIPLES ENABLED BY BIM

The results of Table 2 present the relationship between lean and BIM in the public construction sector, specifically in the design phase of the case study. From a lean construction perspective, the BIM functionalities analyzed enable eight lean principles. To facilitate the explanation of the interrelated connections among some of the lean principles and the BIM uses that enable them, some lean principles are going to be presented paired.

Reduce Variability

All BIM uses enable this lean principle, and the public managers believe that *"BIM allows building two times the project, and as a consequence, less waste (fewer sources of variability) will happen when the projects are constructed."* Some of the public managers most knowledgeable in lean construction mentioned that combining early 4D-BIM modeling with lean tools and methods (i.e., target value design and value stream mapping) might allow for reducing even more sources of variability in the early stages of the projects. Furthermore, there is evidence of conducting training programs in specific lean tools and methods, being The Last Planner System the most common one among the training programs in the public sector. Additionally, the contracting methods currently employed in public projects provide greater flexibility for conducting operations management studies and gathering data on the impact of variability, thereby facilitating efforts to mitigate these sources of variability.

Go and see for yourself & Verify and Validate

All the interviewees mentioned their practices of engaging with the team members and seeing the "sources of waste" as part of their duties, as well as how BIM models support this activity by providing a "virtual *gemba* walk." These activities are now considered a collaboration section in the BIM policies, expecting to enable more positive interactions among stakeholders. These lean principles are also validated and improved through BIM by authoring and reviewing design models in the early stages of the project, which enables to understand better future issues and ways to mitigate them. Additionally, these lean principles insert transparency during the project's design phase, and transparency is a major value in public construction. This principle of BIM is a significant cornerstone of the current BIM mandate.

Use Visual Management

The use of BIM models and outcomes of the BIM uses for reporting, and dashboard development in design seems to be the most common interpretation of how BIM enables this lean principle. Obtaining data to feed the project's visuals since the early stages is a current initiative that most public managers are conducting. Additionally, some public managers mentioned including BIM models and BIM deliverables to develop A3 reports, which shows a combination of lean tools and methods supported by BIM uses. They mentioned they learned these lean tools and methods from different sources, which include institutional training. Moreover, the use of 4D BIM models to develop on-time interaction dashboards and evaluate several design options from a constructability perspective were other examples collected through the interviews conducted.

Reduce cycle time

The combination of having different templates to apply BIM uses provided by public clients and process maps for lean tools and methods makes it seem that BIM allows the reduction of cycle times of several pieces of the design scope supported by BIM. This cycle time reduction mainly happens with design documentation production because it facilitates an almost automated documentation standard in each public institution and a standard process for reviewing procedures and submittals within the private sector institutions. However, there was no emphasis on how reducing cycle time is related to production systems optimization when the interviews were conducted. Additionally, it seems that there is no understanding or acknowledgment of production systems, or production management applications in projects, which are foundational concepts in the lean construction body of knowledge.

Decide by consensus considering all options

Public managers pointed out that designers use BIM models to evaluate different alternatives, reducing potential changes because of the previous visualization of potential issues and helping to incur in a set-based design approach. In this regard, the owner's involvement in the project comes with collaborative efforts from both parties, which is stated in the BIM policy. However, the public managers seem reluctant to understand how this collaborative effort might work, considering the current problems related to corruption allegations in public projects. This is a major root cause of the high levels of bureaucracy and poorly managed accountability of public projects.

Ensure comprehensive requirements capture & Ensure requirements flow down

These two lean principles are related as they intend to keep the value throughout the whole delivery phase of the project, considering building standards and end-user requirements, and properly translating these needs into technical decisions. For this reason, implementation of BIM uses such as design review, visualization, and automation through BIM models allows to keep track of the value and benefits of the project to their users and beneficiaries. These BIM uses allow for the overseeing of any potential building standard infraction and the keeping of the "value" intended for the project by visualizing and analyzing the early design during the design review process with BIM models. Furthermore, one of the interviewees mentioned that in one police department project, the designers were able to show the final product to the police officers (beneficiaries) to use the building, and they were able to discuss project decisions thanks to the BIM models. This example highlights how BIM allows to maintain value by facilitating the interaction with the other stakeholders (primarily the ones not related to construction-related disciplines).

DISCUSSION

The findings of this research seek to understand the opportunities for lean construction implementation (*formally* or *informally*) by enabling lean principles within the context of BIM implementation policies. While the findings of this study show several opportunities for lean construction implementation in public projects, some concepts related to lean construction were required to be explained while conducting the interviews with the public managers. This study also did not ask for specific tools and methods (such as the Last Planner System or Target Value Design), but rather for the lean principles embedded in the lean tools and methods. The public manager's misconception of the relationship between lean construction and production management represents a challenge to the application of lean in the public sector. Furthermore, the concept of value in projects, along with its various implications, appears to be complex and is subject to varying interpretations by public managers. Lujan & Murguia (2022) also discussed this concept and how the Lean Project Delivery System can facilitate the definition of value in public projects.

In terms of the BIM uses or BIM functionality, the interviewees showed some confusion with the specifics and implications of each BIM use, such as the digital deliverable required to complete the application of each BIM use. The interviews were facilitated by providing different names for each BIM use depending on the literature used by the public managers. Regardless, the BIM uses table developed by Plan BIM Peru is supposed to be used as the standard for this type of effort. The BIM Dictionary developed by the BIM Excellence Initiative (BIM Dictionary, 2024) is expected to clarify this concern and have only one source, if possible, to obtain BIM-related definitions. This research needed to "cluster" BIM uses to match the BIM functionality stated in the original lean and BIM interaction matrix. Furthermore, obtaining a more granular table between the interaction of lean construction and BIM uses (not BIM functionality) might provide different results from the ones obtained in Table 2.

Previous studies on the interactions between lean construction and BIM for specific principles and functionalities have not used case studies in developing countries. This study shows empirical results on how these relationships emerge in public construction projects. However, since the authors used the preestablished lean principles associated with the BIM functionality in the design phase of projects, there might be more lean principles enabled by the same BIM functionality. Considering a different lean construction and BIM interaction framework, such as the ones proposed by Karatas & Budak (2023), can also provide a different perspective on the implications of lean construction and BIM implementation altogether in public projects.

These results also provide a broader perspective of two significant opportunities. First, the option of enabling lean principles as part of the BIM mandate, considering the benefits of implementing these two construction paradigms together. This can also be useful in setting a new trend in the Latin American region towards an improved construction sector as eight countries follow a similar BIM implementation journey. Second, considering an even broader perspective, LIPS can also include more case studies of the enablement of lean construction in public projects (and public organizations in general) as it represents a very challenging topic to implement lean towards a more holistic approach. This second opportunity is also related to other efforts trying to implement lean-related concepts (not only within the construction industry). An example of these efforts was presented by Bathia & Drew (2006), Monyane et al. (2018), and Andersson et al. (2020) in the literature review section of this paper.

By adding lean principles to the current BIM mandate for public projects, benefits will arise as the interaction of lean construction and BIM are virtuous, and these two innovations support each other. Moreover, this research presented a baseline to understand better the interaction of lean and BIM from a developing country perspective.

CONCLUSIONS

This research aimed to understand the opportunities for lean implementation using BIM as an enabler in the public sector. To achieve this objective, this study focused on the lean construction and BIM interactions presented in the Sacks et al. (2010) interaction matrix to construct a more specific framework, which was then used to interview public managers of the Peruvian public construction sector and validate the enablement of lean principles. The findings show that the implementation of BIM enables eight lean principles uses: reduce variability, go and see for yourself, verify and validate, use visual management, reduce cycle time, decide by consensus considering all options, ensure comprehensive requirements capture, and ensure requirements flow down. Although these lean principles seem to appear "informally" during the delivery of public projects, more practical applications of lean were also pointed out in the case study, such as The Last Planner System, value stream mapping, set-based design, A3 reports, and other lean tools and methods being used in public projects.

This study has some limitations including the project phase under examination and the unique context of the Peruvian public sector. Future studies could conduct in-depth case studies to reveal more insights into the body of knowledge of how lean construction and BIM interact. Moreover, this study reveals new perspectives of a more integrative umbrella for implementing digitalization and production management in construction, which are being exposed in the construction industry through BIM and lean construction, respectively. Therefore, conducting future research considering these wider perspectives could be beneficial to understanding a more integral improvement process of the construction industry.

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FROM CONCEPT TO CONCRETE: DIGITAL TWINS ENABLING DIFFERENT LEVELS OF LEAN CONSTRUCTION

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ABSTRACT

The integration of Digital Twins (DTs) in Lean Construction (LC) represents a transformative approach to enhance collaboration, efficiency, waste reduction, and decision-making in construction projects. This paper explores the potential of DTs across different levels of LC through a comparative analysis method, aiming to establish a robust implementation foundation for lean organisations. Firstly, at the philosophy level, DTs foster collaboration, transparency, and respect for people by providing real-time data and virtual representations. They enable value maximisation, waste minimisation, and continuous improvement through visualisation, simulation, and data-driven decision-making. Besides, continuous improvement through monitoring and feedback loop. Secondly, at the principles level, DTs align closely with key LC principles such as value maximisation, continuous improvement, waste elimination, pull planning, continuous flow, and fast switch-over. By optimising processes, enhancing monitoring capabilities, and facilitating collaboration, DTs contribute to efficient project delivery. Thirdly, at the methods level, DTs complement LC methods such as Error Proofing, Value Stream Mapping, Target Value Design, and Last Planner System by facilitating real-time collaboration, visualising workflows, engaging stakeholders early, and providing error prevention capabilities. Overall, the strategic integration of DTs and LC thinking leads to improved project efficiency and value delivery, fostering ongoing innovation and improvement in the construction sector.

KEYWORDS

Lean construction (LC), Digital Twin (DT), Philosophy, Principles, Methods.

INTRODUCTION

In the ever-evolving landscape of construction, digital technologies integration has become a cornerstone for achieving efficiency, reducing waste, and ensuring optimal project outcomes (Tuhaise et al., 2023). One such revolutionary technology is the concept of Digital Twin (DT). It can be defined as an emerged transformative technology, offering a virtual replica of physical objects, systems, or processes (Maksimović, 2023). This means constructing a virtual duplicate

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of a physical asset or process, to enable ongoing monitoring, data analysis, and simulation of diverse scenarios. Its applicability spans various sectors, including manufacturing, construction, and the oil and gas industry (Ferrigno & Barsola, 2023).

On the one hand, DTs have significantly lowered the development cost of new manufacturing methods, enhanced efficiency, decreased waste, and minimised batch-to-batch variability (Attaran et al., 2023). On the other hand, DT has emerged in the construction sector to introduce innovative methods of controlling production during projects (Sacks et al., 2020). It combines information from a range of onsite monitoring technological equipment to offer precise and up-to-date information for effectively evaluating and enhancing the entire project process outcome. According to Sacks et al., this can be achieved through the integration of Building Information Modelling (BIM) technology, Artificial Intelligence (AI) functions, DT concepts, and lean construction (LC) thinking to create a data-centric approach to construction management aiming to enhance the overall construction sector. For instance, the integration of these technologies has the capacity to facilitate decision-making and operational processes for general contractors throughout all phases of construction. This leads to several advantages, including cost reduction, improvement in collaboration, efficient information exchange, and the implementation of construction management practices driven by data (Lv et al., 2022).

In the construction sector, DT aims to achieve several objectives. Firstly, it offers live information and evaluation of physical assets, enhancing building design, construction, and performance in architecture, engineering, and construction (AEC) sectors (Nguyen & Adhikari, 2023). Secondly, it facilitates the evaluation of potential business models by utilising stored data, aiding decision-making for future innovations (van der Veen et al., 2023). Thirdly, a DT holds the potential to revolutionise various areas in construction, including virtual design, project planning, asset management, safety, energy efficiency, structural health monitoring, sustainability, quality control, supply chain management (Omrany et al., 2023). Fourthly, its integration in construction offers benefits like improved project management, reduced errors, increased productivity, despite challenges such as initial costs and data management (Nalioğlu et al., 2023). Additionally, DTs synergise with LC, fostering collaborative efforts and aiding in the identification of benefits, costs, opportunities, and risks in LC projects.

Lean Construction (LC) is a methodology designed to reduce time, efforts, and waste of resources while optimising value in production systems (Koskela et al., 2002). It focuses on efficiency, collaboration, and waste reduction across four levels: philosophy, principles, methods, and tools and implementation (Do, 2022). Firstly, philosophy establishes foundational principles of LC incorporating “respect for people, maximising value while minimising waste, and continuous improvement”. Focusing on philosophy initially establishes the fundamental “WHY” of the lean journey. Secondly, the principles constitute the “HOW” concepts, encompassing timeless ideas such as Visual Management, Continuous Flow, Kanban, Fast switch over, Takt, Poka-yoke, etc. Thirdly, method such as Takt Planning, Set-Based Design, Last Planner System (LPS), Target Value Delivery (TVD), Choosing by Advantages, among others, guide LC implementation. Finally, these methods are applied in real-world settings using Lean tools or implementations, categorised as hybrid, analogy, or digital.

Therefore, LC aims to enhance time, cost, and resource management in construction projects by minimising waste, improving communication, and fostering collaboration (Altan & Işık, 2023; Oke et al., 2021). The adoption of LC practices has shown benefits, such as shortened project durations, reduced costs, and optimised resource allocation (Barkokebas et al., 2023). However, Do (2022) emphasised on aligning the three fundamental levels (philosophy, principles, and methods) during LC implementation, a crucial aspect often overlooked by many lean organisations. Moreover, DT is emerging as a transformative technology in construction, aiming to provide real-time data and analysis of physical assets, support decision-making, revolutionise the industry, advance processes, and interact with the LC concept. Therefore, the combination of lean principles and technological innovation might be a powerful tool for reducing waste and uncertainty in the construction operational process (Owais et al., 2023; Sacks et al., 2020).

Problem Statement: Despite its potential, the implementation of DT in construction has not been sufficiently addressed through different levels of lean thinking to establish a robust implementation foundation for lean organisations. Therefore, the aim of this research is to explore how DTs complement various levels of applying lean thinking to achieve their objectives. This investigation encompasses both conceptual and concrete dimensions. Conceptually, the study delves into the foundational philosophy, principles, and methods of DTs and LC, elucidating their collaborative potential in enhancing project efficiency and value delivery. At the concrete level, the research investigates the real-world applications of DTs and LC methodologies, aiming to bridge the future gap between theoretical frameworks and tangible outcomes in the construction sector. Through this comparative analysis, the research endeavours to establish a robust implementation foundation for lean organisations seeking to leverage DTs for optimised construction project management.

RESEARCH METHOD

This study employs a comparative analysis method to explore the integration of DTs into LC thinking. Comparative analysis plays a crucial role in theory development across various fields of research by enabling researchers to compare multiple units of study, identify correlations, and draw meaningful conclusions (Devi, 2023). The following steps have been carefully elaborated to explore the integration of DTs into LC thinking:

1. Data Collection:

- Literature Review (LR): A comprehensive LR was conducted to understand the current advancements in LC levels and DTs. Using specific search parameters such as “Lean Construction,” “Philosophy,” “Principles,” “Methods,” and “Digital Twins” on Google Scholar, journals, conferences, and books, a pool of 148 articles from 2016 onwards was identified. Subsequently, the research team analysed and curated articles focusing on LC levels and DTs, resulting in a final set of 18 articles for detailed examination.

2. Data Analysis:

- Comparative Approach: A structured comparative approach was developed to analyse the alignment between DTs and LC across different levels. This approach enables the systematic evaluation of similarities, differences, and synergies between DTs and LC.
- Categorisation: Data from the LR were categorised based on key themes and concepts related to DTs and LC levels, facilitating a deeper understanding.
- Cross-Comparison: Data from various sources were cross-compared to identify common patterns, trends, and implications, allowing for the synthesis of overarching insights.

3. Findings Interpretation:

- Synthesis of Results: Findings from the comparative analysis were synthesised to draw conclusions on the benefits and implications of integrating DTs into LC levels, highlighting key themes, and discussing their significance as shown in Figure 1.
- Practice Implications: Practical implications, challenges, and future research are provided to enhance construction practitioners and organisations adopting DTs within their LC frameworks, emphasising collaboration, efficiency enhancement, and value maximisation.

In summary, the comparative analysis method employed in this study offers a systematic and rigorous approach to examining the integration of DTs and LC, providing valuable insights and actionable recommendations for advancing lean practices in the construction industry.

DIGITAL TWINS ORIGIN AND CONCEPT

While the use of DT has achieved immense recognition in recent years, the idea itself is not entirely novel. Gelernter (1993) book "Mirror Worlds" introduced the concept of DT, envisioning software systems that simulate reality by integrating data from the physical world. He described DT as creating "Mirror Worlds," allowing users to interact with complex systems digitally. This early anticipation indicated DT's widespread application in diverse fields.

In 2002, Grieves' introduced the Mirrored Spaces Model (MSM) within discussions on Product Lifecycle Management (PLM), marking an unofficial presentation of the DT concept (Grieves, 2005). This model emphasised the connection between actual and virtual spaces, highlighting the importance of data exchange for understanding PLM information. In 2006, Grieves renamed the conceptual model to the 'Information Mirroring Model'(Grieves, 2009), emphasising bidirectional linking between spaces and the use of multiple virtual spaces for a single real space, fostering exploration of alternative ideas. However, practical DT applications faced challenges due to technological limitations, including low computing power, limited connectivity, and data management issues, as well as nascent machine algorithms.

In 2010, the term "Digital Twin" was publicly introduced by the National Aeronautics and Space Administration (NASA) within their collaborative technology roadmap, specifically within Technology Area 11: Modeling, Simulation, Information Technology, and Processing (Shafto et al., 2012). The idea was inspired by NASA's Apollo program, in which two identical spacecraft were constructed to allow the circumstances of one spacecraft to be mirrored during its journey (Shafto et al., 2010). The spacecraft that stayed on Earth was identical to the one that travelled in space.

Additionally, Tuegel (2012) highlighted the US Air Force's adoption of DT technology for aircraft development, repair, and forecasting, following NASA's lead. The aim was to replicate the mechanical and physical qualities of aircraft to predict signs of fatigue or cracks, thus extending their usable life. The concept of creating a digital representation of physical systems for analysis has existed for decades. This approach gained momentum in the construction sector with technological advancements, such as BIM, as observed by Nguyen and Adhikari (2023).

BIM entails creating digital models of buildings and infrastructure, continuously updated with real-time data, enabling better project visualisation and management (Nguyen & Adhikari, 2023). The integration of DTs into construction likely emerged alongside advancements in BIM technology. van der Veen et al. (2023) and Omrany et al. (2023) both note the gradual adoption of DTs in construction for enhanced project planning, design, construction, and maintenance, as part of a broader trend towards digital transformation across industries.

EVOLUTIONARY PROGRESSION OF DIGITAL TWINS IN CONSTRUCTION

Academic interest in DT technology, particularly in construction, has surged, resulting in numerous studies highlighting its benefits. Despite being in early stages, research has extensively examined DT applications, benefits, and challenges. For instance, Rasheed et al. (2020) explored the values, challenges, and enabling technologies of DTs, emphasising their potential to revolutionise industries and societal interactions. Their framework of Virtual Twin, Predictive Twin, and Twin Projection pillars offers clarity, with recommendations for collaborative efforts among stakeholders for successful implementation. Standardisation is crucial for facilitating interactions between DTs in a connected world. The authors thoroughly delve into DTs as virtual representations of physical assets driven by data and simulators, aiming to transform real-time prediction, optimisation, and decision-making processes. Recent advancements in computational pipelines, AI, and big data technologies have elevated DTs into a crucial trend across diverse applications.

Lee et al. (2021) explored merging DT and blockchain frameworks to enhance traceable data communication in construction projects. They addressed the challenge of fragmented information sharing among stakeholders by integrating a DT updated in near real-time through IoT sensors. Blockchain ensured authentication and traceability of data transactions, enhancing transparency and security. Testing in a case project confirmed the framework's ability to trace all data transactions and generate compliance statements promptly. The main contribution lies in promoting accountable information sharing, which could streamline contract execution, payments, and decision-making, fostering better collaboration among fragmented participants.

Akanmu et al. (2021) mentioned, also, DT play a pivotal role in revolutionising the construction industry by bridging the gap between physical assets and their virtual counterparts. This transformative technology, as underscored by recent research findings, enhances safety, efficiency, and real-time control in construction projects. The authors emphasises that the integration of DTs with emerging technologies such as virtual design modeling, sensing, and robotics forms the next generation of cyber-physical systems in the construction. These advanced systems not only improve workforce productivity, health, and safety but also offer substantial potential for lifecycle management of building systems and competency enhancement. Despite challenges, the adoption of DTs emerges as a critical catalyst for the industry's evolution toward enhanced automation and sustainable construction practices.

Yeung et al. (2022) explored the Digital Twin Construction (DTC) concept, a data-driven approach integrating BIM, LC, DTs, and AI in construction management. They emphasised simulation's role in DT, highlighting predictive situational awareness, data-driven continuous improvement, and future autonomous real-time production control. Barriers to simulation in DTC workflows are discussed, with proposed criteria for tool evaluation. The study underscores the empowering nature of DT in construction, enabling planners to optimise decisions based on comprehensive project status information and envisioning a future with autonomous production control systems. The research contributes to prototype simulation tool development within the BIM2TWIN project's virtual Plan-Do-Check-Act cycle.

Arsiwala et al. (2023) addressed the impact of Industry 4.0 on the construction sector, with a focus on achieving net-zero carbon emissions through the use of DTs. Focusing on existing assets, the research introduces a DT solution integrating IoT, BIM, and AI to automate monitoring and control of CO2 emissions. The study underscores BIM and IoT's significance for spatial information visualisation and introduces AI for predicting emissions. It proposes a user-friendly DT architecture, validated through a real-life case study, illustrating its potential in visualising real-time indoor air quality. The authors highlighted the broader implications, such as nationwide digitisation for policy making and emphasisse interdisciplinary collaboration for seamless data exchange standards in the construction industry.

ALIGNING DTS WITH LEAN CONSTRUCTION LEVELS

Technology has found its roots in the construction industry, aiming to revolutionise the sector. Many researchers have examined the emerging potential in construction, seeking to improve project outcomes with the aid of various technologies. Despite DT technology being in its infancy stage, this section will examine the emerging benefits and how DTs aid LC at different levels, including philosophy, principles, and methods. Moreover, Figure 1 will illustrate the integration benefits at the end of this section.

DT's IN SUPPORTING LC PHILOSOPHY LEVEL

LC philosophy emphasises, firstly, respect for people by fostering collaboration, value-driven communication, and a positive work environment. Secondly, it focuses on maximising value while minimising waste through optimising processes to deliver quality results efficiently. Lastly, continuous improvement is considered the central point of encouraging ongoing learning, adaptation, and innovation for enhanced project outcomes and efficiency (Do, 2022). Several studies have examined the potential of DT in LC philosophy as an emerging technology that can aid construction project outcomes.

For instance, Sacks et al. (2020) conducted a study on DTC, integrating BIM, LC, and AI for data-centric production construction management. The research identified four key information and control concepts, delineating DTC's conceptual framework. They proposed a DTC information system workflow comprising information stores, processing functions, and monitoring technologies within three concentric control cycles. DTC is positioned as a comprehensive construction management approach, prioritising closed-loop control systems over traditional BIM tools. The authors stressed the importance of effective DTs in construction, highlighting challenges in collaboration, interoperability, and real-time monitoring. They advocated for a cohesive workflow for DTC planning and control across design and construction phases to achieve optimal project outcomes.

Barkokebas et al. (2023) have similarly advocated for the integration of a DT to enhance production flexibility in Offsite Construction (OSC), where building components are prefabricated and then assembled on-site. The OSC industry faces challenges in adapting to uncertainties, multiple projects, and variable market demands. The proposed DT leverages real-time data to autonomously reassign multiskilled workers, addressing the lack of flexibility in labour-intensive processes. Applying lean thinking metrics, the study quantifies improved production performance by considering waste reduction. Through simulation, various scenarios are assessed, revealing significant enhancements in reducing waiting time, production duration, and overall cost, affirming the DT's effectiveness in managing multiskilled workers in OSC.

Nevertheless, the authors of this research have meticulously examined, analysed, and explored the direct connections between the emerging benefits of DT and LC concept. In their pursuit of a robust implementation, they have focused on linking this emerging technology, specifically, with LC philosophy levels as a first step to address the research gap. This strategic linkage aims to enhance collaboration, efficiency, and construction project decision-making. By integrating DT into LC philosophy, the authors envision a culture that fosters lean philosophy foundation. This approach not only enhances project outcomes but also lays the foundation for a more streamlined and adaptive construction process, ultimately leading to more efficient and sustainable projects. The linkage is as follows:

Respect for People:

Collaboration and Communication: DTs offer a centralised platform that enables real-time access and sharing of project data among stakeholders (Lee et al., 2021). This accessibility breaks down silos between different project teams, fostering seamless collaboration. Team members can readily communicate, share insights, and coordinate efforts more effectively. By leveraging DTs, LC practices can be enhanced as the technology supports a collaborative environment that values everyone's expertise and contributions. This aligns with lean thinking, emphasising the importance of leveraging collective knowledge and skills to improve project outcomes.

Transparent Information: DTs ensure transparency by making project data readily accessible to all relevant parties (Rasheed et al., 2020). This transparency fosters open communication, ensuring stakeholders are well-informed about project developments and decisions. Transparent information sharing promotes trust among stakeholders, reducing misunderstandings or conflicts arising from incomplete or outdated information. Moreover, it enables stakeholders to contribute their perspectives to decision-making, leading to informed and consensus-driven decisions. This alignment with lean philosophy optimises project outcomes by leveraging stakeholders' collective intelligence.

Maximising Value While Minimising Waste:

Visualisation and Simulation: DTs offer a virtual representation of construction projects, enabling teams to visualise detailed project aspects before physical construction (Tuhaise et al., 2023). Through simulation capabilities, teams can explore diverse scenarios, test design alternatives, and optimise workflows. Early identification of issues and inefficiencies in the virtual environment allows proactive risk mitigation and waste reduction during actual construction. This capability aligns with lean philosophy by promoting continuous improvement and eliminating non-value-adding activities, ultimately enhancing project efficiency and value delivery.

Data-Driven Decision Making: DTs collect real-time data from sensors and IoT devices deployed across construction sites (Tuhaise et al., 2023). This data encompasses project progress, resource utilisation, environmental conditions, and equipment performance. Analysing this data provides valuable insights into construction process performance, enabling teams to identify improvement areas and make informed decisions for optimising project outcomes. Data-driven decision-making minimises waste by addressing inefficiencies, reallocating resources effectively, and optimising schedules and workflows to maximise value delivery. This approach aligns with lean philosophy, emphasising data-driven continuous improvement and waste elimination throughout the construction lifecycle.

Continuous Improvement:

Real-Time Monitoring and Analysis: DTs facilitate continuous, real-time monitoring of construction processes and performance through data collection from sensors, IoT devices, and project management systems (Omrany et al., 2023). This data encompasses key metrics such as project progress, resource utilisation, quality, and safety. Analysis of this data enables project teams to identify bottlenecks, areas for improvement, and opportunities for optimisation. Real-time monitoring empowers teams to proactively address issues, optimise workflows, and enhance project efficiency. By integrating DTs for continuous monitoring and analysis, LC projects can identify improvement opportunities and implement iterative changes, fostering continuous improvement throughout the project lifecycle.

Feedback Loop: DTs establish a constant feedback loop by continuously updating project information and providing timely insights into project performance (Rasheed et al., 2020). As data is continually updated and analysed, teams can learn from DT-generated insights and adjust processes accordingly. This feedback loop enables teams to adapt to changing conditions, address emerging issues, and implement improvements iteratively. By leveraging DT insights, project teams make data-driven decisions, continually enhancing project outcomes. This iterative approach aligns with lean philosophy, emphasising ongoing learning, adaptation, and refinement to optimise processes and deliver maximum value.

DT'S IN SUPPORTING LC PRINCIPLES LEVEL

The integration of DTs into the construction process aligns with several LC principles, which constitute the HOW concepts focusing on enhancing quality, value, and efficiency while minimising waste in construction projects. LC is a management-based approach that aims to deliver better value to owners by eliminating material, time, and effort wastage (Fennema, 2022). Several studies have explored the benefits of DTs at the LC principles level.

For example, Martinez et al. (2022) investigated how DTC influences LC principles, focusing on production planning. They identified challenges in construction decision-making, such as limited real-time data access and regulatory complexities. Using a matrix, they correlated operational decisions, freedom of action, and professional roles within the DTC framework, revealing its transformative potential. The study highlights DTC's role in optimising construction operations by improving decision-making aligned with LC principles. By enhancing situational awareness and decision-making, DTC demonstrates practical benefits for the construction sector.

Altan and Işık (2023) investigated the integration of DT within LC to manage escalating construction project complexity. They emphasised the collaborative nature of these approaches and analysed the synergies between them. The study identified significant obstacles and enablers in this integration by examining the Benefits, Costs, Opportunities, and Risks (BOCR) associated with DT adoption in LC. Altan and Işık underscored the crucial role of DT in reducing the cost of skilled labour and capitalising on waste reduction opportunities within the LC framework. Their research offers valuable insights into the potential enhancements DT can bring to LC principles, providing a foundational understanding for industry practitioners and guiding future research initiatives. The authors of this research focused on aligning the following LC prominent principles with DT, as a second step in bridging the research gap:

Value: DTs optimise construction processes, foster collaboration, and enhance project efficiency (McHugh et al., 2023), aligning directly with lean principles emphasising value maximisation and waste minimisation. By utilising DT, construction teams identify and eliminate non-value-added activities, thus improving project outcomes and customer satisfaction.

Continuous Improvement: DT implementation provides real-time monitoring and data analytics, enabling construction teams to gather insights for continuous improvement (McHugh et al., 2023), reflecting lean principles focused on refining processes for enhanced efficiency and quality. Analysing performance data from DT allows teams to identify optimisation areas and make iterative improvements over time, aligning with lean's principle of continuous improvement.

Waste Elimination: DT reduces waste by enhancing resource utilisation, planning, coordination, and decision-making throughout construction (Seppänen, 2022), which aligns with LC's aim of eliminating waste in all forms, including time, resources, and effort. Leveraging DT streamlines processes and enhances decision-making, minimising waste, and maximising efficiency, aligning with lean principles.

Pull Planning: DT's real-time monitoring and simulation support pull planning by providing updated information on construction activity status (Omrany et al., 2023). Pull planning, a key LC technique, aims to align production with customer demand. With DT, teams adjust plans based on actual demand and progress, enabling efficient resource allocation, and reducing unnecessary work, aligning with lean's pull planning principle.

Continuous Flow: DT implementation offers a centralised platform for collaboration and communication, enhancing coordination among project teams, suppliers, and stakeholders (Ferrigno & Barsola, 2023). Effective communication and teamwork are LC fundamentals, emphasising collaboration's importance for efficient project goal achievement. DT enhances collaboration and communication, aligning efforts and streamlining workflows, in line with LC principles.

Fast Switch-Over: DTs enable fast switch-over by providing live data and simulations, allowing teams to adapt quickly to project requirement changes or conditions (Jungmann et al., 2023). LC prioritises responding swiftly to changes and disruptions while maintaining project flow and efficiency. With DT, teams assess change impacts and adjust plans to minimise downtime and maintain momentum, reflecting lean principles of agility and flexibility in project execution, ultimately improving overall performance.

DT'S IN SUPPORT LC METHODS LEVEL

LC methods represent a strategic approach to streamline project delivery in the construction industry, emphasising efficiency, waste reduction, and continuous improvement. Grounded in Lean thinking principles, these methods prioritise value creation for clients while minimising resources and time (Do, 2022). They serve as the practical means to achieve LC thinking after adopting its principles, representing the final step in bridging the research gap. These methods include SCRUM, Takt Planning, Reliable Promises, Set Based Design, Choosing by Advantages, TVD, LPS, etc. LPS and TVD, specifically developed and implemented for the construction sector, were highlighted by Do. Moreover, emerging DTs as advanced technology can enhance LC methods by providing a technology-driven infrastructure that fosters collaboration, efficiency, and decision-making throughout the building lifecycle. Several studies have explored the potential of emerging DTs in LC methods.

For example, Mao et al. (2022) highlighted significant research findings on integrating DT technology into LC methods. Their meticulous review identified key constituents crucial for efficient constraint management. They explored DT's fusion with constraint management, pinpointing potential constituents. The research emphasised the importance of: (1) Information technologies like BIM, Global Positioning Systems (GPS), and Automated Data Collection (ADC) for precise constraint modelling and data traceability; (2) Swarm Intelligence and Genetic Algorithm for addressing spatial and resource constraints during construction scheduling; (3) Semantic Web technologies, particularly ontology, enabling advanced constraint modelling; and (4) Lean-based methods such as LPS, WFP, and AWP for structured constraint resolution processes. These insights provide a roadmap for leveraging DT technology to optimise LC project efficiency and productivity.

Ramirez et al. (2022) tackled slow decision-making in multi-family building projects, especially in countries like Peru, causing economic losses and inefficiencies. Their solution integrates LC 4.0 methodologies, blending DTs and visual management. A Lima case study illustrates how DTs enable detailed project analysis, remote stakeholder involvement, and enhanced decision-making in quality controls. The LC and Construction 4.0 synergy proves effective, with over 70 per cent acceptance, validating LC 4.0’s technical feasibility and efficiency for improved global construction project execution and decision-making.

McHugh et al. (2023) investigated the integration of LC methods and digital tools in construction, focusing on a data centre case study. Through action research, they highlighted the LPS in establishing centralised digital command rooms. Digital tools, aligned with lean methods, enhance transparency, collaboration, and innovation. The study emphasised the importance of correct data management and skilled workers. Findings showcased how digital platforms improve communication, visibility, and collaboration, fostering a continuously improving project environment.

Recent research has underscored the emerging role of DT in LC methods. DTs provide virtual representations of physical assets and processes, aiming to revolutionise the construction industry. Within the context of LC methods, DTs hold the potential to enhance efficiency, reduce waste, and improve overall project outcomes. This discussion will explore how DTs complement prominent LC methods, drawing insights from the authors’ research of this paper. Their findings emphasise the significant impact of DTs on LC methods, suggesting the potential for DTs to revolutionise traditional LC approaches, as follows:

Last Planner System (LPS): DTs enable real-time collaboration by centralising a platform for project data among stakeholders, including designers, contractors, and clients (Rasheed et al., 2020). They provide access to live project data, such as schedules, progress reports, and design iterations, fostering effective communication and decision-making. For example, a DT platform can integrate scheduling software with real-time construction site data, allowing stakeholders to monitor progress, identify bottlenecks, and adjust accordingly. Teams can use the DTs to visualise the project schedule, allocate resources effectively, and coordinate tasks among different trades. This enhances communication and coordination, ultimately improving the reliability and efficiency of the LPS.

Value Stream Mapping (VSM): Integrating DT offers visual representations of construction processes, helping teams identify non-value-added activities and optimise workflows (Tuhaise et al., 2023). For instance, DT can simulate materials, equipment’s, and manpower flow, enabling teams to identify inefficiencies, such as excessive waiting times or unnecessary movement of materials and implement strategies to streamline processes. DTs with simulation capabilities can also help teams evaluate different scenarios and determine the most efficient layout or sequence of tasks to reduce lead times, aligning with VSM goals to streamline processes and eliminate waste.

Target Value Design (TVD): DTs facilitate early stakeholder engagement by providing virtual models for assessing design alternatives and their impact on cost and value (Adade & de Vries, 2023). They enable the alignment of project goals with budget constraints and client needs. For instance, architects and engineers create DTs of building designs, utilising parametric modelling to explore various configurations or materials. Stakeholders can visualise the model to evaluate the implications of design decisions on cost, schedule, and project value.

DTs promote collaborative decision-making, enabling teams to iterate on design concepts and align project goals with budget constraints from early stages, ultimately optimising project value in line with TVD principles.

Error Proofing (Poka-Yoke): DTs aid error prevention by simulating and validating construction processes before physical construction starts (Ferrigno & Barsola, 2023). Teams, for instance, can use DTs to simulate assembly sequences, equipment operation, or installation processes to identify potential errors or safety hazards. By analysing the virtual simulation, teams can proactively address issues such as clashes or structural weaknesses, minimising errors during construction. DTs offer a platform for virtual testing and validation, allowing teams to refine plans and ensure compliance with quality and safety standards, aligning with error-proofing and continuous improvement principles in LC methods.

Overall, Figure 1 below explores the outcomes of integrating DTs with different LC levels.

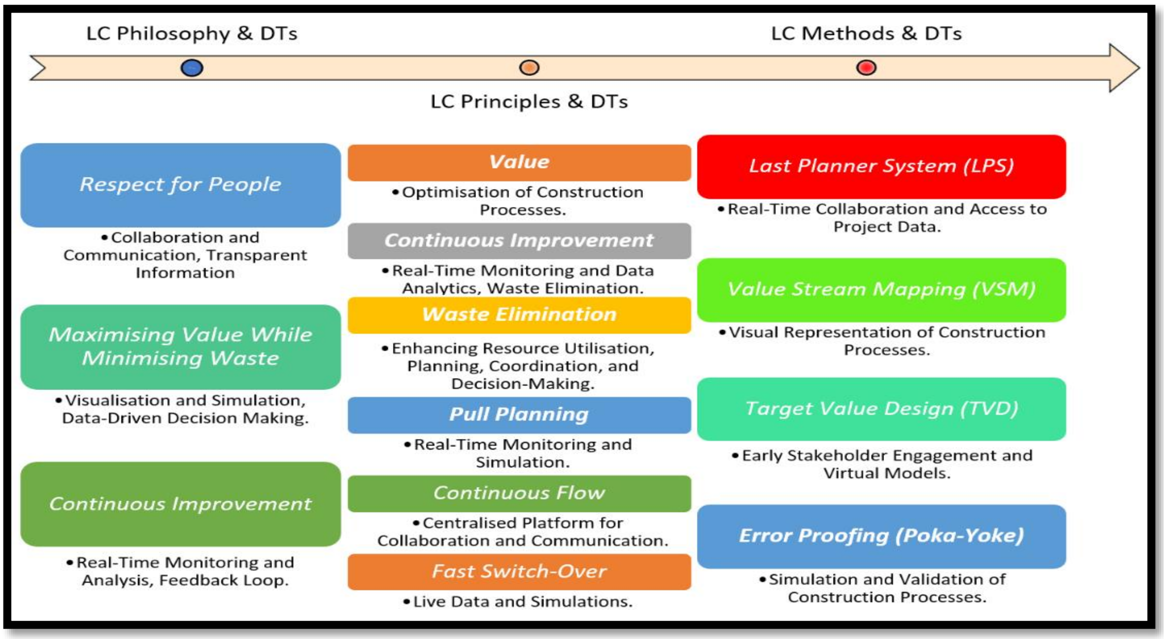

Figure 1: Benefits and Implementation of Integrating DTs into LC Levels

As a result, it is important to encompass the three identified levels of LC while integrating DTs. This is to establish a solid foundation for organisations aiming to adopt DTs within their LC frameworks, emphasising collaboration, efficiency enhancement, and value maximisation.

CONCLUSIONS

The integration of DTs into LC aims to revolutionise collaboration, efficiency, waste reduction, and decision-making in construction projects for optimal outcomes. However, DTs are still in their infancy stage and have not been sufficiently addressed across different levels of LC. Therefore, this research aims to fill the identified gap by revealing DTs' potential in supporting various levels of LC thinking, including philosophy, principles, and methods. The ultimate goal is to improve project outcomes for efficient and sustainable construction practices by establishing a solid implementation foundation for lean organisations.

At the philosophy level, DTs foster collaboration and communication among project stakeholders, promoting transparency and a culture of respect while maximising value and minimising waste through real-time data and virtual representation, aligning with the core thinking of LC through visualisation, simulation, and data-driven decision-making. As well as continues improvement through real time monitoring, analysis, and feedback loop. This philosophy extends to the principles level, where DTs closely adhere to LC principles such as value maximisation, continuous improvement, waste elimination, pull planning, continuous flow, and fast switch-over, contributing to efficient project delivery by optimising processes, enhancing monitoring capabilities, collaboration and communication, simulation, and enabling data-driven decision-making. At the methods level, DTs complement LC methods such as the LPS, VSM, TVD, and Poka-Yoke, facilitating real-time collaboration, workflow visualisation, stakeholder engagement, and error prevention, ultimately leading to enhanced project efficiency and value delivery.

Nevertheless, the integration of DTs with LC faces various challenges, including technological complexity, data privacy concerns, integration barriers, and limited industry adoption. Thus, future research endeavors should concentrate on simplifying DT solutions for the construction sector, addressing privacy and security issues, overcoming integration barriers, and exploring factors influencing adoption to unlock DT's full potential in LC.

In conclusion, integrating DTs into LC embodies a synergistic approach toward achieving lean objectives in construction projects. By harnessing DTs' capabilities to support collaboration, transparency, and data-driven decision-making, construction teams can streamline processes, reduce waste, and deliver greater value to stakeholders. This strategic integration lays the groundwork for more efficient and sustainable construction practices, fostering ongoing innovation and improvement in the industry. This conclusion is drawn from a comparative analysis method aimed at bridging the gap by revealing the linkage between DT and various LC levels.

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DIGITAL LAST PLANNER SYSTEM IMPLEMENTATION: CRITICAL SUCCESSFUL FACTORS

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ABSTRACT

Last Planner System (LPS) is the most popular and most widely adopted lean construction (LC) practice in the LC community. The growing maturity of LPS software encourages the implementation of digital LPS in-lieu of traditional analogue methods. With the boom in infrastructure investment in Victoria, Australia, this study aims to explore the critical factors for implementing digital LPS on Australian infrastructure projects. The study undertaken on one of five program alliances established to carry out rail and road level crossing removal projects. Adopting a case study approach, qualitative data was collected from 19 participants from two projects (Projects A and B). The findings indicate that the critical factors that underscore the successful adoption of digital LPS falls under a combination of technology, people, and organisational aspects. This includes using a suitable digital LPS platform, having LPS champions, getting employees' buy-in, putting organisational support in place, and many others. This study also confirmed the roles that people and organisations play in driving successful adoption of digital LPS. Given this, the implications for roles such as LPS champions at project level and supporting roles within organisations are discussed. Although these are unique contextual factors, it is anticipated that this success story of adopting digital LPS will prove transferable to the Australian construction sector when the critical factors are in place.

KEYWORDS

Lean Construction, Digital Last Planer System, Australia, Infrastructure projects, Critical success factors

INTRODUCTION

It is commonly acknowledged that manufacturing and construction differ in many ways, but the lean movement from manufacturing has become an aspiration for construction. The term Lean Construction (LC) literally means the application of lean principles and practices in construction, aimed at minimizing waste and maximizing value. This approach is gaining popularity globally. Despite the fact that the last planner system (LPS) is the most popular and most widely adopted lean construction (LC) practice in the LC community (Daniel et al., 2015), there is little evidence to indicate LPS has been adopted in Australia's construction industry. A quick search of the IGLC database provides little information. Early studies include Hackett et al. (2019), which developed LPS guidance principles based on a longitudinal research spanning over 18 months investigating LPS adoption on seven sequential refurbishments of a liquified natural gas plant in North West Australia. Fauzan and

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Sunindijo (2021) noted the implementation of a few basic lean tools, including LPS, is adequate but this study was based on a very small sample in Sydney, Australia. The question remains of whether Australia really is lagging in terms of deploying LPS practice. We set this study in Victoria and in the context of level crossing removal projects. This is because Victoria is currently in a transport construction boom, with an $90 billion investment delivering over 165 major road and rail projects across the state. For example, the Victorian government is committed in removing 110 dangerous and congested level crossings across Melbourne by 2030, the largest project of its kind in Victoria's history. With the boom in infrastructure investment in Victoria, Australia, this study aims to explore the critical factors for implementing digital LPS in local infrastructure projects. This adds to the body of knowledge of LPS implementation, not only in terms of its adoption in a relatively new geographical location, but also sheds light on adoption issues with the digital platforms that enables LPS.

LITERATURE REVIEW

DIGITAL LPS

The Last Planner System is a construction-based lean practice that might not be well-known outside of the construction industry. On account of its unique feature of bringing frontline crews in to discuss plans in a collaborative fashion, LPS is also known as collaborative planning in the UK (Daniel et al., 2015). Much has been written about LPS—from what it is and its origins (Ballard, 2000), to its principles, fundamentals, and how to use it effectively (Ballard & Tommelein, 2021). Additionally, the positive impact of LPS on performance (Liu et al., 2010; Tezel et al., 2018), and the barriers to implementing LPS (Perez & Ghosh, 2018) have been well documented. There are many case studies of LPS implementation across the globe, from developed countries like the UK (Daniel et al., 2016) to developing countries like India (Bhatla et al., 2016), allowing readers and even practitioners to find a relevant one to suit their local context. A point that may be worth reiterating here is that the term Last Planner refers to whoever makes the work assignment, often someone close to the site and in the lower levels the hierarchy. It is thus a bottom-up process instead of a way of pushing plans to frontline workers. As a system, it is structured in a tiered way comprising master planning, phase planning, look-ahead planning, and finally weekly production planning.

One area that is relatively less well explored is discussion of digital applications for implementing LPS. There is no doubt that digital LPS is becoming more popular thanks to a few driving forces. First, the increasing maturity of the technology with cloud computing (which many digital LPS platforms operate on). The logic is straightforwardly that of moving the traditional physical white board plus sticky notes to a digital environment. Second, the spread of COVID globally, together with stringent rules from government, is 'forcing' contractors to adopt more flexible systems that support remote working. In this context, digital LPS platforms serve that purpose. Gao et al. (2023) reviewed a few digital LPS applications from multiple case studies, and concluded a number of key requirements for digital LPS including: a reality capture strategy (McHugh et al., 2021), engaging stakeholders (McHugh et al., 2021), IT infrastructure associated with visual management (Hua & Schwartz, 2021), and a low user threshold (Thorstensen et al., 2013). Gao et al. (2023) discovered key barriers to digital LPS implementation include: little support from the supply chain partners, increasing planning efforts required, high staff turnover, and many others.

CRITICAL FACTORS

A critical success factor (CSF) for LPS, is a strategic action or activity necessary for an organisation seeking to promote increased adherence to the use of LPS. The literature notes a long list of CSFs for LPS implementation, falling under four groups:

- Behavioural factors: Research suggests that LPS users are required to respond to a number of enabling behaviours that are related to or promoted by LPS in order to secure successful implementation (Fauchier & Alves, 2013).
- Organisational factors: Organization plays a critical role in LPS implementation, where numbers of enabling factors are identified supporting the use of LPS. Paez et al. (2005) emphasized that organisations should provide recognition to promote the required behaviour change, as mentioned in previous section, together with the enabling factors allow focus on organisation strategy.
- Procurement factors: Research found that procurement methods have an impact on the application of the LPS, but that no single procurement method is a certain way leading to full application of the LPS process on a project. The use of collaborative procurement methods facilitates greater integration among project stakeholders through increased involvement of site teams (Daniel et al., 2018) in order to achieve better performance (Samudio & Alves, 2012).
- Contractual factors: Together with the procurement method, the selection of contract is also critical if the LPS to be well implemented (Daniel et al., 2016).

METHODS

RESEARCH DESIGN

This study is set in the context of Melbourne, Victoria, where the city is investing in and upgrading the road and rail network to accommodate population growth. One of the Victorian government's key transport infrastructure projects is the Level Crossing Removal Project (LXRP) (Victorian Auditor-General, 2017). The delivery model for achieving these is to use a programme alliance-based model. The Program Alliance model allows LXRP to break mega-projects into smaller more manageable packages, enabling more time and effort to be applied in front-end engineering, planning and development. The government established five on-going programme alliances to deliver the work packages within the programme. The first and second authors have worked closely with one of the programe alliances - Western Programme Alliance (WPA) when the Continuous Improvement and Innovation Manager introduced the digital Last Planner System to Project A as a pilot, and later rolled it out to other projects, including Project B. By the time the fieldwork commenced, WPA, was working on five level crossing removal projects. The level crossing removal projects will make road and rail travel easier, faster and more reliable for Melbourne. Instead of using the traditional white board plus stickie note styled LPS, the case projects used digital LPS for reasons like large complex projects, overwhelming information that will make the stickie notes on white board hard to update. This study aims to explore the critical factors of LPS implementation.

There is no shortage of explorations of the critical success factors of Lean implementations or the last planner system, in particular. However, there is one fallacy worth commenting on here: in some research, participants are asked about their perspectives on critical successful factors of LPS adoption, without confirming whether the lean practices or LPS were actually being implemented. To address this particular shortcoming, the present study is based on a case study (Projects A and B) that has witnessed successful digital LPS adoption. We then used the qualitative approach to understand the critical factors associated with the digital LPS implementation. This resulted in more reliable perspectives from research participants—the end-user of the digital LPS platform.

We carried out a comprehensive literature review capturing a long list of critical factors that which can be used for the survey, but we did not do so because we were reminded that potential respondents may not appreciate lengthy survey items of critical success factors. Instead, we alternated our fieldwork strategy by asking three simple questions:

- Do you think implementing LPS is a success?
- What are the critical success factors that drive successful implementation of digital LPS?
- What support is available and needed to improve future implementation of digital LPS?

INTERVIEWS

The research team interviewed 19 end users of digital LPS platform. They were from two WPA projects: Project A and Project B (see Table 1). Each interview lasted approximately 60 minutes. Five interviews were conducted in person, the remainder online through Microsoft Teams. The most experienced interviewee had 21 years of experience, the least, 1 year, and an average was about 10 years. It is interesting to note that, according to Table 1, the average LPS experience is low, except for Interviewee A1, who had previously worked in America, where LPS adoption is more mature. Most interviewees were engineers (11 out of 19), including project engineers, site engineers, and junior engineers. Four supervisors, two superintendents and two construction managers took part in the interviews. From a hierarchical point of view, the superintendent manages supervisors, and project engineers report to the construction manager.

Table 1: Interviewee demographics

Participants	Position	Experience in construction (No. of years)	Experience in project Alliance (Nr. of years)	LPS software (Nr. of years)
Interviewee A1	Superintendent	21	4	8
Interviewee A2	Project Engineer	10	1	1
Interviewee A3	Senior Project Engineer	10	1	1
Interviewee A4	Senior Supervisor	20	1	1
Interviewee A5	Project Engineer	7.5	2.5	2.5
Interviewee A6	Project Engineer	5.5	2.5	1.5
Interviewee A7	Construction Manager	12	4	-
Interviewee A8	Project Engineer	8	3	3
Interviewee B1	Construction Manager	18	2	1
Interviewee B2	Junior Engineer	1	1	1
Interviewee B3	Engineer	7	1	1
Interviewee B4	Site Engineer	2	1	1
Interviewee B5	Site Engineer	4	4	1
Interviewee B6	Project Engineer	2	6	2
Interviewee B7	Junior Engineer	1	3	1
Interviewee B8	Supervisor	12	1.2	1.2
Interviewee B9	Supervisor	10	1.5	1.5
Interviewee B10	Plant Supervisor	20	1.5	1.5
Interviewee B11	Lead Superintendent	20	4	-

RESULTS

SUCCESSFUL INITIATIVE

When asked if they thought the LPS implementation was a success, in general, all interviewees at Project A noted a positive YES. The majority at Project B also agreed that it is a successful initiative, except for some slight reservations from a few interviewees, which are listed below:

- Interviewee B4 (site engineer) indicated a "maybe", noting that digital LPS should not be used as a booking tool.
- Interviewee B7 (junior engineer) indicated "yes to a degree", noting that digital LPS performs its function but that there are many areas where it could improve.
- Interviewee B8 (supervisor) commented that it was "not a failure", noting that "*it has a good start, and gets better as more people use it, embrace it and learn the functionality of it*".

CRITICAL SUCCESS FACTORS (CSF)

Given the positive perception of the introduction of digital LPS, the follow-up question was: *What enables the success of such an initiative?* This hoped to identify the CSF that supported the digital LPS implementation thus far. Table 2 lists the factors, in the form of keywords, that were captured from the interviewees' responses. There is no weighing to it, but the frequency recorded at the bottom row of Table 2 shows the more significant ones than others. The following paragraphs describe the points mentioned most by interviewees: they are digital LPS itself (10), champions (5), buy-in (5), and support (5).

Table 2: CSF of digital LPS implementation

No.	Commitment	Champion	Trust	Organizational Support	Buy-in	Less interface	Team efforts	Digital LPS itself
Interviewee A1	X		X	X			X	X
Interviewee A2		X						
Interviewee A3	X							
Interviewee A4		X	X	X				X
Interviewee A5		X		X	X			
Interviewee A6				X	X			X
Interviewee A7		X			X			
Interviewee A8								X
Interviewee B1				X				X
Interviewee B2		X			X		X	X
Interviewee B3	X				X		X	
Interviewee B4								X
Interviewee B5								X
Interviewee B6								X
Interviewee B7								X
Interviewee B8	X							
Interviewee B9						X		
Interviewee B10	-	-	-	-	-	-	-	-
Interviewee B11							X	
Total	**4**	**5**	**2**	**5**	**5**	**1**	**4**	**10**

Note: Interviewee B10 did not comment on CSF.

The digital LPS platform

The digital LPS platform was the most frequently mentioned CSF, particularly in interviewees from Project B, where the conversation on CSF was more focused on the features of the digital LPS platform than on an end-user perspective. We have masked the name of the digital LPS platform. It was highlighted that: *"All the good advantages of digital LPS contribute to the success of implementation" (Interviewee B8).* A closer examination of the comments on the technology—the features that end-users perceived as success factors—points to the following factors:

- Ease of use – the interviewees had good experience particularly with the offline environment functions and interface. One commented "*the offline environments was so convenient that we could start practising it and getting it right*" (Interviewee B1).

Another (Interviewee A6) noted "*Easy interface to use for most team members. No need for a huge amount of training*."

- Shows benefits quickly: one interviewee acknowledged that "*Everyone seem to be able to understand the benefits of the digital LPS platform…*" Interviewee B6 emphasized that especially "*Activities from different teams are all visible in the digital platform.*"
- Functioning: interviewees from Project B acknowledged that the digital LPS "*does its function, but there are lots of areas to improve on*" (Interviewee B7) whereas others noted that it was acceptable "*as long as it is doing its job*" (Interviewee B3).
- Facilitate behavioural change: "[allowing] *more communication with engineers*" (Interviewee B9) and '*making people more accountable for their scope and resources booked in…. it could be used for interfaces*" (Interviewee B6) were also welcomed.

Champions

Having a champion (or champions) was the top CSF suggestion of Project A interviewees. Project A's superintendent[4] (anonymised as 'XX' in Table 3) was applauded as a passionate champion and strong believer in LPS. More than half of the interviewees mentioned that superintendent's name when answering this question (see Table 3).

Table 3: comments noting importance of having a champion

Interviewees	Comments
Interviewee A2	"Having a champion to drive, follow the process"
Interviewee A4	"XX drives it well"
Interviewee A5	"XX firm on implementation, being supportive" and "XX also trains late entrants"
Interviewee A7	"XX's passion for it really drives the whole system. Jason managed all the resistance from engineers"

Organisational support

Apart from a champion who drives implementation on the ground, support from the organisation is also essential. The Continuous Improvement and Innovation Manager oversees the roll-out of digital LPS platform across all WPA projects, and his support represents the organisational support. His support in the beginning, helping the team set up and use the digital platform, is of particular importance, and his continuous support along the way is crucial. One interviewee (Interviewee B11) recalled "*I was on the phone with him more or less daily when we first started digital LPS at project B*". However, one comment noting "*Leave the Continuous Improvement and Innovation Manager to generate reports*" seems to suggest there was an over-reliance on the Continuous Improvement and Innovation Manager supporting LPS on projects. It is reasonable to assume that the site would quickly slip back to how things were previously planned if it were not for these key people's support.

Buy-ins

The next CSF is the buy-in from the ground. This was echoed by many interviewees, including: *"buy-in from our supervisory team, and engineers as well."* (Interviewee A6) *and "People are committed."* (Interviewee A3). Several interviewees noted that at the start it was not easy because of resistance. As Interviewee A5 echoed, *"resistant from the team at the start but after seeing the results, all settled"*. However, one of the ways to overcome resistance and get the

[4] Project A's superintendent's name is masked here for anonymous purpose.

team's buy-in is to demonstrate the benefits of using digital LPS to them and to help the end users understand the benefits.

Team efforts

Team efforts were also acknowledged, thanks to the digital LPS platform, which allows everyone to be involved and plan the works on the digital platform. As one interviewee noted, "*this is the platform that allows everyone to contribute; everyone in the team should put tickets in"*. In the dashboard, the team's participation and activities are visible. In Project B, there are eight team members who had developed more than 100 tickets. There are other indicators, such as "ticket update" and "plan views", which are useful indicators demonstrating the team's engagement and contribution.

SUPPORTS ALREADY IN PLACE AND FOR FUTURE

The research team also investigated what support is already available and what support is required for future roll-out. Two broad forms of support are made available: training and catch-ups.

Training

Perceptions vary across different levels in projects (see Table 4).

Table 4: perceptions/experience about training

Superintendent/supervisors	Engineers
• Coached by our Continuous Improvement and Innovation Manager and online support from the digital LPS provider (Interviewee A1) • Introduction to what LPS is and then focus on software training (Interviewee A7) • Some people showed me how to add tickets (Interviewee B8) • I haven't had any training on digital LPS software. Only engineers showed me what to do in it. I have seen some emails about it over the last year and a half. But I am busy to get to one of the sessions (Interviewee B9) • I didn't get any training from anyone. I am able to do all I need to do on it. So, if I needed to do anything further, I'd probably look for the training. I just need to know how to add a ticket and show that it has been completed as planned (Interviewee B10) • Our Continuous Improvement and Innovation Manager set up a few training sessions, initially a couple of hours, every two days, and breakaway to weekly. And the same training session for supervisors and engineers. When the team become self-sufficient the team will train the rest (Interviewee B11)	• Initial support from Continuous Improvement and Innovation Manager, together with our superintendent, who talks about adding tickets and does constraints (Interviewee A5) • Late entrant – will do some basic training (Interviewee A8) • Not aware of training; not aware of LPS guide – (Interviewee B2) • No training for me. But can apply to get training from the Continuous Improvement and Innovation Manager. Just read a guide and went ahead, self-explanatory (Interviewee B2) • Not aware of any. Not formally trained; only briefed by manager (Interviewee B3) • Some training and guidelines; teach new engineers how to use the digital LPS software (Interviewee B4) • Some formal training previously (Interviewee B7)

Catch-ups

Regular catch-up were mentioned by several interviewees from both projects, including "our Continuous Improvement and Innovation Manager organises regular session to check the use of digital LPS and potential opportunities for improvement" (Interviewee A6) and "Regular catch-ups and some formal training previously" (Interviewee B7).

WHAT SUPPORT MAY BE REQUIRED

When asked what other support is required in the future, most interviewees indicated that something could be done to improve the implementation of LPS across WPA projects. Interestingly, '*more training*' (mentioned 10 times) and '*site visits and best practices*' (mentioned 7 times) were mentioned most frequently by interviewees. Table 5 provides a summary.

Table 5: More support needed

No.	More trainings	Site visits and best practices	Support and tips from Continuous Improvement and Innovation Manager and	Buy-in from everyone	Workshop and session t	Make it business as usual	Discussion with all key construction leaders
Interviewee A1	X	X	X			X	X
Interviewee A2	X	X					
Interviewee A3	X						
Interviewee A4	X						
Interviewee A5				X			
Interviewee A6		X			X		
Interviewee A7		X					
Interviewee A8							
Interviewee B1							
Interviewee B2					X		
Interviewee B3	X						
Interviewee B4		X					
Interviewee B5						X	
Interviewee B6		X					
Interviewee B7	X				X		
Interviewee B8	X	X					
Interviewee B9	X						
Interviewee B10	X						
Interviewee B11	X		X				
Total	**10**	**7**	**2**	**1**	**3**	**2**	**1**

More training

From superintendents to engineers, there is a consensus that more training is desired. The training is expected to be formal, sufficient, basic, and targeted. Interviewee A2 elaborated "*a more formal approach is needed to train new staff, and internal and external users, as well as subcontractors*." Interviewee A4 also highlighted training can minimise people's resistance to change. Those motivated end users of digital LPS platform such as Interviewees B3 and B8 expected to learn all the features of digital LPS, including the high-level advanced functionality.

- "need formal training and learn all digital LPS features" (Interviewee B3).
- "some basic training of how to use it to everyone will do. People who want to learn more can learn more high-level functions." (Interviewee B8).

Site visits and best practices

Site visits and sharing best practices were also strongly agreed upon. A few typical comments include: *"See actions from another project, dial into their weekly or look-ahead planning sessions in another ongoing project"* (Interviewee A6), and hear from people involved in the project the whole way. See what other people thinks that contribute to the success will be interesting" (Interviewee A7).

DISCUSSION AND CONCLUSION

This study uncovers the critical success factors arising from the successful roll-out of digital LPS in infrastructure projects in Victoria, Australia. This study points out that the critical factors that underscore the successful adoption of digital LPS can be categorised under a combination of technology, people, and organisational aspects. This includes using a suitable digital LPS platform, having LPS champions, getting employees' buy-in, putting organisational support in place, and many other aspects. The most cited critical factor in this study is the digital platform of LPS itself, which, understandably, was not a critical factor in traditional LPS practice as described by previous literature (Abusalem, 2020). This study further uncovers a number of features of digital LPS platform such as 'ease of use', 'show benefits quickly', 'functioning' etc. for practitioners to weigh in on when they are thinking about LPS adoption. This echoes to several studies (Hua & Schwartz, 2021; Pikas et al., 2022) examined digital LPS that acknowledging its power functions. Each feature aligns with the common factors normally discussed in the technology adoption model (TAM) (Davis, 1989), which explains the influencing factors for technology adoption. The other critical factors, especially the people and organisational related ones, aligns with previous research (O. AlSehaimi et al., 2014; Watfa & Sawalha, 2021). Not surprisingly, this study confirmed the roles that people and organisations play in driving successful adoption of digital LPS. Given this, the implications for roles such as LPS champions at project level, and supporting roles within organisations, can be stated as follows:

Firstly, an LPS champion should be nominated at the project level. A few key qualities of LPS champions are worth considering here; these are based on the findings of the study. Champions should (1) be able to drive the implementation and be firm on the implementation; (2) be able to manage resistance; (3) lead by example; (4) be able to pass knowledge onto team members, including late entrants; and (5) be approachable for catchups. Secondly, in addition to having an LPS champion on the ground, organisational support is also valuable: this includes helping the project team set up the implementation process, and providing training, coaching, and mentoring. Organisational support is evident in the two projects where the role of Continuous Improvement and Innovation Manager is highly appreciated. However, the study revealed that although training was provided, the level of penetration differed. Whereas the managerial level may well receive the necessary training, the junior/site engineers, who are the ones adding the tickets to the digital whiteboard, noted they had not received adequate training. Instead, Project B adopted a people-train-people strategy assuming that firstly, digital LPS is self-explanatory and easy to use, and that secondly, the engineers may only need to know how to add the tickets as their primary function, perhaps not needing to understand the advanced features. We therefore recommend that there should be prerequisite or induction-styled training in the use of digital LPS. This aligns with many studies (Hua & Schwartz, 2021; Pikas et al., 2022) which acknowledged the importance of training and support the team members as a lesson learnt in digital LPS adoption. The people-train-people approach seems to prepare new entrants to be onboarded quickly but knowing how to create tickets (e-stickies) in the digital system is far from being competent at working with digital LPS and getting the best out of it.

Having examined a successful adoption of digital LPS with critical factors highlighted leads us to infer that LPS has made its debut in Australia's construction sector but is still far from its counterparts in the USA or the UK. This study has laid the foundation for future work on LPS and Lean construction research in the Australian context. However, the study does have a few unique contextual features, or even limitations.

Firstly, WPA embarked on the LPS journey with a particular digital LPS solution provider. Each digital LPS platform has unique features. Some are highly sophisticated and can be integrated with other technology such as BIM. In this study, some of the features of the particular digital LPS platform were highly commended by the end-users. It will be interesting to compare the perspective of various digital LPS tools in order determined whether technology is indeed a critical factor in driving digital LPS.

Secondly, the local LPS champions and the Continuous Improvement and Innovation Manager are also unique in this context, as they happen to be strong believers in LPS and have great passion in driving it. It is hard to imagine what the results of this study would be like if these two roles were absent. Conversely, if there were more active champions and supports across the team, one might assume and even greater adherence and performance may have been achieved.

Lastly, the projects were undertaken in the Alliance arrangement, where innovation and continuous improvement are heavily encouraged. Continuous Improvement and Innovation Managers are constantly seeking and testing innovative practices in order to learn and continuously improve the existing processes. Without this culture, it would be challenging to see digital LPS being selected as a new way of managing project production with medium-term and short-term planning.

Although these are unique contextual factors, we remain hopeful that this success story of adopting digital LPS will prove transferable to the Australian construction sector with the benefit of knowing these critical factors to put in place.

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QUANTITY TAKE-OFF IN ROUGH CONSTRUCTION OF HIGH-RISE BUILDINGS BASED ON CAD AND BIM METHODOLOGIES: A CASE STUDY

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ABSTRACT

Building Information Modeling (BIM) prepares the quantity take-off (QTO) of the construction elements, helping in the management of the design and construction process and preparing the 3D visualization of the construction phases. BIM increases efficiency and gives users more control over construction-related tasks. This study identifies the New Cycle building as a Case Study, in which inconsistencies were detected in the QTO, compared to the real quantities of budgeted materials, so the interested parties decided to implement BIM in the use of QTO as a mechanism of control. The central question addressed was: If BIM had been implemented at the tender stage, could it have provided benefits to the project? To do this, various parameters were evaluated to conduct a comparative analysis between the results obtained through the use of the CAD and BIM methodology in the same project. Using the Analytical Hierarchy Process (AHP) method, it was possible to evaluate and compare the two alternatives, CAD and BIM, in order to determine which of them would have been more effective in satisfying the objectives set in the project. The results obtained offer a valuable and informed vision for making informed decisions for future construction projects, contributing to a change in perception about the adoption of new work methodologies.

KEYWORDS

Building Information Modeling; quantity take-off; work flow; collaboration.

INTRODUCTION

Lean Construction is the delivery process that uses Lean theories, principles, techniques and tools to maximize stakeholder value and minimize waste by emphasizing team collaboration on a project. The goal of Lean Construction is to drive productivity, profits and innovation in the industry, enabling the entire construction project lifecycle to benefit from the application of many Lean principles.

BIM (Building Information Modeling) is a well-known tool to improve the design and construction of buildings. It is based on the digitalization of all project information, which allows better control and monitoring of the project. BIM not only changes the technology used, but also the way of working. This is a cultural change that involves all the agents participating in the project, from architects and engineers to builders and owners. Although these approaches are different initiatives, there are synergies between Lean and BIM that are most effective when implemented together and not separately (Garcés & Peña, 2023; Michalski et al., 2022; Sacks

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et al., 2017). The precision of BIM and the Lean approach to eliminating errors minimize the costs associated with rework and modifications. The combination of Lean Construction and BIM in the early stages of the project allows you to optimize the design and construction processes, eliminate waste and generate a more efficient, profitable and sustainable project.

LITERATURE REVIEW

While BIM addresses the reliability of information in construction projects, Lean addresses the reliability of processes to reduce or eliminate waste (Fosse et al., 2017; Nguyen & Akhavian, 2019; Garcés & Peña, 2022). Regarding the use of building information models (BIM) in design and construction projects, which cover work processes and team organization, it is worth highlighting the pioneering work of the Center for Integrated Facilities Engineering (CIFE) of the University. from Stanford. This center developed a new concept called Virtual Design and Construction (VDC), which is based on the integration of new BIM technologies with Lean philosophy and practices (Kunz & Fischer, 2020). VDC tools can be very effective in achieving Lean Production Delivery System (LPDS) objectives (Aslam et al., 2021).

In this sense, BIM (Building Information Modeling), VDC (Virtual Design and Construction) and Lean Construction are three methodologies that overlap and complement each other to significantly improve the efficiency and success of the construction project (Fosse et al., 2017; Nguyen & Akhavian, 2019; Aslam et al., 2021). For example, 1) BIM provides the database and platform for the integration of VDC and Lean; 2) VDC uses the BIM model for simulation, planning and project management, and 3) Lean guides the implementation of VDC and BIM to eliminate waste and optimize the process. This overlap improves communication and collaboration between different disciplines, reduces errors and costs during design and construction, optimizes project planning and execution, improves project quality, safety and sustainability, and reduces delivery time and project costs.

That said, in the construction industry, effective cost and time management is crucial to achieving project success, which is why various investigations have addressed it through the BIM methodology and Lean Construction techniques and tools. Where, timely completion, cost control, and compliance with quality and performance requirements define achievement (Parsamehr et al., 2023). Improving work and production processes is essential for this success. Construction project stakeholders, including owners, architects and general contractors, are increasingly aware of ways to reduce time and costs, including cost estimating using BIM, as the architecture, engineering and Construction (AEC) adopts building information modeling (BIM) in its construction (Gholizadeh et al., 2018; Jin et al., 2017). Compared to conventional estimating methods, research studies have shown that using BIM for estimating reduces work time and errors and improves estimator performance (Kim et al., 2019; Peterson et al., 2011).

However, the use of BIM estimation comes with several challenges, including: (1) a lack of knowledge and understanding of BIM on the part of the estimator; (2) implementing data sharing between various applications such as estimating software and BIM creation tools; and (3) limitations in maintaining relationships between cost information and construction elements modeled in three-dimensional (3D) objects (Aibinu & Venkatesh, 2014; Kim et al., 2019).

BIM is characterized by being a methodology that optimizes performance and productivity in construction projects, achieving greater efficiency and collaboration in the processes. This methodology allows architects, engineers and builders to develop projects effectively throughout their life cycle, which, in turn due. An inconsistency in the quantity extracted from building components can make the quantities calculated difficult. This is because the quantities used to prepare a budget during the design phase serve as a basis for calculating the tender price, and evaluating the suitability of construction cost when deciding on a general contract, therefore, accurate measurements must be made to reduce the possibility of the total construction cost increasing or decreasing during construction (Ashworth & Perera, 2015; Hyari, 2016).

Due to the lack of investigations of real cases of quantity take-off (QTO) of high-rise buildings, this research compares the results of QTO based on traditional methodology, such as CAD, and on BIM methodology through a case study, which is a 16-story building plus two basements. The QTO of concrete, reinforcing steel bars, and formwork, prepared through CAD for the budget of the New Cycle project, is referred to as “QTO CAD”; and the QTO using the BIM methodology for this research is called “QTO BIM”.

Combining various studies and analyses, this research assessed whether Building Information Modeling (BIM) would present advantages or benefits to the Computer-Aided Design (CAD) in a specific case study. The aim was to identify the best approach for achieving accurate quantity take-off (QTO) results and minimizing material waste. To make this complex decision, the Analytical Hierarchy Process (AHP), a structured technique for evaluating multiple factors, was employed.

The AHP Method is a useful tool for making complex decisions with multiple factors to consider. It is based on decomposing the problem into a hierarchy of elements and then comparing them pairwise (one against one) to determine their relative importance (Darko et al., 2019). The AHP Method has the following steps: 1) Define the problem: What decision do you want to make?; 2) Decompose the problem: Identify the different factors that influence the decision; 3) Organize the factors in a hierarchy: Create a structure that groups the factors by levels of importance; 4) Compare the factors: Compare each pair of factors at each level of the hierarchy to determine which is more important; 5) Calculate priorities: Assign numerical values to comparisons to determine the relative importance of each factor; 6) Synthesize the results: Combine the priorities of the different factors to obtain a final decision. AHP is a powerful tool for making complex decisions with multiple factors to consider. It is simple to understand and use, and can help you make more informed and objective decisions.

CASE STUDY

The present research focuses on the comparative analysis of the uses of CAD and BIM in QTO of the core work of the New Cycle building, located in the city of Concepción, Chile. During the developing of this research, New Cycle has been in the construction and completion stages. This case study consists of a residential building for apartments. In addition, its design includes 16 floors, 2 basements and various spaces for uses and services (see Figure 1).

BIM Model of the New Cycle Building | Render of the New Cycle Building | Simulation of the construction process

Figure 1: BIM model and render of the case study building.

The Real Estate Company that manages New Cycle made a 3D model of the building, in the early stages of the project, which was more linked to the architecture, so it was used only as a rendering of the building. Given this, the project's Construction Company decided to remake the model, integrating all the specialties, where the concrete modeling was considered.

For the structural part, a new 3D model was developed, given that its design characteristics required different skills that the construction company´s modeling area did not have. They were developed in collaboration with modeling contractor companies specializing in the design and installation of steel bars. Finally thanks a "plugin" (PROISAC-encofrados) allowed obtaining the m^2 of formwork based on the concrete model BIM. The objectives set with this structural model were: 1) optimize the purchasing process, 2) identify incompatibilities of the reinforcing steel bars project, and 3) increase efficiency in execution, since, if the bars are designed to be easily sized and installed, the purchasing process would be faster, thus avoiding delays in the execution of the heavy work process due to the high latency in the response of the estimator, and on the other hand, the amount of steel on the ground would be reduced, avoiding the performance of repetitive work, thus increasing the work efficiency of workers.

With this, at New Cycle BIM was implemented with 2 models: one to manage the control and execution of the installation of steel bars and another model that integrates and coordinates the specialties, in order to keep track of both modifications and real-time progress of the project.

PROBLEMATIC

Due to differences in the budgeted QTO of materials versus the actual ones used, the need arises to create a quantity control mechanism, including the modifications that may bring about changes in requirements and design. Given this, the use of CAD methodologies in the case study for the QTO is evaluated to contrast it with the QTO obtained through BIM models (QTO CAD vs QTO BIM), in order to study the impact on the project if BIM had been implemented at the beginning, over the traditional applied work methodology, this is CAD. To study the impact on the difference in quantities of materials, the bulk construction stage is analyzed exclusively, The integration of BIM in the construction industry presents a comprehensive solution to enhance material usage efficiency, notably curbing waste across projects. By enabling precise and detailed planning, BIM facilitates surplus minimization and efficient inventory management, thereby fostering a cleaner and more sustainable work environment.This approach closely aligns with Waste Management principles in construction, where waste reduction and value maximization stand as pivotal objectives in enhancing sectoral efficiency and sustainability, resonating with Lean Construction principles, which prioritize waste elimination and process optimization towards achieving more efficient and profitable outcomes.

The main items within the gross construction work are concrete (m^3), reinforcing steel bars (tons) and formwork (m^2) (Choi et al., 2015; Garcés & Molina, 2023; Liu et al., 2022; Olsen & Taylor, 2017; Whang & Park, 2016), and correspond to the instances that require more time and costs, therefore, the QTOs carried out and studied correspond to these three items.

SOFTWARE USED

The QTOs were made with CAD files (Autodesk AutoCAD) with which the building project was budgeted. The information collected from plans was transferred to Excel spreadsheets for data processing. The entire model was made in Revit, only the ironing machine model was made by TSC Company in Tekla Structures and then transferred to the Trimble viewer through an IFC format. Finally, for the application of the AHP method as a decision maker to determine the best alternative for QTO, the Total Decision software was used, a program specialized in the matrix development of this method.

Certain ranges of percentage differences based on current industry references were established to define how acceptable the results obtained are when comparing the QTO in CAD and BIM of the New Cycle building with the QTO carried out in this research, these are: (1) <2% acceptable; (2); 2-5% moderately acceptable; and (3) >5% not acceptable.

ANALYSIS OF RESULTS

To carry out the QTO comparison, three parameters were considered: (1) the QTO of Concrete, reinforcing steel bars and formwork, made using CAD with which the New Cycle project budget was developed (hereinafter "CAD NC"), delivered at the bidding stage of the construction project; (2) and the QTO of Concrete, steel bars and formwork, using New Cycle BIM models (hereinafter "BIM Research"). Thus, with these QTO parameters, through the comparison "CAD NC vs BIM Research" you can know the differences between what was budgeted and what was required in the execution of the project. It should be noted that these are geometric calculations without considering the waste of execution. See Figure 2.

QTO comparisons are presented using results by level, from the foundation slab, basement -2 and -1 and floors 1 to 16.

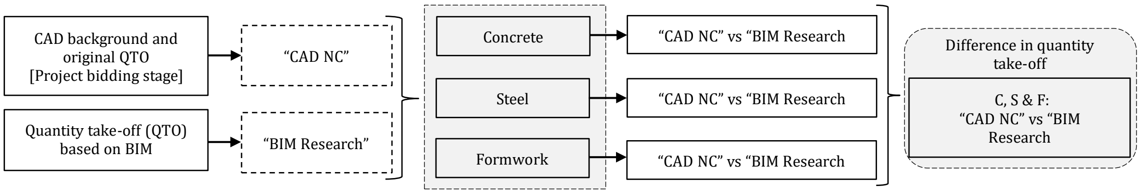

Figure 2: Quantity take-off of the New Cycle (NC) building.

CONCRETE: "CAD NC" VS "BIM RESEARCH"

Table 1 shows that "CAD NC" calculated 5856.00 m³ of concrete, while "BIM Research" recorded 5719.87 m³. The totals differ by 136.13 m³, representing a 2.32% percentage difference. The high level of detail in the "BIM Research" models provides a more precise and realistic estimate of the volume of concrete required for the New Cycle project. In the foundation slab and basement -2 and -1 the differences are negative, indicating that "CAD NC" quantities of concrete were underestimated. Under the acceptability criteria, the foundation slab presents an unacceptable difference, while both basement have moderately acceptable differences between CAD and BIM applications. On the other hand, for Floors 1 to 16, the differences are considered unacceptable, which implies that "CAD NC" calculated a volume of concrete above the real needs of the project.

"CAD NC" carried out the calculation by elevations, considering the total lengths of each level. In addition, "BIM Research" takes into account empty spaces where concrete is not required, such as shafts, which contributes to a calculation adjusted to reality.

It is important to mention that the difference that occurs on the 16th Floor is due to a redesign on said floor, reducing its area, and therefore, its amount of concrete. This modification was not considered by "CAD NC".

Table 1: Concrete CAD and BIM Results

	CAD NC	BIM Research	Difference	% Difference
TOTAL	5856.00 m³	5719.87 m³	136.13 m³	2.32%
Foundation slab	1394.84 m³	1665.94 m³	-271.10 m³	-19.44%
Basement -2	445.81 m³	455.81 m³	-10.00 m³	-2.24%
Basement -1	470.40 m³	487.53 m³	-17.13 m³	-3.64%
1st Floor	244.05 m³	219.12 m³	24.93 m³	10.21%
2nd Floor	227.90 m³	186.99 m³	40.91 m³	17.95%
3rd Floor	234.85 m³	214.91 m³	19.94 m³	8.49%
4th Floor	234.85 m³	214.89 m³	19.96 m³	8.50%
5th Floor	234.85 m³	215.40 m³	19.45 m³	8.28%
6th Floor	234.85 m³	215.63 m³	19.22 m³	8.19%
7th Floor	234.85 m³	215.69 m³	19.16 m³	8.16%
8th Floor	234.85 m³	215.79 m³	19.06 m³	8.12%
9th Floor	234.85 m³	214.78 m³	20.07 m³	8.55%
10th Floor	234.85 m³	214.50 m³	20.35 m³	8.67%
11th Floor	234.85 m³	214.68 m³	20.17 m³	8.59%
12th Floor	234.85 m³	210.51 m³	24.34 m³	10.37%
13th Floor	234.85 m³	215.25 m³	19.60 m³	8.35%
14th Floor	234.85 m³	187.35 m³	47.50 m³	20.23%
15th Floor	211.24 m³	131.97 m³	79.27 m³	37.52%
16th Floor	43.53 m³	23.13 m³	20.40 m³	46.87%

STEEL BARS: “CAD NC” VS “BIM RESEARCH”

The observed differences caused problems in terms of project processes and costs. There is a difference of -61.93 tons of iron, which represents a discrepancy of 10.02% compared to the amount budgeted by “CAD NC” (see Table 2). Both positive and negative differences are identified in Floors 3 to 14, but all of them are within the acceptable and moderately acceptable range. However, the foundation slab, basement -2 and -1, and Floors 1, 2, 15 and 16 present differences that are not acceptable according to the established criteria. It is important to highlight that the greatest differences are evident in basements -2 and -1, where “CAD NC” considerably underestimated the amount of steel bars required compared to “BIM RESEARCH”

“BIM Research” considers all the elements of the steel bars, even those that do not have a structural function, but are necessary from a construction point of view, such as extra locks, splices and hooks, to support slabs, and master bars, among others. These additional elements are not detailed in the plans, but are required during the installation of the steel bars. This difference in the consideration of non-structural elements explains why “BIM Research” shows superior steel QTO results than “CAD NC”.

Table 2: CAD and BIM results of reinforcing steel bars

	CAD NC	BIM Research	Difference	% Difference
TOTAL	617.88 Ton	679.81 Ton	-61.93 Ton	-10.02%
Foundation slab	64.14 Ton	70.82 Ton	-6.68 Ton	-10.41%
Basement -2	44.05 Ton	81.45 Ton	-37.40 Ton	-84.89%
Basement -1	43.19 Ton	67.45 Ton	-24.26 Ton	-56.17%
1st Floor	39.85 Ton	52.06 Ton	-12.21 Ton	-30.65%
2nd Floor	44.68 Ton	40.76 Ton	3.92 Ton	8.78%
3rd Floor	36.09 Ton	34.53 Ton	1.56 Ton	4.33%
4th Floor	32.42 Ton	33.45 Ton	-1.03 Ton	-3.17%
5th Floor	30.85 Ton	30.14 Ton	0.71 Ton	2.31%
6th Floor	29.58 Ton	30.31 Ton	-0.73 Ton	-2.47%
7th Floor	28.33 Ton	27.86 Ton	0.47 Ton	1.65%
8th Floor	27.96 Ton	28.53 Ton	-0.57 Ton	-2.03%
9th Floor	26.68 Ton	26.66 Ton	0.02 Ton	0.07%
10th Floor	26.43 Ton	27.15 Ton	-0.72 Ton	-2.71%
11th Floor	26.02 Ton	25.77 Ton	0.25 Ton	0.97%
12th Floor	26.00 Ton	26.66 Ton	-0.66 Ton	-2.56%
13th Floor	25.37 Ton	25.32 Ton	0.05 Ton	0.19%
14th Floor	24.56 Ton	25.62 Ton	-1.06 Ton	-4.31%
15th Floor	24.38 Ton	20.90 Ton	3.48 Ton	14.28%
16th Floor	17.31 Ton	4.39 Ton	12.92 Ton	74.64%

It is important to note that there was modification to design of the 16th floor that decreased the buildable area and was not considered by “CAD NC”, which shows that the amount of steel was greater than that actually required for that level.

The “BIM Research” study shows the superior precision of BIM for calculating the QTO of steel. Including non-structural elements in BIM is crucial for accurate estimating, resulting in better project management and transparency in real cost. The literature on BIM and construction project management supports these findings. Furthermore, the inclusion of non-structural elements in BIM is crucial for accurate estimation of steel QTO, and the lack of these elements in CAD NC underestimates the QTO, which can lead to problems during construction. Therefore, BIM offers greater precision in material estimation, which makes real cost transparent and optimizes project management.

FORMWORK: “CAD NC” VS “BIM NC”

Between the results of “CAD NC” and “BIM Research” there is a difference of 229.36 m² of formwork, which translates into a differential of 0.81% between what was budgeted and what was used (see Table 3). The total difference turns out to be very slight, with various differences, positive and negative, existing in the calculations for each level of the building. in foundation slab, basement -2 and -1, floors 1, 2 and 16 the differences are negative, that is, what was budgeted was less than what was required. The "not acceptable" results are offset by the results that are "moderately acceptable", finally having a total difference categorized as "acceptable" between the CAD and BIM methodologies in formwork QTO.

Table 3: CAD and BIM results of formwork

	CAD NC	**BIM Research**	**Difference**	**% Difference**
TOTAL	28421.00 m²	28191.64 m²	229.36 m²	0.81%
Foundation slab	112.80 m²	126.47 m²	-13.67 m²	-12.12%
Basement -2	2154.24 m²	2482.91 m²	-328.67 m²	-15.26%
Basement -1	2294.80 m²	2583.88 m²	-289.08 m²	-12.60%
1st Floor	1490.60 m²	1577.68 m²	-87.08 m²	-5.84%
2nd Floor	1551.16 m²	1813.38 m²	-262.22 m²	-16.90%
3rd Floor	1582.69 m²	1502.75 m²	79.94 m²	5.05%
4th Floor	1582.69 m²	1508.76 m²	73.93 m²	4.67%
5th Floor	1582.69 m²	1507.23 m²	75.46 m²	4.77%
6th Floor	1582.69 m²	1503.03 m²	79.65 m²	5.03%
7th Floor	1582.69 m²	1505.59 m²	77.10 m²	4.87%
8th Floor	1582.69 m²	1506.66 m²	76.03 m²	4.80%
9th Floor	1582.69 m²	1506.18 m²	76.51 m²	4.83%
10th Floor	1582.69 m²	1499.78 m²	82.91 m²	5.24%
11th Floor	1582.69 m²	1506.78 m²	75.91 m²	4.80%
12th Floor	1582.69 m²	1507.38 m²	75.31 m²	4.76%
13th Floor	1582.69 m²	1472.15 m²	110.54 m²	6.98%
14th Floor	1582.69 m²	1507.26 m²	75.43 m²	4.77%
15th Floor	1462.26 m²	1204.45 m²	257.81 m²	17.63%
16th Floor	362.90 m²	369.34 m²	-6.44 m²	-1.78%

The difference with "CAD NC" vs "BIM Research" comparison is minimal: 0.81% (229.36 m²). This reinforces what was previously stated, that the formwork QTOs do not require a major analysis for the calculation of areas.

It should be noted that in order to obtain the quantities in m2 of the formwork, it is necessary to use a "plugin" given that the formwork is a temporary element that cannot be obtained directly from the BIM models.

AHP METHOD

Analytic Hierarchy Process (AHP) is a decision-making method in which alternatives are evaluated using a mathematical model, based on a series of criteria, to define which best meets the objective of a process (Darko et al., 2019). In this research, AHP is applied to define which alternative, CAD or BIM, best satisfies the requirements to develop QTO in the bidding stage.

To develop the AHP, the objective must be defined ("Define whether the CAD or BIM methodology is the best alternative to perform QTO and budget calculations in the bidding stage of a construction project"), and the criteria and alternatives (CAD and BIM) to make the best decision. The criteria were established based on input from experts consulted during the assessment phase of the Analytical Hierarchy Process (AHP). Six criteria are presented in Table 5 along with their corresponding sub-criteria. The first 4 criteria consider technical aspects that have direct implications in the use of CAD and BIM methodologies. Criteria 5 and 6 respond to qualitative aspects, which consider perceptions of barriers to overcome for the adoption and use of software related to work methodologies.

Due to the complexity of decision-making in construction projects, the AHP methodology emerges as a robust approach (Darko et al., 2019). It offers a systematic framework for evaluating and comparing multiple criteria, facilitating an informed selection between alternative methodologies such as CAD and BIM. The flexibility and adaptability of AHP allow for customization to address the specific needs of the research, ensuring a comprehensive evaluation that encompasses both technical and qualitative aspects (de Paris et al., 2022). Furthermore, in comparison to other decision-making methods like Cost-Benefit Analysis (CBA), AHP excels in its ability to consider a broader range of factors beyond purely monetary considerations (Arroyo et al., 2020; Natarajan et al., 2022), thus providing a more holistic and nuanced approach to decision-making in construction projects (Razi et al., 2019).

Table 5: AHP criteria and sub-criteria

N°	Criteria	Sub-criteria
1	Precision in quantity take-off	• Ability to identify elements in plans/models • Accuracy in the quantity of the elements identified
2	Efficiency in the quantity take-off process	• Speed of the QTO process • Degree of automation of the QTO process
3	Compatibility with other systems	• Ability to import and export data to other systems • Interoperability with other systems
4	Resource availability	• Availability of personnel trained in the use of the software • Availability of technical support and updates
5	Investment cost	• The initial cost of licenses • Cost of maintenance and updates
6	Easy to use	• Level of technical knowledge required to use software • The friendliness of the software interface

The first step to develop the AHP method in Total Decision is to enter the already established objective, criteria and alternatives. The criteria are then compared to each other, one by one, using ratings that indicate their degree of importance. With this process, the weights of each criterion are obtained in order to define the hierarchy between them, knowing which criteria are the most relevant within the analysis. The evaluations to compare criteria and alternatives based on the objective obey scores from 1 to 9 as presented in Table 6.

Table 6: AHP rating scale

Equal Importance	Moderate importance	Great importance	Very great importance	Extreme importance
1	3	5	7	9

The ratings entered into the software are based on information collected from interviews with experts. From this, each criterion was scored, understanding the degree of importance that each one has when carrying out the QTO, both by QTO CAD and QTO BIM. In this stage, the hierarchy of criteria is established, obtaining that the “Investment cost”" criterion is the one with the greatest weight, followed by the “Precision in QTO” criterion as the second most relevant. This indicates that the “Investment cost”, although not a technical aspect, is the most important criterion when making decisions about which work methodology to adopt to carry out QTO. Furthermore, the two main criteria are followed in the ranking by: “Efficiency in the QTO process”, “Compatibility with other systems”, “Resource availability” and, finally, “Easy to use”.

The next step is to evaluate each criterion concerning each of the alternatives. The same assessment scale used previously is used to rate the performance of each alternative based on the objective, as shown in Figure 3.

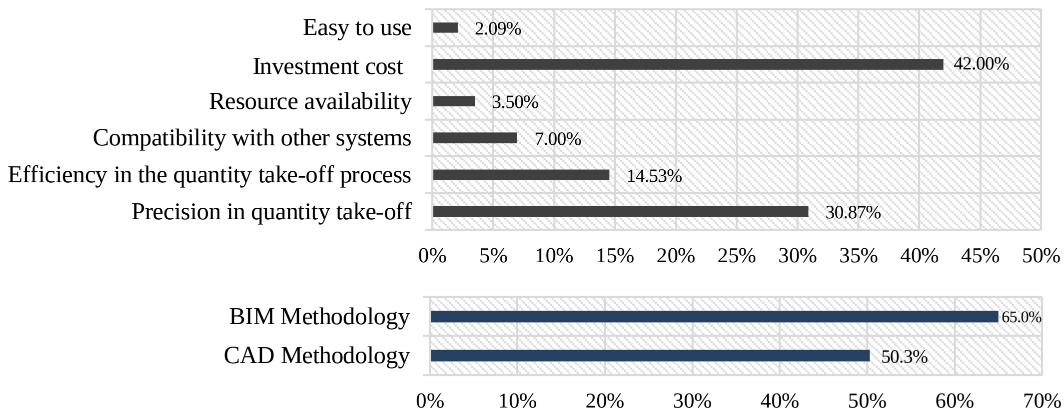

Figure 3: AHP structure of hierarchies.

These evaluations provide a measure of the performance of each alternative in relation to the objective. The evaluations are developed by matrixly ordering the results for each comparative instance. From each matrix, the eigenvectors are obtained that indicate the relative weights of each comparative pair. By obtaining all the eigenvectors, a global decision matrix is constructed with which, finally, the alternative with the greatest weight for decision-making can be obtained. This entire mathematical process was carried out using the Total Decision software.

Finally, with the AHP Method, through the calculation software, it is concluded that the best alternative to perform QTO and budget calculation in the bidding stage of a project is the BIM methodology over CAD.

Given that the “investment cost” criterion has high relevance in the study, considering that the costs associated with BIM are higher compared to CAD, the gap between alternatives may not turn out to be completely representative. That is why by carrying out the same study without considering the “investment cost” criterion, the decision-making is decisively more conclusive, defining BIM as the alternative with almost ideal performance to satisfy the objective, as shown in Figure 4.

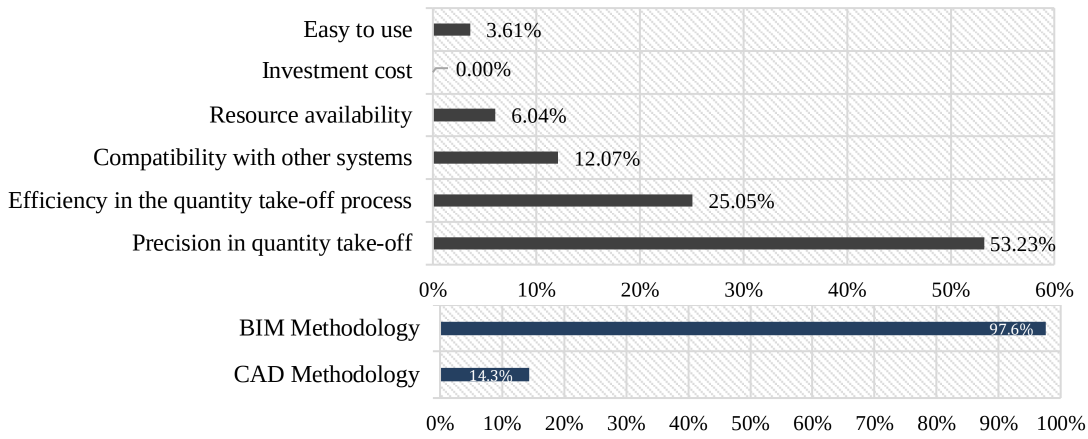

Figure 4: AHP sensitivity analysis - Simulation of results without Cost criteria.

This supports that the "investment cost" variable has a fundamental role in quantifying the best decision. However, in both cases, the BIM alternative presents the best performance, based on the criteria and its hierarchical analysis, to satisfy the objective of defining CAD or BIM as the best alternative to carry out QTO and budget in the bidding stage of a project.

QTO with CAD, unlike BIM, is based on individual 2D or 3D drawings, requiring manual calculation or using additional tools. This leads to errors due to the lack of integration between elements, making it difficult to update the calculation in the event of changes in the design. Instead, BIM creates an intelligent 3D digital model, allowing an automatic and precise calculation of materials from the model, minimizing errors and enabling rapid updating in the event of changes. This efficiency is applied to the calculation of concrete, reinforcement and formwork, optimizing the use of resources and collaboration between teams.

It is important to consider that the AHP method provides precise results after a mathematical development that integrates and weights various variables, delivering solid outcomes. By way of analysis, it is also important to understand that the use of AHP in decision-making can be affected by biases and limitations that must be addressed to ensure reliable results (Darko et al., 2019; Munier, N., & Hontoria, E. (2021). The judgments of experts, crucial in AHP analysis, may be influenced by personal preferences, limited knowledge, or external influences, which could bias evaluations (Liu et al., 2020). Additionally, the quality and availability of information for experts may vary, requiring measures to ensure equitable and comprehensive access to relevant information. The rating scales used in AHP analysis may be subjective and require validation to ensure accuracy (Darko et al., 2019). Faced with all this, it is necessary to carry out iterative processes and sensitivity analyses to evaluate the effectiveness of these scales and their impact on analysis results.

CONCLUSIONS AND RECOMMENDATIONS

The comparative analysis between the QTOs carried out with "CAD NC" and "BIM Research" has revealed important information regarding the precision and accuracy of the results. In the case of concrete, it is observed that "BIM Research" provides a real and precise quantity, avoiding overestimation of quantities, while "CAD NC" shows a tendency to overestimate volumes. This demonstrates the advantages of BIM in terms of obtaining accurate information and avoiding deviations in project processes and costs, and it could make projects more competitive by using them in earlier stages. Similarly, when comparing the QTO of steel bars, it is again evident that "BIM Research" offers a more detailed and complete analysis for the required elements, considering even those that do not have structural purposes but are necessary for construction. On the other hand, "CAD NC" presented discrepancies and errors in the study of plans, which generated imbalances in the processes and associated costs. It is important to highlight that the errors detected in the QTO are related to CAD, which supports the need to adopt more advanced methodologies such as BIM to avoid carryover of errors and detect incompatibilities early; This generates claims for defects in the design, which then end up being awarded to the client or assumed as a loss. In the case of the formwork, the results were quite similar in the totals, however, this required the help of a plug-in to have the calculations in BIM per floor, where the differences are within the moderately acceptable margins. described as criteria.

The study, using the AHP method, found that BIM (65%) outperforms CAD (50.3%) for performing QTO at the bidding stage. This is based on six criteria: accuracy, speed, ease of use, flexibility, collaboration and integration. The percentages are not absolute, but rather represent the relative performance of the alternatives. The AHP performs an independent analysis between alternatives.

While BIM is the best option, cost is a major barrier to its adoption. The implementation risk must be considered against the benefits of structuring, parameterization and process optimization that BIM offers. For construction professionals it is recommended: 1) Consider BIM as the best option for QTO in the bidding stage; 2) evaluate the cost of BIM implementation compared to the long-term benefits; and 3) seek strategies to mitigate the risk of BIM implementation. For researchers in this field, it is recommended: 1) Develop studies that demonstrate the value of BIM in terms of ROI (Return on Investment); 2) investigate strategies to reduce the cost of BIM implementation; 3) study the risk perception of BIM in the construction industry.

BIM adoption faces obstacles such as the need for training, investment in hardware and software, and adaptation to new work processes (Olanrewaju et al., 2022; Sriyolja et al., 2021). However, it is crucial to demystify the idea that BIM alone improves a project. While BIM offers great benefits, efficient processes are required to make the most of them. Resistance to change and lack of technological updating are also barriers that must be overcome (Shin & Kim, 2021). It is necessary to change the perception of BIM as something expensive and risky, and see it as an investment in improving the efficiency and quality of construction projects.

To overcome the challenges of BIM implementation, it is crucial to integrate the Lean Construction philosophy. Lean focuses on waste elimination and continuous improvement, which improves the efficiency of the BIM process and optimizes project performance. The integration of Lean and BIM offers benefits such as: 1) Reduction of costs and time, eliminating unnecessary activities and optimizing planning; 2) improved quality, minimization of errors and greater precision in construction; 3) greater collaboration among stakeholders, and 4) more effective decision making, based on accurate and up-to-date information and more effective decision making. Therefore, by integrating Lean into BIM from the early stages of the project, you boost competitiveness and ensure greater success in BIM implementation, optimizing overall project performance and minimizing waste.

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IMPLEMENTING LEAN PRACTICES AND A MODERN CONSTRUCTION METHOD IN A SOCIAL HOUSING PROJECT

Sergio Kemmer[1] and Leonardo L. Marin[2]

ABSTRACT

The paper aims to explore the implementation challenges and advantages of utilising lean practices along with a modern construction method, i.e. timber frame prefabricated system, to accomplish a challenging goal in a social housing project in Brazil.

It presents a case study on the construction of 518 housing units, which were built in a short period to help victims of a climate catastrophe relocate. Data was collected through semi-structured interviews, participant observation, site visits, and documental analysis. The findings suggest that relying on a single lean practice or a modern construction method may not be enough to achieve demanding project objectives, such as completing a construction project within a tight deadline. Instead, it is the appropriate combination of these initiatives that will result in a better outcome.

Moreover, the study contributes to a particular issue that has not been adequately addressed by the lean community. Specifically, it sheds light on the connection between a project objective, lean concepts and managerial tools that can be used to accomplish it.

KEYWORDS

Lean practices, Last Planner® System, off-site construction, prefabrication, prototype.

INTRODUCTION

In February 2023, during the Carnival festival, the coastal city of São Sebastião in the state of São Paulo, Brazil, experienced the worst rainfall ever recorded (G1, 2023). Within less than 24 hours, approximately 600mm of precipitation fell resulting in dozens of fatalities, extensive damage to local highways, and hundreds of people left homeless (Figure 1).

After the disaster, the local government quickly relocated the affected population to sports arenas and provided temporary housing. They worked on a permanent solution and decided to construct 518 housing units within a short period of 10 months to allow the displaced people to move into their new homes and begin rebuilding their lives.

In order to achieve this challenging goal, the local government decided to utilise a modern construction method to ensure quick completion of on-site work. The modern construction methods promote a shift from fragmented project delivery methods to a more controlled environment. (Taylor, 2010). Specifically, the timber frame prefabricated system was chosen, which is one of the methods outlined in the Modern Methods of Construction Definition Framework (MHCLG, 2019). To minimize waste and add value to the population affected by such catastrophic climate event, lean practices were also applied in the design, planning, and

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construction processes. The project was led by Brazil's top company in efficient and sustainable social housing.

Figure 1: The damage caused by a catastrophe resulting from heavy rainfall. (G1)

This study explores the challenges and advantages of using lean practices and a modern construction method to complete the construction project within a tight timeframe. Moreover, it highlights the relationship between a project goal, lean concepts (i.e. conceptual ideas related to the lean construction philosophy), and managerial tools.

LEAN AS A SYSTEM

The key to successfully applying and sustaining Lean Construction concepts and tools lies in a thorough understanding of the fundamentals and consistent practice (Koskela et al, 2002).

The Toyota Production System (TPS) has served as an inspiration for the development of the Lean Construction theory (Koskela, 2000). It changed the paradigms of production management, bringing to light simple and innovative ideas based on a common goal: increasing production efficiency by eliminating waste consistently (Ohno, 1997). The following figure, known as the TPS House, shows the basic elements of the system.

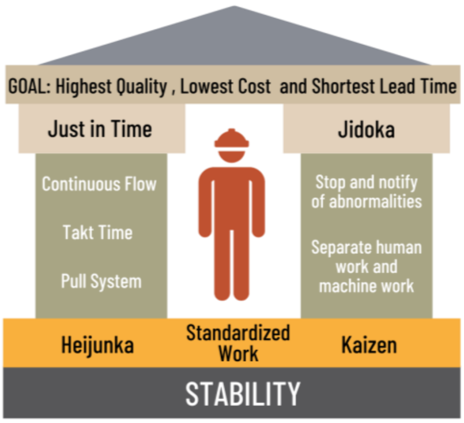

Figure 2: Toyota Production System House (Adapted from Lean Enterprise Institute).

On the roof of the house are the TPS goals (highest quality, lowest cost, and shortest lead time). Just in Time and Jidoka are the system's support pillars. Stability is the foundation. The person at the centre represents respect for people. Understanding the meaning of each of these elements is a mandatory task for anyone who wants to embark on a Lean transformation journey. It is also worth highlighting the idea of a system brought by the TPS House, that is, for the expected results to be achieved, all parts need to be applied. Systems thinking is essential.

Furthermore, the TPS House (Figure 2) indicates the initial step in a lean implementation, namely, the achievement of production stability, which is represented as the foundation of the house. The creation of a stable workflow is a prerequisite for the deployment of more advanced lean concepts (e.g. continuous flow) that will enable the achievement of project objectives (e.g. compression of lead time).

The Last Planner System® (LPS) is a well-known lean tool in construction for production planning and control (Ballard and Tommelein, 2021). LPS aims to promote stability in production flow and facilitate rapid learning (Ballard, 2000). Therefore, it is advisable for construction companies to start their lean journeys by implementing LPS (Koskela et al., 2002).

It is worth mentioning that the LPS is not the only lean practice available for supporting the creation of stability. There are many other initiatives that can be employed during design and planning processes with the purpose to remove uncertainties associated to the product and its production process such as the early involvement of cross-functional teams (Ballard et al., 2002; Laurent and Leicht, 2017; Laurent and Leicht, 2019), Design for Manufacturing and Assembly (Rankohi et al., 2022), Building Information Modelling (Sacks et al., 2018), First Run Study (Saffaro, 2007; Hackett et al., 2015; Aslesen et al., 2023), and Production System Design (Ballard et al., 2001; Barth et al., 2020). The literature on these management practices is extensive and it is assumed to be well-known and thus omitted from this section.

THE PROJECT

This paper presents research conducted as part of a project to reconstruct housing for those affected by landslides. The construction involved 518 housing units, which were distributed across 30 four-story blocks. Each floor of the blocks contained four apartments, with an average area of 47.29m². In addition, there were 38 houses, each averaging 44.16m². In total, the entire project spanned over an area of 24,377m².

Three companies were hired by the São Paulo State Government to undertake a project. Each company was responsible for a specific aspect of the project, which was divided into infrastructure, assembly and installations, and finishes. The industrialised timber frame panels were manufactured in a city located 500km away from the site. A total of 6,124 panels were then transported by truck to the assembly location. During the 10-month operation, approximately 450 people worked on the project, which covered the period from the beginning of the first excavation and manufacturing to the delivery of the housing units to the residents.

In addition to the challenges related the tight timeframe, the project attracted significant media attention due to its status as a public work contracted by the government, employing a construction method considered innovative in the country.

RESEARCH METHOD

A case study was carried out to investigate the implementation issues and benefits of utilising lean practices along with a modern construction method, i.e. timber frame prefabricated system, to construct 518 housing units within a short period of 10 months. The research was structured in three phases: diagnostic, training, and implementation. The objectives set for each phase along with the methods used in this investigation is presented in the following table.

As shown in Table 1, the first phase of the study was exploratory. Data was collected prior to the commencement of works on site through semi-structured interviews (engineering manager, production planning and control coordinator, head of operations, process engineering coordinator, quality manager and site agents), direct observation of works on the prototype built offsite, and documental analysis (production plans, production rates, and problems faced in previous projects).

Table 1: Research process.

Items	Phase 1 (Diagnostic)	Phase 2 (Training)	Phase 3 (Implementation)
Objectives	(a) understanding the characteristics of the project and typical issues faced in previous projects (b) discussion on which managerial tools should be implemented to compress project lead time	(a) raising the awareness on lean fundamentals (b) practical application of lean concepts and tools such as Takt Planning, Production System Design, Last Planner System	(a) discussion on the implementation issues and the benefits reaped through the application of lean practices
Research methods	Semi-structured interviews, direct observation, documental analysis	Training sessions delivered to the project team	Participant-observation in planning meetings, documental analysis

The second phase involved training sessions on lean fundamentals such as value, continuous flow, and continuous improvement. Besides, production system design, takt planning, Last Planner System® were also addressed throughout the sessions through practical exercises.

The deployment of the lean practices was conducted in a collaborative fashion during the third phase. A cross-functional team involving the the engineering and innovation director, project manager, design representatives, procurement manager, site agents, safety coordinator and planners were engaged to promote collaboration in order to ensure a successful implementation. Follow-up meetings were led by the production planning and control coordinator on a fortnightly basis to discuss the implementation issues, project progress, opportunities for improvement and the benefits reaped through the application of lean practices.

Due to the objectives set for this study, the findings reported in this paper are focused on phase 1 (i.e. discussion on which managerial tools should be implemented to compress project lead time) and phase 3 (i.e. discussion on the implementation issues and the benefits reaped through the application of lean practices).

ON THE INITIATIVES TO COMPRESS PROJECT LEAD TIME

Several initiatives were taken to shorten lead time as this was the aim of this project. The first decision made in this regard was the selection of a construction method appropriate for a project with a tight timeframe. The timber frame prefabricated system was chosen because it increases the efficiency of the construction process as opposed to the artisanal process traditionally used in Brazilian construction sites. The timber frame panels are produced off-site in a controlled environment with the support of an automated production line, thus increasing the levels of quality, safety, and productivity. The panels are sent to site fitted with electrical and plumbing installation kits and windows, hence simplifying the construction process by reducing the number of steps to be done on site.

Besides the choice of a suitable construction method, lean concepts and tools were deployed across project phases (Figure 5) to ensure that works on site was completed as quickly as possible. To achieve a design solution that would help the production teams to avoid stoppages on site as well as increasing product quality and safety during installation, the DfMA (Design for Manufacturing and Assembly) approach, BIM (Building Information Modelling) and a physical prototype were adopted. In the planning phase, a Production System Design was conducted by a cross-functional team with the support of BIM Models to remove uncertainties in order to promote a stable production workflow. Takt Planning was also applied to create a continuous flow that would help shorten production lead time. In the construction phase, the

Last Planner System® was implemented to ensure works on site were conducted as planned along with Visual Management and a Continuous Improvement approach to enable agility in dealing with deviations from the original plan. The following figure summarises the lean practices implemented across the project phases. Further details on the implementation of these initiatives are provided in the next sections.

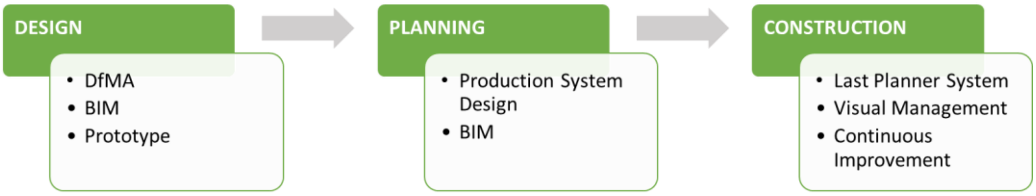

Figure 3: Lean practices implemented across project phases.

DfMA

The DfMA principles, which DfM involves minimizing the number of components whereas DfA focuses on streamlining assembly (Gao et al., 2018), were introduced to the engineering teams after the conclusion of the conceptual design phase and prior to the creation of detailed drawings. This collaborative effort involved design engineers, the safety manager, as well as production and assembly coordinators and analysts. The primary objective was to streamline and optimize production and assembly operations with a focus on safety.

During this phase, two four-hour meetings were conducted, engaging all team members. The initial focus was on defining the manufacturing and assembly sequencing to ensure the most efficient operational utilization. Subsequently, following the initial planning, 15 new subproducts were identified and categorized as potential project risks. This identification prompted the necessity to prototype these elements, encompassing 2 structural components, 2 roof-related elements, 5 installations, and 3 external finishes.

BIM

The application of BIM was undertaken with a focus on industrialisation, with a view to achieving a high level of detailing and fidelity to reality through the use of a specified Level of Development (LOD). The resulting model was then analysed to validate solutions and interfaces, providing the basis for informed discussion and decision-making involving people, technology, processes, and policies to ensure the achievement of business objectives, during the production process. – as it is common when BIM is applied as a working methodology.

As highlighted by the Engineering Manager, "developing a design for an emergency project that requires rapid delivery demands a high level of decisiveness in engineering decision. There is no room for error during construction, which makes decisiveness even more crucial when it comes to industrialisation and repetition of the same typology. Even a minor error can easily become a systemic problem, which is why the use of BIM is essential. By utilising BIM models, clashes between different disciplines can be detected at an early stage, design solutions can be better assessed and discussed, construction stages are properly defined, training sessions can be delivered in a higher quality in order to get the operational team ready in the best way possible. This ensures that there are fewer issues due to design omissions or project failures". Also, the information contained in the modeled objects allows for an accurate quantity takeoff, thus making it easier to achieve assertive purchases and providing better on-site inventory control.

Prototype

To validate design and engineering solutions as well as reducing the risk of unexpected issues (e.g. time waste) on site, a two-story prototype with a roof was erected within two weeks. It was an accurate full-size mock-up of the building. All electrical and plumbing installations were executed, and a complete dwelling was finished. Figure 4 shows results from the prototype implementation.

Figure 4: Two-Story Prototype built off-site.

The development of the prototype was a collaborative effort involving the engineering manager, operations manager, project coordinator, manufacturing and assembly teams, and the electrical and plumbing subcontractors. Upon its completion, a thorough assessment of the prototype revealed the existence of 16 non-conformities. These issues were attributable to either flaws in the product definition or errors during the execution process. A depiction of these non-conformities is illustrated in Figure 5. Subsequently, measures were taken to address and mitigate these issues before commencing the mass production phase.

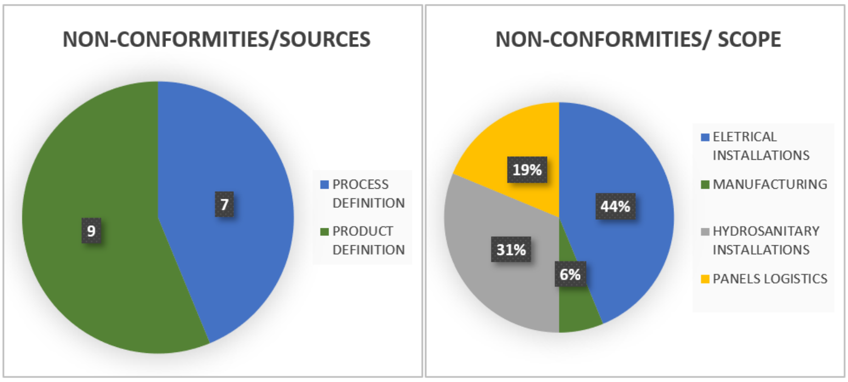

Figure 5: Number and type of non-conformities.

The oversight conducted by the project team facilitated the validation of the hourly schedule for the execution of electrical and plumbing installation activities. These activities were deemed critical due to the significant number of non-conformities identified. The project coordinator emphasised that the prototype provided valuable insights such as the importance of carrying out all activities until their completion and ensuring the precise measurement of parameters such as production rates and materials.

Production System Design and Takt Planning

The Production System Design aimed at organizing the production system by establishing a structure that served as a reference for production planning, control, and improvement. The scope of decisions involved: definition of work packages, production sequence and activity durations, analysis of the workflows of crews on site, definition of the project execution strategy, capacity analysis of production resources, site layout and logistics planning. The Takt principle was also applied with the purpose of enabling continuous flow, hence allowing the compression of project time. The engineering and innovation director, project manager, design representatives, procurement manager, site agents, safety coordinator and planners were involved in this phase.

Four meetings of four hours each were necessary to conclude the work. They were structured according to the scope of works abovementioned, namely, the first and second meetings focused on work structuring and sequencing as well as production flow analysis whereas the third and fourth meetings addressed the definition of project execution strategy, capacity analysis of production resources, site layout and logistics planning. These collaborative sessions were held in the headquarter of the general contractor prior to start of works on site. The main outcome of this work was the development of the strategic production planning, which was represented in a line of balance. The work packages and resources (labour and equipment) required to carry out the production tasks were also sorted by the team.

LAST PLANNER SYSTEM®

The Last Planner System® was deployed with the purpose to stabilize production workflow to allow the implementation of continuous flow as well as promoting a culture of continuous improvement. Two pull planning sessions were carried out to specify handoffs and conditions of satisfaction of two key processes defined by the team, namely, electrical installation and plastering. Lookahead meetings were conducted on a fortnightly basis. Weekly meetings were held for assessing production progress as well as learning from mistakes. Daily huddles were also implemented to allow front line supervisors to share commitments completed as well as making clear what commitments need help with or cannot be delivered. These daily meetings happened at the end of the day and lasted 30 minutes approximately.

VISUAL MANAGEMENT

Visual tools such as line of balance and charts displaying attributes related to production planning (e.g. Percent Plan Complete, reasons for task non completion, countermeasures, etc.) were deployed on site to increase process transparency and allow the project team to quickly identify deviations from the plan. Furthermore, a Big Room was set up on site to foster communication and collaboration among project participants as well as supporting management routines such as daily huddles and weekly meetings. It is worth mentioning that visual aids such as BIM Models and wallcharts with sticky notes were also used during the development of the production system design and takt planning.

CONTINUOUS IMPROVEMENT

A continuous improvement approach was implemented by identifying and analysing the root causes of problems. The 5 Whys technique was used for this purpose. The project team applied countermeasures to promote stability and improvement in processes, which were reviewed daily during huddles at the end of each workday. Weekly meetings were held to assess project progress. The continuous improvement approach was also applied during the design and planning phases of the project, with management practices such as DfMA, prototyping, and production system design prompting changes to improve performance.

DISCUSSION

In this section, the authors describe the implementation challenges and advantages of utilising lean practices and a modern construction method, i.e. timber frame prefabricated system, to accomplish the construction of 518 housing units in 10 months. This analysis is structured according to the project phases, namely, design, planning, and construction. Furthermore, the connection between project objective and the lean concepts and managerial tools that can be used to accomplish it are also discussed by the authors of the paper.

DESIGN PHASE

A relevant issue faced in this phase was the short time available for developing and validating the design. As this project had a particular feature, namely, it was a response for a catastrophic event where people had been displaced from their homes, the engineering team had to develop the design solution faster than what they usually do in traditional projects in order to releasing the production of prefabricated panels to be shipped to the construction site. According to the Engineering Manager, the design development for a new building normally takes 60 to 90 days. However, due to the tight timeframe, the engineering team decided to use a design solution that had already been tested before. Consequently, only a few minor enhancements were made, therefore reducing the design lead time to less than 30 days.

Another important challenge was to start the production of prefabricated panels as soon as possible to meet the on-site demand. The ideal approach would be to produce a prototype first, validate its components, and then proceed with further production. According to the project coordinator "it's important to fully validate each component of the prototype, including time, execution processes, and materials used, before moving on to further production. If any component is only partially validated, it may result in waste generation". However, it was not feasible to produce all the required timber frame panels within the given timeline due to the limited production capacity of the factory. As a result, some of the panels were manufactured beforehand and kept in storage offsite. This led to rework on site due to technical problems discovered only at the end of the prototype evaluation phase.

It is important to note that despite the challenges mentioned earlier, the virtual model created using BIM, along with the physical prototype, proved to be effective in helping the team to evaluate potential issues, refining solutions and ultimately achieving a high level of precision and accuracy throughout construction. Besides, it helped validate some key factors for the project. This includes the validation of engineering assumptions and the production rates for electrical and plumbing installation activities. These activities were found to have a higher number of inconsistencies in design specifications and constructability, and were identified as the most critical, making them the focus of special attention during the planning and construction process.

PLANNING PHASE

The main issue faced during the planning phase was the lack of collaboration between the three main contractors hired by government to undertake the project. The company responsible for carrying out the infrastructure services, which was a basic requirement for allowing the assembly of timber frame panels, did not participate in the meetings held to carry out the production system design. There was no commitment to the dates considered in the strategic production planning hence affecting the work conducted by company responsible for installing the prefabricated timber panels.

Another relevant issue faced by the project team was the lack of reliable data on production rates to perform the Takt Planning. Without a sound database it was difficult to adjust the level of work to achieve the production pace set for the project. Although some data were gathered during the execution of the physical prototype (e.g. electrical and plumbing production rates), there was no information available for all services required to be carried out on site. Besides, the data collected in the prototype did not consider the site conditions where material logistics was more difficult to be handled than what was faced during the simulation conducted in the prototype built in a controlled environment. Hence, adjustments had to be made on site after the construction of the initial blocks, but this exposed the project to a risk of having to allocate extra resources to cope with the production pace originally planned. Hiring additional crews in a timely manner to work in an underway project located in a remote area was not an easy task. This issue ended up having a negative impact on the works on site due to the dependencies among services. The delay in one task affected the start of the next and this created an undesirable effect, namely, deviation from the original plan.

The production system design meetings prompted the early involvement of cross-functional teams from the company hired to install the timber frame panels. People from different departments such as engineering, supply, quality, safety, production (factory), operation (site agents), besides the engineering and innovation director worked in a collaborative fashion to create an effective production plan. The presence of a senior-level leader along with a multidisciplinary team improved the quality of the discussions as well as the commitment to the plan because people felt appreciated to take part in its development.

Another benefit noted during the production system design meetings was related to the use of BIM models to speed up the process of quantitative take-off. This information was required for calculating the amount of work that needed to be done by the crews on site. These quantities are an important input for Takt Planning, hence calculating them in an automated manner saved time and increased accuracy.

CONSTRUCTION PHASE

The lack of consistency in conducting the routines established by the Last Planner System® (LPS) was one of the main issues faced during the construction phase. According to the production planning coordinator, this was due to the lack of training on the fundamentals of LPS for the subcontractors engaged later in the project. This problem was tackled by a three-day training session held on the construction site to raise awareness on basic lean concepts with a focus on the implementation of LPS. As a result, the engagement of the subcontractors increased and their behaviour during the planning meetings improved, i.e. they became more collaborative. Another important action taken to improve the commitment to the planning process was the provision of a financial incentive for achieving goals. The team received a bonus when production targets were achieved. It is noteworthy that the LPS training was not carried out for the three main contractors hired by the government. Only the company responsible for installing the timber frame panels and its subcontractors were involved in the lean implementation.

The application of LPS resulted in a more stable production flow. This condition enabled the implementation of the takt principle and allowed construction processes to be carried out in a nearly continuous flow, hence contributing to the accomplishment of the project deadline. The daily huddles had an important role in in providing agility in the resolution of issues found out on site. The use of visual aids in the Big Room displaying the production targets against the actual performance was also instrumental to enable the rapid identification of deviations from the original plan, hence prompting improvement actions in a timely manner. Equally important was the use of a software tool for modelling the line of balance as it allowed a more agile approach to project control during the weekly planning meetings.

THE LINK BETWEEN PROJECT OBJECTIVE AND THE LEAN CONCEPTS AND TOOLS

The compression of lead time was the main goal of the project investigated in this research due to the context mentioned in the introduction section of this paper. Therefore, the selection of lean practices aimed at achieving that specific objective. The following figure summarises the rationale applied by the authors.

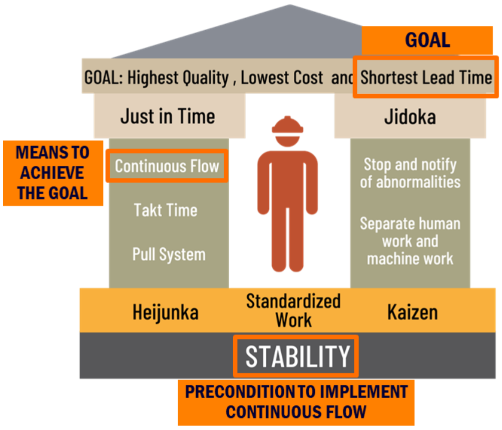

Figure 6: Connection between the elements of the TPS House.

Based on Figure 6, it can be argued that there is a logic behind the sequence of actions taken to achieve the project goal. If one wants to compress lead time (goal), then applying the principle of Takt is an effective way to attain continuous flow (means to achieve the goal), which in turn will lead to the achievement of project objective. However, there is an important precondition to implement continuous flow, namely, stability. Therefore, the selection of lean practices to be applied in the project aimed at creating a stable workflow on site to enable the implementation of a continuous flow and, hence, the compression of lead time. Visual management and continuous improvement practices were also adopted to support the identification of deviations from the original plan, project stabilisation, and rapid learning.

CONCLUSIONS

This study demonstrates that the application of lean practices across different project phases (i.e. design, planning, and construction) coupled with a modern construction method (i.e. timber frame prefabricated panels) can be an effective approach for delivering an emergency construction project in a tight timeframe. It leads to efficiency gains, waste reduction, and value to the customer. The main evidence of such benefits was the achievement of the challenging goal set by the government, namely, the delivery of the 518 housing units in 10 months.

Among the implementation issues described in the paper, it is highlighted the lack of integration between the three main contractors responsible for undertaking the project. Only the company responsible for installing the timber frame prefabricated panels and its subcontractors engaged in the lean implementation whereas the other two main contractors had not adhered to that. This undermined a better performance of the project as a whole since there were dependencies between those companies.

Another key issue noted in the study was the lack of a reliable database on production rates, which have impacted the quality of the production system design and exposed the project to unnecessary risks. Prototyping was an important initiative for helping with this issue and the knowledge on site status was deemed as critical for adjusting the data collected offsite.

Finally, regarding the selection of lean practices to be applied in the project, an important lesson was learned by the managers of the company. Lean should be seen as a system. Thus, having a solid understanding on the relationship between the lean concepts and choosing appropriate lean tools is crucial to achieving project objectives. Systems thinking is vital!

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ANALYSING THE ALIGNMENT BETWEEN LEAN CONSTRUCTION AND CIRCULAR ECONOMY IN PREFABRICATED CONSTRUCTION

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ABSTRACT

With the recurring challenge of resources scarcity in the world, the construction industry needs to shift its attention towards sustainable practices. Prefabricated construction (PC) or modular construction has become increasingly popular in recent with its potential solution for the challenges faced, through increase of efficiency and reduction of waste. Some researchers have explored the integration of lean construction (LE) and circular economy (CE) into PC projects and highlights the benefits. However, they conclude that the implementation is in its early days and require a need for research as it holds significant potential in transition into a sustainable industry. This paper aims to exploring the alignment between CE and LC in PC through relevant resources to understand the full extent on this topic. The paper presents the research findings of 25 relevant publications that met the inclusion criteria in a statistical manner. This is to identify and summarise the known body of knowledge relevant to the topic. It shows that there is a strong link between focusing on the whole process for design, construction, and end-of-life of a building. Content was examined to discover what type and application of PC and relevant benefits and/or limitations.

KEYWORDS

Lean construction, circular economy, prefabricated construction, alignment, review.

INTRODUCTION

Generational waste and high consumption of natural resources is a global issue that the construction industry is currently facing due to its contribution from traditional construction methods (Akhimien et al. 2021). Factors include minimal exploration, lack of research and reluctance in embracing new sustainable concepts that the industry can transition into (Ayarkwa et al. 2022). However, as newly emerged methodologies and concepts arise, there has been interests in all parties to the possibilities and adaptations from just thinking of sustainability practices as recycling. A focus is seen on lean construction (LC) principles and circular economy (CE) applications through prefabricated construction (PC) (Luo et al. 2021).

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PC is a process where components of a building are manufactured in specialised facilities (off-site) other than the site location, then specifically designed to be transported and assembled on-site (Ferdous et al. 2019; Innella et al. 2019). The integration of the two concepts is compliable as they aim to reduce waste and shorten the project life cycle, resulting in a more efficient and sustainable way (Du et al. 2023). It optimises the production process and has a high potential to effectively address resource wastage and inefficiency (Ferdous et al. 2019). The research found that various LC tools aim to cut waste and shorten project cycle have been used in lean prefabricated construction, they were: (1) kanban that is a visual card system displays steps and materials, (2) value stream mapping (VSM) which is a visualisation of a process and, (3) last planner system (Du et al. 2023; El Sakka et al. 2016; Innella et al. 2019). Furthermore, Caldarelli et al. (2022) conceptualised the application of LC and PC through focusing on modular construction as a hybrid production system. It treated off-site construction as a manufacturing system, as it reorganised the sequences of the construction as a layout of stages, which led to reduction of waste and efficient usage of time. However, it also mentioned that this concept is within its initial stages. Nahmens and Ikuma (2012) identified the effects of LC on modular homebuilding, where the barriers faced in widespread application of sustainable construction is the high initial costs, lack of education in the industry and applications of technologies. It was found through seven case studies that LC resulted in reduction of material waste by 65% and production hours by 31%. Innella et al. (2019) reviewed application of lean methodologies and indicated that techniques to modular construction has the potential to reach new levels of productivity while has yet to be achieved. It highlighted that the challenges faced is how to fully integrate lean strategies to all production process stages of PC. Du et al. (2023) pointed out future direction of the integration of LC and PC through a new concept called lean prefabricated construction. Although there is limited research on the application of the integration of LC through PC applications, they all aim to aid practitioners with an overview of potential benefits and suggest further research is needed.

CE concept derived from the opposed of traditional economy which has not evolved since the industrial revolution (Benachio et al. 2020). The traditional model or linear economy uses the concept of take-make-disposal, where raw materials are extracted from the environment, processed, and are transformed into products and discarded once they have reached their end of life or no use of them (Afteni et al. 2021). Pomponi and Moncaster (2017) stated that although the implementation of CE model is within infancy in the construction industry, there is momentum and support, and examples can be drawn from the Netherlands where European nations are at the forefront of circularity. Benachio et al. (2021) and Munaro et al. (2020) concluded that the CE was involved within the industry which shine a spotlight on research themes, findings, and gaps. In result, they found that there was a need for standardised practices to benchmark the concept and government incentives to promote CE models.

The integration of the CE practices and PC is compliable as PC has the potential to reduce costs and times, whereas CE promotes building resilience and reducing waste (Zairul 2021). Xu and Sun (2019) found that PC have contributed to green building literature through integrating CE applications. Although the integration of CE in PC is a newly emerged concept, there has been research conducted on how the alignment can not only achieve circularity but an efficient construction process. Dams et al. (2021) suggested a framework towards on how the built environment can transition into circularity through integrating modular construction as an application for CE. 15 guidelines were created tailored around achieving Sustainable Development Goals that foster the applications of CE to buildings. Furthermore, Machado and Morioka (2021) extended the idea of integration through how modular construction can further contribute to CE benefits and the link between them has become more evident. It found that most research papers did not mention circular economy directly, but rather the benefits within the implementation of modular construction practices. Zairul (2021) investigated the recent trends within the built environment on PC with the integration of CE. The paper identified that there is an absence of research of the integration as the concept has recently emerged. The research objective of this paper is to investigate the alignment between LC & CE in PC and the potential synergies, challenges and opportunities of integrating in the industry.

The existing body of literature highlighted the importance of the LC and CE concepts and how they can be integrated into PC to achieve further sustainable benefits. The main agreement in the literature displayed that each concept has benefits individually but can be achieve further from integrating them as a collective. Gaps exist such as minimal research and full integration of these theoretical concepts to be implemented practically in the built environment. There is area for future research in collecting data, applying, and implementing the researched ideas in a project. These concepts require additional exploration and how to manage the industry being reluctant to apply these ideas.

RESARCH METHOD

A systematic literature review is a research methodology that identifies, selects, and critically evaluate material to address a specific formulated question. This is thought to be an effective strategy to execute extensive review and identify the research gaps on the topic(Innella et al. 2019).

DATA COLLECTION

For the literature research, the Scopus database has been implemented as it is one of the most accurate, high quality, creditable, and peer-reviewed databases. A three-stage criteria was developed to accurately capture relevant data, which aimed at focusing on papers that demonstrated strong contributions to the three concepts and topic.

In Stage one, the research was conducted using keywords in 'Article title, Abstract, Keywords' field and limited to articles and review papers. The keywords that were implemented in the research field was "Lean Construction* AND Modular* OR Prefabrication* OR circular*". The search result found that there was a total of 223 documents matching these keywords. The research was limited for publication years for a 10-year range between 2023 to 2013 to ensure relevant literature for the topic. There were 158 documents matching the research parameters. The research was further refined through subject area, in this case the relevant area is "Engineering", "Environmental Science" and "Business, Management and Accounting" reducing the number of articles to 138 documents.

In Stage two, the 138 papers were reviewed by evaluating the title and abstract to discover relevant papers concentrating on the alignment of LC and CE in PC within the built environment. A total of 90 publication which do not contain the key terms in titles, author keywords and abstracts were excluded or was not accessible to the public.

In Stage 3, the remaining 48 papers were deeply analysed by reading the full paper to fully understand the relevance towards completing the research aim. A total of 16 paper were found that had relevance towards the paper. Additionally, a manual search was conducted to include the possible omission of CE, LC, and PC archive by the search engine. There are 9 papers were added to the total number of research papers from references. As shown in Figure 1 of the flowchart of data collection, 25 papers were selected for review and analysis.

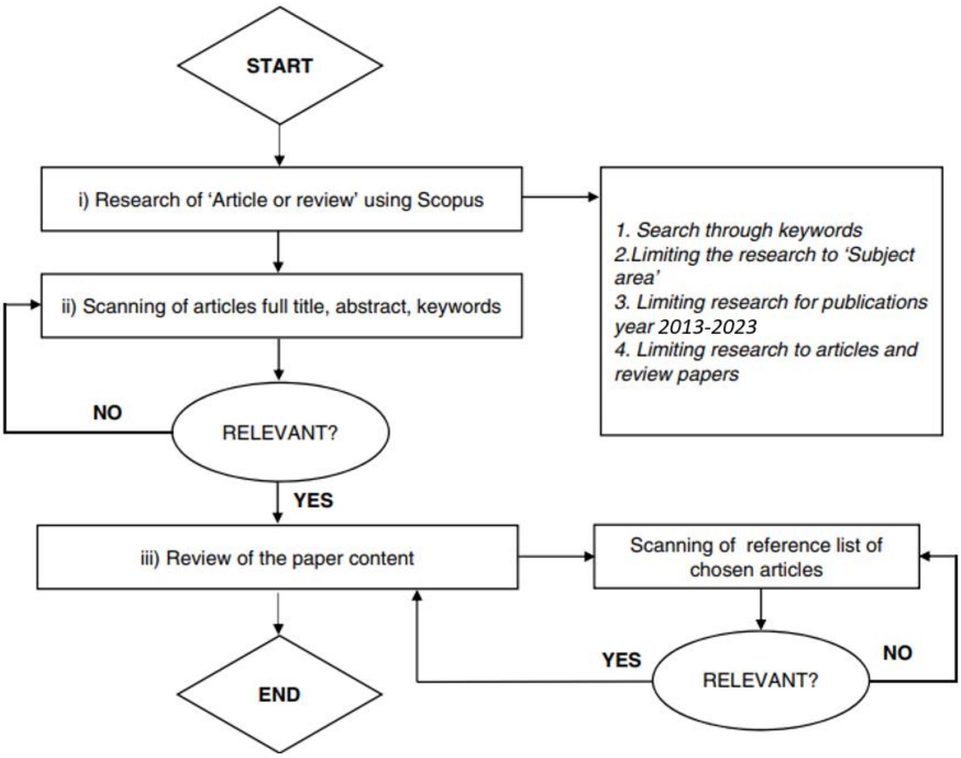

Figure 1: The Flowchart of Data Collection

DATA ANALYSIS

A content analysis was conducted to determine the presence of certain words, themes or concepts surrounding the papers titles. As shown in Table 1, this paper explored the interactions between lean and modular, modular and circular, lean and circular, and the integration of three concepts and the barriers of the integration. The table below

Table 1: Code of Analysis

Code	Definition of code
Alignment of themes	Research contribution and connection and/or explicitly stated in the source.
Analysis of barriers	Addresses or explores the barriers that the concepts may face.

RESEARCH FINDINGS

The researching findings subheading and tables were established to directly address practical challenges of waste cause, stringent construction programmes and budgets involved with traditional construction.

ALIGNMENT OF CE & LC IN PREFABRICATED CONSTRUCTION

A table of alignment was created to explore the alignment of LC principles and CE practices. As shown in Table 2, it is structured to present key components of LC principles and CE practice, along with the specific life cycle stages of a building that the integration has applied. The purpose of the table is to create a visual representation of the relationships between the alignment of these concepts, which allows for a clear understanding of where they overlap and how they complement one another. The life cycle stages, depicted below in the first column represents the different stages that a building undergoes, from a concept to a tangible operative building, to the deconstruction of a building. There are four main stages of a building's construction, project design, construction phase, operations, and end-of-life.

From the created matrix it is possible to obtain a series of results to help understand the relationship between the studied subjects. The number of occurrences refers to when a paper mentioned the alignment between the two areas, regardless of if positive or negative. The alignment of LC principles and CE practices which has the most interactions were "focus on the complete process" with 11 occurrences for LC principles and "deconstruction, reuse, waste management" for CE practices. This was mentioned almost two times than all other alignments. This was followed by "focus on the complete process" with 6 occurrences for LC principles and "prefabricated construction, disassembly and adaptability" with CE practices. The alignment that occurred the least was "Build continuous improvement" with 1 occurrence for LC principles and "prefabricated construction, disassembly and adaptability" for CE practices. Similarly, the life cycle stage that occurred the most was "End-of-life" with 17 occurrences collectively, followed by "Project Design" with 12 occurrences collectively, showing that these are the vital stages where the alignment appears. Whereas the least occurred life cycle stage was operations with 0 (zero) occurrences. This furthers supports how the operations stage of a building is not considered for LC principles and CE practices can be applied to.

Table 2: The Alignment of LC Principles and CE Practices in Lifecycle Stages

		LC Principles			
Life Cycle Stage	**CE Practices**	**Reduce on non-valuing adding activities**	**Reduce cycle times**	**Focus on the complete process**	**Build continuous improvement**
Project Design	Prefabricated construction, disassembly, adaptability	3	2	6	1
Construction	Reuse, waste reduction, off-site construction	2		5	
Operation	Minimise maintenance				
End-of-Life	Deconstruction, reuse, waste management and refurbishment	2		11	4

Table 3 was created to show the alignment between LC principles and CE practices as they are applied to PC. The table lists the alignment that occurred within the Table 2 and outlines their corresponding connections and how they are applied further in PC.

Table 3: the Alignments of LC&CE in PC Application (data extracted from the 25 filtered papers)

Number of publications	Alignment of LC & CE	PC Application
11	Focus on the complete process & Deconstruction, reuse, waste management and refurbishment.	Focusing on the manufacturing process to reduce steps needed while applying disassembly design and allowing the use of reuse materials
6	Focus on the complete process & Design for disassembly and adaptability.	Mapping out the entire process of the production process (Waste & material handling) and focusing on modular and standardized components
5	Focus on the complete process & Reuse, waste reduction and off-site.	Evaluating and refining the off-site prefabricated process layout and activities to implement reclaim materials and waste management
4	Build continuous improvement & Deconstruction, reuse, waste management and refurbishment.	Adopting a life cycle approach to manufacturing methods of PC which achieves waste reduction.
3	Reduce on non-valuing adding activities & Design for disassembly and adaptability.	Optimising a production process of modular construction through eliminating unnecessary transport or material usage.
2	Reduce cycle times & Design for disassembly and adaptability.	Shorting the design phase of PC through standardising the designs and incorporating disassembly principles
2	Reduce on non-valuing adding activities & Reuse, waste reduction and off-site.	Removing activities through the off-site manufacturing production of modular panels, where exact amounts of materials are ordered.
2	Reduce on non-valuing adding activities & Deconstruction, reuse, waste management and refurbishment.	Optimising the production process through eliminating nonvalues activities within the prefabricated construction process and reuse of reclaimed materials in a controlled environment
1	Build continuous improvement & Design for disassembly and adaptability.	Designing modular building components that can be removed and producing them in an offsite location where it is easier to introduce continuous improvement.

BENEFITS AND LIMITATIONS OF THE INTERACTIONS IN PREFABRICATED BUILDINGS

Table 4 shows the main benefits that were mentioned within the papers. The papers were analysed completely and any main points taken regarding the benefits were noted. The results showed that the benefit of PC was “Shorter construction time” and “Design for disassembly” occurred the most frequency with the occurrence of 2. Whereas the least mentioned was the “Higher quality of work”.

Table 4: Definition of identified benefits

Benefit items	Definition	No.
Higher quality work	Refers to fabricating building components with precision and accuracy with small tolerances which results in a consistent quality product. This can be strong, durable, uniform dimensions higher resistance items. In the context of PC refers to: precise dimensional accuracy, consistent finishes, improved safety and stringent quality control.	1
Shorter construction time	Refers to the reduction in time in which is needed to construct or complete a project. In the context of PC it refers to using off-site fabrication in a controlled environment.	2
Design for disassembly	Refers to designing a building to be disassembled at the end of the life of the building. In the context of PC refers to modularisation sections such as façade panels.	2

Table 5 was structured to present the three main limitations mentioned, which was captured from the filtered 25 papers. The results showed that the limitations of PC were “Limited Knowledge known in the field / Uncertainty” had the most frequency with the occurrence of 3. Whereas the least mentioned was “Design Restriction”.

Table 5: Definition of identified Limitations

Limitation items	Definition	No.
Limited Knowledge known in the field / Uncertainty	Refers to a situation where there is lack of information or understanding about a certain topic or element. In this context, PC.	3
Design Restriction	Refers to the limitations or constraints that the designer must consider while creating a product or system. This can include cost, material availability, and aesthetics.	1
Need for business model innovation / Lack of technology	Refers to the necessity in which a business needs to develop new strategies and approaches to either have a competitive advantage or maintain their position. Whereas lack of technology refers to where businesses or individuals have limited access, or unable to utilise, modern tools and processes.	2

DISCUSSION

THE ANALYSIS OF THE ALIGNMENT OF LC & CE IN PC

Analysing the created matrix of the alignment of the interactions of LC and EC and how these can be applied to PC results, it is possible to interpret what those results mean for the relationships of the alignment and applying it to PC in the built environment.

First in the table 2, shows the alignment of LC application and CE practices had the greatest number of mentions of interaction with “Focus on the complete process" & “Deconstruction, reuse, waste management and refurbishment” with 11 occurrences throughout within the 25 papers. This happen mostly because they are interrelated and are crucial for promoting circularity and achieving sustainable construction practices. A comprehensive approach or focusing on the complete process guarantees that every phase of the building process, from design to demolition, is efficient and optimises minimisation of waste and use of available resources (Benachio et al. 2021). Reuse, deconstruction, waste management, and refurbishing are examples of circular economy techniques that are crucial for reducing waste and fostering resource efficiency (Akhimien et al. 2021). Table 3 and the supporting citations further support and explain how this interaction of aligning LC principles and CE applications can be optimised to construct sustainable and efficient buildings through utilising resources and focusing on the complete process.

The other alignment of LC application and CE practices had the second highest number of interactions with "Focus on the complete process" & "Design for disassembly and adaptability" having occurred 6 times throughout the 25 papers. This happened because they are essential to implementing life cycle optimisation and resource efficiency in the built environment. By focusing on the entire process ensures that all the stages of construction process from design to disposal are streamlined to optimise reduction of waste and improve overall resource utilisation (Ghisellini et al. 2018), whereas, designing for disassembly and adaptability is an essential part of CE practices to promote the effective use of resources and reducing waste. This is through creating structures and building systems that are simple to disassemble and reuse at end-of-life stage or when buildings no longer fulfil their purpose. By aligning this LC principle and CE practice they can work together to opposite the goal of resource utilisation and waste generation can be minimised.

The other alignment of LC application and CE practices had the third highest number of interactions with "Focus on the complete process" & "Reuse, waste reduction and off-site" having occurred 5 times throughout the 25 papers. This happened because they are both essential in optimising resource utilisation and reducing waste generation in the built environment. As mentioned previously, focusing on the complete process is an essential part in achieving maximisation of resources used and in reducing waste production. Whereas, reuse, waste reduction and off-site construction focuses on the construction process by minimizing on-site waste generation, promoting efficient resource utilization, and reducing the carbon footprint (Parker et al. 2023). While these practices are essential for encouraging sustainability in the built environment, they have a less effect than procedures such as deconstruction and refurbishment that lead to more optimal resource utilisation (Johns et al. 2023). Additionally, off-site construction may contribute to the reduction of on-site waste, and it can have an impact of increasing transportation of module components which relate emissions produced, thereby partially offsetting the benefits. In result, the synergy between the alignment of LC and CE remains a crucial part to reducing waste generation and promote sustainability, hence why there is less emphasis than the other alignments ranked higher.

THE BENEFITS AND LIMITATIONS

Table 4 lists out three benefits of PC that were found within the analysed 25 papers and the occurrences of them. It is noted that not all 25 papers explored nor mentioned PC in them. The highest occurrence of the benefit of applying PC in the built environment was both "shorter construction time" and "design for disassembly" with 2 occurrences. Shorter construction times occurred the most as prefabrication enables the manufacturing of components off-site, whereby contractors can put together the structures simultaneously on-site without interfering with other on-site activities. This happened because PC components are constructed off-site away from the site location and generally in enclosed environments, enabling works to be completed favourable without weather-related delays, leading to less delays. The controlled environment of a warehouse eliminates weather rated interruptions such as rain, heat and other extreme conditions that would stop works using conventional techniques on site, as they are deemed unsafe for workers that frequently contribute to delays. Although there are allowances within the construction program for weather delays, this factor is unpredictable as weather conditions can vary (Purchase et al. 2022)**.** This leads to more controlled and predictable delivery programs, ultimately contributing to accurate constructions times. Additionally, using PC streamlines the site process, thus reducing the time of equipment and materials movement on site. Traditional on-site construction can vary from project to project as how the site is operated is up to the Principal Contractor. However, items such as Crane time, Manitou bookings and delivery slots are all items that can contribute to delaying materials for workers to be able to install/build. Therefore, factories can design layouts specifically for assembling components to reduce non-valuing adding activities such as material movement on site and deliveries. Design for disassembly occurred the most as it has become a popular concept of PC in the built environment as it promotes the ideology of considering a buildings whole life cycle not just its purpose during the operation stage. This happen because all contributors in the built environment such as architects, engineers, consultants, clients, and principal contractors are more conscious of the negative impacts construction has to the environment and how resource extraction is not sustainable. Designing for disassembly has been seen and applied within the Australian construction industry, through Design for Manufacturing and Assembly (DfMA). A principal contractor, Built Pty Ltd, has implemented DfMA in a recent project for a 200-worker office for Sydney Metro and who is delivering the new airport project. Built incorporated CE thinking, through an innovative modular structure design. This allowed the building to be disassembled and reassembled (relocated), providing a successful example of the possibilities and opportunities of PC (Graham 2023).

While prefabricated building provides numerous advantages in the built environment, there are certain drawbacks that must be addressed. Understanding and managing these constraints can lead to more successful and efficient construction projects. This talk will delve deeper into some of the key constraints of using prefabricated building in the built world. Table 5 lists out three limitations of PC that were found within the analysed 25 papers and the occurrences of them. It is noted that not all 25 papers explore nor mention PC in them. The limitation that had the most occurrences was "Limited Knowledge known in the field / Uncertainty" having occurred 3 times throughout the 25 papers. A significant limitation in the application of PC to the built environment is the lack of knowledge and uncertainty surrounding the field. This is because although the PC method is a sustainable solution to reduce labour and materials demand, PC methods are less preferred over conventional construction. This results from a lack of understanding regarding the advantages, restrictions, design, and construction of PC within the industry. From the lack of knowledge and experience about PC design, logistics and installation of PC and influenced by the lack of technical standards, contributes to the limitation of implementing this method in the built environment (Navaratnam et al. 2022). Due to the lack of knowledge and experience of PC within the built environment, it can cause clients and stakeholders wary of the concept and result in oversights or omissions in implementing it.

CONCLUSION

Through the systemic review, this paper collected, analysed, and interpret the credibility of academia and industry materials. This process provided a comprehensive understanding of the current state of knowledge regarding the alignment of LC and CE principles in prefabricated construction within the built environment. The research paper, as a result of this review, successfully identified the key benefits and limitations associated with the integration of lean and circular economy principles in prefabricated buildings. The research findings succinctly presented the most frequently occurring alignment of LC principles and CE applications concerning various stages of a building's life cycle. This information was utilised to determine how the alignment influences prefabricated construction applications, thereby contributing to the strengthening and evolution of prefabricated construction practices within the industry.

However, it's crucial to recognise the inherent limitations of a systematic literature review. The effectiveness of such a review is contingent upon the quality of the research it incorporates. Despite the availability of various techniques for quality evaluation, this paper utilized Scopus as a singular source to obtain filtered papers, employing several steps to refine the selection. While Scopus is a reputable source, it is not without potential limitations. Human errors or the unavailability of all relevant resources from this single source can introduce biases. Additionally, the process of selecting materials meeting the paper's requirements might inadvertently include or omit low-quality resources, impacting the overall validity of the study's conclusions.

Future research should focus on examining specific materials or elements of prefabricated construction that could benefit from circular economy approach while meeting lean construction principles. Here are some areas to be considered for further research and avenues:

Case Studies: Conduct case studies on prefabricated construction projects that integrate the concepts of lean construction and the circular economy. Such case studies can provide insights into the practical application of these ideas in real building projects.

Comparative analysis: Contrast prefabricated construction projects applying circular economy and lean concepts with traditional construction projects to demonstrate the advantages of each strategy and identify potential areas for improvement.

Integration of life-cycle assessment: Explore the inclusion of life-cycle assessments (LCA) in the examination of lean construction and circular economy principles in prefabricated buildings. LCA allows for a comprehensive evaluation of the environmental impact of a system or product throughout its entire lifecycle.

Sustainability assessment: Further investigate the sustainability benefits of incorporating lean and circular economy concepts in prefabricated construction. Evaluations could assess the advantages in terms of the economy, society, and the environment, including reduced waste, lower material usage, and increased productivity.

Furthermore, recognising the potential and difficulties in aligning lean and circular principles could direct the creation of creative solutions to integration roadblocks. The potential effects of applying lean and circular economy principles to prefabricated construction within the broader context of sustainable construction practises could also be explored in more detail. This would highlight the chances to cut waste, boost efficiency, and improve the environmental, social, and economic impact of the construction industry.

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INSERTION OF MODULAR CONSTRUCTION ALIGNED WITH LEAN PRINCIPLES: A CONCEPTUAL MAP MODEL

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ABSTRACT

The construction industry presents increasing levels of competitiveness among sectors, increasingly demanding products with higher value-added and sustainability. However, problems such as: production capacity, product quality, meeting deadlines, cost control and low productivity are always in evidence for this industry. Therefore, this work aims to present strategies for inserting modular construction in projects in the housing sector. This constructive method allows the application of innovations, increased productivity, control of costs and deadlines, products with greater added value, as well as the development of lean principles in the sector. Due to the complexity involved in the theme and the limited academic development and market for the application of this construction method, this work presents a conceptual map with strategies for inserting modular construction, offering a synthetic vision for companies in the sector that wish to follow the path of modular construction can better understand the main opportunities, barriers, risks and strategies. Market externalities and alignment with lean principles are also presented. For this purpose, the Design Science Research methodological approach was used.

KEYWORDS

Conceptual Map Model, Modular Construction, Lean Construction, Real Estate.

INTRODUCTION

The construction sector is important throughout the world economy. Due to the high competition, project-oriented industries such as the construction industry need to introduce more efficient systems (Toosi & Chamikarpour, 2021). The sector coexists with the design of complex products and has some peculiar characteristics, inherent to its environment (Koskela, 1992).

Efforts to promote innovation and modernization into the construction sector are in development, however, less than other sectors, classified as a low-technology sector in research, development, or innovation practices application (Reichstein et al., 2005). It is perceived as a sector constantly at risk, given the reduced profit margins, high production costs and little

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concern for the end customer, also considering its slowness in adopting new knowledge (Seaden & Manseau, 2001). The lack of knowledge induces the use of conventional materials, products or services, inhibiting the use of innovative construction technologies.

In scenarios where real estate heats up and increases in input and labor costs, construction companies are forced to look for alternatives to conventional construction systems. In this sense, the use of off-site construction elements can be considered a path (McKinsey and Company, 2020).

Modular construction (MC) has shown superior results in terms of efficiency, when compared to the results of traditional construction. However, MC presents barriers that should be considered and overtaken, such as knowledge gaps regarding the high initial cost, the requirement for an innovative design process, the complexity of the supply chain and social perception (Broadhead et al., 2023).

Another fact that should not be unconsidered when thinking about the transition of traditional construction systems to MC is the growing need to produce housing units around the world. The world population grows at a rate of approximately 200K inhabitants per day in large urban centers (WEF, 2016). This growth imposes the need to provide adequate housing infrastructure. Considering the issue of productivity and conventional technologies, it is unlikely that the production of housing units will be able to meet this growing need for new buildings.

MC can help reduce the housing deficit, given the characteristics of such a constructive mode. Providing off-site prefabricated components with precision, efficiency, controlled cost, quality, safety and functionality increases the overall productivity of architecture, engineering and construction (AEC) industry. Countries such as the United States, United Kingdom, Sweden, Australia and China have been adopting modular construction to solve the housing deficit (Bello et al., 2023).

The use of industrialized construction methods may help solve important and historical construction problems, such as workflow instability, low productivity, lack of punctuality and delays (Deakin et al., 2020). These problems are also solved by applying lean practices. The benefits of applying lean concepts in MC have been documented in various case studies (Velarde et al., 2009; Nahmens and Mullens, 2012; Yu et al., 2013; Heravi and Firoozi, 2017). The main benefits are increased productivity; reduced waste, especially costs; improved safety conditions; increased job satisfaction and improved sustainable solutions.

The MC industry has an affinity with the manufacturing industry. This increases the synergy between lean concepts and MC, without forgetting the challenges that MC brings, such as the need for product customization, variable market demand and the involvement of the supply chain (Höök and Stehn, 2008). Thus, lean practices can be incorporated into the entire production flow of MC, involving the application of lean design management, lean supply chain management, lean production management, lean transportation management and lean site-assembly management (Innella et al., 2019).

The main questions of this work are: What is the contribution of MC in the construction sector?; What are the main barriers, opportunities and risks for expanding the use of MC in line with lean principles and how to consider them in viability studies?

The path to be taken by companies in the civil construction sector, which seek to align and implement modern and sustainable construction methods (such as MC) still has numerous barriers and doubts. Therefore, this work aims to present the beginning of a solution to this problem, with the aim of facilitating, through a conceptual map, the choice of the best path for the insertion of MC.

MODULAR CONSTRUCTION

DEFINING THE CONCEPTS AND PURPOSES

MC is a different way from the traditional building system and can be defined as an industrialized construction system compatible to be transported between the factory and the construction site (De Carvalho & Scheer, 2019). In this construction mode, work at the final construction site is minimized and prefabrication is maximized. Technologies are employed that facilitate off-site manufacturing and the transport to the assembled site, like a Lego® (BCA, 2022).

The term used for MC may suffer considerable variations. The definition is different in distinct parts of the world, as it considers different views and interpretations, more or less complete. The following terms are found in the literature: prefabrication, pre-assembly, modular construction or off-site construction, which can make understanding difficult (Gosling et al. 2016). Other terms may still exist: prefinished volumetric construction, permanent modular construction, prefabricated modular construction (Doermann et al., 2020). These terms are used interchangeably and encompass a variety of different approaches and systems (Bertram et al., 2019).

Industrialized construction is the rationalization of the work process in the construction industry to achieve cost efficiency, greater productivity and quality (Girmscheid and Scheublin, 2010). Off-site construction is the planning, design, manufacture and assembly of construction elements in environments outside the construction site (Australia, 2022). In this work, the definition adopted is that modular construction is the process in which a building is constructed off-site, under factory plant conditions with a controlled environment, using materials, codes and standards that resemble conventionally built facilities (MBI, 2019).

In addition to the definition of MC, this can be considered as the pinnacle of prefabrication, involving the most integrative measures of modules made in a factory with greater added value (Pan & Hon, 2020). It refers to the manufacturing and assembly of modules in a location other than the final installation location, after which such modules are sent to the installation location and assembled to form a complete building (Doermann et al. 2020). In general terms, modular construction involves the production of standardized components of a structure in an off-site factory, for subsequent assembly at the final construction site (Bertram et al., 2019).

STRATEGIES TO MODULAR CONSTRUCTION

Modularization, prefabrication of subsystems, standardization and industrialization of processes, increasing product value and making processes more efficient in terms of resources and time (Jonsson & Rudberg, 2013). Strategies to modularization of construction have recently attracted interest from academics and professionals in the sector. However, there are few studies that comprehensively classify different strategies. These must be suitable to develop innovative design solutions, improve the quality, cost, schedule performance of a project, allow flexibility in the use and maintenance of a building (Peltokorpi et al. 2017).

Modular product design is at the heart of any effort to utilize modularization in the production system. A "modular" design differs from the conventional strategy in that it includes a discrete mapping of functional elements to product components and specifies interfaces between them (Ulrich, 1995). Modularity becomes an attribute of the product (activity of structuring a product into modules). Coupling between modules allows product variants to be created, mixing and matching components according to the functions each user needs (Bask et al. 2011). Functions are hierarchical and that a single component must implement a specific "package of functions" rather than a single specific function (Peltokorpi et al. 2017).

To the production strategy, decisions regarding the necessary equipment are required, as well the factory layout, the level of automation required, production organization and planning methods (Ravn et al., 2015). Therefore, attention must be paid to this issue from the beginning of the project, considering the competitive priorities defined for investment in the enterprise (Jonsson & Rudberg, 2013).

Peltokorpi et al. (2017) presents four paths to modularization, according to the degree of product standardization and off-site production, with traditionally constructed buildings at the lower end evolving to the upper end with fully modular buildings. The paths are: – a. modular buildings (3D - pre-assembled volumetric units, composed of whole or connected modules, meaning the highest degree of off-site production and standardization); b. volumetric pre-assembly (building modules are produced off-site and assembled at the final construction site inside an independent built structure – example – the insertion of a bathroom or a kitchen; c. non-volumetric pre-assembly (2D - pre-assembled elements that do not create usable space – example – wall panels, floors or roofs); d. conventional buildings (raw materials and components, such as bricks and mortar, are used in construction at the final building site, indicating a high degree of customization and a lower degree off-site production and standardization).

The set of the first three categories provides a good basis for investigating modularization strategies, since the distinction between them is based on the hierarchical "packaging" of functions embedded in a single component. Understanding the different dimensions of MC, their interconnections and possibilities for achieving various objectives may support professionals select the most appropriate strategies for a specific context (Peltokorpi et al. 2017). Such strategies, for this work, are defined in three: construction with panels (2D), volumetric (3D) and hybrid (2D + 3D).

OPPORTUNITIES AND BARRIERS TO MODULAR CONSTRUCTION

In general literature on this topic, similar impressions from different authors, from different schools and parts of the world are found (BCA, 2022; Bello et al., 2023; Bertram et al., 2019; Broadhead et al., 2023; Deakin et al., 2020; Doermann et al. 2020; McKinsey and Company, 2020; Pan & Hon, 2020). In one hand, the main opportunities for MC: accelerated construction cycle, increased productivity, increased quality, safer and healthier working conditions, enables cost control, reduced volumes of construction components to be stored, improved sustainability (reduced waste of materials, the generation of dust, noise and carbon emissions, water consumption, as well as the possibility of greater recycling or relocation of such modular buildings). In other hand, the main barrier are: high initial costs for production and training, more complex of transport and logistics, production capacity limitations, market vulnerability, lack of technical knowledge, adversarial/resistant culture of potential customers, inadequate business model and supply chain configuration, lack of specific standards, codes and regulations, government support, lack of qualified professionals.

LEAN PRINCIPLES IN MODULAR CONSTRUCTION

Lean principles have greatly evolved through the Toyota Production System (TPS). When developing their products, companies must seek greater competitive advantage, launching better products onto the market more quickly, with attractive prices for their potential buyers and eliminating waste in production.

Since the origins of this new production paradigm, several sectors have made efforts to apply it. The pioneering work to introduce these principles in civil construction was Koskela (1992). Since then, researchers and companies have sought to interpret and adapt to this environment, as well as discussions and case studies can be found in the International Group for Lean Construction papers (Picchi, 2003).

However, lean principles became known worldwide through the publication of Womack et al. (1990), where briefly, the objective is to produce more value for the customer with less waste. Some of the lean tools are present in the AEC industry, like: Last Planner System (LPS), Value Stream Mapping (MFV), Integrated Project Delivery (IPD) and 5S. The benefits linked to their application are improved quality, reduced waste, increased productivity, increased safety and health at work (Almeida & Picchi, 2018).

Considering the five lean principles proposed by Womack & Jones (1997), disseminated and adopted in several industrial sectors, this work seeks to present their alignment with strategies for insertion of MC – a. Value: understand what value is for the customer and offer greater added value; b. Value Stream: identify and eliminate waste throughout the value chain; c. Flow: production in stable flow, without interruptions; d. Pull: produce only when demanded by the customer or previous process; e. Perfection: continuous improvement through rapid detection and resolution of problems at the base. Lean principles aim to continually improve the competitiveness of companies in the sector, employing methods that seek to reduce waste and meet customer requirements. Issues involving sustainability are important lean guides (Koskela et al., 2010). Through methods and tools, we seek to mitigate common problems in the sector, such as the high environmental impact and lack of efficiency in production (Almeida & Picchi, 2018).

Some of the main impacts and benefits arising from the implementation of lean principles may be collected in publications: standardization of work, improvement in productivity and working conditions, focus on value, formation of specialized teams, improvement in planning and control of work, transfer of knowledge between projects, collaborative project, integration with suppliers, reduction of lead time, reduction of waste and costs, greater customer satisfaction, increased company competitiveness (De Freitas & Costa, 2017).

The existing literature about modular construction addresses dispersed points of view. It is common for MC to be approached with individual factors such as design, planning, coordination, automation or benefits and barriers. At the same time, the literature about the synergy between lean principles and MC is also dispersed. Each work usually evaluates the specific use of a concept or tool. So, there is a gap in the understanding of the alignment of these concepts in a systematic way. Thus, the main constructs of MC are dispersed, especially when related to lean principles. For this reason, this work uses concept maps to define and relate the main constructs of the subject. This creates a logical sequence between the constructs to guide the adoption of MC by organizations.

RESEARCH METHOD

Design Science Research (DSR) was applied as a research methodology. DSR is a method which seeks to solve a specific problem, develop innovations, methods, models, product and process improvements (Dresch et al., 2015).

The objective of DSR is to develop concepts for solving complex and relevant problems in a given context, often based on a multidisciplinary study. DSR combines description and prescription (Aken & Joan, 2004). This approach is seen as a way of producing scientific knowledge that aims to lead to innovative solutions and artifacts to solve real problems and, at the same time, contribute to the evolution of theory in the area in which it is applied (Cole et al., 2005).

The literature provides guidelines for the DSR process (Shrestha et al., 2018). DSR presents six phases summarized from: development of a relevant practical problem; definition of objectives and expected results; development of a artifact (models, methods, constructs, instantiations, and design theories); demonstration of artifact effectiveness; evaluation; and diffusion (Dresch et al., 2015).

This research is part of a doctoral research, in which it is expected to formulate a complete model for the insertion of MC in the sector. Thus, the research we sought to understand the alignment of the MC concept and its contribution to the construction sector. For this, a literature review was developed to understand and identify MC strategies, and opportunities for its application. Studies on MC were assembled and data were collected to construct the conceptual map model.

ARTIFACT - CONCEPTUAL MAP MODEL

The development and use of a new theory may present some challenges to ordinary understanding. Conceptual maps, among many other tools, may be used to clarify the understanding of a new theory. Such maps present a visual structure that can graphically explain what is being studied (Maxwell, 2012).

Concept maps can be created for a variety of purposes, such as: making information from existing theories visible, clarifying an existing theory (allowing implications and limitations to be observed), developing a theory (helping to observe connections) and identifying gaps or contradictions, helping to find better solutions for a particular theory (Maxwell, 2012).Concept mapping has been shown to help learn, create new knowledge, structure and better manage organizations (Novak & Cañas, 2008).

Although concept maps may seem like just a graphical representation of information, understanding this tool and using it properly will lead the user to see that this is a powerful tool. The organization of concepts with connecting words can be simple at the same time, but also full of complexity and important meanings. A conceptual mapping was developed in this research to understand the concept of MC and its association.

MODULAR CONSTRUCTION CONCEPTUAL MAP MODEL

The Conceptual map model (Figure 1) presented the main characteristics, limitations and points of attention for each of the strategies considered, as well as seeking to relate the main barriers, opportunities, risks and externalities that surround MC. The tool (Figure 1) is composed of two parts: the first, which involves the concepts contained in boxes, and the second, which involves the relationships between these theoretical concepts. Furthermore, it also presents connectors, words that connect concepts and express relationships between them (Novak & Cañas, 2008). In line with each of these aspects, connections with lean principles were also presented.

As a way to guide the good understanding and application of the conceptual map model, a brief explanation of its use and the main themes involved is interesting. The MC is organized through six strategies: opportunities, risks, externalities, 2D MC, 3D MC, hybrid MC, which are associated with lean principles. For each strategy, information gathered in literature to construct the conceptual map are presented, as follows.

OPPORTUNITIES

Control
Safer
Quality
Sustainability

Initially, the opportunities of MC are verified, such as control and reduction of construction deadlines, cost control, healthier and safer working conditions, better control of quality standards and the possibility of developing a more sustainable environment. The deadline to execute these works is shorter than those for conventional works, and significant reductions can be achieved (McKinsey and Company, 2020). Cost control comes with the possibility of increasing productivity, due to better defined construction standards. This connects with the lean principle of standardization of work applied to construction and can increase performance with the use of lean cost management, the Target Value Design (TVD) (Koskela, 1992; Ballard, 2011). Regarding working conditions, there is less physical workload and fewer workers at the final construction site, improving the general organization and increasing work safety (Deakin et al., 2020). Lean practices address the concept of safety in its essence, bringing it from the theory of the Toyota Production System to lean construction (Koskela, 1992). Sustainability is also improved, being perhaps one of the greatest benefits of opting for MC, with the reduction in consumption of energy sources and natural resources, carbon emissions, waste generation, and general impacts on communities around to constructions (Bertram et al., 2019). The use of lean principles improves the sustainability of products, especially with the use of Value Stream Mapping (VSM) (Rosenbaum et al. 2013).

RISKS

Construction Standards

Business model

Suppliers

There are additional risks mapped, collected through the authors' work experience in construction and literature. To insert MC, it is necessary to develop specific standards, codes and regulations for this type of construction (Bello et al., 2023), without which, linked to incentives from government entities, the dissemination and encouragement of industrialized construction cannot be advanced. There is also a need for a new business model for companies in the sector and the adoption of a collaborative project, including the required digital transformation and improvement of relationships with suppliers. This can be achieved through the effective use of the value stream principle, using the VSM, for example.

EXTERNALITIES

Traditional methods

High competition

Resistant culture

Value understanding

Resource

Delimitation

Previous studies (Deakin et al., 2020; Bello et al., 2023; Doermann et al., 2020) have demonstrated that the main externalities and challenges focus on issues involving market conditions and the culture of potential customers to the MC. This collaborates with the first lean principle, which deals with value. It is necessary to evaluate the value chain, especially considering customer requirements (Womack & Jones, 1997). The high competition between companies in the sector and the preference of agents in the production chain for traditional methods, has an arrow indicating the box that the decision by MC, since these are aspects that must be considered in the decision. Searching for improvements in the production system and breaking away from the use of traditional methods is related to the lean principle of perfection, which involves the search for continuous improvement (Womack & Jones, 1997). Regarding the opposing culture and understanding the value propositions of potential customers, it was decided to indicate the opposite direction for the indicative arrows, since they are basic and conditioning aspects and must be analyzed even before any intention to the construction method. Finally, we have the challenges related to financial resources for production - which are considerably higher, since it is assumed the need to install and maintain production in an off-site manufacturing environment (Deakin et al., 2020) and price delimitation that keeps the product competitive compared to the market in general (De Mello et al, 2015). For these last two, a two-way relationship was used, as it is understood that they are necessary for the decision of the MC insertion, as well as being feedback with information within the process. Thus, the use of lean concepts and principles can reduce these challenges by eliminating waste and optimizing resources, as has been widely presented in lean literature.

2D MC

Design process
Workforce
Needs
Capacity
Flexibility
Entry, Cost

When evaluating the 2D strategy, a simpler modular construction method, it appears that it is quite attractive as a gateway to this world. Transport costs are lower, since the panels are two-dimensional, allowing a greater number of elements in loads. Like all labor involved in MC, it requires workers with greater training compared to traditional construction. It is important to highlight the production capacity of panel suppliers, a large quantity of flat elements are required.

3D MC

Impacts
Resources
Productivity
Construction speed
Specialized labor
Flexibility

As MC strategies are considered, when evaluating the 3D strategy, a greater number of considerations are made. This construction mode, even today, is disruptive, with almost all construction being off-site. Issues relating to logistics and transport stand out, given the size of the volumetric modules, transport conditions and costs, as well as the need for large equipment for lifting and coupling the modules. In this scenario, there is a greater need for initial resources in the manufacturing units to enable the construction of modules (Bello et al., 2023), on the other hand, there is difficulty in obtaining resources from financial institutions, both to finance production and to finance potential buyers of the units, who have a much shorter period of time to amortize payment for the product during the construction phase (which in many cases is a fraction of the time compared to traditional construction). There is also low architectural flexibility and great difficulty in changing the project on site, which requires more sophisticated and integrated projects, in addition to more specialized labor.

HYBRID MC

Flexibility
Vulnerability
Optimisation
Workforce, Areas, MC use
Impacts

As for the hybrid strategy (2D+3D), at the current stage of MC knowledge and application, it can be considered the most ideal scenario. Combining flat and volumetric elements optimizes transport and logistics, as well as allowing wider use of off-site elements. These factors lead to medium architectural flexibility, allowing greater customization of buildings.

The lean principles are indicated in the conceptual map model, linked to the constructs, in order to indicate the principle evaluated as most adherent and aligned. What can be seen is that most of the alignment of lean concepts are related to "value", where one must seek to understand what value is for the customer and offer greater added value through the chosen strategy. This is in line with customer resistance, one of the main barriers to adopting modular construction. By analyzing, managing and delivering value, the customer reduces their resistance. Reducing customer resistance can increase the procurement of modular products, bringing a gain in scale. Increased scale helps to reduce other barriers, such as direct and indirect costs and financing. For some constructs, lean principles were not aligned, due to the difficulty of establishing the most appropriate principle or because this establishment was not possible.

The main contributions of this research were the following: (i) Classification of the MC concepts into strategies groups and associations between them; (ii) Proposal with opportunities of MC context with inclusion of different models (iii) Results of the organization and relationships between the constructs, within of a group of strategy. The conceptual map classifies and organizes the main constructs of MC and evaluates their relationships with each other. The map includes the relationship of the constructs with lean principles and presents the externalities that impact the main constructs.

With the conceptual map, the Architecture, Engineering & Construction sector may identify possible paths for adopting MC, evaluating different modularization strategies based on their needs, conditions and points of attention. With the externalities, organizations can structure strategies to overcome the challenges pointed out. The MC may contribute to MC adoption perspectives, considering externalities (barriers) and main opportunities in each strategy.

Overall, the conceptual map provides a basis and direction for decision-makers to choose paths for adopting MC, taking into account the requirements and resources needed for each path. This leads to a more conscientious and informed adoption, with well-defined paths.

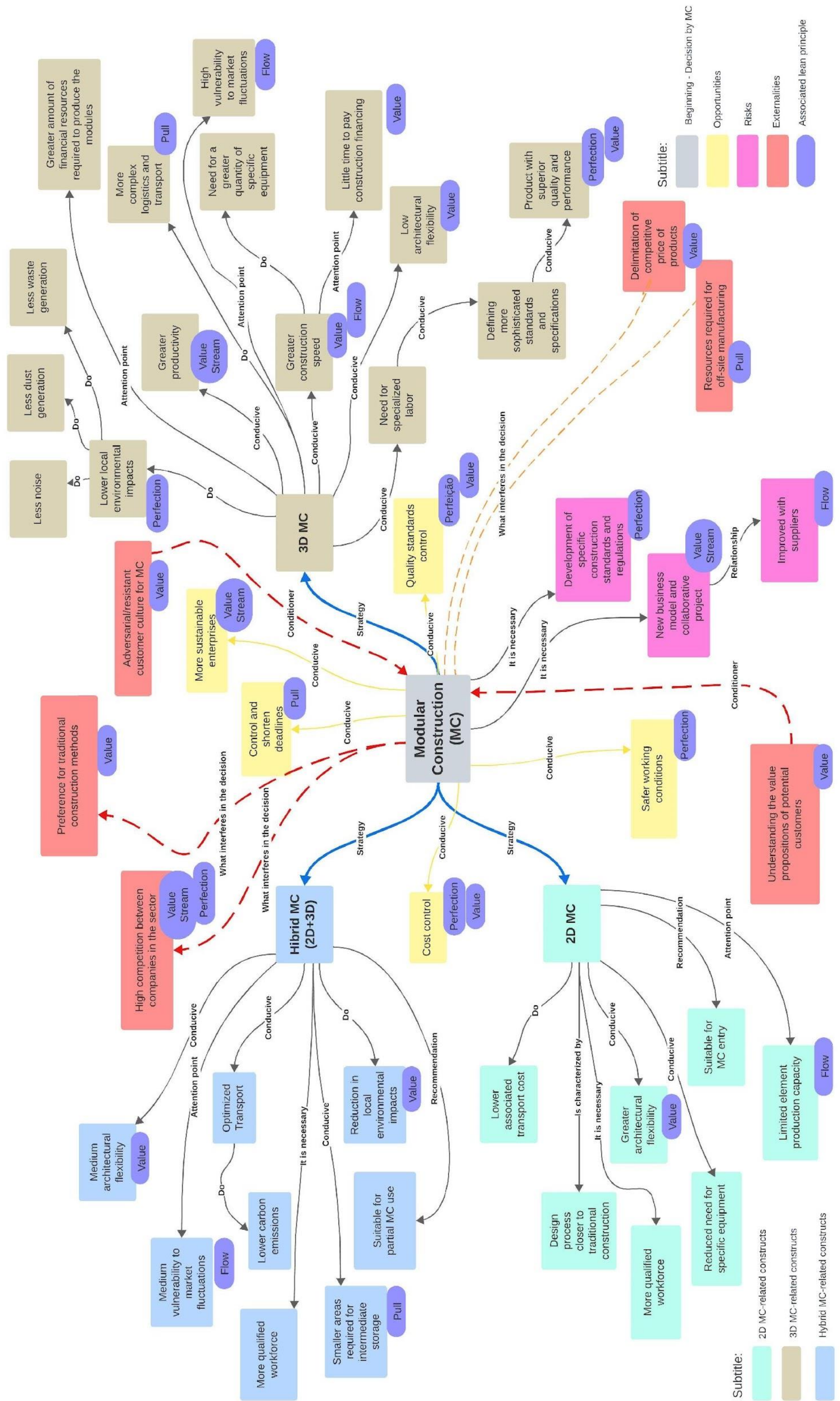

Figure 1: MC Conceptual map model. Source: The Authors.

CONCLUSIONS

Lean principles allow complete alignment with MC, since it is a mentality already widely spread in the manufacturing industry, as well as bringing new paradigms, applicable to the business, involving the development of the product as a whole and the relationship between agents of the production chain.

Precisely because MC requires that construction companies, markets and potential clients have new conceptions about this construction method, the application and alignment of lean principles allow choosing the best paths to be followed for the insertion and expansion of employment of this constructive way, considering the necessary reviews of project flows, supplies and execution of works, as well as the production and business model of each company in the sector.

The conceptual map model presented facilitates the understanding of possibilities and paths through the synthetic visualization of alternatives. Each one of the constructs presented can be analyzed in more detail, allowing one to choose the most appropriate MC strategy for each company or enterprise.

The lack of studies that analyze the MC application through different strategies, in different contexts, mainly where traditional construction models are more effective limit the analysis of MC applicability in a real context. Thus, future and complementary work may explore each MC strategy, adapting and analyzing the particular ones in light of the main opportunities and barriers identified. As for lean principles, specific works may study each alignment proposed for each construct present in the conceptual map model. Increased studies in this area will certainly lead to the development of more innovative, sustainable construction techniques with greater added value.

ACKNOWLEDGMENTS

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DEFINING INTERFACES TO FACILITATE BUILDING MODULE CHANGE

Peter Zieth[1] and Cecilia Gravina da Rocha[2]

ABSTRACT

Modular construction in the building industry remains largely misunderstood, despite numerous studies on the subject. With confusion around what constitutes a module, how it is defined and differentiated from other modules, and how they interface. This study examines interface characteristics; types, standardization, and reversibility (three measurable categories based on Fixson (2005) function-component allocation (FCA) tool for product architecture assessments) and assesses product architecture interfaces to apply them to building product architecture. The intent of this examination is to understand the interface's role in any transfer of module functions across modules. Defining interfaces to better differentiate building modules from each other should ultimately facilitate the identification of what specific functions of the building component modules that need to be designed, manufactured, assembled, changed, and disassembled. From the examination, the discussion arising seeks to advance on how a building spatial module function designation might transfer functions at an interface, to provide clarity on the functional requirements for component modules to meet.

KEYWORDS

Modular construction, prefabrication, flexible manufacturing, interfaces.

INTRODUCTION

Modular construction in the building industry remains largely misunderstood, despite numerous studies on the subject. With confusion around what constitutes a module, how it is defined and differentiated from other modules, and how they interface. In the context of product architecture (or product modularity) each component, or module, can be made up of modular sub-components, or connected subassemblies. Likewise, each module, when connected, forms a product (Ulrich, 1994). Further explained in the referenced authors' study, these connections, or interfaces, can be coupled, such that a change to one component requires a change to the other (e.g., changing a ball hitch size on a car requires a change to the hitch on the trailer which is to be attached) or de-coupled (Figure 1) where no such dependency exists (e.g., a mobile phone and protection case). While a modular architecture includes one to one mapping of the function to the component (e.g., for a car trailer, the function being the transfer of a load to the road is mapped to the wheel component), an integral architecture includes complex mapping of functions to components (e.g., a car chassis) (Ulrich, 1994).

As has been studied, those interfaces may be 1) coupled (nuts and bolts), tightly coupled (welded joints), decoupled (furniture in a room), or loosely coupled (door hardware and door

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leaf) (Sanchez, 1995; Schilling, 2000; Ulrich, 1994), or 2) an interface type across families of modules (doors to walls across room types) (Pine, 1999; Salvador et al., 2002). Both sets of interface types have applicability in building modularity.

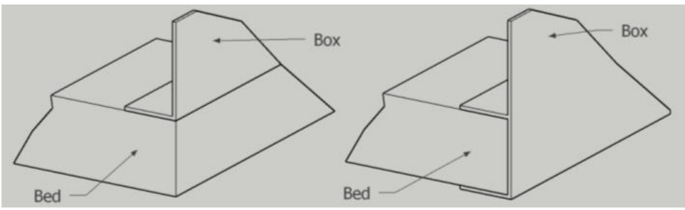

Figure 1: De-coupled Interface, left, Coupled Interface, right.
(Adapted from Figure 4 in Ulrich, 1994)

Using Ulrich's definition of a module, a study (Fixson, 2005) looked at (i) what is a function, (ii) what is a component, and (iii) how the function was allocated to a component. While the first part of the Fixson study is important in framing a discussion on modules, how a function is allocated to a component (modular or not) could apply to a product and a building product equally and is therefore not the focus of this study. Understanding interface characteristics though and their role in the functional allocation transfer from one component to another potentially has the greatest ability to facilitate building module decoupling and change.

Ulrich proposed six motives for change in products (upgrades, add-ons, adaption, flexibility, wear, and consumption) (Ulrich, 1995). Changing, making, and unmaking a building product is of particular interest since buildings are typically designed and constructed to serve a specific function for an expected period (Askar et al., 2021), namely, its design (or service) life. When applying Ulrich's motives for change to the design life of building product components, they could be organized into three groups: (i) replacement (wear and consumption), (ii) retrofit (add-ons and adaption) and (iii) change in use (flexibility and upgrades).

Regardless of the mechanism initiating change, design strategies (specific plans of action to accomplish an objective or set of objectives) which increase the flexibility of a building, and allow for change to be easily carried out, have been studied (Gosling et al., 2013; Keymer, 2000; Slaughter, 2001). These include strategies grouped into; the use of interchangeable system components, increased layout predictability, improved physical access, dedicated areas for systems, among others, but do not examine a process designers can use to facilitate these strategies. Other authors have looked at the absence of initial design consideration for potential change that leads to different levels of disruption in building operations once component parts of a building need to be changed (Gleeson et al., 2011; Grussing & Liu, 2014; Knyziak et al., 2017). Indeed, occupants can be subjected to a diminished use of the building in normal day to day activities once changes need to be performed (Tokede & Ahiaga-Dagbui, 2016). One of the studies (Gleeson et al., 2011) categorized disruption and demonstrated that different levels of disruption are connected to the complexity/extent of change (intervention), and highlighted the importance of identifying change potential to guide the design of components and the relationship to adjacent components. What the components do, what their interfaces are, and their arrangement with the rest of the product is referred to as the product architecture (Eppinger & Ulrich, 1995; Fixson, 2005; Gershenson et al., 2003; Ulrich, 1995; Vickery et al., 2015). What these studies don't do, and is needed, is to provide a consolidated process for designers to use that lead to design outcomes that can facilitate change activities while limiting disruption.

The second part of the Fixson study examined product interface characteristics, types, the degree of interface standardization, and the interfaces' role in making, changing, and unmaking (disassembling) the product (its reversibility). When considering a building as a product, it becomes important to understand the definition of an interface between modules to better identify the type of coupling, what is the level of modularity (modular or not), and what the modules are. The aim being to evaluate an alternative interface definition to help identify and distinguish building modules more clearly so they can be manufactured and assembled, while also facilitating change, the speed of construction, disassembly, maintenance activities, and environmental outcomes for material reuse and recycling.

Conducting desktop research of literature identified an issue with applying a definition for interfaces from product modules to building modules. The literature review looked at the basic differences between building product architecture as compared to product architecture before examining how building module interfaces are identified between building modules. This review conceptually examined how interfaces might be used to facilitate change. The study then considered parameters that define an interface, before devising and applying an alternative conceptual interface definition to the Fixson study, specifically when conceptually applied to buildings. Particular attention is given to the interface characteristics of type, reversibility, and standardization before a conclusion is drawn and implications are identified. The developed knowledge from the research and analysis will help to better identify and differentiate one building module from another and can be further tested using more analytical research methods.

BUILDING PRODUCT ARCHITECTURE

When applying the concepts of product modularity to buildings, there is a key difference between buildings and products. Buildings utilize components to create spaces typically occupiable by people, whereas products typically involve only the physical components (C. Rocha et al., 2015). An obvious exception may be cars, that contain spaces occupied by people, but differently, buildings are anchored/founded on a specific piece of land. Buildings also typically have longer life cycles and involve multiple different stakeholders influencing their change over that period (Menassa & Baer, 2014), and they often remain occupied while changes occur to them. Whereas modular (or integral) products, like a car, tend to be deactivated completely while change occurs (e.g., changing a wheel, or a battery). It also implies that if a building typically remains occupied while changes occur to it over time, there is a potential high degree of change variability inherent due to the diversity of potential stakeholder input. Whatever those changes are should also facilitate the ability for occupants to remain while the changes happen to the affected components, and those components should be made to be easily changeable to limit the disruption to occupants.

BUILDING MODULE INTERFACES

To facilitate the potential for change to modules in buildings, there must be an initial recognition of the differences between product and building modularity. Examining the concept of product modularity levels (a chunk, divided into sub-chunks), and how they could be divided, as applied to buildings, was a study (C. G. da Rocha et al., 2018) that focused on modules being spatial voids (rooms) with components being used, or not used, to create spaces (with walls and doors, for example, being used to differentiate one module family from another, Figure 2). There are two outcomes of this study worth highlighting: (i) components are not needed on all sides to define a space, but the interface connection between spatial modules is, and (ii) spatial voids are formed by at least six surfaces (the latter logically assumes rooms are cuboid).

The Rocha and Koskela (2018) study conclude there are interface connection surface problems at the junction between two modules. In this case, the interface connection surface is a single shared wall of two different spatial modules like a Bedroom (Room B) and a Bathroom (Room A) on either side of the wall in Figure 2. With the interface connection problem being where the two modules have potentially different requirements for that shared wall, like the location of a door that necessitates changes to the components forming another module like the

Bathroom cabinet in A1 to B2 modules in Figure 2. It implies the interface may not be correctly identified or located between modules.

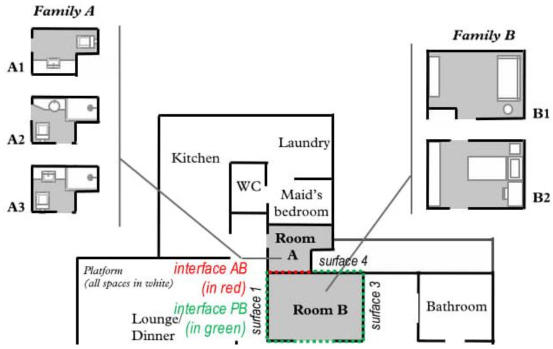

Figure 2: Example of building module component variances from the differing positions of fixtures, doors and windows, and services. (Adapted from Figure 2 Rocha and Koskela 2002)

The Rocha and Koskela (2018) study considered spatial modules to also contain building components such as walls surrounding a spatial void, along with other associated doors, windows, and fixtures. While component-oriented building modules are not always bounded by components on all sides, due to the arrangement of boundary components, a change to one module necessitates a change to an adjacent module. The result implies these modules are more integral and requires clarity of the interface definition if a modular outcome is desired.

Maintaining the assumption that spatial void modules are cuboid and formed by at least six 'surfaces' implies that modules are limited in their ability to be universally adaptable (sectional modularity) with other modules since the surfaces (including doors, windows, fixtures etc.) of a particular module are fixed. Hence that module is limited in its ability to be universally adaptable for use with other modules because of the location of those features that conflict with the adjacent module at that interface. Further a module interfacing with another module along the length of a shared wall, between Rooms A and B in Figure 2, points to potential difficulties of constructing, manufacturing, and coordinating individual modules to facilitate a connection.

However, the interface surface problems could be resolved if modules are more clearly differentiated by viewing and defining the interface differently. Firstly, a building product architecture could be a combination of both component-oriented and space-oriented modules. This is not a new concept, but it needs to be described to understand the second point. A building module could be a component (door, wall, window, floor) and it could be a spatial void (room) (Figure 3) to make the appropriate scale of these module interfaces invariant. While a component may be an object, like a wall, a spatial void could also be considered a component because a function can be mapped to it. For example, placing a bed in a room implies the function of a room is for sleeping and is therefore a Bedroom. Applying this perspective to building modularity means that every surface of a spatial void (room), and every surface of an object component (wall), all being different modules, could interface with each other.

Secondly, if the proposal was that spatial voids are formed by at least six 'planes' (e.g. boundaries without physical mass between two spatial voids) instead of 'surfaces' (e.g. associated with a solid mass such as a wall), then there is flexibility in the definition of a building module to allow for interfaces with other modules that are not dependent or linked to a surface. This approach places emphasis back onto the role and characteristics of the interface.

The notion that a module could interface via a 'plane' with either a component that has surfaces (i.e. physical mass), or another spatial void constituting any number of 'planes' (i.e. voids), provides a more appropriate product architecture module definition to a building. It allows, for example, walls, portions of walls, or the absence of a wall (the void that might otherwise be occupied by a wall defined by its 'planes'), all to be modules, and rooms (or voids) to be modules, with or without walls.

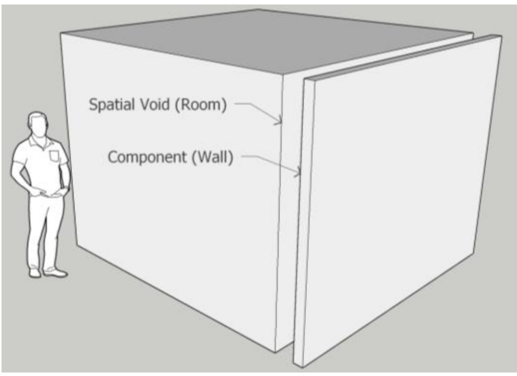

Figure 3: Component-oriented (wall) and Space-oriented (room) building modules where every surface of each module is an interface.

By extension, if consideration of the spatial void definition is applied to a component, then, a component, having surfaces that are co-located with a plane means that all building modules, be they spatial voids or components, are bounded by planes (having no physical mass). This means that all building modules have planes that interface with other planes. Simply, the building module plane is the interface, regardless of it having a surface or not.

BUILDING MODULE INTERFACE DEFINITION

The concept of product modularity initially focused building modularity on being spatial voids (rooms) with building components being used, or not used, to create the spaces. Further analysis of literature resulted in concluding that a product architecture module definition for a building could be that (i) a module (spatial or component) could interface with either a component, that has surfaces, or a spatial void constituting any number of planes, and (ii) while components are not needed to define a space, and a space could itself be a component, an interface connection between modules is required. This definition raises two questions 1) if a module could interface with either a component that has surfaces, or a spatial void that has planes, would it be simpler to refer to the component surfaces as planes, and 2) if components are not needed to define a space (ceiling or walls for example), is there a limit to the number of adjacent components required in order for that space to be considered a component module?

If a module's surface coincides with a plane, then the first question is addressed. However, if the second question was not addressed, it could be surmised that a cubic void of air not within a building could be considered a building module. While there are practical benefits to defining exterior air 'space' as a module when allocating functions from that space to a building module to address (wind, radiant heat from the sun, rain, atmospheric pressure, humidity, for example), this interpretation is useful only in allocating those atmospheric functions to the building and its constituent component parts. Namely, from an overall building module set of functional requirements allocated to the rooms and wall modules being examined here. Maintaining the limitation of applying building modularity to physical buildings, and not outdoor natural environments, it therefore implies that a building module must be bounded by components: a built environment having a floor at least. How people perceive a defined space is not the subject of this paper, however, the purpose of the distinction is to clarify a revised product architecture module definition for a building. That definition being that a building module (i) constitutes any number of planes that coincide with component surfaces and spatial void boundaries, and (ii) an interface connection between modules is required. A building module could therefore be either a spatial void that has met certain boundary conditions, or a component, and requires an interface connection. This conclusion is reinforced by a study (C. Rocha et al., 2015) that aimed to adapt product modularity to be used for house building that concluded solid mass components (walls, roof, floors) create spatial voids for the activities of the people within.

Returning to Ulrich's concept that a modular architecture includes one to one mapping of a function to the component, and an integral architecture includes complex mapping of functions to components (Ulrich, 1994), requires examination of the application of functions to building modules when considering the module interfaces. Using Ulrich's definition of a module, a study (Fixson, 2005) looked at (i) what is a function, (ii) what is a component, and (iii) how the function was allocated to a component. As referenced previously, while the Fixson study is important in framing a discussion on modules, it is the interface characteristics and role in the functional allocation transfer from one module to another that potentially has the greatest ability to facilitate change of building spatial or component modules. It is the examination of product interface characteristics, types, the degree of interface standardization, and the interfaces' role in making, changing, and unmaking (disassembling) the product (its reversibility), that is of interest, and applying them to a building product architecture to see if they can facilitate change.

The result of the Fixson study was the development of a tool (a device or implement to carry out a particular function) for assessing interface linkages between the product, process, and supply chain of different designs of similar products. This tool, albeit intended for manufactured products, could be adapted for application to assessing building modules and is the subject of what is tested in this study. The intent of adapting the tool would then be to reverse engineer it for possible use to define adjacent component modules more clearly for manufacturing purposes.

To assess how the tool could be adapted for application associated with building modularity, an understanding of the interface role needs to be examined against the product function for its nature and intensity as applied to a building using the definition of an interface being a plane. For the purposes of demonstrating the concept as applied to building modularity, I will use a building in the form of a six-sided cuboid that contains a series of cuboid forms (room spatial modules) linked together and separated by other, narrower cuboid forms (walls and floors component modules) like those of other studies (Ching, 2023; C. Rocha et al., 2015). Figure 4. For further simplification and clarity, the exterior boundary cuboid forms (exterior walls, floor, and roof component modules) will not be used in the demonstration and can be examined in further studies. Using two adjacent room component modules of similar function, for example, a bedroom-to-bedroom relationship, there are characteristics (privacy, insulation, visual amenity, for example) of the component function (bedroom 1) that must be transferred through the interface plane (interface characteristics) into the component function of another product (wall) for that product to perform (opacity for privacy, insulate for warmth, color and texture for visual amenity, for example) prior to transferring through another interface plane (interface characteristics) to another component function (bedroom 2) for it to perform (opacity for privacy, insulate for warmth, color and texture for visual amenity, for example) and vice versa. Figure 5.

The Fixson study (Fixson, 2005) assessed three different interface characteristics: (i) type (the interfaces role for the product function), (ii) reversibility (the interfaces role for making, changing, and unmaking the product), and (iii) standardization (the interfaces role regarding substitutes). These will be recapped below with interpretations of how they might be applied to a building product architecture.

TYPE

According to the Fixson study, the type of interface is initially determined by (i) their number and distribution across the product, (ii) their nature, and (iii) their intensity.

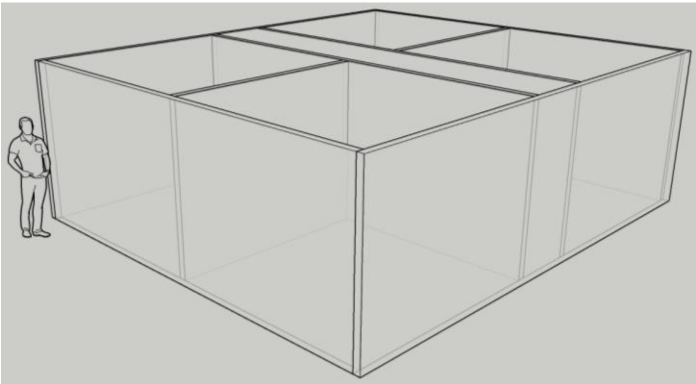

Figure 4: Cuboid that contains a series of cuboid forms (room component modules) linked together and separated by narrower cuboid forms (walls and floors component modules). Roof/Ceiling removed for visual simplicity.

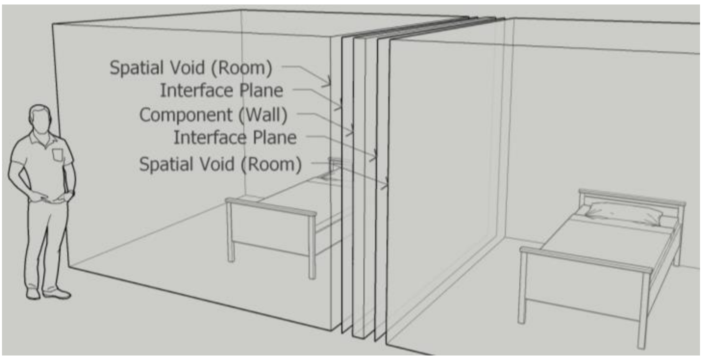

Figure 5: Bedroom-to-bedroom component function (bedroom 1) transfers through the interface plane into the component function (wall) to another interface plane to component function (bedroom 2) and vice versa.

Determining the number involves a simple counting of the interfaces. In the example, these interfaces are the boundary planes. A room component module shown in Figure 5 has primarily six; the ceiling, the floor and four walls. This number could be expanded if there was a window component module in one wall and a door component module in another, for a total of eight. Honing the example, for a wall separating the other room, there is only one interface plane to each adjacent component, the room to wall, or two interface planes if you add a door. Services (electrical, ventilation, communications systems, for example) interfaces are not referenced here for simplicity. They are sub-components for this example and an outcome of how the interfaces of the room to adjacent components are managed and functions are allocated.

Distribution examines if a component interface interacts with a limited or significant number of other components (relative to the total number of components) (Fixson, 2005). If the interface does interact with a significant number of other components, the component may be general or central to the functionality, indicating if the product architecture is not very modular but fragmented. Fixson postulates that a fragmented product architecture is more likely to have many components that show interactions with many other components. This also generally applies to a building since the room component modules generally interact with a variety of other adjacent modules (walls, floor, ceiling, doors, windows, other rooms, and services of varying types) through their interface planes and is consistent with Ulrich's Integral product architecture. However, this is not the focus of this study.

It is the function of a room module that distinguishes it from another room module. At a very basic level, a Bedroom is called a Bedroom because it has a bed in it and is used for sleeping. A Dining Room has a table and chairs used for eating at. That is not to say that either of these examples cannot be used for other functions, but those other functions influence the functional allocation of that space, and hence the transfer of those functions to the interfaces for the adjacent components to meet, or not. Hence, the functional allocation has the potential to affect the adjacent component being manufactured.

Fixson's tool utilizes the outcomes of another study (Pimmler & Eppinger, 1994), that combines the nature of the interface (reflecting the physical effects that occur for the interface to play its intended role), and its intensity (its strength and desirability with respect to its nature), to assess the interface between components. At the component level, the tool assesses four types of interactions: (i) a spatial interaction (the need for adjacency or orientation – room to room adjacency for functionality, room to wall), (ii) an energy interaction (the need for energy transfer – room to wall for insulation, of heating), (iii) an information interaction (the need for information or signal exchange – room lighting activation), and (iv) a material interaction (the need for an exchange of materials – the passage of people through a door, or wind through a window opening). These interactions are further assessed by their importance and desirability levels. Each of these four interactions, at the interface, apply to building modularity and can be tested accordingly as was studied by da Rocha et al. (C. Rocha et al., 2015).

REVERSIBILITY

Considered to be an advantage of modular product architectures reversibility is the ability to change products over the product life, such as upgrades, add-ons, adaptation, wear, consumption, or reuse, and depends on the interface. The ability of a module to change depends on the difficulty to disconnect at the interface, and the interface's position in the overall product architecture (wall to floor being more inaccessible than a wall to room interface). In the example, the ability to change the room function, from Bedroom to Living Room, will be dependent on the ability of the interface planes reversibility with boundary components. Changing from one spatial module type to another requires changing function allocations at an adjacent wall component interface plane. If the wall component module meets the requirements of the interface, then reversibility conditions have been met. However, if the wall needs to be replaced due to it not meeting the performance requirement needed, then the ability to remove and replace the wall as facilitated by the wall components other interface planes (floor, ceiling, and adjacent wall component modules) is a measure of the components reversibility. For a wall it is not just one interface plane that is required to be reversible, but six. An example of low-level of reversibility of a component module might be a wood framed gypsum board wall that requires destructive removal of the gypsum board to expose stud framing nailed to the floor, that also needs destructive removal. Refer to the left side of Figure 6. A high-level reversibility might be a prefabricated wall finish panel clipped onto a wall frame that is bolted to a floor and ceiling. Undoing these clips and bolts facilitates removal and replacement without the levels of destruction the former example necessitates, as shown to the right side of Figure 6.

Fixson uses two measurables for reversibility; (i) the interfaces' own technical specifications (skill and equipment requirements to change the component), and (ii) how deep the component is 'buried' in the product. In the former, the room (spatial module) to wall (component module) relationship requires the interface plane to require the room function to be accommodated by the wall component function through the interface plane exchange and vice versa. What those requirements are will be the subject of further study. For the depth a component is buried, the room module is entirely accessible, however the wall component has other interfaces (the joints to the floor, ceiling, and other walls), that are less accessible. It may be easier therefore to change the function of a room module for technical and depth reasons, but harder to change the wall module since the wall to floor interface is connected and hidden.

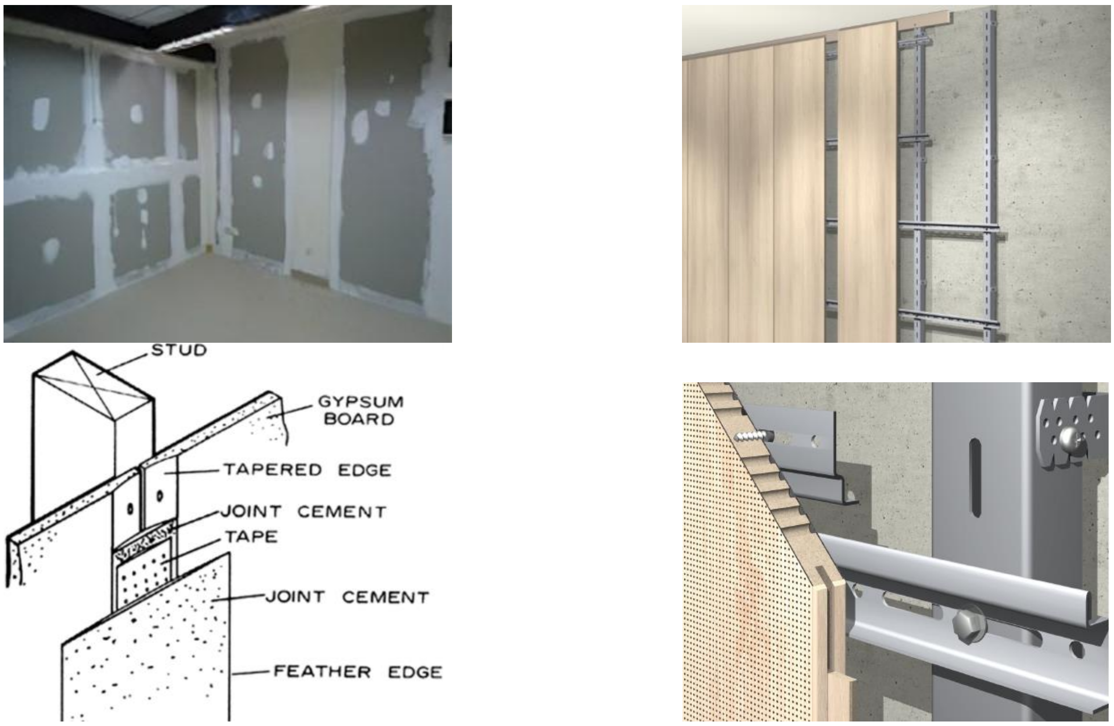

Figure 6: Left: Low-level reversibility wood framed gypsum board (Adapted from Civilguidelines.com images), and Right: high-level reversibility prefabricated panelized wall finish (Adapted from Ambienta Architectural Systems images)

STANDARDIZATION

The third characteristic Fixson describes, standardization, relates to the interface's role regarding substitutes. Considered to be critical for product variety, interface standardization measures the interfaces' role to facilitate module substitutes (components and spatial voids) and, in this case, building module component product families (room/spatial void types, wall modules, floor modules, ceiling modules, for example). Room types, like student accommodation rooms, or hotel rooms are highly repeatable, while a railway control center room is often a one off. For sub-components making up a module, the junction between a wall lining and the supporting wall is often a standard system (regardless of the degree of reversibility) as represented in both examples in Figure 6, versus a one-off rammed earth wall.

Standardization describes the degree to which an interface facilitates the swapping of components on either side of the interface. While standardization could be easily confused with Reversibility, a building example distinction for a component would be the difference between a nail and a screw. Both could be standard, but a nail does not facilitate reversibility, while a screw facilitates reversibility. Fixson clarifies that 'component swapping modularity and component sharing modularity do not describe the interface itself, but rather the alternatives that exist on either side of the interface.' The distinction being that component swapping, is usually where the larger component remains in the system, like a room, and the interface allows the exchange of the other one, like a wall. In our example of a room and wall, the larger component is exchanged by changing the function of the room from Bedroom to Living Room, hence it would be considered component sharing (the wall is shared), provided the wall component interface (the plane separating the two components – wall and room) with the room can accommodate the change of function. As a plane, this might seem straightforward for the interface between the two. However, the interface must be capable of exchanging all critical functions. Using the wall as the example, if the wall was acoustically rated for 40 dB (Decibels), and the Living Room requires separation to another Bedroom of 60 dB, the interface (plane) has failed to transfer the functional performance requirement since the wall component has only managed to address 40 dB of the interface requirement. The result being that the interface requirements must be maintained, and therefore the wall component module needs to be changed with another wall module type that meets those requirements.

Since interface planes in a building are similarly common across component types within a family, room to walls, for example, the interface systems are considered to have bus modularity. If the interface planes become standardized to the point they facilitate connection of every component with every other component, they would be considered sectional modularity. Looking at the types of interfaces at various similar module levels, rooms (spatial voids) to walls (components), for example, is where Fixson's Lego standardization example is fitting.

CONCLUSION

This study has taken a view from product architecture that a building could be a combination of both component-oriented and space-oriented modules. A building module could be a component (door, wall, window, floor) and it could be a spatial void (room) to make the appropriate scale of these module interfaces invariant. Further, spatial voids are formed by at least six 'planes' (e.g. boundaries without psychical mass between two spatial voids) instead of 'surfaces' (e.g. associated with a solid mass such as a wall). A building module plane is the interface for both spatial and component modules, regardless of having a surface or not. This view gives greater flexibility in the definition of a building module to allow for multiple interfaces with other modules that are not dependent or linked to a surface.

By applying product modularity definitions to building modularity, testing interfaces through a different lens to what other literature has used, and applying them to Fixson's tool, this study suggests the tool can be adapted and applied for use in building product architecture to define component module requirements. Following Ulrich's (1995) product architecture definition, after the function of the spatial void (room) is determined (and arranged in a floor plan), the functions can be mapped to the adjacent physical components (walls, ceiling floor, for example), through the interface plane connecting those components. Where interface planes (having interface characteristics, but no physical mass or thickness) are defined between spatial (rooms) and component (walls, floors, ceilings) oriented modules, with functions allocated to them from those modules, a clearer, more succinct set of component modules for manufacture and assembly can be defined.

IMPLICATIONS

The implications being that interface parameters assigned by the functional allocation from the spatial voids can be applied to an invariant interface database parametric management tool to be used for module component identification, selection, and meet functional spatial performance criteria. If used by designers initially, this tool, once developed, should provide building owners and maintainers greater certainty that the building designed will perform as intended, and can be maintained and changed easily while limiting disruption to occupants.

To inform an interface database functional allocation tool, more analytical research needs to be conducted into the design life of various components in various building types that make up assemblies, along with identifying the various change frequencies. This research will help inform the level in an assembly a modular or integral component might need to be. Additional research also needs to be conducted into the levels of disruption tolerable to building occupants in the various building usage types to help organize the modules.

The next step would be to define building module function categories (performance standards) from room requirements. These would be mapped to the interface characteristics (type, reversibility, and standardization) for transfer from a spatial module (rooms) across an interface plane to a component module (walls, floors, ceilings) and vice versa.

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WHY DO SOME PREFABRICATE MEP WHILE OTHERS DO NOT?

Tuomas Valkonen[1], Otto Alhava[2], Jaakko Viitanen[3] and Olli Seppänen[4]

ABSTRACT

Prefabrication of mechanical, electrical, and plumbing (MEP) systems seems to be an obvious choice to some, while others are struggling to reach the same conclusions. Most of the literature is focused on benefits, implying prefabrication is an obvious choice. To understand reasons why different conclusions are reached, we studied two cases where one decided against, and one decided to use MEP prefabrication. While some reasons can be contributed to differences in project type, there are general conclusions to be drawn. Reluctancy to use prefabrication seems to correlate to first time experience of prefabrication, namely overestimation of direct costs, and underestimation of indirect benefits (obstacles). Moreover, in the second case, prefabrication was used as a tool to enable lean practices such as short takt time, low amount of waste, levelled production, and efficient flow of materials. The key difference between the two cases is, Case 2 uses prefabrication to reach a valued goal while Case 1 evaluated its utility without a real problem that could be solved by prefabricating. Based on the two studied cases prefabrication becomes a more attractive alternative when it is used as part of a systemic change to achieve a valued goal.

KEYWORDS

Prefabrication, Choosing by Advantages (CBA), Lean construction.

INTRODUCTION

The construction industry is far from other industries if measured by industrial revolutions (Lasi, 2014; Sharma and Singh, 2020). If compared to factory environment, construction industry has passed Mechanisation (Industry 1.0) and has entered to Electrification (Industry 2.0). As an example of current state, the workstation lighting is an essential part of electrification but is often not a normal part of the site's working conditions. For construction, Automation (Industry 3.0), Digitalisation (Industry 4.0) and Personalisation (Industry 5.0) are still waiting for realisation. Construction is done on-site by craftsmen as opposed to work being divided into manufacturing and assembly operations as in Industry 3.0. Womack et al. (2007) describe craft production of 1890's as follows: workforce was highly skilled in machine operations and fitting, organisations were extremely decentralised, although concentrated within a single city, general purpose machine tools were used, and production volume was very low. Same applies to on-site production in construction industry. Lean methods towards industrialisation are applied as isolated solutions, and the need for systemic change is often overlooked or not understood.

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Prefabrication of mechanical, electrical, and plumbing (MEP) systems is an example of such an isolated Lean method. It has been suggested to solve the problem of low productivity and poor quality in construction. The term prefabrication does not have a clear-cut definition, but in general, it means moving work from construction site to factory environment, thereby reducing installation time on site. Documented benefits associated with prefabrication include lower time and material waste, better ergonomics, shorter lead time, fewer accidents, improved productivity, and better quality (Easmann & Sacks, 2008; Poirier et al., 2015; Lavikka et al., 2018). In addition to these non-monetary benefits, direct cost savings have also been reported, although evidence is contradictory (Khanzode et al., 2008; Jang and Lee, 2018). Decision-making frameworks have been developed to make non-monetary benefits visible for project members, as direct costs are easier to evaluate. Based on these previous results, adoption of MEP prefabrication seems like an obvious choice. However, the adoption rate in Finland and other countries remains low.

Studies have documented multiple obstacles hindering or preventing the adoption of MEP prefabrication. The following obstacles in adoption of MEP prefabrication have been reported by Lavikka et al. (2021) and Lopez et al. (2022):

- Prefabrication requires detailed designs earlier in the process, necessitating early design freezes. In traditional procurement, designs are not detailed enough for bidding prefabrication accurately.
- Lack of prefabrication procurement knowledge and resistance to change.
- Direct costs are the main bidding criteria.
- Lack of detailed modular designs due to lack of capabilities and the custom of designing one-of-a-kind buildings.
- Contract and union agreement boundaries.
- Lack of flexibility (design revisions).

Obstacles of prefabrication are making its adoption difficult but not impossible. Objectively balancing benefits and obstacles to decide whether to prefabricate is not simple, hence various evaluations methods have been introduced. Based on previous research Chauhan et al. (2019) proposed a Choosing by Advantages (CBA) based method for evaluating MEP prefabrication. Their proposed model answered to the need for transparency in evaluating non-monetary benefits in addition to direct costs. The need for such a framework was derived from the overemphasis on direct costs and the difficulty in translating other benefits to monetary benefits reliably. In CBA method, these non-monetary benefits are ranked between on-site and prefabrication alternatives to determine their relative advantage over each other. Finally, prefabrication is compared to on-site construction by combining the direct costs and relative advantage in one figure(Suhr, 1999; Arroyo, 2012).

Research literature lacks an explanation of why some companies choose to implement MEP prefabrication, and succeed in it, while others deem it unprofitable or impossible. In this research, two cases are evaluated. One decided to construct on-site and another decided to prefabricate. Differences in reasons contributing to these decisions are evaluated. The following research question is answered:

RQ: What are the differences in decision-making processes and motives resulting in the adoption and rejection of MEP prefabrication?

Prefabrication has the potential of being a more interesting alternative to a more significant number of projects by demonstrating why some choose to prefabricate. Broad adoption of prefabrication has the potential to significantly increase the quality and productivity of construction industry by enabling adoption of other Lean methods like takt production.

METHODS

Two case studies were conducted to determine differences in decision-making leading to different outcomes related to MEP prefabrication. Workshops, interviews, document reviews, and site visits were used as part of case study research. Case study research was selected to study differences in decision-making processes retrospectively.

New construction of an educational building was studied as Case 1, where the main contractor was interested in studying possibilities of cost savings by using MEP prefabrication. The main contractor had started the project using traditional on-site construction. They were interested in studying the possibility of MEP prefabrication for the current project and with future projects in mind. The phase of the current project would have enabled utilisation of some prefabrication. The company decided against prefabrication due to higher cost.

Renovation of residential buildings was studied as Case 2, where the main contractor had chosen to implement MEP prefabrication. The case company uses prefabrication for competitive advantage. They had decided to prefabricate before the study.

CASE 1

Three workshops were arranged to evaluate potential applications for MEP prefabrication and related benefits. The workshops were organised by the first author on initiative of the main contractor, having interest in studying possible advantages of MEP prefabrication.

In the first workshop, the project was introduced to all participants and a prefabrication programme was drafted listing all possible use cases for the project. Then positive and negative effects for project were listed for all alternatives, including effects on designing, schedule, additional responsibilities, and purchasing.

The second workshop focused on choosing two most attractive options for further assessment and determining of non-monetary benefits for both on-site and prefabricated solutions. This evaluation was done by utilising choosing by advantages method.

The third workshop was focused on determining costs for two application comparisons and comparing the combined effects of monetary and non-monetary factors in parallel. Possible implementation of prefabrication and reasons for these decisions were discussed.

The case project was a large new construction of an educational building with various use purposes. None of the participants had any significant previous experience in prefabrication, and they were all experienced professionals. Table 1 lists the participants. During the workshops construction was ongoing while designing and customer requirements were still developing.

Table 1: Workshop participants and their roles in Case 1.

Workshop participants	Role in project
MEP foreman 1	Electrical
MEP foreman 2	HVAC
Project manager 1, GC	
MEP designer	Design project manager
MEP expert, GC	Initial design
Construction manager, GC	
Project Manager 2, GC	

CASE 2

Case 2 was a renovation of an apartment building where the general contractor had chosen to implement MEP prefabrication. To study the prefabrication process and to document the reasons for adopting prefabrication, interviews, site visits, and document reviews were conducted. The interviewed people are presented in Table 2. The interviews were semi structured interviews focusing on reasons for adopting prefabrication and specific methos of implementation of prefabrication. Document review and site visits were used to study the process of designing and manufacturing prefabricated assemblies.

Table 2: Interviewed people and their roles in Case 2.

Interviewees	Role in project
Construction worker	MEP (on-site)
Construction worker	Prefabrication
Designer	MEP (prefabrication and site installations)
Team Leader	Foreman on-site (workers)
Group Leader	Foreman on-site (team leaders)
Development Manager	Development

RESULTS

CASE 1, COST IS KING

In the first workshop, a prefabrication programme was drafted recognising 15 possible use cases of MEP prefabrication in the case project. This included discussions of design scope, requirement for special prefabrication contractor, site and design schedule, material acquisition, site logistics, safety, and contractor capabilities. At this point, none of the alternatives were deemed impossible, while schedule of designing and construction was seen problematic in many cases. This was due to planned element installation during frame erection, which was not possible due to the project and design schedule.

In the second workshop, two most potential alternatives, a ventilation shaft with HVAC systems and a fully equipped door frame with Electrical systems, were selected for detailed CBA analysis. The ventilation shaft would consist of a supporting structure containing all ductwork within the shaft and be either one or two floors high. These elements would be installed during frame erection and manufactured in a separate location by the selected contractor. The door frame would include electrical installation in the panel adjacent to the door, including lighting switches, sensors, displays, and indicators. Both installations are typically made on-site.

The CBA compared onsite construction to prefabrication separately for both alternatives. For both evaluations, the prefabricated alternative was decisively preferred over on-site construction in the case of non-monetary factors. In the case of the ventilation shaft, 5 out of 7 benefits were assigned for prefabrication alternative. In CBA analysis, prefabrication had 270 importance points against 90 for on-site. For the doorframe, all benefits were assigned to prefabrication alternative, the total importance points being 320. The three most important factors in both evaluations were assessed to be safety, ergonomics, and material waste. The detailed evaluation is presented in Tables 3 and 4 for ventilation shaft and door frame respectively.

Table 3: CBA analysis of ventilation shaft, prefabrication versus on-site construction.

Factors	Prefabricated ventilation shaft	Imp.	On-site ventilation shaft	Imp.
Material waste	Attribute: Causes less waste. Better utilisation of cut pieces. Cleaner storage and handling. Adv: Causes less waste.	40	Attribute: Causes waste due to unused cut pieces and damaged ducts. Waste in insulation also.	-
Safety of workers and environment	Attribute: Risks in lifting of the elements. Decreases working in areas with a risk of falling. Adv: Smaller safety risks overall.	100	Attribute: More work in open shafts, risk of falling or dropping tools and materials.	-
Ergonomics	Attribute: Possibility to work in positions of better ergonomics and horizontal installation of ducts. Adv: Better working positions.	60	Attribute: Working in high and cramped spaces. Especially insulation is challenging, very small spaces.	-
Quality	Attribute: Supports and insulation are easier to install in steel frames. Adv: Fewer quality issues.	50	Attribute: Support of ducts need to be designed on site to fit the local conditions, variation to installation.	-
Flexibility of designing	Attribute: Design changes are more expensive or impossible.	-	Attribute: Design solution can be changed for as long as the installation is made, installation later compared to prefabrication. Adv: More flexible solution.	50
Logistics	Attribute: Lifted immediately to the right location and installed. Less site storage. Adv: Ready installation quickly from delivery.	20	Attribute: Hauling large ducts from site storage to shafts is challenging.	-
Design schedule	Attribute: Designing must be completed significantly earlier and takes more time due to increased LOD.	-	Attribute: Later installation and lower LOD, more available design time. Adv: More time for designing and, therefore, more flexibility for designing.	40
Total		**270**		**90**

Table 4: CBA analysis of door frame, prefabrication versus on-site construction.

Factors	Prefabricated door frame	Imp.	On-site equipped door frame	Imp.
Material waste	Attribute: Smaller risk for damage, affects waste, a significant factor. Adv: Elimination of broken equipment during installation.	90	Attribute: More waste caused by equipment broken during installation.	-
Safety of workers and environment	Attribute: Fewer accidents. No working in high places. Cleaner site. Adv: Fewer accidents.	80	Attribute: Many openings drilled on site to high locations. Causes debris to surroundings.	-
Ergonomics	Attribute: Possibility to work in an ergonomic position and use industrial methods. Adv: Better working ergonomics.	50	Attribute: Working in high places. Unergonomic working positions.	-
Maintenance and flexibility for changes	Attribute: Door frames equipped with extra conduit pipes, allowing for easy addition later. Adv: Better flexibility during the life cycle.	60	Attribute: Only what is needed will be installed; changes later are more difficult.	-
Logistics	Attribute: No need to store or transfer equipment on site. Adv: Less logistics and storage on site.	40	Attribute: Need to store equipment on site close to doors when door frames are opened.	-
Total		**320**		**0**

The third workshop focused on determining direct cost differences and adding the cost component of CBA. For the ventilation shaft, the direct cost of prefabrication was estimated to be 6% more expensive. Respectively for the door frame the prefabricated version was estimated to be 11% more expensive. Costs related to factors evaluated in CBA were not calculated due to the lack of an objective method for determining costs. The resulting CBA analysis is presented in Figure 1. In both cases, the prefabricated alternative scored significantly higher and was only slightly more expensive.

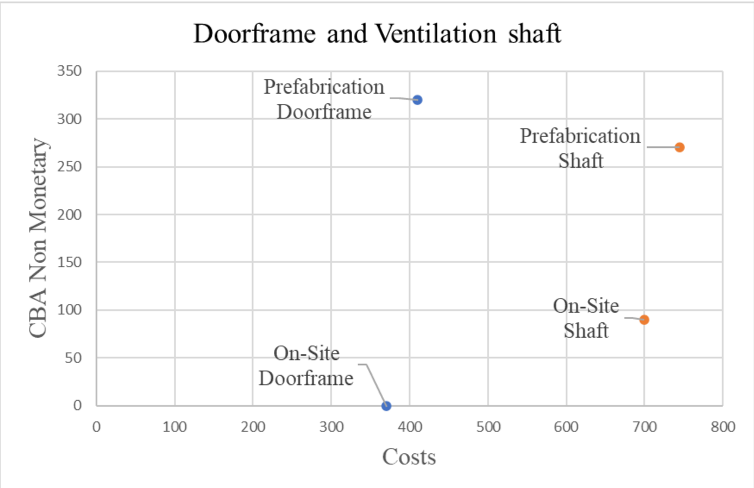


Figure 1: Effects of monetary and non-monetary factors of prefabricated and on site manufactured for ventilation shaft and doorframe with electrical installations.

All participants agreed that based on these results, on-site would be favoured in both cases. Competition for contracts being solely based on total cost was given as the reason for this choice. Participants acknowledged that quality and safety affect costs. They had ranked these as important factors. However, they did not trust the cost savings to be sufficient in comparison to direct cost without calculations. Without experience in prefabrication, they found it difficult to estimate the magnitude of cost saving. While there were no barriers preventing prefabrication, some aspects were found to hinder its adoption. These were designer capability (detailed modelling and schedule), construction schedule (designing concurrent to construction), and difficulty in evaluating possible savings from CBA factors in advance.

CASE 2, PREFABRICATION ENABLES INDUSTRIAL CONSTRUCTION

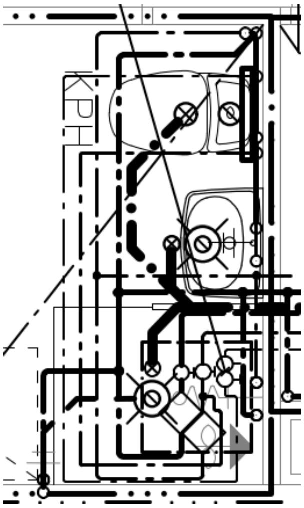
The case company prefabricated MEP systems for apartment building renovation. Prefabricated products included water, sewer, ventilation, electrical cables, heating, and suspended ceilings. The company had a goal of achieving competitive advantage by shortening lead times and improving quality by introducing practices of industrial construction. The company is considered a pioneer in the application of flow and takt production in Finland.

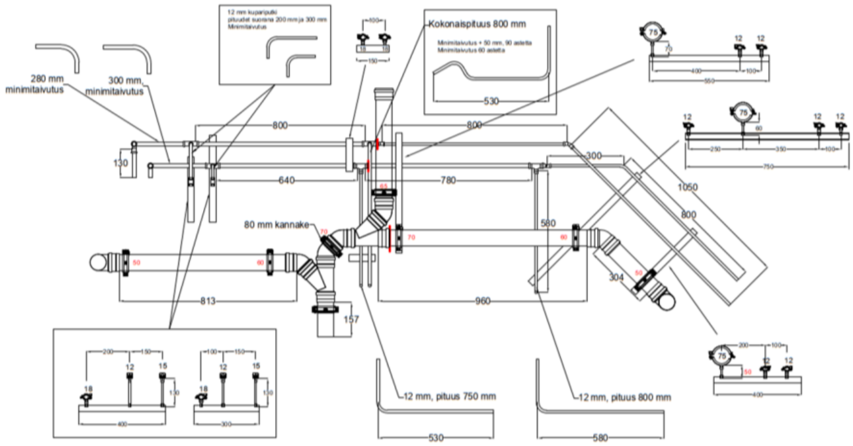
The business unit in question first adopted the Theory of Constraints (ToC) and Alliance business model but, in 2019, switched the production system to using Constant Work in Progress (CONWIP). This transformation was based on large amount of variability and difficulty of creating an efficient flow by using outsourced processes with multiple subcontractors. Additionally, the project team implemented a business model change by separating materials from work and using standard partners for work instead of per-project bidding. These standard partners were contracted on an hourly base as opposed to traditional contract work and quotas. The interviewees reported adopting these methods in stages during 2020-2022 in accordance with the Toyota organisation model (Liker, 2020) and Deming principles 11-14 (Deming, 1991).

Applying CONWIP enabled examining workflows in a high level of detail. Used parts, materials, work methods, and work sequences were documented at a minute level. As a result, traditional construction drawings and their low level of detail were abandoned. Instead, the company aimed at a standardised product by standardising work and materials using Manufacturing Bill of Materials (M-BOM). Knowing the exact M-BOM at each location made it possible to implement four-hour takt and move to precise takt logistics by utilising the Plan for Every Part concept described by Harris et al. (2011).

After standardizing work and drafting accurate M-BOM, increasing flow and shortening takt times require moving work from construction site to a separate workshop. Prefabrication was first adopted 2021. This separation of manufacturing from assembly was a transition towards industrialisation. Tests by the case company indicated a 23-46% time saving in total installation time by using prefabrication. Large-scale adoption of prefabrication with advanced on-site logistics further led to the shortening of takt times from four hours to two hours to realise shortened lead times. The effect on lead times was significant as the company reported having increased their yearly production rate from 150 to 320 apartments/year, while number of personnel has grown by 20%.

In the prevailing construction mode contractors bid both materials and work as fixed price (black box purchasing), based on construction drawings. These construction drawings, however, are not buildable, and as a result installers are responsible for installation designing. This undocumented designing by installers leads to significant variation in installations of identical apartments. The following installer, wagon in takt production, must take this variation into account and adapt, leading to ever increasing variation. Examples of traditional construction drawings and designs for manufacturing are presented in Figures 2 and 3.





Figures 2 and 3: Figure 2 (left) is a traditional construction drawing for water and sewer installation (LOD below 200). Figure 3 (right) is a design for prefabrication (LOD 400) containing three sub-assemblies (separated by red lines in drawing).

As traditional construction drawings do not enable the creation of M-BOM due to their low level of detail, separate designs for manufacture and assembly are needed. A detailer drafted high LOD designs using AutoCAD and their own library of manufacturer-specific parts. All support systems were also designed, and possible clashes were resolved. These assembly drawings contained millimetre-level cut lengths. Reuse of designs from project to project reduced design time as the number of projects increased. Figures 4 and 5 show the manufacturing and installation of underfloor heating.

Figures 4 and 5: Cardboard template (1:1, prototype design) for laying underfloor heating pipes in one bathroom type and later installed prefabricated module (white pipes on steel net).

Fabrication was scheduled according to a takt schedule, and work was divided into packages per takt area for one day. Team leader presented the fabrication schedule on a white board for workers in daily huddle. Team leader also either solved with the construction workers the arisen problems or escalated them to group leader in team leader's daily huddle. The logistical takt was based on on-demand deliveries of materials and parts with a two-day buffer. Figures 6 and 7 show subassemblies of pipes ready for transportation and installation itself. Four different consolidation points (wholesale, factory, site warehouse, and workstation) were in use, and logistics were carried out by specialised personnel.


Figures 6 and 7: Prefabricated pipe elements for vertical ascent in shaft ready for transportation (left) and connecting horizontal pipe elements with shaft elements (right).

DISCUSSION

Prefabrication was evaluated in Case 1 to win in almost all non-monetary factors and to be slightly more expensive. While most of the non-monetary criteria have a cost reducing effect, reliably evaluating their magnitude is difficult. As a result, the case decided against prefabrication. Since cost was the deciding factor, companies would benefit from an objective tool for assessing monetary benefits in case of non-monetary criteria. For Case 1, even relatively small cost savings could have favoured prefabrication over on-site construction. When determining direct costs for Case 1, the participants were able to assign additional costs to prefabrication (e.g., higher design cost or higher cost of manufacturing) but were unable to see monetary benefits from shortened lead time or fewer quality issues.

For Case 2 prefabrication allowed shortening lead times, improving quality, and profitability. Case 2 was focused on adopting Lean practices, one piece flow, takt production, and industrial construction where prefabrication was eventually used as a mean to achieve these targets. Case 2 shows all the obstacles identified by Lavikka et al. (2021) and Lopez et al. (2022) can be overcome. When construction drawings were not suitable for prefabrication, M-BOM was created, and a detailer was employed to draft construction drawings. It was also shown that the detailer does not need to have formal training in MEP engineering, but understanding of installation methods is required.

The decision-making processes for the two studied projects were very different. For Case 1 the process started with the question “Can prefabrication save us money?”. This question was eventually answered by difference in estimated direct cost compared to on-site construction. For Case 2 the process had started years ago with the goal of improving flow and shortening lead times, eventually resulting in competitive edge by being able to bid at a lower cost and complete more projects during the same time. Eventually through gradual lean implementation the company was in a position where transition to prefabrication was the natural next step to further improve, and they had gained the necessary knowledge for smooth implementation. Conversely, in Case 1 adoption of prefabrication would have been the first step towards industrialisation and would have caused the need for rapid development of culture, logistics, schedule, and designing, all at the same time.

While the projects in cases 1 and 2 were of different type, both companies operate in the same Finnish market and compete for projects in a market where contracts are won or lost based on cost. The two cases have differences in design schedules. Apartment renovations are bid on ready construction drawings. In larger projects designing is more concurrent with construction. This difference becomes less significant with the observation that construction drawings for bidding must be completely redesigned for prefabrication (Case 2) causing eventually similar concurrency as in larger projects.

The studied cases also differ in contracting. In case 1 the main contractor uses a separate MEP contractor. In Case 2 the company had previously used similar subcontracting business model but had observed that change to industrial construction necessitated removing subcontracts. This allows the case company 2 to control material acquisitions and logistics and efficiently lead the work of installers contracted on hourly basis, as opposed to fixed price contracts. Keeping prefabrication in-house drives costs down and prevents partial optimization by minimizing the cost of every subcontract. For example, in Case 1 the main contractor would certainly get higher bids for MEP contracts if asking for prefabrication since they would have to invest in capability. This gives the impression of saving money by choosing the cheapest non prefabricating bidder. When prefabrication is implemented by an experienced main contractor, keeping costs down and developing the process are more important compared to an independent subcontractor.

Bidding based on construction drawings is not necessary for prefabrication to be possible. Both customer and prefabrication will benefit from bidding with more schematic designs. This removes rework as detailer does not have to redraw all systems. As a result, customer saves money by reduced design costs for bidding phase and lower overall cost as the detailer does not spend time fixing original designs.

Based on our findings, similarly to O'Gorman et al. (2023), we suggest that only considering MEP prefabrication and direct costs related to it is not recommended. Contrary to O'Gorman et al. (2023), we however argue, that this is not due to lack of cost savings from prefabrication, but the incomplete question framing where prefabrication is considered alone without all other necessary transformations towards industrial construction. The only way for prefabrication to succeed is to implement and improve it over time as part of other methods of industrial construction. For example, a study by Chauhan et al. (2018) demonstrated that takt production and prefabrication benefit from each other. Simply suggesting to only consider non-monetary aspects is not feasible when contracts are won or lost based on the cost only.

This study is limited by low number of cases, which limits the reliability of drawn conclusions. Further investigations to a larger number of cases is needed to confirm the results and determine how project type affects the decision-making process. Additionally, these cases represent the situation in a predominantly non prefabricating market, and differences could be found from countries of advanced application.

CONCLUSIONS

The two studied cases highlighted fundamental differences in reasons motivating the use of MEP prefabrication. To answer our RQ about differences in decision making processes the following can be concluded. Participants of Case 1 were keen to study if prefabrication can be used to obtain cost benefits and Case 2 decided to use prefabrication to enable short takt time, short lead time, and increased quality, eventually translating to increased profitability. The main difference being instrumental use of prefabrication for immediate realisation of cost savings (Case 1) as opposed to a far-reaching cultural change towards industrial construction with prefabrication as part of it (Case 2).

Based on the observations of advanced lean adoption in Case 2 it is necessary to acknowledge the need for large cultural changes in moving towards prefabrication. Gradual transformation towards prefabrication through other lean adoptions increases the likelihood of success.

ACKNOWLEDGMENTS

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BUSINESS MODELS EMERGING FROM INDUSTRIALIZED CONSTRUCTION ADOPTION

Alejandro Vásquez-Hernández[1], Luis Fernando Alarcón[2] and Eugenio Pellicer[3]

ABSTRACT

Industrialized Construction (IC) has been recognized as a promising approach to improving project performance. However, its benefits are not evident in the building as an entity. The background of IC reveals approaches limited to production methods, overlooking issues related to process, collaboration, supply chain, and market. IC represents a novel strategic approach for the construction sector, introducing a business logic distinct from that of project-based companies, which is timely to understand within the context of managing IC adoption. Business models (BMs) are constructs that can be employed as tools to describe and analyze such business logic. This article aims to identify in the literature the constructs proposed for analyzing BMs associated with IC adoption, their approaches, and business-configuring elements, and to identify the business models associated with cases reported in the literature. A systematic literature review and content analysis were conducted. The results revealed fourteen proposed BMs frameworks and two approaches to IC BMs. Furthermore, following the analysis of reported cases, thirteen BMs were identified, associated with seven groupings based on the roles and value chain clustering strategies linked to IC adoption.

KEYWORDS

Industrialized construction, modular construction, off-site construction, business model.

INTRODUCTION

The construction industry can mitigate the adverse effects of its relatively unstable production environment in two ways: by minimizing its peculiarities to leverage methods developed in other industries, or by developing techniques within the sector itself to address its dynamic nature (Vrijhoef & Koskela, 2005). These two approaches are closely related in the pursuit of lean construction, as aligning construction with manufacturing logics is a conducive scenario for lean (Egan, 1998). In turn, minimizing construction peculiarities involves achieving the lean objective of controlling processes (Vrijhoef & Koskela, 2005). Industrialized construction (IC) serves as a structural means for the former approach by adopting project-independent strategies and transferring site activities to the supply chain. However, the expected benefits of this approach have not yet been fully realized in the case of buildings as entities (Richard, 2012).

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The background of IC reveals a focus that is limited to production methods, neglecting aspects of process, collaboration, supply chain, and market issues (Lessing, 2015). Many emerging problems in IC implementation experiences relate to adoption processes under a conventional context, in terms of organizational structures, project development models, working methods, and procurement methods (Ahamad et al., 2020). IC represents a new strategic approach for the construction sector (Hall et al., 2022). Its business logic differs from that of conventional construction companies, which are project-based (Lessing & Brege, 2015). Therefore, it is timely to understand how companies that have adopted IC operate. Business Models (BMs) are constructs that can be used as tools for such descriptions and analyses (Lessing & Brege, 2015). BMs are mechanisms through which a company's strategy is translated into a model of the logic for making money (Osterwalder et al., 2005) (Zott & Amit, 2008), emphasizing a systemic perspective on conducting business and aiming to explain both value creation and capture (Pan & Goodier, 2012). In this sense, it constitutes a unit of analysis in addition to product, company, industry, or network levels (Pan & Goodier, 2012).

In light of the above, this article seeks to identify in the literature the constructs proposed for the analysis of BMs associated with the adoption of IC, their approaches, and business elements. Furthermore, by understanding business models as configurations of business elements (Brege et al., 2014), this study aims to identify the business models associated with reported cases in the literature of companies adopting IC, through the analysis of patterns in how the different configuring elements of BMs are presented.

RESEARCH METHOD

A systematic literature review was conducted to identify the frameworks for analyzing BMs of IC and to identify case studies of companies adopting IC based on BM frameworks. Using database searches in electronic databases Scopus and Web of Science, a targeted search was carried out to identify related papers. The selection criteria for these databases were their extensive coverage in the research field (Chadegani et al., 2013). The search terms included "business model" combined with "industrialized construction," "industrialized building system," "modular construction," "off-site construction," "modern method of construction," or "prefabricated construction." Additionally, an exclusion criterion was applied to remove irrelevant articles, specifically those not including a BM analysis framework or descriptive reporting of BMs of IC-adopting companies identified empirically through case studies. A complementary search was performed using backward snowballing (Webster & Watson, 2002) to ensure thorough coverage of relevant literature.

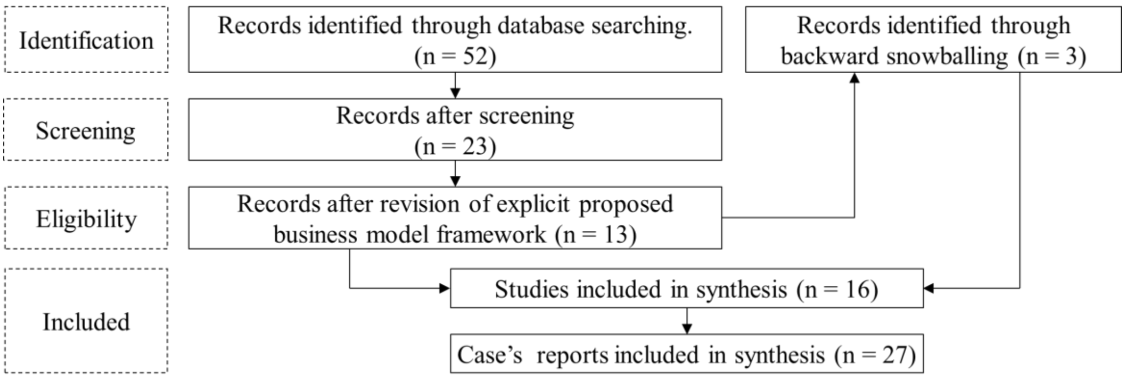


Figure 1. Information collection record. PRISMA Flowchart.

A content analysis approach (Krippendorff, 2004) was employed to examine the data gathered from the literature. Various frameworks for analyzing BMs of IC proposed and/or used by researchers were identified and analyzed. Different approaches and specific constituent elements of each BM analysis framework in IC were identified. Based on the identified BM elements, an analysis framework was adapted for characterizing the identified case studies. Through the identification of patterns in the presentation of different BM configuration elements in the case studies, the various business models of the analyzed cases were identified.

BUSINESS MODELS IN INDUSTRIALIZED CONSTRUCTION

From the literature review, sixteen studies were identified. These studies, along with their country of origin and the identifiers of the case studies they report, are presented in Table 1.

Table 1: Studies and cases resulting from the literature review.

Authors	Country	Reported case IDs
(Rinas & Girmscheid, 2010)	Switzerland	-
(Johnsson, 2011)	Sweden	1, 2
(Girmscheid & Rinas, 2012)	Switzerland	-
(Pan & Goodier, 2012)	UK	3, 4, 5, 6
(Kamar et al., 2012)	Malaysia	7,8, 9
(Brege et al., 2014)	Sweden	10a, 10b, 11a, 11b, 12, 13a, 13b, 14a, 14b
(Höök & Stehn, 2014)	Sweden	-
(Höök et al., 2015)	Sweden	-
(Lessing & Brege, 2015)	Sweden	16, 17
(Lessing & Brege, 2017)	Sweden- US	11a, 15, 16, 17, 18, 19, 20, 21, 22, 23
(Mohamed et al., 2019)	Malaysia	25, 26, 27
(Mueller, 2021)	Germany	-
(Mohamed et al., 2021)	Malaysia	-
(Lepinoy et al., 2022)	US	-
(Hall et al., 2022)	Sweden- US	15, 21, 27
(Saad et al., 2023)	UK	-

*Cases with subscripts ("a" and "b") in the identifier correspond to different business models within the same company. **Some case studies were reported in more than one article.

APPROACHES AND ELEMENTS OF BM

The set of elements that constitute BMs and their involved relationships allow for the articulation of a particular company's business (Osterwalder et al., 2005). There are differing viewpoints among researchers regarding the specific constituent elements of a BM (Brege et al., 2014). However, the offered value proposition and the way in which the offered value is configured and delivered are two aspects commonly held (Höök & Stehn, 2014).

Magretta describes BMs as "stories that explain how enterprises work" and suggests that a good business model answers the questions: Who is the customer? What does the customer value? How do we make money in this business? What underlying economic logic explains how we can deliver value to customers at an appropriate cost? (Magretta, 2002). Building on this, the configurative elements of BMs can be classified into four groups that respond to the question: What? Whom? How? And how much? These groups account for the company's value offering, the targeted customer, the way value is configured, and the benefits equation.

Furthermore, there are varying perspectives on whether adopting IC acts as a driving force in forming new BMs or if the IC adoption fits within established BMs. Figure 1 presents the BM configuration frameworks as a combination of elements proposed by different authors in their approaches to analyzing BMs in IC contexts, their associated elements with the mentioned questions, and the approaches identified.

In the exploration of BMs within the realm of IC, a diversity of approaches has been discerned. These approaches delineate the strategic frameworks proposed by researchers to understand the interplay between IC adoption and BM innovation. Presented herein are the varied perspectives unearthed from the analysis, each underscoring distinct facets of business model configuration in the context of IC.

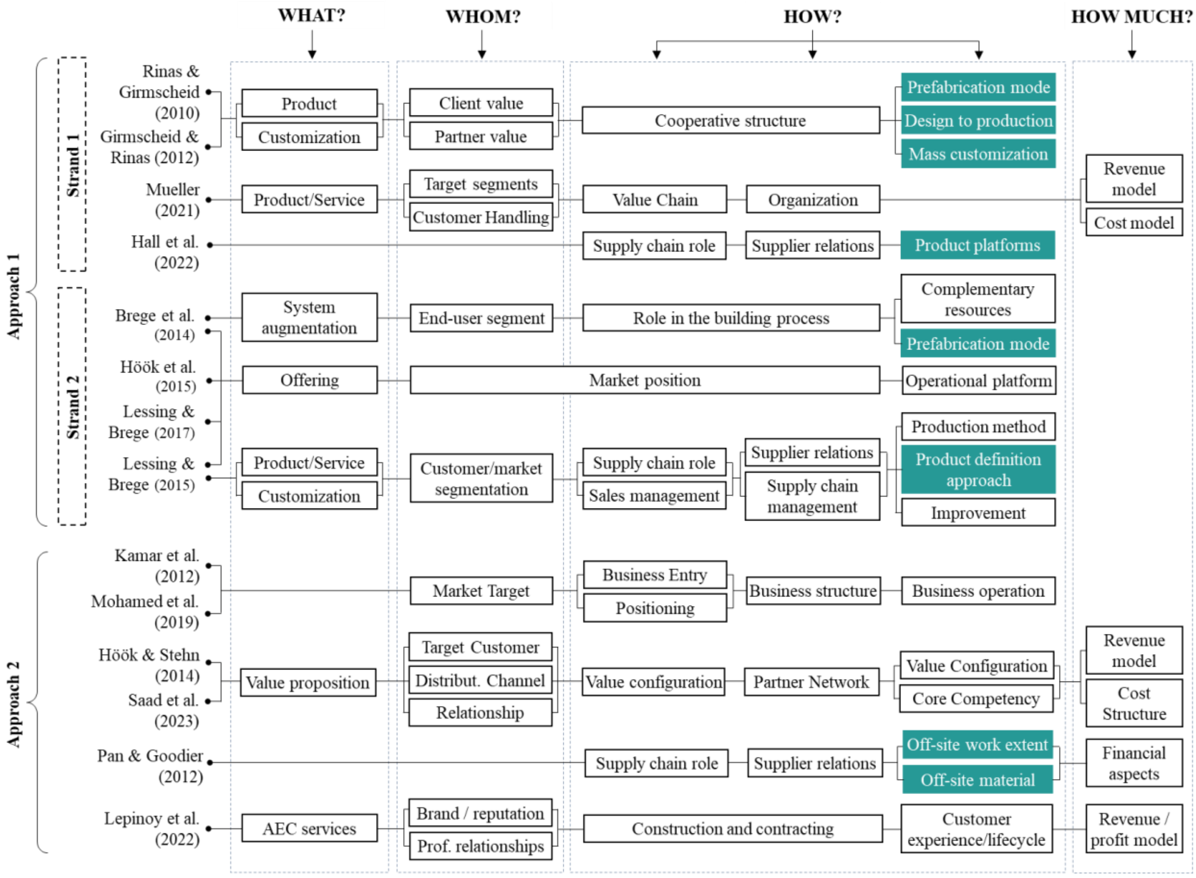


Figure 1: Approaches and elements of BM

Approach 1: IC as a driving force in the formation of BM

This perspective views IC as a driving force in the creation of new or modified business models (Brege et al., 2014). This view is echoed by Lessing et al. (2017), who highlighted that production strategies, business models, and company organization should be specifically designed and structured for IC to reap the benefits of industrialization. From this viewpoint, a clear demarcation exists between project-oriented BMs, which are traditional models for constructing unique projects using on-site methods, and product and/or process-oriented BMs, which are based on prefabrication strategies and product platforms characteristic of IC adoption (Lessing & Brege, 2015). From this approach, two strands were identified:

Strand 1: BM as a supply chain aggregation strategy. Contrasting with the extreme fragmentation characterizing the construction industry, where independent companies temporarily organize to design and build a new project, IC is seen as an effort to reorganize and build continuous production systems (Hall et al., 2022). New business models within this approach represent efforts to deliver buildings in a more integrated manner throughout their lifecycle (Hall et al., 2022), spurred by the adoption of IC methodologies. While this approach also touches upon product ranges and market goals, the BM focus is on models of actor integration; hence, the identified business models are configured based on these variations.

In this direction, the framework proposed by Rinas & Girmscheid (2010) advocates for a cooperative approach, viewed as promising for linking complementary competencies and providing holistic solutions. This model emphasizes cooperation among various actors, such as prefabrication companies, local architects, and other partners, to bolster IC. It includes two cooperative dimensions: one oriented towards production, encompassing development and manufacturing, and another towards sales, covering assembly and sales. Furthermore, Mueller (2021) introduces a framework to categorize the spectrum of IC approaches from a business strategy perspective. This framework conceptually outlines six dimensions classified in pairs on scales: market vision (targeting segments and solution characteristics), the underlying business model (value chain position and value chain organization), and technological approach (scope of industrialization and level of pre-specification). As such, market elements and strategic focus are regarded as distinct strategic dimensions apart from the business model, which incorporates value chain elements. Additionally, Hall et al. (2022) suggest that the new BM for IC is characterized by longitudinal continuity, as opposed to a project-based orientation. It is the focus on IC that facilitates this novel form of longitudinal continuity, through the development of product platforms, providing a mechanism for continuously establishing and enhancing organizational knowledge about the construction technical system. Products not manufactured by the company are sourced through long-term partnerships within the supply chain, rather than through competitive bidding.

Strand 2: BM as a construct supported by three pillars: offer, market position, and operational platform. Beyond efforts to reorganize the value chain, this line of approaches supports the understanding of BMs from the construct proposed by Brege et al. (2014), which is predicated on three pillars: offer, market position, and operational platform. This framework articulates a clear distinction between strategic effectiveness and operational effectiveness, with market platforms indicative of the former and operational platforms denoting the latter.

This analytical framework is further explored in the works of Höök et al. (2015), Lessing & Brege (2015), and Lessing & Brege (2017). Within this framework, Brege et al. (2014) and Lessing & Brege (2015) delineate the foundational element for model construction from an IC perspective, alongside the necessary complementary elements. Brege et al. (2014) posit the level of prefabrication as the model's central element and identify four essential complementary elements: system enhancement (offer), end-user segments (market position), roles in the construction process (market position), and complementary resources for design and on-site construction (operational platform). Conversely, Lessing & Brege (2015) posit the product platform as the inception point for BM design and as the principal resource of the operational platform. This product-oriented approach is considered complementary, extending the scope of investigation to encompass construction companies not necessarily tethered to specific productive resources at the outset of BM design.

Furthermore, Lessing & Brege (2015) distinguish between IC business models: production-oriented and product-oriented BMs. Product-oriented BMs are characterized by their reliance on a product-based offer, anchored in a product platform, serving as the foundational or initial point. Conversely, production-oriented BMs prioritize off-site production methods as the starting point, concentrating on the production facet of novel construction concepts.

Approach 2: IC fits into established BMs

The proposals within this approach are predicated on the notion that IC does not inherently introduce distinguishing attributes between BMs. The proponents of this viewpoint concentrate on how IC adoption aligns with, or necessitates adaptations to, pre-existing BMs.

Some researchers investigating BMs in IC leverage the Business Strategy concept, drawing on the foundational ideas of Porter, who articulates strategy as the crafting of a unique and valuable position through a distinct set of activities (Porter, 1996), and Thompson et al., who envisage strategy as management's action plan to grow the business, secure a competitive market position, attract and satisfy customers, compete successfully, conduct operations, and achieve targeted objectives (Thompson et al., 2006). The analytical framework employed is delineated by Kamar et al. (2012), encompassing five key elements: business entry, business positioning, market target, business structure, and business operation. This framework was utilized by Kamar et al. (2012) in examining IC adoption among large contractors and by Mohamed et al. (2019) among small and medium-sized construction enterprises.

Höök & Stehn (2014) and Saad et al. (2023) ground their models in the framework developed by Osterwalder et al. (Osterwalder et al., 2005), known as the Business Model Canvas. This model is structured around four foundational pillars—product, customer interface, infrastructure management, and financial aspects—and articulates nine interconnected elements: Value Proposition, Target Customer, Distribution Channel, Relationship, Value Configuration, Core Competency, Partner Network, Cost Structure, and Revenue Model.

Similarly, Pan and Goodier (2012) base their approach on the BM categorizations proposed by Ball (Ball, 2010), specifically tailored to the UK housing construction sector. These categorizations are developed with a focus on the construction process and its associated activities, highlighting the role of the company within this framework. Through an analysis of the practices of leading private home builders in the UK, who are progressively embracing IC, the authors pinpoint innovative procurement and supply chain strategies that emerge or are catalyzed by the adoption of off-site construction methodologies. Likewise, Lepinoy et al. (2022) introduce an analytical framework supported by four pillars: value proposition, generating demand, fulfilling promises, and sustaining growth. These pillars are paired with six elements: architecture, engineering, and construction services; revenue and profit model; brand and reputation; professional or other influencer relationships; construction and contracting; and customer experience and lifecycle. This framework aims to provide a comprehensive understanding of how IC can be integrated into existing business models, emphasizing the strategic and operational adjustments necessitated by this integration.

IDENTIFICATION OF BMS

Some of the studies included in the analysis (50%) feature case reports associated with companies that have adopted IC (see Table 1). To analyze these case studies, a common analytical framework was established to integrate the information reported and to identify the types of BMs associated with the different cases. The defined framework is an adaptation of the proposal by Bregue et al. (2014), which is the base framework associated with Strand 2. The choice of this framework is based on two premises: *(i)* the number of case studies reported using this analytical framework; 37.5% of the articles that reported case studies used this framework as a basis and the case studies reported in these articles account for 51.8% of the total. *(ii)* It explicitly includes IC as a driving force in the formation of new or modified BMs.

The framework by Bregue et al. (2014) was adapted in terms of elements in two ways: the inclusion of the element 'supplier relations', as adapted by Lessing et al. (2015), to explicitly outline the value chain reorganization strategies, which are the focus of the frameworks associated with Strand 1. Furthermore, the inclusion of 'predefinition level,' as adapted by Lessing et al. (2017), as a complementary element to 'prefabrication level' in the IC approach.

Accordingly, the analytical framework employed for examining the case study data is anchored in three core pillars: Offering, Market Position, and Operational Platform. It further is delineated by six elements: Scope of Offering (pertaining to Offering), Marketplace Role and Value Chain Role (relating to Market Position), as well as Value Chain Relations, Predefinition Level, and Prefabrication Level (associated with Operational Platform). Each of these components is elaborated upon as follows:

Offering: It embodies the company's value proposition (Lessing & Brege, 2015). It encompasses the amalgamation of physical products and services provided to customers and is often conceptualized as a blend of hardware, software, and services, sometimes coupled with a revenue generation model (Brege et al., 2014).

- Scope of Offering: It represents the breadth of the offering in terms of added value, manifested in the combination of the level of prefabrication and the company's role in the value chain (Brege et al., 2014).

Market Position: It delineates the company's role within the market and value chain.

- Marketplace Role: It describes the customer segments to which a company aims to deliver value (Osterwalder et al., 2005). The spectrum of segments ranges from variable concepts of offering with broad market coverage to niche market orientations with highly standardized and specific solutions.
- Value Chain Role: The company's position in the building process, which is associated with the level of control it exercises over the value chain (Lessing & Brege, 2015).

Operational Platform: Company's internal resources and competencies, alongside complementary external resources from suppliers and partners, and how these elements are organized and utilized.

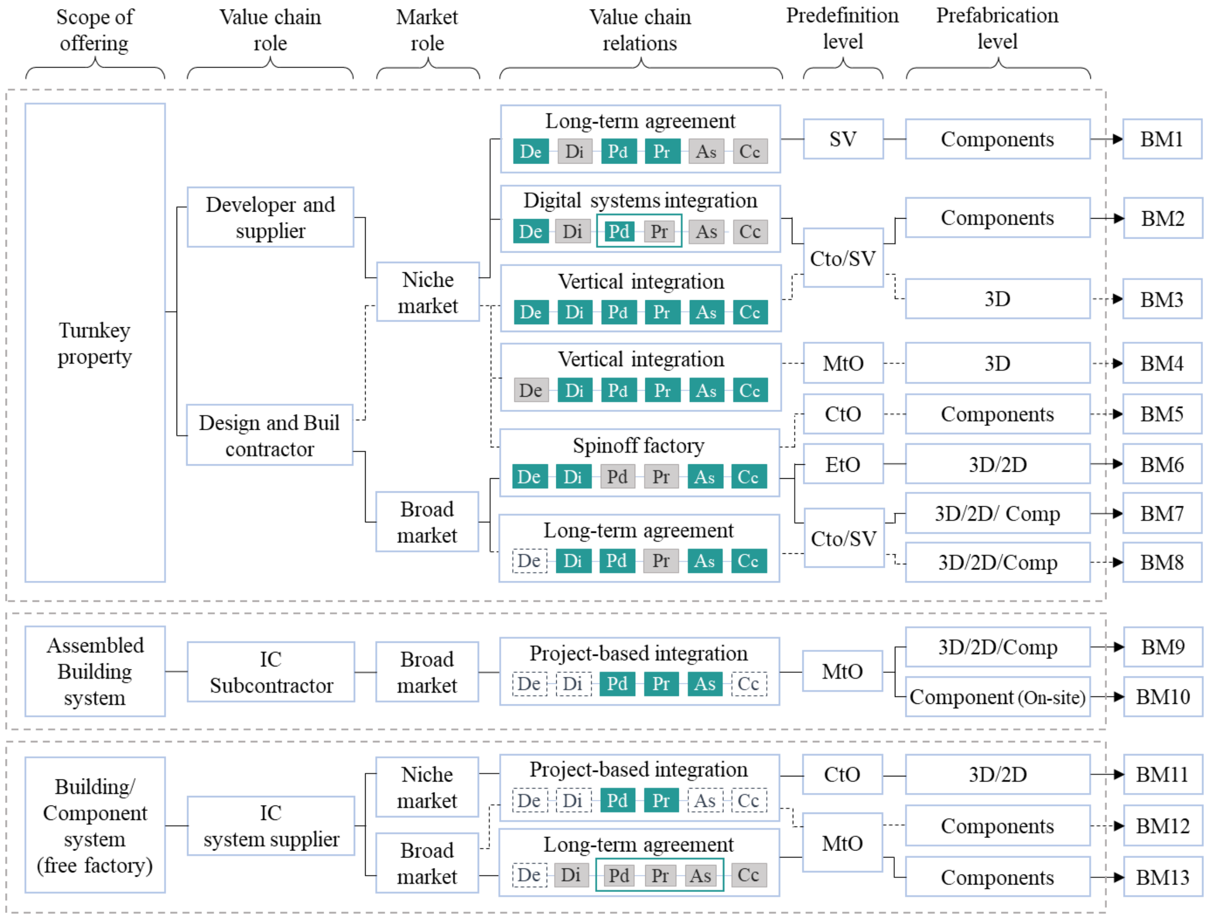
- Value Chain Relations: Access to external resources from suppliers and partners involves five strategies: *Vertical Integration*, referring to companies that maintain control over product architecture and processes internally (Hall et al., 2022); *Digital System Integration*, where long-term relationships with partners in design, procurement, manufacturing, and assembly stages are built through digital platforms (Hall et al., 2022); *Spinoff Factory*, related to the creation of a new factory or business line originating from an existing project-based company (Hall et al., 2022); *Long-term Agreement*, linked to long-term commercial and collaborative agreements with external companies, not limited solely to the project scale; *Project-based Integration*, associated with formal and informal integration strategies confined to the project scale.
- Predefinition level: Indicates the standardization level and defines the entry point for design customization (Mueller, 2021). Following Hvam et al. (2008), Lessing and Brege (2015) outline four levels: *Engineer to Order (EtO)*, employing industry norms as starting points in client-controlled project design; *Modify to Order (MtO)*, using established technical solutions and predefined geometries for essential components within project-specific designs; *Configure to Order (CtO)*, employing set parts and modules in a uniform configuration approach; and *Select Product Variant (SV)*, achieving near-final construction with predetermined variations, significantly reducing the need for project-specific designs by pre-setting most details (Hvam et al., 2008).
- Prefabrication level: Three levels of prefabrication in construction systems are identified: 3D elements, 2D elements, and component systems, all associated with off-site production. Additionally, within the component systems level, a distinction is made between off-site prefabricated elements and those associated with mobile factories, where the process occurs on-site. This distinction is highlighted in two of the case studies reported by Mohamed et al. (2019).

BMs of IC identified

Through the analysis of patterns in the various combinations or configurations of elements presented in the reported cases of companies adopting IC, thirteen BMs were identified, as depicted in Figure 2. These identified BMs can be categorized based on similarities in roles and value chain aggregation strategies adopted. The categorizations are outlined as follows:

(i) Contractor-developer and owner of the construction system and manufacturing facilities (BM3 and BM4). The value chain is integrated vertically, whereby contractors maintain complete control, allowing them to directly reap the benefits associated with repetition and systematic improvement. This strategy fosters horizontal, vertical, and longitudinal integration

but requires taking on the risks associated with the development and deployment of fixed capital assets, as well as the costs of operating and maintaining manufacturing facilities. In the studied cases, the companies adopting this strategy are contractors that have embraced IC from their inception, offering turnkey property solutions and prefabrication at the 3D element level. However, this approach is observed in companies targeting specific market niches with high levels of predefinition (CtO/SV) (BM3), as well as in companies aiming for broad market coverage with low levels of predefinition (MtO) (BM4).



De = Project development; Di = Project design; Pd = Product design; Pr = Off-site production; As = Assembly; Cc = Construction and coordination.
■ = In-house; ■ = Partner/Long-term relation; ⬚ = Outsourced.

BM1: case 16; **BM2:** cases 17, 21; **BM3:** cases 1, 6, 8, 9, 10a, 10b*, 11a, 12, 15; **BM4:** case 23; **BM5:** case 20; **BM6:** cases 19, 27; **BM7:** cases 3, 4, 22, 25; **BM8:** cases 2, 7**; **BM9:** cases 13b; **BM10:** cases 24, 26; **BM11:** cases 5, 11B; **BM12:** cases 13a, 14a***, 14b; **BM13:** case 18.
*In addition to turnkey property, the company's offer includes the operation (build-to-own).
**The company established a joint venture agreement for off-site production.
***The company offers technical support in the design and on-site production/coordination phases, which implies having complementary resources.

Figure 2: Identified BM´s

(ii) Contractor-developer of construction systems and manufacturing facilities via spinoff (BM5, BM6, and BM7). This strategy is employed by 100% of the studied cases where the company is a conventional contractor adopting IC. These project-based contractor companies integrate system development and off-site production phases through a new product/process-oriented business line. This approach allows project-based companies to balance project demands with the need for longitudinal continuity centered around the factory. However, the integration achieved is partial and depends on an internal integrator agent continuously updating and educating the existing supply chain about the new factory's capabilities (Hall et al., 2022). This strategy is linked to turnkey property solutions. It is adopted by companies targeting specific market niches with a high level of predefinition (CtO) and component-level prefabrication, as

well as by companies offering low levels of predefinition (EtO/MtO), covering various prefabrication levels, aimed at broad market coverage.

(iii) Contractor-developer and owner of externally manufactured construction systems (BM8). This model is utilized by contractor companies that establish long-term agreements to integrate the off-site production phase. The prefabrication of construction systems is conducted off-site and outsourced to external industrial suppliers, yet the contractor remains the developer and owner of the construction system. The primary rationale behind this approach is that contractors seek to control the design of the construction system while avoiding the risk of fixed capital investments in manufacturing facilities. Although off-site production is outsourced, it necessitates commercial relationships that extend beyond individual construction projects and framework agreements that ensure a steady supply of construction systems at the required rate. Such agreements are also vital for industrial suppliers, providing them with a guarantee of consistent demand, thereby reducing the investment risk in capital goods. This arrangement also facilitates early-stage involvement of the industrial supplier (Andersson & Lessing, 2017). In the cases studied, companies adopting this strategy are contractors that have incorporated IC from their inception, offering turnkey property solutions, low levels of predefinition (MtO), covering various prefabrication levels, and aimed at broad market coverage.

(iv) Contractor as purchaser of IC goods and services (BM9, BM10, BM11, and BM12). This strategy aligns with IC implementations in value chains characterized by minimal integration, stemming from a fragmented process dominated by short-term relationships (Cox & Ireland, 2002). Contractors procure construction systems developed and manufactured by external entities, subcontractors in the case of BM8 and BM9, which include on-site assembly, and free factory system providers in the case of BM11 and BM12. Relationships with these subcontractors and suppliers are limited to the project scale, hindering effective cooperation, efficient information exchange, and innovation drives, leading to suboptimization and productivity losses (Winch, 2010). To mitigate the impacts of this fragmentation, the company associated with case 14a, implementing BM12, provides technical support in design phases, construction, and on-site coordination, requiring additional resources. However, the achieved integration remains informal (Hall et al., 2022). The studied cases include adoption of this strategy with offerings both aimed at specific market niches, with construction systems of high predefinition level (CtO) and prefabrication at the 3D and 2D element levels (BM12), and broad market coverage offerings, with construction systems of low predefinition level (MtO) covering various prefabrication levels (BM9, BM10, and BM12). BM10 features a unique aspect regarding the mode of prefabrication, observed in cases where industrial suppliers do not have a permanent manufacturing facility but rather a mobile factory that is commissioned per project to save on logistics costs.

(v) Project developer and supplier of own construction system manufactured in-house (BM1). These are project-configuring companies that own a construction system developed and manufactured in-house, within their own facilities. Assembly, construction, and on-site coordination tasks are performed by long-term collaborative partners. The associated offering is turnkey property solutions, with component-level prefabrication, high predefinition (SV), and targeted at a specific market niche.

(vi) Project developer and supplier of proprietary construction system manufactured externally (BM2). These companies are project configurators owning a construction system developed in-house. However, instead of establishing their own production facilities, they partner with specialized manufacturers and suppliers. Local contractors carry out the assembly. The company retains ownership of the concept, managing and orchestrating the delivery of component kits to project sites. Value chain integration is achieved through a digital systems integration approach, allowing for the manufacture of parts through peripheral supply chain partners (Hall et al., 2022). Digital platforms enable the building of long-term relationships with

partners in design, procurement, manufacturing, and assembly stages. This strategy enables growth by establishing new partner networks without the need to invest in creating their own production facilities. The associated offering is the supply of a component system (free factory) with a high level of predefinition (CtO, SV), targeted at a specific market niche.

(vii) Supplier of own construction system manufactured externally (BM13). The company supplies a construction system with a low level of predefinition (MtO), targeting broad market coverage. The prefabrication level is component-based, and the company-owned structural system can be adapted for various building configurations. The company also partners with subsystem suppliers to integrate them into the complete building system. Product design, production, and assembly are all outsourced, aligning with the company's strategy to avoid high-capital investments and specific manufacturing commitments. This BM is defined by subcontracting as a fundamental principle, suitable for companies with limited internal resources. Close relationships with partners ensure access to external product development, production capabilities, and market presence, all while maintaining minimal financial risk (Lessing & Brege, 2017).

CONCLUSIONS

A systematic review of the literature on BM analytical frameworks within IC was undertaken, and a content analysis oriented to identify the distinct constitutive elements of a BM, the approaches, and the BMs associated with documented instances of IC adoption by companies. This inquiry uncovered fourteen proposed BM frameworks and delineated two approaches to BMs in the context of IC. Furthermore, 27 case reports detailing the operational practices of companies that have implemented IC, framed within a BM analysis, were found. Analysis of these cases led to identifying thirteen distinct BMs, which were categorized based on their roles and the strategies they employ for value chain integration within the realm of IC adoption.

The identified frameworks present two main perspectives: considering IC as a driving force in creating new business models and viewing IC as not defining attributes that necessitate new models but rather fitting into conventional BMs or deriving adaptations from them.

An adaptation of the model proposed by Brege et al. (2014) was presented, enabling the integration of information from reported cases. This adaptation faced limitations related to the integrated elements. The customization element is crucial for categorizing both a company's offering and the market standard it targets. However, only three of the discovered frameworks included explicit descriptions of this aspect, thus not constituting a common element that would allow for a joint characterization of the identified cases.

Seven BM groupings were identified based on the roles performed and the value chain aggregation strategies: *(i)* Contractor-developer and owner of the construction system and manufacturing facilities; *(ii)* Contractor-developer of construction systems and manufacturing facilities via spinoff; *(iii)* Contractor-developer and owner of externally manufactured construction systems; *(iv)* Contractor as purchaser of IC goods and services; *(v)* Project developer and supplier of own construction system manufactured in-house; *(vi)* Project developer and supplier of proprietary construction system manufactured externally; and *(vii)* Supplier of own construction system manufactured externally.

LIMITATIONS AND FUTURE RESEARCH

The cases analyzed originate from six countries, with a notable concentration of 55% coming from Sweden. This uneven distribution may introduce inherent bias, particularly considering that most Swedish literature on BMs of IC focuses on residential construction. This bias limits the generalizability of the findings to other geographical contexts and market sectors. It is recommended that future research explores BMs of IC from a broader perspective, including other market sectors and business practices from different regions.

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MASS CUSTOMIZED PRODUCTS FOR INDUSTRIALIZED CONSTRUCTION: CHALLENGES AND OPPORTUNITIES

Manoela Conte[1], Iris D. Tommelein[2], Carlos Torres Formoso[3] and Randall Miller [4]

ABSTRACT

Developing mass customized products for industrialized construction (IC), including single- and multi-family modular housing, requires multidisciplinary, collaborative, and iterative approaches from the first stages of product development. Despite this, decisionmaking based on data pertaining to companies' capabilities and increasing diversity of customers' needs in IC is still in its infancy. Catalogs of houses are often extensive yet fail to take advantage of IC strategies (such as mass customization (MC), product platform, modularity, and product families), thereby undermining the competitiveness of IC against traditional construction. An opportunity exists to enhance communication among stakeholders, fostering decisions about catalog offerings based on clear understanding of their requirements, robust data analysis, and continuous improvement. This paper discusses practices, challenges, and opportunities related to the development of products and integration among stakeholders in the IC context. The research method comprised three steps: developing theoretical understanding, conducting two ongoing studies in Brazil and the United States, and leading a workshop with experts to identify practices, challenges, and opportunities regarding the development of IC products. The preliminary results indicated the imperative need for stakeholders to work together on improving product development and production system, fostering a more competitive IC industry.

KEYWORDS

Mass customization, industrialized construction, modular construction, product development, collaboration.

INTRODUCTION

Early developments of industrialized construction (IC), especially in the house-building sector, were strongly based on the Mass Production paradigm, resulting in a negative perception from customers due to the high degree of standardization, focus on cost reduction, and poor quality of products (Nadim & Goulding, 2011). More recently, Mass Customization (MC) has emerged as an approach to improve value delivery in house-building projects (Noguchi, 2003). MC aims to provide a certain degree of flexibility, while keeping production cost and delivery time within

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acceptable limits (Pine, 1993; Da Silveira et al., 2001). It seems that recent developments in IC, combined with the adoption of MC represent an opportunity to achieve high levels of efficiency in the building industry (Larsen et al., 2019) and, at the same time, to accommodate different customer requirements (Yashiro, 2014).

Product platform, modularity, and product families are key concepts in MC to respond to the diversity of demands (Salvador et al., 2009; Khalili-Araghi & Kolarevic, 2018). Those concepts can change the way in which new products are developed in the construction industry, e.g., by pre-defining a range of modular components to be used and creating a certain degree of process repetition (Brege et al., 2013). This allows the delivery of a limited variety of product solutions while sharing parts and production steps within the manufacturing capabilities, achieving economies of scale and scope (Robertson & Ulrich, 1998; Tseng et al., 2017).

The development of this type of solution requires early identification of stakeholders and collaboration among them, so that both customers and operations' requirements are considered in the definition of a finite solution space (SS) (Piller, 2004; Ferguson et al., 2014). The SS is a limited or stable space in which customization offers can satisfy the needs of customers (Piller, 2004). This involves the alignment between three MC areas: (1) customer integration, (2) product design, and (3) operations management (Rocha, 2011; Ferguson et al., 2014), with information exchange and knowledge dissemination between them being critical (Hentschke et al., 2020). The capacity of combining these elements in a meaningful way may have a strong impact on competitive advantage (Piller, 2013; Schoenwitz et al., 2017).

Companies apparently fail to understand how relevant information can support decisionmaking for SS definition (Hentschke, 2021) at a strategic level. There is often a lack of integration among different stakeholders in IC, such as developers, designers, manufacturers, general contractors, and regulators, and solutions are often defined considering the perspective of only a single one (Rocha, 2011). Only a few previous studies have addressed this fragmentation (e.g., Jiao & Zhang, 2005; Rocha, 2011; Ferguson & Olewnik, 2014; Andújar-Montoya et al., 2015; Schoenwitz et al., 2017; Khalili-Araghi & Kolarevic, 2018; Sjobakk et al., 2018; Hentschke, 2021; Popovic et al., 2021). The lack of understanding of market- and customer demand prior to the definition of a building system causes the need for later adaptations to projects, resulting in problems related to poor quality, occurrence of waste, and failure to implement continuous improvement. Manufacturers end up absorbing the issues resulting from the lack of refinement of design solutions which results in limited process efficiency (Popovic et al., 2022). Therefore, the development of solutions for capturing, analyzing, and presenting information about customer requirements, together with the understanding of operations management constraints may improve decisionmaking in product design, resulting in an effective way of developing and adjusting the SS (Sjobakk et al., 2018).

The aim of this paper is to report on a study to identify practices, challenges, and opportunities related to development of mass customized products in the IC context. The topic was approached from the perspective of the MC areas and their integration, which depends on the collaboration among stakeholders. This paper is distinct from previous research due to the emphasis on the need of deeply understanding customers' demands. This study is based on a literature review, two ongoing Empirical Studies, one in Brazil and the other in the United States (US), and insights from a workshop involving leading IC experts from California, US.

LITERATURE REVIEW

MASS CUSTOMIZATION (MC)

Trading off standardization desired by IC against flexibility required by customers is challenging (Schoenwitz et al., 2012). Nevertheless, MC attempts to fulfil these contradictory requirements (Pine, 1993). The level of customization allowed in the SS (Von Hippel, 2001) depends on the analysis of customers' requirements and existing operational capabilities (Da Silveira et al., 2001), and it is defined at the customer order decoupling point (CODP) (Rudberg & Wikner, 2004). In construction, it is not uncommon to have more than one decoupling point (Rocha, 2011), which allow different levels of customization of the same production system, depending on the market segments.

For MC to be feasible, a fixed- but still flexible SS is necessary (Ferguson et al., 2014). Differently from personalization, in MC value must be delivered with no need to reinvent products or processes for every new customer (Piller, 2004). Although customers may get the impression that the product is customized, several standardized components are being used in project delivery (Gibb, 2001). The definition of SS must be based on customer requirements, which are captured, analyzed, and translated into product specifications (Piller et al., 2004). Product solutions must also respond to the regulations, site, and climate conditions of different locations (Popovic et al., 2021). According to Otto et al. (2013) it is necessary to design products for specific market segments or customer clusters, instead of defining a general product that tries to meet all possible needs.

Maximizing repetition helps MC to achieve efficiency and lead-time reduction not only in production, but also in sales, design, and logistics (Tseng & Jiao, 2001). Economies of scale and scope are reached through commonality and reusability of both design and process capabilities across modules, tools, knowledge, processes, components, and specific market segments with respect to repetition in customers' needs (Tseng & Jiao, 2001). The reuse of solutions furthermore allows continuous improvement to be pursued, and facilitates the dissemination of practices within the company (Kotha, 1996).

DEVELOPMENT OF MASS CUSTOMIZED PRODUCTS FOR IC

The development of products for Industrialized House-Building (IHB) should be very different from traditional construction (Jansson et al., 2014). Structured solutions to handle multiple projects simultaneously, integrated decisionmaking, short lead-times, and adoption of new concepts, such as MC, modularity, and platform (Meyer & Lehnerd, 1997; Thajudeen, 2023), and a large number of engineering design activities, are necessary for manufacturing and site assembly (Lennartsson et al., 2021). These solutions may help companies that use MC reach competitive advantage (Hvam et al., 2008).

Product-platform and modularity concepts have been used to manage product variety in many other sectors (Hvam et al., 2008; Salvador et al., 2009) by sharing parts and production steps (Robertson & Ulrich, 1998). However, the application of those concepts requires much product development[5] effort (Bonev et al., 2015), involving several stakeholders throughout several project stages (Lessing, 2006). There is a need to shift to multidisciplinary product development from the early design stages (Jansson, 2013).

The term product platform refers to the collection of assets that are shared by a set of products (Robertson & Ulrich, 1998) or production lines (Meyer et al., 2018), allowing companies to offer products that show front-end variety based on back-end commonalities (Eriksson & Emilsson, 2019). These assets can be divided into components, processes, knowledge, people, relationships (Robertson & Ulrich, 1998), subsystems and technologies (Meyer et al., 2018). Lessing (2006) suggests that IHB development should include a Technical- as well as a Process Platform. The first consists of modularized solutions for building parts with interfaces that allow interchangeability and parts that can be combined to create a variety of end-products. The latter includes modules for collaboration, logistics, and information flow. Lessing also states that collaboration in multidisciplinary teams is a powerful way to develop solutions, methods, and tools designed to fit together.

[5] Product development is a set of activities to create, design and market a product (Ulrich; Eppinger, 2000).

The modularity concept is used to decompose complex products and processes into smaller and simple parts (Hvam et al., 2008). The ability to modularize a catalog of products is of great importance to offer a wider range of solutions for customers (Hofman et al., 2006). Voordijk et al. (2006) pointed out three different types of modularity: product-, process-, and supply chain modularity. The distinction between a modular- and an integral architecture is associated with the flexibility of the system to absorb changes. The first allows changes to impact only one component, whereas the second may see changes reverberate globally to several components of the system (Ulrich, 1995), making it harder to adapt products for diverse customers' needs without incurring penalties in product development costs and lead times.

RESEARCH METHOD

The point of departure of this investigation was a literature review on the management of information in the development of IC products, including the capture, processing, analysis, dissemination, and use of information to support decisionmaking among MC different areas. Our investigation also draws on learnings from two ongoing studies conducted in IHB companies (Table 1). Each case study involved two companies. The difference is that in Empirical Study 1, product development is carried out by the manufacturer, while in Empirical Study 2, it is carried out by the seller and real estate developer. In both studies, the companies delivered single-family houses. Those companies were chosen because they had been implementing some Lean Construction concepts, and also were interested in implementing an integrated approach in product development strongly based on the concept of modularity.

Table 1: Empirical Studies 1 and 2

<table>
<tr><th colspan="2"></th><th>Empirical Study 1
(Company A + B)</th><th>Empirical Study 2
(Company C + D)</th></tr>
<tr><td colspan="2">Duration</td><td>23 months</td><td>3 months</td></tr>
<tr><td colspan="2">Country</td><td>Brazil</td><td>United States</td></tr>
<tr><td colspan="2">Building System</td><td>Panelized</td><td>Volumetric</td></tr>
<tr><td colspan="2">Construction Type</td><td>Wood frame</td><td>Steel frame</td></tr>
<tr><td rowspan="3">MC area</td><td>Customer Integration</td><td>Company A
(manages and sells)</td><td rowspan="2">Company C
(develops, manage, and sells)</td></tr>
<tr><td>Product Design</td><td rowspan="2">Company B
(develops, manufactures, assembles and deliver)</td></tr>
<tr><td>Operations Management</td><td>Company D
(manufactures and assembles)</td></tr>
</table>

Multiple sources of evidence were used in both Empirical Studies, including open- and semi-structured interviews with companies' staff, direct observation on construction sites and manufacturing units, analysis of existing database of customer profiles (Empirical Study 1), participant observation in meetings, and seminar participation for discussing results.

The literature review and the learnings from both Empirical Studies grounded the proposition of the questions about product development in the IC context that guided the discussions described in this paper. These questions were presented for discussion in a workshop with expert practitioners and academics selected based on their practical or academic experience in recent developments in IC in California and also for their complementary backgrounds (Table 2). This study is part of a collaboration between the Federal University of

Rio Grande do Sul in Brazil, and the University of California, Berkeley in the USA. The goals of the workshop, held at UC Berkeley, were to create a collaborative learning environment and provide an opportunity for IC representatives to share thoughts, convey practices, and suggest opportunities to overcome industry challenges.

The workshop started with a presentation with the aim of (1) sharpening the understanding of MC strategy and key concepts related to the IC context, e.g., product platform, modularity, product family; (2) reporting the research gap regarding the integration between MC areas in the development of IC products; and (3) introducing the practical problem based on insights obtained from Empirical Studies 1 and 2. A set of questions were posed to the experts in order to identify practices, challenges, and opportunities to overcome the challenges. The experts wrote their contributions in Post-it® notes that were grouped on a large panel on the wall. After that, the academics who facilitated the workshop carried out a discussion with the experts to get additional understanding of their answers. Last, experts presented their work and proposed topics to be explored in future collaborative initiatives among companies and universities.

Table 2: Workshop participant roles and companies

Expert	Role	Company Type
E1	Director General, PhD candidate	Volumetric modular construction manufacturer
E2	Co-founder and CEO	Software for offsite construction
E3	Principal	Global non-profit organization in sustainability
E4	Senior Associate	Global non-profit organization in sustainability
E5	Sr. Manager for Lean Project Development	General Contractor
E6	Director of Product Design	Global volumetric modular construction manufacturer, designer, and contractor
E7	Senior Technical Advisor, Researcher	Research and Policy Center for Housing Innovation
E8	Distinguished Professor of Engineering and Project Management	University
E9	PhD candidate	University

FINDINGS

EMPIRICAL STUDIES: A BRIEF SUMMARY

The practical problem noted in Empirical Studies 1 and 2 is that companies use an extensive catalog of single-family houses with low adoption of the MC strategy and related concepts, such as product platform, modularity, product families, and standardization. Other problems included: (a) a wide variety of products developed by using a traditional design approaches that do not adopt multidisciplinary work from the early design stages; (b) low levels of commonality, leading to rework and incompatibilities that tend to be identified late in the detailing design or construction stage; (c) engineering overload due to the need to detail many projects with low reuse of solutions; (d) uncompetitive prices; (e) very limited flexibility offered to the customers; (f) continuous improvement hindered by the low reuse of solutions. Most of these problems stem from the lack of understanding and proper communication of stakeholders' requirements from the early design stages onward.

Seeking a solution to these problems, in both studies companies have been working together on making some changes to reduce the size of catalogs, offering more flexibility and reaching economies of scope and scale through repetition. The changes include: (1) improving the capture, structure, analysis and communication of key customer information; (2) defining clearly the levels of customization to be offered for each market segment, based on data analysis; (3) exploring opportunities to implement IC key concepts and strategies; (4) understanding and communicating operations management constraints; and (5) improving communication and collaboration among stakeholders that represents different areas in order to iteratively develop solutions.

INSIGHTS FROM THE WORKSHOP

The most prominent issues raised by the experts during the workshop are discussed in this section. The insights were structured according nine questions posed to the experts, following a "Practices", "Opportunities", and "Challenges" sequence. The expert who suggested the issue is labelled by means of a code (e.g., E4 in Table 2).

How to reduce the gap between what customers want and what IC companies have offered? (Question 1.1)

One way to narrow the gap between wants and offers is to incorporate design practices that facilitate the reuse of solutions (E4). These practices would allow for changes or additions later on, suggesting a more flexible design that enables adjustments as customer needs evolve.

By contrast, a set of challenges were identified. First, the experts recognized that understanding customers and market needs remains underexplored in companies. "We don't know our customers" (E7) is a shared perception. Second, the customers of many IC companies are not the users (e.g., multifamily developers) (E7). Demand analysis is often carried out by developers based on their perception of the market, rarely on customer requirement data and structured analyses. Third, the dynamic nature of market preferences over time, influenced by factors such as tastes and macroeconomic cycles, further hinders efforts to align offerings with customer expectations (E3). Moreover, it is challenging to predict how family structure and living groups will change in the future (E4), requiring a forward-looking approach. Fourth, the siloing of design, engineering, manufacturing, and customers is identified as a crucial challenge (E9). Fifth and finally, the challenge of "sharing ideas and solutions across projects" (E9) may be associated with the lack of commonality between products and the reuse of solutions.

The experts recognized two opportunities to bridge this gap. First, solutions can be drawn from past and current projects (E9), leveraging lessons learned and successful strategies. Second, the prospect of establishing a nationwide industry coalition (E7) emerges as a strategic opportunity. Such a coalition could serve as a collaborative platform, fostering knowledge exchange, innovation, and the collective development of solutions to overcome challenges and reach economies of scope and scale.

How does a company define the level of product customization to be offered? Does it vary according to the business model or market segment? (Question 1.2)

Experts have highlighted a variety of practices employed by companies in determining the level of product customization. One is the informal and subjective case-by-case assessment (E1), suggesting that these decisions are often based on individual circumstances and unique project requirements. Another is based on business-to-business (B2B) customer catalogs (E1), by using predefined options from previous projects to guide customization levels. This definition is also based on the business goals, which means that companies with high product output tend to offer less flexibility in order to maximize efficiency and effectiveness (E6). Furthermore, a dynamic strategy involves initially paring down options based on specific requirements and subsequently increasing options as needed (E2). This strategy was adopted by Companies A and B from the Empirical Study 1 in order to gain understanding on the adopted concepts (e.g., modularity, product family, among others) from a more restricted product platform and then increase the level of customization according to the level of maturity of the company.

Maintaining focus and establishing a robust strategic definition is a challenge (E6). The lack of clarity about the level of flexibility to be offered in each market segment and the urge to ensure the sale leads companies to allow customers to make small adjustments, overloading the product development and engineering departments, and expanding the catalog.

Companies invest too little effort in customer data capture and processing, hindering the ability to fully understand market demands (E2). Additionally, shifts in market-segments, demanding adaptive strategies (E7) and continuous data capture and analysis. It is even more difficult to deal with this type of complexity due to the different perspectives brought by different stakeholders, and also by a limited understanding of manufacturing processes (E1). The lack of suitable performance metrics, which should be time-dependent, such as fabrication capacity and required slack, further complicates decisionmaking (E8).

The prospect of reducing fragmentation in decisionmaking (E7) and unlocking focus-goals related to manufacturing capabilities and planning (E6) stands out as another strategic opportunity. Research and Development (R&D) and prototyping emerge as promising avenues (E7) to explore innovative solutions, clarify questions about the construction system, help in the visualization of the product, and collect customer data. The development of a coherent product platform is also an opportunity (E1) to understand the boundaries of each market segment and its level of customization based on specific orientations, rules, and standards.

How to manage trade-offs between customization (generating value to customers) and operational efficiency and effectiveness (keeping costs low)? (Question 1.3)

Work in multidisciplinary teams was highlighted as essential to manage trade-offs, fostering collaborative, and iterative decisionmaking (E7). Another practice is to allow for customization options in simple areas and maintaining consistent interfaces in the same location between them (E6). This helps to isolate complexity in a specific function or subsystem, which means that exercising an option will not affect the whole system. A third practice emphasized by the experts was the importance of balancing intention with high customization expectations (E6), recognizing that achieving extensive modifications on a daily basis may not be realistic. This approach emphasizes balancing product flexibility and streamlined processes, ensuring that customization efforts align with operational efficiency and effectiveness.

One challenge involves identifying large segments of common opportunities (E3). This requires the understanding of customer needs and market trends to effectively tailor products or services without compromising operational capabilities. Another is providing the perception of flexibility and choice while keeping boundaries (E6), and the escalating redundancy and complexity associated with having more interfaces between modules (E2). Experts highlighted the difficulty of resisting revenue opportunities, particularly for early-stage businesses, even if the product may not align well with efficient manufacturing (E1). One challenge, but also an opportunity, is to secure a long-term pipeline of customer orders (E7). This includes proactively managing projects and establishing stable and reliable supply chains to secure long-term contracts, to support product platform standards, and to ensure a sustained workflow.

One strategic opportunity involves the development of trade-off models with virtual reality interfaces to explore various what-if scenarios (E8). These models, accompanied by associated cost and process models for both customers and producers (E8), offer a powerful tool for evaluating the impact of product development choices on both value generation and keeping costs low. These models could enable early visibility on production impact (E2).

What are the best data sources to understand what the market and customers want? (Question 2.1)

Experts suggested a diverse set of practices to understand the market and customers' needs, such as: large historical databases, permitting data at both local and regional scales, experience of homebuilders whether private or fragmented and market research (E3); past projects, surveys, interviews, and market trends (E9); sales data in the company (E6). Hiring skilled and innovative designers with a discerning aesthetic sensibility was mentioned as a good practice to support the understanding of the demand (E1).

Experts identified several challenges in finding the best sources of demand data. Some examples include: variability of data, both regionally and over time (E3); fragmentation and cost of data sources (E3); distortion of company data, introducing potential biases that require careful examination (E6). Additionally, some customer segments do not allow for choice, as in affordable housing, where limited options constrain data-driven decisionmaking (E7). The unavailability or proprietary nature of certain data sources adds an additional layer of complexity (E7). Fragmented and prescriptive building codes were highlighted as a challenge that affects the three questions regarding customer information to support product development (E7). Specific regulations for transportation and minimum dimensions differ across states, cities, and allotments. Structuring a database with these diverse regulations can assist companies in determining which parameters to adopt in order to accommodate various contexts.

Opportunities exist in terms of (1) understanding the focal points of the sales team, aligning product development efforts with areas of concentrated sales activity for optimal market responsiveness (E6); and (2) providing the development of solutions that address urgent, critical situations (E7). The National Association of Home Builders of the US (NAHB) was suggested as an opportunity to access market information and industry trends (E7).

How should this information be captured, analyzed, and communicated to the company and stakeholders? (Question 2.2)

Experts recommended registering, analyzing, and communicating information through workshops, trainings, customer-company meetings (E9), surveys, and analysis of sales data (E1). 'Dogfooding', which means experiencing the company's products or services first-hand, provide quantitative, qualitative, and experiential perspectives of customer information through the test of solutions in the market (E1). Another practice suggested was creating functional and features description without specific product details or brands, as done with Target-Value Design (E6). Presenting customer information as a cohesive story supported by visual aids can contribute to a clear and impactful communication strategy among stakeholders (E6).

Challenges include diverse workflows among companies, requiring different processes (E2) often for the same project, hindering standardization. "Skewed data can tell the wrong story" (E6). Informal and incoherent sales information poses hurdles in effectively translating insights back to the design phase (E1). Another challenge is privacy concerns that require handling or lack of access to sensitive customer information (E7).

Communicating the cost impact of the customization options offered to customers, particularly in the early stages of product development, presents a tangible opportunity (E2). Moreover, strategically positioning the product to align with current customer needs (E6) undermines companies' ability deliver value to customers and to compete effectively with more traditional design and construction processes.

How to use customer information to support decisionmaking regarding product development? (Question 2.3)

One approach involves leveraging customer data to define Minimum Viable Products (MVPs) for different product families (E6). This ensures that product development efforts are targeted, aligning with the most critical requirements. Another approach is assigning the responsibility for managing customer information and making it available to support decisionmaking (E7).

A major challenge is to have different stakeholders and customers represented in decisionmaking, especially in multi-family housing (E4), in which contact with customers is rare. By designating someone to present customer perspectives in the decisionmaking process, companies can foster a customer-centric culture that prioritizes and integrates customer insights into every stage of product development, enhancing overall responsiveness to customer expectations. However, who should do the customer analysis (E5) is still an open question. Customer preferences (stated preferences) may not always be associated with customers' choice (revealed preferences), i.e., people are not necessarily good at defining what is more important for them vs. their willingness-to-pay (E3).

A persistent challenge manifests in the lack of a steady project pipeline, complicating the consistent integration of customer demand into product development and among projects (E5). The pipeline and the development of a product platform from a collaboration effort among universities and companies were suggested as opportunities (E5).

How to manage trade-offs between stakeholders' interests (i.e. developers, manufacturers, GC, customers) in product development? (Question 3.1)

According to the experts, finances often dictate decisions (E1). Based on that idea, building close, long-term partnerships emerges as a key strategic practice (E7) to promote the mutual understanding among stakeholders, as well as fostering an open forum for transparent discussions about trade-offs, spanning from ideation to test sign-off (E6). Another important practice is to prioritize designs that are not necessarily easy to install but hard to install incorrectly, aiming to minimize issues related to GC and site crew errors (E3).

The challenges include fragmented and frequently conflicting interests across various stakeholder groups (E1, E2). Misalignments in interests require a moderator to control and guide the conversations, managing divergent priorities (E6). Moreover, a challenge emerges from the lack of performance metrics that are time-dependent (E8).

Overcoming these challenges implies the opportunity of fostering industry collaborations and coalitions (E2). This can create a better understanding of constraints across stakeholders, facilitating decisionmaking (E1). Another opportunity arises with organizations that encourage collaboration for collective change. One example is the Builders Lab, an initiative that supports developments from start to scale through the launch of tools for political decisionmaking or the modernization of construction methods (E7). Experts also mentioned the use of Lean Design tools to identify the best solutions among various options (E6). This approach enables a data-driven assessment of design alternatives, streamlining the decisionmaking process.

What are the best strategies adopted to support the design decisions in the IC context, considering operations' requirements from the early design stages? (Question 3.2)

Design Thinking (E6), Integrative Design, Interactive Effects, and Option Value (E7) were mentioned as practices adopted by the experts to support design decisions considering operational requirements from the early design stages. According to E7, Option Value considers the future evolution and potential trajectories of the project, assessing how current design decisions may either preclude or enable future developments.

Regarding challenges, the dynamic nature of design can result in a long design process, leading to low engagement levels among stakeholders (E6). Moreover, measuring the impact of design decisions can be hard, especially across projects (E7). Another challenge mentioned by the experts is the cost impact, as costs rapidly rise as Levels of Development (LOD) increase (E2). These challenges emphasize the need for approaches that address temporal, evaluative, and financial aspects of product development.

The prospect of platform integration of code requirements, potentially facilitated by artificial intelligence (AI), stands out as a promising opportunity (E4). Additionally, the development of product platforms offers an opportunity to structure design decisions through rules and guidelines that promote flexibility within a standardized set of solutions (E1). Cross-training initiatives among design and manufacturing representatives is another opportunity to foster a shared understanding of possible solutions in both domains (E9). Experts emphasized the importance of R&D and prototyping as strategies to support design decisions (E7).

How to fulfil demand for customization in product development while achieving operational efficiency in fabrication and assembly? (Question 3.3)

The experts reiterated previously-mentioned practices in answering this question, such as iterative improvement (E7), competent software(s) integration (E7), use of tools to continuously measure the impacts of customization on fabrication (E2), and establish robust product platform boundaries (E6) to ensure that both customer wants and operational demands are achieved.

By contrast, the first-time fabrication poses several unknowns (E2). Some of the opportunities raised to respond to these challenges were cost transparency (E7), designing and engineering with the understanding of what is a good operational performance and how to achieve it (E9), and utilizing projects to build platforms when possible (E1, E6). This suggests utilizing individual projects not only to fulfil immediate requirements of a specific context, but as opportunities to develop more consistent product platforms for use on subsequent projects.

DISCUSSION AND CONCLUSIONS

This paper discussed practices, challenges, and opportunities related to the development of single- and multi-family modular housing products and integration among stakeholders in the IC context. Results of this study can be summarized and categorized into five topics:

1. There is a need to align decisions and interests from different stakeholders at a strategic level. This includes defining someone in charge of managing conflicting interests and ensuring that customers and companies' requirements are considered and aligned with the level of customization and the defined business model goals;
2. Ensuring collaboration among stakeholders from the early design stages is imperative for improving product development and production system design. It is also necessary to use data on customer requirement and production capabilities, in order to foster a more competitive IC industry. This includes the implementation of initiatives for a better visualization and understanding of constraints, and the analysis of trade-offs;
3. Capturing, structuring, analyzing, integrating, and presenting information about customers' needs, companies' capabilities, and distinct code requirements within and among companies is crucial to support decisionmaking and for the IC industry to work together to overcome the challenges of competing with traditional construction;
4. Developing product platforms to define SSs can help IC companies to establish the boundaries of each market segment and its product families while reaching economies of scope and scale through repetition. The product platforms should be flexible to absorb changes over time and intuitive for the stakeholders to follow standards;
5. Promoting continuous improvement and learning through iterative development of products and reuse of solutions. This includes measuring performance across projects; prototyping and using MVP to shorten cycles or refinement; investing in data capture and analysis; understanding and communicating what good performance is and how to achieve it; and what is the response of the market to the offers.

The following steps of this investigation include the development of prescriptive knowledge that can be used to support the development of mass customized products for IC, and conducting a second round of interviews with experts to assess the utility and applicability of those prescriptions. Finally, suggestions for further research include to improve understanding on how to capture, structure, analyze, communicate and use design, engineering, manufacturing, and customers' requirements to support product development and production system design.

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PROCESS MODULARITY – A LEAN APPROACH TO DEVELOP INDUSTRIALISED BUILDING PLATFORMS

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ABSTRACT

The concept of modularity within product platforms and lean thinking has drawn attention in recent years, to achieve a balance between standardisation and customisation in industrialised building (IB). Modularity plays an important role in IB, where companies use standardised modules on common platforms for product development. Although the application of product modularity is widely discussed in the literature, the concept of modularity is not fully explored as a mechanism for process development, aiding to improve cost efficiency, quality and coordination across the IB value chain. Previous research within lean construction emphasises the importance of modularity in both product and process dimensions. However, a lack of clear understanding has impeded the full adoption of process modularity in IB platforms.

This paper examines the work processes of a Japanese case company to identify modular patterns in the technical systems for varied house production. By analysing qualitative data, the findings present potential advantages of modularity in the case company's lean approach to standardise the design, production, assembly and logistics processes. The study contributes in presenting a concept of process modularity to support developing process platforms in IB.

KEYWORDS

Process modularity, industrialised building, lean construction, platforms, technical system

INTRODUCTION

Industrialised building (IB) is seen as a means for streamlining building processes and promoting efficient and cost-effective activities to reduce resource waste (Björnfot & Stehn, 2004). IB comprises various constructs that require integration and continuous development to enhance productivity, product variety and quality through product and process predefinition (Lessing, 2006, 2015). This approach aligns with the concept of lean construction that defines a methodology for work structuring, aiming at streamlining the whole construction process across design, production and assembly (Ballard *et al.*, 2001a; Koskela *et al.*, 2002). Recent studies suggest that such efficiency has been achieved by a number of IB companies through

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the adoption of a product platform approach (Jansson, 2013; Jensen *et al*., 2013; Johnsson, 2013; Thuesen & Hvam, 2011). Originating in manufacturing, a product platform is defined as “the collection of assets (i.e., components, processes, knowledge, people and relationships) that are shared by a set of products” (Robertson & Ulrich, 1998, p. 20).

Hvam *et al*. (2008) contributed to platform-related research by examining varying degrees of pre-engineering in four production strategies: Engineer-to-Order (ETO), Modify-to-Order (MTO), Configure-to-Order (CTO) and Select-Variant (SV) (Figure 1). At the lowest level – ETO strategy, traditional project-oriented norms and standards predominantly define pre-engineering. MTO involves increased use of standardised technical solutions. CTO employs predefined parts, components, and modules for building configuration, while SV involves the pre-definition of entire buildings with minimal project-specific solutions (Hvam *et al*., 2008). ETO and MTO strategies typically result in increased flexibility in traditional building production, with project-specific solutions. On a contrary, in CTO and SV strategies, limited flexibility in product offerings allows high levels of platform predefinition, where modularity plays an important role in product and process standardisation (Gosling & Naim, 2009; Johnsson, 2013; Lessing & Stehn, 2019). Extending this concept, Johnsson (2013) suggests that the dominant production strategy in construction is ETO, which allows different settings for the utilisation of platforms in house-building: design-to-order, adapt-to-order, and engineer-to-stock. By utilising an adapt-to-order structure – a subset of ETO, components of the design solution are pre-engineered, and the final product is achieved by assembling these pre-engineered parts. According to Johnsson (2013), such a strategy allows standardising and modularising processes along with the products.

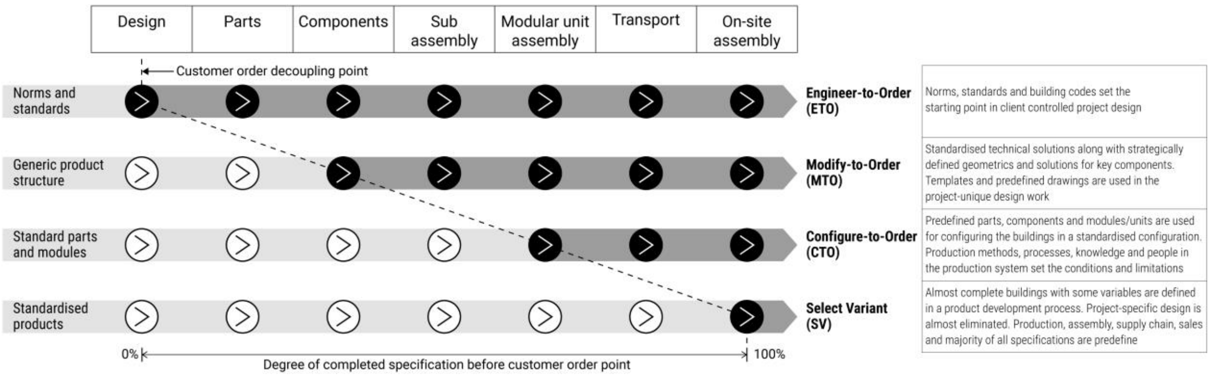

Figure 1: Four platform strategies in construction. Figure 1 adapted from Hvam *et al*. (2008)

Although modularity as a concept has received considerable interest among academics and practitioners, for product standardisation, there has been less research on the aspect of modularising IB work processes. Johnsson (2011) underscores the significance of standardising technical systems as strategic assets across the IB value chain. This involves structuring building activities, rules and decisions as process modules (Lessing, 2006; Lidelöw *et al*., 2015). The paper argues that these process modules have common attributes enabling their flexible rearrangement and interchangeability across multiple projects.

Reviewing the literature on modularity, lean thinking and technical systems as a basis, this study explores existing approaches to modularising work processes in IB. Empirical data are gathered from a Japanese case company and include live observation and document analysis, where the house design-to-production process and platform application were examined based on lean thinking. The aim is to analyse the technical systems across the IB value chain to evaluate the approach in modularisation, reuse and scalability of processes in varied projects. The analysis identified modular patterns within the case company’s technical systems across the design, production, assembly and logistics workflow, including relationships between actors, activities, and assets. From the evaluation of the findings this paper presents an understanding of the concept of process modularity from a lean perspective. Such an understanding of modular building processes is useful for developing IB process platforms and identifying opportunities for future research on this topic.

LITERATURE REVIEW

MODULARITY

Modularity has been an important topic within engineering literature and it refers to the structure of a product or process that comprises smaller subsystems (i.e. chunks or modules), and is managed independently, yet can perform together holistically (Baldwin & Clark, 1997; Ulrich, 1995). A module is perceived as a self-contained unit with its own functionality and standardised interfaces that interact based on the systems' definition. (Miller & Elgard, 1998). From a product design perspective, such independence of module development allows a company to standardise components and create product variety, with minimal impact on production. These concepts view modularity as a product development strategy, utilising a product platform approach (Simpson, 2004). In the construction context, modularity is frequently viewed through a product lens, referring to the utilisation of basic building blocks (Rampersad, 1996). Furthermore, research in construction on production systems and pre-engineering approaches (i.e. ETO, MTO, CTO, SV) have left modules with a rather narrow role as highly standardised volumetric units (Jonsson & Rudberg, 2014).

Nevertheless, modularity influences not just the architecture and structure of products but also the organisation and processes involved in their design and production (Baldwin & Clark, 1997; Fine, 1998). A modular process becomes significantly useful when a system becomes so large that interdependence between physical components for integrated design and production becomes difficult (Rocha & Koskela, 2020). Fine (1998) argues that the level of modularity present in the final product aligns directly with the level of modularity in the construction processes and supply chains. Fine's claim consequently presents three perspectives of modularity – product, process and supply chain modularity. In light of these insights, this paper aims to explore the concept of process modularity, shifting focus from mere product-driven considerations towards reshaping and streamlining organisational structures and supply chain dynamics to enhance adaptability and efficiency in IB.

PROCESS MODULARITY

The building process involves project-specific work activities that are often not pre-defined (Knotten *et al.*, 2015). These activities result in highly varied combinations of workflows for each project (Sibenik *et al*., 2022). Sibenik *et al*. (2022, p. 1) argue that single activities within the building workflows "are similar and constitute patterns that could allow for modularisation and eventual standardisation." According to Sibenik *et al*., identifying modular patterns becomes possible when building processes are divided into shorter processes or subprocesses as work activities. A modular process enables the use of shared production system, parallel assembly, along with standardised manufacturing, delivery, and assembly activities (Lennartsson & Björnfot, 2010; Peltokorpi *et al*., 2018). Lennartsson and Björnfot (2010) refer to this approach as process modularity, which is concerned with standardising building operations with shared interfaces. In IB, such standardised building operation means to utilise a set of technical solutions and processes for varied product developed, i.e design decisions, planning methods, component and interface configuration, workflows, supply chain logistics, production systems etc., across the entire building value chain (Lessing, 2006, 2015). Building on this, Peltokorpi *et al*. (2018) emphasise the process asset within the product platform definition. In their view, platform assets contributing to enhanced outcomes in IB are not necessarily standard components but rather standardised processes for manufacturing, preassembling, delivering, and assembling components on-site. These concepts relate to Bjornfot & Stehn's (2004) claim that process modularity effects in the IB value chain can be examined through the following criteria (Table 1):

Table 1: Effects of process modularity in IB. Table 1 adapted from Bjornfot & Stehn (2004)

Development of new modules	Its approach to the development of new modules with standardised processes
Allowing external variety	Its approach for minimising internal complexity and enhancing external variety
Production optimisation	Its strategy for designing and using standardised products and processes to achieve optimised production
Reusability and reconfigurability	Its approach to reuse standardised processes while recycling and reconfiguring modules to develop differentiated end products

In achieving these modularity effects, Bjornfot & Stehn suggest two strategies for viewing the construction process: top-down or bottom-up. The top-down view looks into streamlining processes by implementing lean thinking. It relates to the production system of new products that are volume-based, often caters for end customers' needs and allows the reusing of previous processes and technologies (Björnfot & Stehn, 2004). On the contrary, in the bottom-up view, the design of the product and the unique needs of end customers guide the production processes. This is more relevant to an ETO-based strategy in project-specific construction (Koskela, 2003). In lean terms, the top-down approach is suitable for CTO-based IB companies to achieve both product and process value, leveraging modularity and reusability of building processes.

Lean thinking

As previously discussed, modularity of processes can optimise the entire building workflow from design through production, assembly and delivery of the completed building. This relates to lean thinking, where the primary goal is the elimination of waste and the creation of value (Green, 1999). The term "lean" stems from the Japanese manufacturing industries as "Lean Manufacturing (LM)", where the aim is to optimise the value stream in mass production (Ballard *et al*., 2001b; Koskela, 1997; Womack & Jones, 1997). In the building industry, the concept is called "Lean Construction," aiming at improving site-level production, as well as increasing the value delivered to the customers (Ballard & Howell, 1994). Bjornfot & Stehn (2004, p. 6) define lean construction as "a process management discipline offering management during the whole construction process, aiming at streamlining production."

In lean construction, the organisation of production is referred as work structuring (Ballard *et al*., 2001a; Koskela *et al*., 2002). In this manner, applying modularity of processes leads to achieving lean construction principles, as it allows work structuring to reduce complexity and waste from design-to-completion stages in IB (Bertelsen, 2005). Bertelsen (2005) argues that modularisation allows an efficient construction process, asserting that such an approach is lean as it minimises customer influence on design while enhancing product quality and process flow. Lidelöw *et al*. (2015) further highlight that process modularity can support knowledge innovation and the breakdown of activities, helping to structure work processes through the interdependencies between them. Such work structuring relates to developing and reusing technical systems as a way to improve the IB platform strategy (Jansson *et al*., 2015).

Technical system

Within the concept of lean construction, the approach to streamlining the complex IB processes and modularising workflows entails standardising technical systems as strategic assets across the building value chain (Johnsson, 2011). Technical systems involve not only defining product configuration but also a set of rules, instructions and guidelines that govern the design, installation and operation of those building systems (Lidelöw *et al*., 2015). Standardising technical systems means analysing building activities and decisions to optimise all stages of the building processes with a focus on reusability across diverse projects. In analysing technical systems, information is partitioned into visible rules – comprising architecture, interfaces and standards. Architecture describes the modules that are part of the applied building system, whereas interfaces describe interactions between the modules, and standards govern how the modules are functioning in the system (Baldwin & Clark, 1997). In this relation, building systems relate to physical component configuration and are generally categorised into five types (Figure 2): site, structure, skin/enclosure, services, and space including furnishing and fixtures (Smith, 2010). According to Johnsson (2011), the choice of a building system defines not only what technical systems are required for standardisation, but also the organisation within the company, its market position and future growth.

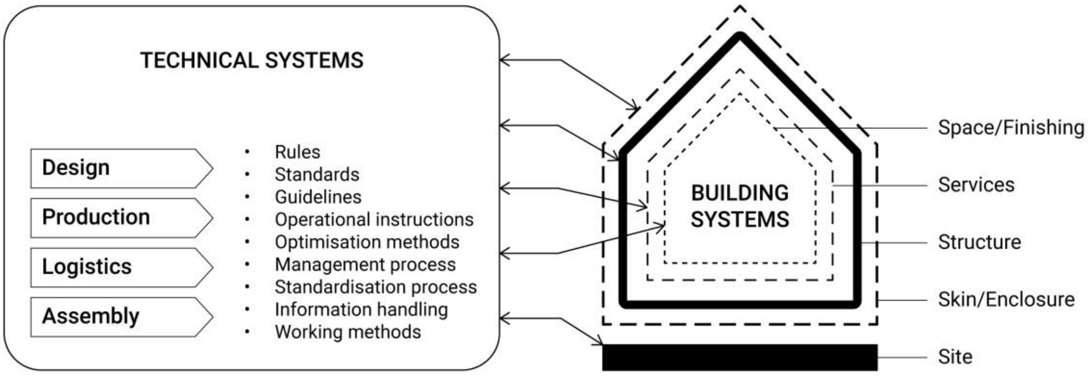

Figure 2: Relationship between technical systems and building systems in IB. Figure 2 adapted from Smith (2010)

Lessing (2006) includes a process model for IB that is supported by a technical and process platform. The process model emphasises the significance of technical systems in IB platform development. The technical systems include structural frames, installations, façade, roof systems etc., and are used for configuring complete buildings. According to Lessing, a technical platform configures technical solutions: establishing standards, and developing technical systems suitable for effective production, transportation, and assembly of building components; whereas the process platform involves a systematic collection of instructions and organisation of process modules concerning collaboration, design, planning, production and logistics methods, information handling systems etc. (Lessing, 2006, 2015). Lessing's (2006, 2015) concept of utilising technical systems, however, relates to the product side, concerning the configuration of building systems. However, building on the earlier literature, it can be argued that developing technical systems is not limited to standardising physical configurations of building systems and rather requires structuring associated work activities (i.e. workflows, collaborative decisions among different stakeholders, design, production and assembly methods etc.). In this manner, the modularisation of technical systems requires an efficient process platform to allow work structuring across the IB value chain. In Lennartsson and Elgh's (2018) view a properly developed process platform should facilitate structuring technical systems and enable lean practice both in design and production in IB. In this paper, the concept and implication of modularity are tested by analysing the building processes of a case company that enables a lean approach in their platform application.

RESEARCH AIM AND METHOD

This paper aims to understand the modular patterns, concerning work activities, actors, and assets, across the design-to-production phases, to evaluate the effects of process modularity

(Sibenik *et al*., 2022). To achieve this aim, a Japanese IB company (named in this paper as "H") was studied by mapping their technical systems as design and production interfaces. The company was chosen due to its extensive application of lean construction while meeting customers' requirements during house production. A visit to the factories of case company H was organised to observe the design, prefabrication, assembly and logistics processes of their varied modular house products. Through a Case Study Research (CSR) method, qualitative data concerning design and production processes, technical systems, supply chain management, working methods, knowledge resources, product and platform development strategies were captured and also through studying the supplied documents, i.e. drawings, reports etc. CSR is useful for studying a phenomenon in its natural context, as it enables the comparison of different theories and observations from empirical data (Miles & Huberman, 1984). In this method, a qualitative approach to collecting empirical data provides an opportunity to obtain a sufficient level of detailed information (Gummesson, 2000). While assessing the company's technical systems and platform strategy the research seeks to respond to the following questions:

1. Are there any recognisable modular patterns in the technical systems of the IB company?
2. How process modularisation strategies are currently utilised in the technical systems to support the development of a process platform?

Through the observations and documentation, and the analysis of the captured data, this study a) identifies modular patterns within the case company's technical systems across the design, production, and assembly processes, b) suggests a concept of process modularity that supports the development of an efficient process platform, and c) presents an opportunity for conducting future research on process modularity from a lean perspective.

CASE DESCRIPTION

The studied company has been a market leader in factory-built residential housing in Japan since the 1970s. The company manufactures volumetric houses across eight strategically located factories in Japan. These facilities utilise highly automated systems for the production of a variety of standardised components, aiming to attain greater economies of scale. The company applies a platform-based IB strategy for component production, with up to 80% - 85% of final production completed on the factory's automated assembly lines. The company utilises standardised building systems such as façade systems, building frames, wall and floor panels, and modular interfaces across a wide variety of project types to enable non-repetitive and unique product offerings. A lean modular approach has allowed the company to work towards optimising the entire building process, achieving an efficient flow of projects across multiple production lines. The building system is based on volumetric blocks, utilising both steel and timber-frame volumetric units. The system is defined as a Unit Method, where the functional spaces are produced as units and then several units are assembled on-site using standardised interfaces. The company is vertically integrated, incorporating sales, design, production, construction, after-sales, servicing and remodelling - all under the same organisation.

BUILDING PROCESS

This section presents an analysis of the collected qualitative data providing an overview of the product development process across the design-to-assembly stages for various house products. These findings are synthesised in the next section to discuss modular patterns that are identified.

The house product developed by the case company incorporates product families, building systems and previous house models. Most units, accounting for 80 per cent, are constructed with light gauge steels, while the remaining 20 per cent are built using light wood frames. In the factory, light gauge steel frame units, acting as "chassis", undergo customisation according to customer specifications, and serve as the primary structural support. The top factory floor fabricates the chassis while the bottom floor applies external & internal finishes, internal fit-outs, cables, pipes and indoor sub-components such as stairs, cabinetry and other equipment, with a just-in-time approach. The company has developed 6 basic house types, which can be customised using 70 types of units, including 40 standard cuboids available in 10 different lengths, 2 heights, and 2 weights, while the rest are uniquely shaped units, like trapezoids. Square steel tubes are used in different sizes for different applications, including: (i) 100 to 120mm tubes for posts, (ii) 200mm tubes for the beams, and (iii) 150mm non-flexible tubes for the floor beam. Typically, 10 to 15 of these steel-framed volumetric units, adjusted based on the house size and customer demands, are assembled to construct a two-storey family house with an approximate floor area of 130-150 sqm. For manufacturing efficiency, the units are designed for transportable dimensions, typically measuring 1.8 - 5.4m in length (nine standard lengths), 2.5m in height, and 2.4m in width. Moreover, the company provides units in half-sized dimensions for each measurement and also uses partitions at fixed 900mm intervals.

While configuring units for varied house types, the exterior and interior finish combinations vary (compound panels, composite panels with pre-attached veneers, aluminium plates, gypsum boards, etc.); so do roof styles (flat, sloping etc.), stairs, kitchen and bathroom fittings, plumbing fixtures, and light-switch locations. An average house contains approximately 30,000 distinct component types out of a vast selection of over 300,000 available options. The IB company also created an Open Engineering System (OES) that possesses the capacity for further development or transformation into new product models. For production efficiency the company employs a two-part order system, each unit divided into parts, prepared to basic standard specifications (concerning frames, floor, wall, and ceiling panel etc.) and standardised options (i.e. colour and finishes). Upon receiving a customer's order, the sales company drafts the floor plan and passes it on to the factory point with component specifications. A computer-controlled production management system handles received data necessary for diverse component assembly on the 400-meter production line. Constructing a house within the factory typically takes about three hours. It starts with cutting steel components for framing the units and progresses through the zinc coating process. This includes frame fabrication, including robotic automatic arc welding of ceiling and flooring elements to form a skeleton. After the welding process, the steel frame chassis progresses through the conveyor belts and receives finishing touches across more than 50 workstations. Workers proceed to install all essential panels, windows, doors, staircases, services, bathroom and kitchen units, and fittings according to work schedules. In this step, varied suppliers deliver materials, parts, components, and prefabricated sub-systems (such as bath and kitchen units) just-in-time and just-in-sequence through the gates placed on both sides of the assembly lines. Installation of external cladding, electro-mechanical services and plumbing are conducted in the next stage. At the final workstation, some units are stored and others are prepared for delivery. The on-site tasks encompass site preparation (2-3 weeks), assembling units, immediate weatherproofing, airtightness and connecting to utilities (1-3 days). After the initial assembly, additional work including minor interior and exterior finishing is completed within a month. To maintain quality and 100% error-free product handover, rigorous inspections occur post each production step. The stringent factory processes, supported by lean principles lead to decreased failure rates while improving the overall quality and long-term reliability of the building products. Figure 3 shows the streamlined design-to-assembly workflow for house production by the case company.

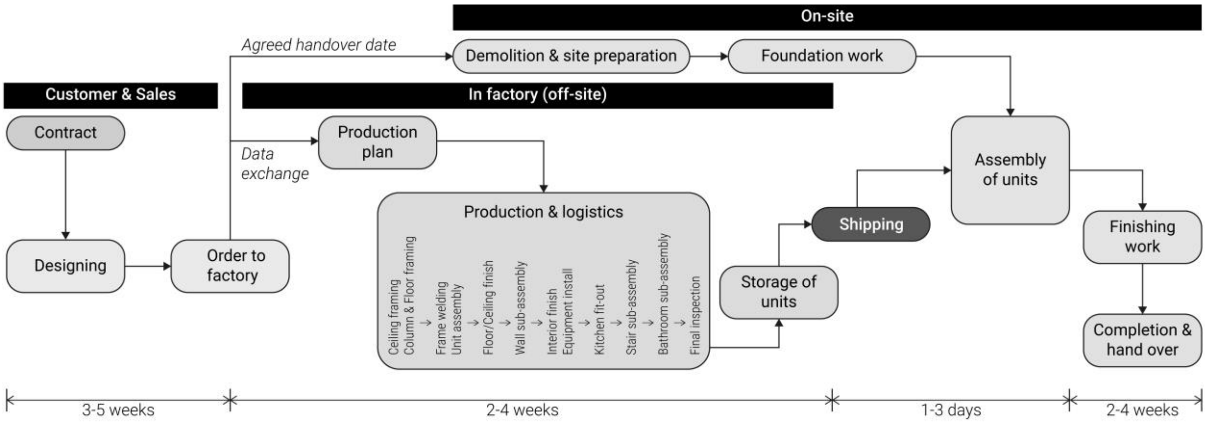

Figure 3: Standardised design-to-assembly work processes by the case company.

DISCUSSION

The case company presents a top-down view from a lean modular perspective to streamline processes (Björnfot & Stehn, 2004). This allows for reusing previous processes and technologies, achieving economies of scale. In this sense, the company adopts an adapt-to-order subset of ETO strategy as referred by Johnsson (2013) in developing its product platform with pre-engineered solutions. By applying such a strategy, the company responds to the individual demands for housing solutions while enabling modularised processes, product architectures, and supply chains. The platform assets (components, processes, knowledge, people, and relationships) described by Robertson & Ulrich (1998) are well-established in the case company through (1) a modular structure of the product - Unit Method, (2) a well-described technical system across design-to-production process, (3) technical know-how and reusability of knowledge, and (4) a well-managed supply chain and logistics system. Referring to Lessing's model, the interchangeability and reusability of the work processes (e.g. collaboration, design, planning, production and logistics methods, information handling systems) support the development of an efficient process platform by H. Building on Bjornfot & Stehn's (2004) concept, the analysis of the collected data identifies process modularity patterns as follows:

Development of new modules: The Open Engineering System (OES) developed by the company, based on parameters, enables the direct translation of customers' desired floor plans into production sequences, logistics, and work tasks. This reflects a lean approach to streamline the design-to-production processes. This innovative system has the potential to create new platforms and product variants using existing components and reconfigure building processes for new house production.

Allowing external variety: The houses made by H are assembled from several volumetric units. These room-sized units offer variety in the room layout, house shape, roof type, kitchen and bathroom pattern, materials, colours, finishing, fixtures, and fittings. By accommodating these varieties of standardised options, the units are customisable, allowing distinctiveness from each other. Moreover, the interfaces of the components and units are also standardised, reducing internal complexity while increasing external variety. Table 2 presents a synthesis of how standardised components are used to allow a certain level of customisation in the case company's varied house production.

Table 2: Standardised components by company H allowing customisation options

Standard components	Modular product architecture, allowing customisation	
Steel frames	n/a	100-120mm tube for posts, 150-200mm tube for beams
Room units	Dimensions	10 to 15 units: 1.8 - 5.4m in length (nine standard lengths), 2.5m in height, and 2.4m in width
Wall, Floor and Roof panels	Dimensions & finishes	900mm intervals and half-sized measurements
MEP work	n/a	
Fixtures, Fittings, Finishing	Choice	Approx. 30,000 component selections from 300,000 options
Paintwork	Colour Choice	
Joining interfaces	n/a	

Production optimisation: The production process follows a lean modular approach in terms of value flows across a sequence of 50 workstations, with a focus on process optimisation in each step. The standardised interfaces of the house parts allow interchangeability of the production process for six different house configurations across the six parallel production lines. The planning, production rate and transportation sequence for these components and units are predefined and support a repetitive process strategy. Table 3 presents the modular patterns that are observed across six parallel production lines for six basic house designs:

Table 3: Modular patterns observed in varied house production by company H

Common steps	Modular patterns in the work processes
1. Customer order and design	[3-5 weeks] The involvement of customers in the design process using a CAD system is modular and reusable across multiple house productions.
2. Data transfer for order entry	[1-2 hours] Modular patterns in design involve 80% predetermined parts and 20% custom parts, with a factory order system for component selection.
3. Conversion of design to objects	[1 day] The automated conversion of design data into objects and BOM, along with weekly batched production plans are modular and standard for all projects.
4. Unit production	[1-2 weeks] The production sequence on six assembly lines is modular, with predefined tasks, and standardised and interchangeable components.
5. Site preparation	[2-3 weeks] The procedure for site preparation (including demolition and recycling of old materials) follows a modular pattern across all projects
6. Delivery and assembly	[2-4 weeks] Modular activities on-site assemble units in 1-3 days, including weatherproofing and airtightness, optimizing completion timeline in 20-30 days.

For production optimisation, the company employs a parameter-based system that helps to modularise the entire workflow encompassing design, configuration, planning, order reception, logistics, fabrication, and delivery. Furthermore, modular work patterns are also evident in production checks by inspectors at different stages for quality assurance, using a system of green, yellow, and red demarcations of defect rates. Yellow suggests required corrective action; red means unacceptable defects. All processes follow the same modular pattern, however, depending on the house product type, the duration could differ for each of the steps.

Reusability and reconfigurability: The manufactured units developed by the company are not project-specific, and can be used interchangeably in a range of house products. This allows the reuse of a considerable proportion of technical systems, pertaining to the design, production, assembly, disassembly and recycling of the units for a completely new building. The technical systems work as a knowledge repository for process modularisation, allowing for the realisation of an efficient process platform. Moreover, the company relies on long-term relationships with numerous suppliers (approximately 200) for key product components, supported by a modular supply chain structure. In reference to Jansson's (2013) claim, in this case, experience feedback from the supply chain is utilised in the platform, a strategy that follows the principles of lean thinking, where long-term strategy and holistic view are the keys. From this perspective, process modularity is closely related to the degree of vertical integration.

To summarise, the IB company H has developed modular production processes, including a well-defined modular production facility and a modular supply chain structure. Standardised work activities and experience feedback support the development of an efficient process platform to optimise building processes across the entire value chain. The long-term benefits of defining, streamlining and refining activities by experience feedback follow the perspectives of Koskela *et al*. (2002), Bjornfot & Stehn (2004), and Bertelsen (2005) on lean thinking, as discussed in the literature review section.

CONCLUSION

This paper explores the concept of process modularity and its potential to drive lean construction in IB companies. The research comprises qualitative analysis on a Japanese case company, recognising their modular work patterns and how their application of a platform-based approach enables process modularity across different stages including design, production, and assembly. Previous studies have identified the concept of modularity in product, process and supply chain dimensions, however, a clear understanding and application of process modularity is missing in an IB context. This study argues that analysing IB work activities for repetitive patterns creates the base for process standardisation, ultimately leading to process modularisation, and in turn creating the conditions for increased lean construction.

In response to the research questions, this paper first conducted a literature review to establish an understanding of relevant concepts such as modularity, platforms, lean thinking and technical systems in an IB context. Then the effects of modularity on technical systems was examined, including work processes, actors and assets, through a qualitative analysis of the observations and extracted data from the building processes of the Japanese IB company H. Through evaluation of the case study analysis this research contributes by –

1. identifying a set of modular patterns in the IB value chain that supports the technical systems involved in the development of volumetric units;
2. mapping a flow of standardised activities that are common across house products; and
3. presenting a concept of process modularity that allows reusing technical systems, supporting lean principles, and enabling the realisation of an efficient process platform.

However, the findings from the case study suggest the applicability of modular processes in an adapt-to-order subset of ETO context, where the IB company is vertically integrated. The wider scope of modularising technical systems requires further examination in other platform contexts, i.e. ETO in general and MTO, to broaden the concept of process modularity in lean construction. Also, the dependency of the work activities and the amount of allowable deviation for interchangeability of process modules are not fully explored. Moreover, the boundaries of the level of modularity of work activities are not clearly defined, which presents future research opportunities in this area. Nevertheless, the evaluation of the case study may offer future guidelines for similar IB companies who intend to implement a platform strategy where modularity of process enables an efficient process platform. Owners, designers and developers may be benefitted from this case study findings to determine how work processes could be structured and modularised to develop their technical systems, and what kind of platform strategy would best support the modularisation effects to benefit from process modularity in IB.

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NET-ZERO & DIGITALISATION IN OFF-SITE CONSTRUCTION

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ABSTRACT

The UK Government set targets to achieve net-zero buildings by 2050. Consequently, there is a need for off-site construction companies to achieve net-zero over the coming years. However, small and medium-sized enterprises in off-site construction face challenges in implementing net-zero, as well as in implementing digitalisation, which can greatly support achieving net-zero targets. This paper reports on initial findings of a project focused on improving digitalisation and net-zero within an SME off-site construction company. Through process mapping and observations, implementation barriers to digitalisation and net-zero were identified, and a set of actions are suggested. The paper also discusses tools for optimising the lifecycle carbon impact of buildings. The recommendations include accurate carbon footprint measurement, creating a realistic reduction strategy, and adopting sustainable/low-carbon materials. Additionally, the paper recommends the use of smart technology to monitor as-built and compare it with the as-designed building.

KEYWORDS

Off-site construction; Net-zero; Lean construction; BIM.

INTRODUCTION

The construction industry is seen as a low-innovation industry, with a poor track record in schedule and budget compliance, and industrial accidents. Off-site construction has been posed as a means to help improve quality, productivity, reduce waste, and lower the carbon footprint of buildings (Generalova et al., 2016). Off-site is especially important now, given the current climate crisis, as the built environment has a crucial role to play in limiting global warming to 1.5°C and enabling the transition to net-zero by 2050 (UK Green Building Council, 2023).

To reduce overall emissions by 2050, it is recommended that the industry improve energy performance and reduce the carbon footprint of building materials through carbon emissions analysis and calculation models and by using sustainable materials (Sheikh, 2022; Chen et al, 2023). Furthermore, there is a need to multiply policy commitment alongside action and increase investment in energy efficiency (Sheikh, 2022). Figl, Ilg and Battisti (2019) explain that carbon neutrality must be considered at the early stages of building design and planning for the industry to meet the 2050 target.

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It is known that Building Information Modelling (BIM) and Lean provide diverse opportunities for improvements. However, most companies are not yet exploiting this to its full potential. The implementation of BIM, Lean, and net-zero carbon is evolving and is a significant area where academic research can create solutions applicable in practice.

This research aims to support net-zero and digital transformation within one off-site construction company, implementing new processes and technologies to enhance productivity. It seeks to achieve BIM adoption, carbon footprint measurement and reduction, and the adoption of sustainable/low-carbon materials within the off-site construction process. The focus of this paper is to discuss the existing application of BIM and Lean towards the design of net-zero buildings in the company, to enable it to move forward in achieving the UK Green Building Council (UKGBC) net-zero targets by 2050.

LITERATURE REVIEW

DIGITALISATION AND BIM

Construction is one of the least digitalised industries (Veselka et al, 2019), even though there has been an increasing adoption of digital technologies, such as BIM (Gan et al, 2023). BIM encourages collaboration between project stakeholders fostering an integrated project delivery (Rowlinson, 2016; Gan et al, 2023). Furthermore, BIM allows for evaluating alternative designs, and hence design optimisation (Gan et al, 2023).

However, according to Holzer (2011) and Rowlinson (2016), drawbacks for BIM implementation include a focus on software rather than improving the design process, and ambiguity concerning BIM features which causes confusion across the industry. Interoperability issues also exist, and where team members use software programs from different distributors, a neutral transfer format is required for the different data to work on a common building model (Figl, Ilg and Battisti, 2019). Additionally, the use of BIM is still very monodisciplinary and profession-based, which does not encourage an integrated process (Rowlinson, 2016). There is therefore a continued need for supporting the implementation process before BIM benefits can be fully realised.

In the UK, the construction sector has the highest number of small and medium-sized enterprises (SMEs), approximately 882,770 (Clark, 2023). Zhang et al. (2016) highlight that the use of BIM provides great opportunity to improve the performance of off-site construction, however, there is still a lack of adoption within smaller construction companies. Figl, Ilg and Battisti (2019) also highlight that SMEs may not be able to invest in expensive software or training for BIM. According to Makabate et al. (2020) the adoption of digitalisation through BIM is a necessity for most of SMEs in the coming years.

CARBON NET-ZERO

Construction is one of the highest consumers of energy (Llatas et al, 2019). Globally, buildings and the construction industry account for 36% of final energy use and 39% of energy and process-related carbon emissions, of which 28% is operational carbon emissions and 11% is from the manufacture of building materials and products (International Energy Agency, IEA, 2019; World Green Building Council, 2019). Over the years, several strategies have been applied to tackle this, for instance, through the implementation of lean, adoption of renewable energy for operations, adaptive re-use of existing buildings, reuse and upcycle of waste by promoting a circular economy, use of digital technology, and use of environmental assessments and ratings. However, by 2035, a significant portion of the emissions from the built environment is predicted to be attributed to embodied carbon, due to the ongoing efforts to reduce operational carbon emissions from buildings (UK Green Building Council 2021a; 2023).

The World Green Building Council (2019) has therefore stipulated that by 2030, new buildings, infrastructure and renovations will have at least 40% less embodied carbon and net-zero operational carbon. By 2050, new buildings, infrastructure or renovations will have net-zero embodied carbon, and all buildings must be net-zero operational carbon. The industry needs to combine efforts and take decisive actions towards achieving these targets.

NET-ZERO DESIGN AND METHODS OF ASSESSMENT

According to the UK Green Building Council (2021b), net-zero carbon in building operations is achieved when the amount of carbon emissions associated with the building's operational energy on an annual basis is zero or negative. The World Green Building council, WGBC (2019) define a net-zero carbon building as one which is highly energy efficient and fully powered from on-site and/or off-site renewable energy sources, with any remaining carbon balance offset. Several assessments such as green building rating systems and sustainability certifications, have been developed over the years targeted at improving the environmental impacts of buildings (Llatas et al, 2019). Cole and Fedoruk (2014) explain that although green building performance and assessment methods have always aimed at achieving net-zero impact, net-zero energy buildings have now become a specific performance goal for attaining high recognition within the Leadership in Energy and Environmental Design (LEED) or Building Research Establishment Environmental Assessment Method (BREEAM) amongst others.

Furthermore, the focus has previously been on achieving net-zero in building operations. However, globally, embodied carbon related to materials manufacture accounts for a lower percentage of whole life carbon compared to operational carbon emissions (Gan et al, 2023). In the UK, buildings and infrastructure contribute to about 25% of greenhouse gas emissions and with the inclusion of transport emissions, this rises to 42% (UKGBC, 2023). 80% of this is associated with operational carbon from existing building stock and 20% from embodied carbon of new construction (London Energy Transformation Initiative, LETI, 2020). Although operational carbon is higher at present, embodied carbon emissions are expected to rise in the coming years. With increasing advances to improve the carbon emissions related to building operations, embodied carbon emissions will represent a larger portion of the carbon production of buildings and this figure could increase to 40-70% of new buildings in the UK (LETI, 2020).

According to the UK Green Building Council (2021b), a building can only achieve net-zero carbon "when the amount of carbon emissions associated with a building's product and construction stages up to practical completion is zero or negative, through the use of offsets." There is a potential to improve the performance of buildings at the design phase, by calculating the environmental, economic, and social impacts produced by the buildings during its life cycle. Therefore, obtaining an understanding of the lifecycle performance and incorporating quantitative assessments will improve building design and operation and foster a low-carbon built environment (Gan et al, 2023). It can also provide insights into possible economic gains and will also advance measures targeted towards achieving net-zero emissions in buildings.

The British Standard BS EN 15978:2011 sets out the overall principles of embodied and whole life carbon measurement in the built environment. The embodied carbon of a building refers to the emissions emitted producing building materials, their transport and installation to site as well as their disposal at the end of their life (LETI, 2020; BS EN 15978, 2011). Operational carbon, on the other hand, refers to emissions associated with the in-use operation of a building throughout its life (LETI, 2020). This includes emissions associated with heating, hot water, cooling, ventilation, lighting systems, cooking, equipment, and lifts. A visual representation of this is provided below in Figure 1.

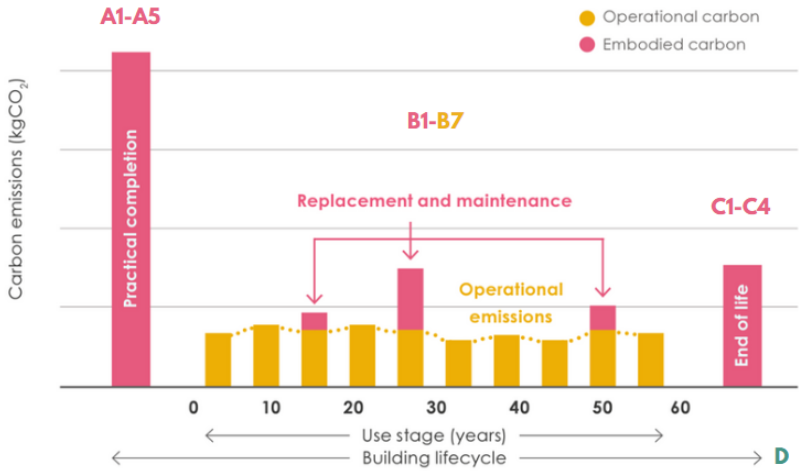

Figure 1: Carbon emissions breakdown over building's life cycle (Adapted from LETI Embodied Carbon primer 2020 and BS EN 15978:2011)

The potential to reduce carbon emissions reduces throughout the stages of a building project. According to Tsikos (2023), the lack of detailed data in early design makes it difficult to assess the impact of design decisions. Being able to quantify the embodied and operational carbon emission impact for a building project, that is the whole life carbon impact, would have a positive effect on construction and go a long way to achieving the net-zero carbon emissions. Furthermore, Collinge et al (2015) and Llatas et al (2019) explain that compared to other assessment methods developed over the years targeted at environmental aspects such as green building rating systems and sustainability certifications, the lifecycle assessment (LCA) is considered the most appropriate as it quantifies the buildings performance for sustainability through all life cycle stages. However, although LCA can be integrated in building design stages, one of its limitations is its time-consuming nature and vast amount of data required.

Gan et al (2023) explain that the use of BIM facilitates the calculation and mitigation of both embodied carbon and operational carbon emissions of buildings. BIM can be used to define construction material options and facilitate automatic derivation of material quantities for accurately determining embodied carbon (Hollberg, 2020; Roggeri et al, 2021). Furthermore, BIM has the capability to incorporate and manage a large amount of building information thus simplifying the Life Cycle Assessment (LCA) analysis by providing a visual representation of its impact (Llatas et al, 2019). Roggeri et al (2021) combined BIM with building energy modelling (BEM) to design a timber modular prototype and extract information to determine the energy impact in the building's lifecycle. To ensure net-zero design, the embodied energy/carbon, the environmental impact and the energy consumption were calculated. Similarly, Gan et al (2023) developed a BIM model to calculate upfront embodied carbon and aid energy simulation in determining operational carbon over the building's lifecycle whilst considering net-zero. They propose opportunities such as selection of low-carbon materials, operational efficiencies, modular integrated construction, and so on.

Nevertheless, although guidelines have been developed over the years by organisations such as the London Energy Transformation Initiative (LETI), UK Green Building Council (UKGBC), and the World Green Building Council (WGBC) since the announcement of the carbon net-zero targets by the WGBC and UKGBC, there is still a knowledge gap within construction industry regarding the implementation of net-zero.

BARRIERS TO THE IMPLEMENTATION OF NET-ZERO WITHIN CONSTRUCTION

According to Terblanche (2019), barriers to the implementation of net-zero buildings include high costs, limited resources and technology, client's perception of value, and lack of incentives from local authorities to promote net-zero buildings at the planning phase. There is also a lack of knowledge regarding net-zero buildings by construction professionals across the whole building design, operation and maintenance stages, leading to low implementation. Similarly, Aelenei et al (2023) mention the cost required to effectively integrate necessary technologies. Furthermore, there is not enough demand for low-carbon materials and technology and most companies just focus on low-cost products instead. Additionally, beneficiaries are not being fully aware of net-zero and its benefits for their projects (Aelenei et al, 2023). They do not have information on the materials, construction technologies and available funding opportunities. With more knowledge and understanding of the standards and guidelines by the beneficiaries and construction professionals, there will be an increase in the market demand thus encouraging construction professionals to develop themselves. This will also produce more reliable data on which policy makers can use to evaluate the success of these policies and measures.

Although several studies considered design towards net-zero and methods of assessment (Llatas et al 2019; Terblanche, 2019; Roggeri et al, 2021; Gan et al 2023), these studies have focused on quantitative data within their studies. However, the feasibility of using digitalisation and methods towards carbon net-zero design lies in its simplicity of use and effectiveness in verifying and quantifying its impacts (Llatas et al, 2019). With the transition from traditional construction to modularised and off-site construction, it is important that net-zero design and practice can be achieved within modular and off-site construction, especially as they consist of SMEs. This paper, therefore, seeks to add to the efforts of existing studies by providing qualitative data regarding the adoption of digitalisation and net-zero design in off-site.

METHOD

This study employs a qualitative methodology utilising Action Research (AR) which seeks to resolve practical problems. AR integrates research and action and involves collaborative participation from the case study participants to enhance the credibility and authenticity of the results (Argyris & Schön, 1991; Erro-Garcés & Alfaro-Tanco, 2020). For this paper, a literature review was first conducted to understand the efforts made so far regarding net-zero design and identify barriers limiting its practical adoption within off-site companies. The research also involved an in-depth understanding of a specific off-site construction company's operations, and the identification of barriers towards digitalisation and Net-zero in design, and the proposition of strategies for improvement. Data collection tools employed include process mapping, interviews with the operations manager, and observations of the company’s processes. Through the analysis of the design, off-site manufacture and on-site installation processes within the company, patterns were identified. Table 1 demonstrates the literature search applied in this study. It also highlights a lack of studies considering net-zero within off-site construction.

The selected case study – Company A - is an SME off-site volumetric construction company located in the North of the UK. The company specialises in the production of modular units, particularly in the healthcare sector, such as wards, theatres, endoscopy facilities, training facilities, etc. They also provide temporary buildings for site accommodations. These typically have a service life of less than two years and are either returned to the factory upon project completion or rented out to the next client. The company has a good client base as off-site construction is advantageous in the healthcare sector, because it causes the least disruption to the existing hospital environment and the construction is partially completed off-site, thereby reducing the total on-site construction time. The company was selected as there is an ongoing Knowledge Transfer Partnership project being developed between the company and the research team, funded by Innovate UK. The first stage of the project involved getting acquainted with the company and understanding their strategic objectives, key processes, products, and clients. It also involved getting an understanding of the volumetric modules’ workflow from design through to off-site production and on-site installation, including transport. This also involved understanding the typical design and construction of modular units off-site in the factory.

Table 1: Literature Search strategy (Data from UOH online library repository)

					No. of results	Scholarly and Peer reviewed	Engineering/ Architecture
Modular construction	AND	BIM			854	322	229
Off-site construction	AND	BIM			593	145	115
Modular construction	AND	Net-zero			161	58	42
Off-site construction	AND	Net-zero			66	29	21
Construction	AND	BIM	AND	Net-zero	123	56	41
Modular construction	AND	BIM	AND	Net-zero	2	2	2
Off-site construction	AND	BIM	AND	Net-zero	1	1	1

RESULTS

PROCESS MAPPING

This section summarises the processes from planning and design to handover of the project to the clients (see Figure 2). The company’s projects are typically obtained via two routes. In the first route, they receive design briefs directly from clients for the full design of off-site structures. Here, they are the main contractors and provide all the drawings and details required for the project. In the second route, they receive the drawings from bigger construction firms and here they are sub-contractors to deliver modular buildings. RIBA Stage 3 or 4 architectural drawings are provided to Company A, and they create detailed modular designs to fit closely with the architectural drawings. They also have sub-contractors for structural, mechanical, electrical, and other required designs. Once all is agreed by the client, detailed drawings are prepared for the factory production of the modules off-site and the final installation on-site.

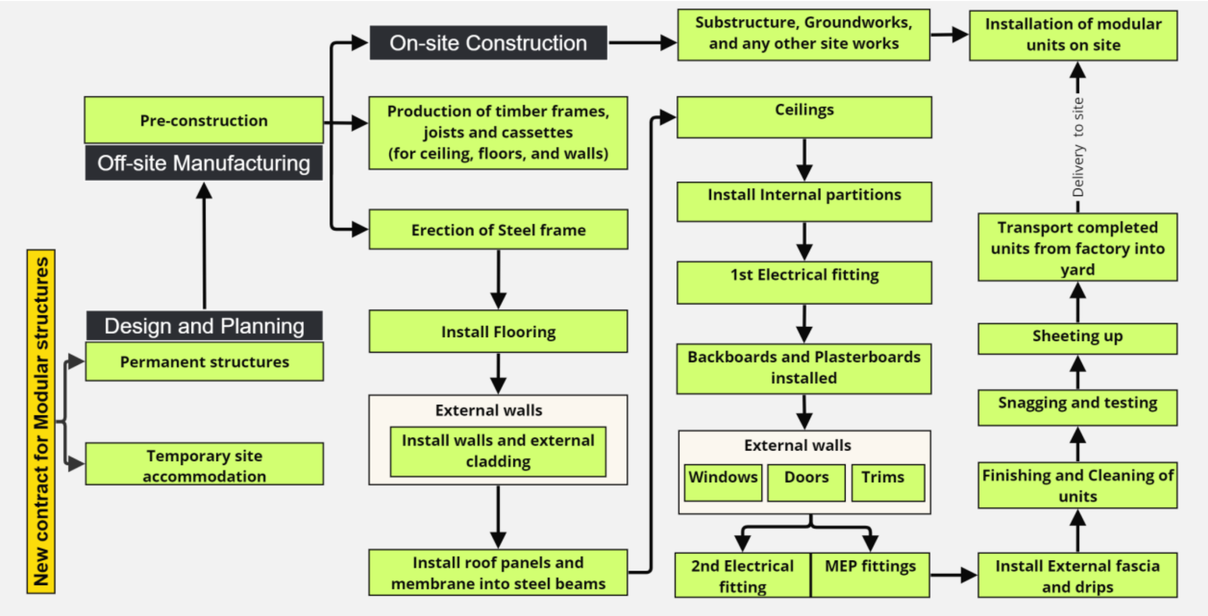

Figure 2: Summary of Production workflow at Company A

Through the production of the process map using flowcharts, the authors were able to identify areas for further improvement within the company.

KEY ISSUES IN DIGITALISATION AND NET-ZERO AT THE COMPANY

Current application of BIM

The use of BIM at Company A is currently limited to the big projects where it is mandated by clients or large construction companies. Although the company has architects sub-contracted to assist with BIM, they usually rely on 2D drawings and only started creating 3D models in-house using Autodesk Revit recently. It is worth noting that the company has not adopted all features of BIM such as 4D or 5D BIM. Autodesk Revit was initially introduced to enable them to view 3D models from the architects or incorporate modular design layout before sending off to steel fabricators for structural analysis.

Additionally, the team's design capabilities regarding BIM are still being developed, with only one design staff having the skillset to generate 3D models. Moreover, most of the factory and installation team still work off 2D paper drawings, which sometimes create issues with changes to drawings not being reflected, thus affecting the production process. In addition, the company produces material quantities and schedules for projects manually, especially for timber. Similarly, where clash detection is needed, this is currently done using 2D drawings. This has caused problems on-site, where the company needs to reconfigure designs to address clashes that were only identified during installation.

Current state of Net-Zero

In terms of the company's operations, one challenge is the lack of readily available data to quantify corporate carbon emissions, such as waste quantities. The waste generated from off-site manufacturing processes is not clearly quantified, except for paper waste. Additionally, data on the end-use of waste is not easily accessible from local waste management contractors. Moreover, manual material take-offs for materials like timber lead to high waste production, and sawdust is not quantified and often mixed with other dust waste from materials like plasterboard and plastic.

Despite these issues, the company has made significant strides in reducing their carbon footprint. For instance, they have included a biomass wood burner in their factory to aid with heating, and timber off-cuts are used as biomass fuel for the wood burner while the rest are sold.

They have also obtained electric vehicles for company use and converted most of their factory lights to dimmable LED lights.

Regarding net-zero building design, there is a lack of information regarding the embodied carbon of building materials used for the module envelope design. Life cycle assessments are not yet conducted for projects, and embodied carbon of materials is not considered during procurement. However, the company ensures that the timber they purchase is certified by either the Forest Stewardship Council UK (FSC) or Programme for the Endorsement of Forest Certification (PEFC) to ensure environmental sustainability. The main considerations for material selection are fire performance, thermal transmittance co-efficient (u-values), and cost.

To improve operational energy and carbon emissions, the company conducts BREEAM assessments and/or obtains Energy Performance Certificates (EPCs) for their big projects. Building energy modelling and analysis are currently outsourced and typically conducted after the technical design has been completed. Although Simplified Building Energy Modelling (SBEM) is conducted for many projects, dynamic thermal modelling to carry out full building performance analysis is done when requested by clients or when complex HVAC systems are used. To achieve carbon net-zero in all future projects, it is recommended that the whole life carbon analysis is conducted from the design stage through to final construction.

BARRIERS TO BIM AND NET-ZERO AT THE COMPANY

Regarding digitalisation, one of the barriers identified is that the construction process is very fast-paced, which stops the company using BIM more widely, due to the initial lack of productivity, which is common during the initial stages of BIM implementation. Similarly, many of the company's smaller jobs are still done in 2D as the clients do not require 3D models.

Another limitation is that many of their sub-contractors work in 2D, so it is not possible to do, for instance, automated clash detections. There are also interoperability issues with diverse file types used by different sub-contractors or the client and lack of coordination using BIM (except for big projects where BIM is mandated). Another limitation is the cost of training and software required, such as licenses for Autodesk AEC collection. The cost of training and software required to use advanced tools like energy modelling or whole-life carbon analysis is another current limitation.

PROPOSED BIM AND LEAN STRATEGIES TOWARDS NET-ZERO

Off-site construction aims to reduce project costs through standardisation, unification, and typification (Generalova et al, 2016). However, considering the net-zero targets, it is imperative to consider the whole life carbon impact of materials used. The implementation of Lean and digital strategies will facilitate better value generation and profitability through improved productivity, reduced waste, and the development of carbon efficient products. Lean principles are aligned with sustainability goals as they offer positive economic, environmental, and social impacts to a project. For instance, waste elimination and process streamlining enable efficient project completion and cost reductions, improve schedule adherence, improve predictability, and minimise uncertainties and delays. Additionally, projects can benefit from energy efficiency, use of sustainable materials, and safety on site for all workers. The identified areas for improvement were developed with the company's team and are summarised as follows:

Building Information Modelling (BIM)

The use of BIM will improve integration between planning, design and construction. This can lead to shorter design processes and better outputs, which meet industry targets. Additionally, increasing in-house design capabilities will help in reducing reliance on third parties. The design process will be better aligned with off-site processes, enabling more standardised physical production at the factory. According to Zhang et al (2016), data from the BIM model could provide relevant information to enable an integrated design, manufacture, and construction and in-use/maintenance process. It could also support the manufacturing process from procurement of materials to the end transport and installation on construction site. Errors can be identified during design rather than production through the implementation of BIM.

According to Gan et al (2023), building energy modelling allows the advanced calculation and analysis of building performance considering the location and geometry of the building, its construction and materiality, thermal zones, occupancy schedule, equipment, HVAC systems etc. Developing a digital model and simulating virtual construction environment will allow for building performance modelling and whole life carbon assessment during the design stage to final construction, aiding the evaluation of project carbon emissions. Furthermore, BIM adoption will make it possible to optimise the planning of works in the construction phase.

Carbon Footprint

In addition to the project carbon emissions, the authors further recommend strategies to improve the corporate carbon footprint in terms of business operations. This involves developing a carbon reduction plan and striving to achieve the carbon reduction targets, building on existing design and construction experience and utilising state-of-the-art and knowledge to refine construction methods. The corporate carbon emissions resulting from the company's operations and assets will also be calculated and avenues for further improvement will be highlighted. This involves calculating the annual scopes 1, 2 and 3 carbon emissions using tools and guidance set out by the UK government (2021) and the Greenhouse Gas Protocol (2022). Scope 1 emissions are incurred directly by the company, Scope 2 emissions are indirectly incurred by the business and Scope 3 emissions are indirectly incurred emissions from upstream and downstream activities within their value chain.

Material and Resources

There is also a need for the company to evaluate its resources and improve procurement processes for materials. This will involve an assessment of procured materials and wasted materials to look at cost savings and opportunities for reuse where possible. Also, considering new materials and incorporation of low carbon materials that have better capabilities for reuse, recycle or upcycle at the end of their life while still meeting regulations for fire performance, thermal performance, and considering cost. One common use of BIM is to obtain bill of material quantities (Soust-Verdaguer et al, 2017) which will be useful to Company A and save them from deriving this through manual calculations.

Building product information can assist in accurate measurements of embodied and whole life carbon emissions and can improve accuracy around carbon reporting. There is a need to consider third-party certification for construction products to show the reliability of the data; these could include responsible sourcing certification, Environmental Product Declaration (EPDs) and so on. EPDs are internationally recognised and communicate the environmental impact of a product. For construction products, life cycle assessment (LCA) is carried out to estimate the environmental impact at different stages of the lifecycle using EPDs, and there is an increasing demand for construction products to have EPDs.

Smart Building Technology

The use of smart building technologies, such as building management systems, can improve efficiency and monitor building performance, enabling also existing performance data to feed forward the improvement of new projects. The evaluation of energy performance is based on the estimated or measured amount of energy consumed annually for providing heating and cooling for comfort, as well as for meeting the domestic hot water requirements (Cole and Fedoruk 2014). According to Aelenei et al (2023), a gap exists between the energy performance of buildings as-designed and as-built which can be ascribed to various factors. Therefore, better monitoring of buildings using smart technologies can help fill this gap and improve the quality of simulations (Sturgis, 2017).

According to Zhang et al (2016), there is a need to further improve the performance of the industry, to better incorporate sustainability into building design and construction practises. Although this study has provided insights using one off-site construction company as case study, the outcome of this study could be adopted within similar off-site SMEs construction companies. The incorporation of these strategies throughout the project phases will enable them to evaluate the effect of their designs and building materials on a building's lifecycle carbon performance and follow opportunities for further optimisation.

CONCLUSIONS

This paper presents the initial steps towards achieving net-zero within an off-site construction company and the possibilities of adopting BIM and Lean principles to improve digitalisation, calculate whole-life carbon emissions and improve overall building performance. Future work will involve the implementation of these strategies and quantify their effectiveness. This will involve whole life carbon assessment of sample projects within the company. Additionally, the authors will implement a BIM execution plan within projects; and continuous and up-to-date carbon footprint calculation to develop a carbon reduction plan with achievable targets. A materials database for typical materials will be developed by the team considering not just fire performance and thermal performance but also embodied carbon and end of life of materials.

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ROLE OF COLLABORATION IN PRODUCTION PLANNING AND CONTROL IN THE CONTEXT OF MODULAR CONSTRUCTION

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ABSTRACT

Modular construction projects have complexity attributes that differ from conventional projects. To address this complexity, collaboration within production units and between different units is essential, as it contributes to resilient performance. The aim of the investigation is to understand the role of collaboration in the implementation of production planning and control (PP&C) in modular construction projects, considering complexity attributes. A case study was conducted at a Brazilian modular construction company. The unit of analysis was the PP&C system developed in this company for managing construction site installations, strongly based on the Last Planner System. As a result, a list of collaborative processes for planning and controlling modular construction projects was presented. Each process was thoroughly evaluated across six categories of collaboration factors: behavior, communication, team, management, technology, and contractual aspects. Collaborative processes related to meetings addressed the highest number of collaboration categories, suggesting that these are the most collaborative processes. In a high-complexity project, as it is typical of this modular construction company, addressing the highest number of collaboration factors contributes to alignment between sectors and achieving project objectives.

KEYWORDS

Lean construction, Production Planning and Control, Modular Construction, Collaboration.

INTRODUCTION

Modularity can be defined as the decomposition of a product into subsets and components, which facilitates standardization and increases the variety of products (Gershenson; Prasad; Zhang, 2003). Furthermore, it is considered that a modular product is composed of modules consisting of independent units with their own functionalities and standardized interfaces (Miller; Elgard, 1998; Gershenson; Prasad; Zhang, 2003). These units, according to Gibb (1999), can have a high degree of finishings installed in external environments (off-site), reducing the amount of activities carried out on-site, or they can also be limited to structural components, with the remaining activities completed on-site.

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A new approach for industrialized construction has emerges from the application of the concept of modularity, named Modular integrated Construction (MiC). According to Pan and Hon (2018), MiC is a disruptive and innovative approach that transforms traditional fragmented construction with site-based installations into a value-oriented process with integrated manufacturing and assembly processes, providing greater quality, productivity, safety, and sustainability, when compared to traditional construction.

Due to the benefits provided by this new approach, such as increased speed, cost reduction, improved quality of construction, and reduced environmental impacts, it has grown substantially in many parts of the world, by replacing traditional construction methods (Molavi; Barral, 2016). Unlike traditional on-site construction, MiC usually involves a broad supply chain, with a complex network of stakeholders involved, in all construction stages, such as planning, design, legal approval, site preparation, modular manufacturing, transportation, storage, and on-site installation (Wuni; Shen, 2020). In this context, in order to get the full advantages of industrialization, proper planning for modular construction is necessary, especially in ensuring that manufacturing, transportation, storage, and installation occur in a timely and integrated form (Molavi; Barral, 2016).

The application of the modularity concept, from one hand, reduce the complexity of on- site construction operations, but, on the other hand, adds complexity by the need to coordinate several production units, e.g. design teams, manufacturing plants, construction sites. According to Saurin and Gonzalez (2013), complexity in socio-technical systems involves four attributes: (i) a large number of dynamic interactions among elements; (ii) a wide diversity of elements; (iii) unforeseen variability; and (iv) resilience to deal with an uncertain and dynamic environment. Considering these attributes, it can be stated that modular construction fits into a complex socio-technical system mainly due to the large number of manufacturing, transportation, and intensive assembly procedures, as well as the high degree of uncertainty and variability among processes. Additionally, other characteristics such as project and production fragmentation, coordination of activities in the factory and on-site, delivery process constraints due to large and heavy assembly and installation equipment, coordination to ensure that manufacturing, transportation, and assembly occur in the desired sequence and time, the need for highly skilled workers and specific construction techniques, also increase the system's complexity (Jensen; Bekdik; Thuesen, 2014; Molavi; Barral, 2016).

The complexity in modular construction systems is the combination of the intrinsic complexity of the modules and the composition of the system as a whole, which affects decision-making (Alkan; Bullock; Galvin, 2021). In this context, the management of these systems must be resilient, meaning that the managerial team should respond when undesirable events occur, monitor and anticipate developments, threats, and future opportunities, as well as learn from past experiences (HOLLNAGEL, 2018). Since it is not possible to completely eliminate variability, the production planning and control play a key role in coping with complexity in a modular construction system, and can make major contributions to resilient performance.

The Last Planner System (LPS) (Ballard, 2000) has a set of practices that have a positive impact on resilient performance, such as hierarchical planning and control, identification and removal of constraints, collaborative meetings, and a combination of delay and anticipation indicators (HAMERSKI Et Al., 2023). In fact, Pourrahimian et al. (2023) emphasize that a vital component for the success of LPS implementation is collaboration among all parties involved. Additionally, LPS promotes collaboration by bringing problems to the surface timely and enabling conversations that contribute to problem solving (Skinnarland, 2012). Those practices can also contribute to develop resilience potentials.

This research work is based on the premise that collaboration within production units and among different units is essential in Production Planning and Control (PP&C) of modular construction projects as it contributes to resilient performance.

Previous studies have explored several aspects related to production management and the implementation of the Lean philosophy in modular construction. Innella et al. (2019) discuss the implementation of lean techniques in the modular construction industry, covering all production stages, based on a systematic review. Olawumi et al. (2021) analysed digital tools and technologies in modular construction and how these impact production planning and control processes. Additionally, Khodabocus and Seyis (2024) investigated risk management in modular construction projects, providing insights into effective risk management approaches, which are strongly related to production planning and control.

Lerche et al. (2020) investigated the application of LPS in modular construction in the context of offshore wind farms. That study pointed out some benefits of applying the LPS in the specific context of modular construction, emphasizing collaboration as an essential element for effective production management. However, those authors have not deeply analysed the role of collaboration within this scenario.

The research question that guided this investigation was: How to improve the role of collaboration in planning and controlling modular construction projects? Therefore, the aim of this research work is to understand the role of collaboration in the implementation of production planning and control in modular construction projects, considering complexity attributes that differ those projects from the conventional ones. The collaboration considered in this study is related to the coordination among stakeholders involved in PP&C, both within each production unit, or between them. The expected practical contribution of this investigation is to devise a framework for assessing the degree of collaboration in the implementation of production planning and control systems, while the theoretical contribution is to understand the nature of collaborative processes, considering the context of modular construction.

COLLABORATION FACTORS

Collaboration is a process that requires the involvement and integration of different stakeholders, promoting a sense of involvement and ownership. In construction projects to collaboration plays a key role in improving reliability of project planning, leading to improvements in project performance (Elsayegh and El-adaway 2021a).

Elsayegh and El-Adaway (2021a) identified and defined collaboration factors impacting construction planning, based on an analysis of literature on collaborative planning in the construction industry over the past 30 years. In a subsequent study, Elsayegh and El-Adaway (2021b) divided the 50 proposed factors into six categories: behaviors, communication, team, management, technology, and contractual aspects. Table 1 presents the proposed collaboration categories by those authors and their definitions adapted according to the respective factors.

In this investigation, collaborative practices have been analyzed from the perspective of those six categories proposed in Elsayegh and El-Adaway's (2021a) initial study. The choice of this research as a reference for the concept of collaboration is justified as it is very recent study, based on an extensive literature review on construction planning and control.

Table 1 - Categories affecting collaboration in planning (adapted from Elsayegh and El-Adaway, 2021).

Categories	Description
Behaviors	Adaptive or resistant reactions to changes, dedicated commitment to the collaborative process, influence and dependency among parties, presence of leadership, building mutual trust and respect, and continuous effort to improve the collaborative process.
Communication	Formality and effectiveness of communication, frequency and type of meetings, sharing of lessons learned, early involvement of key project participants, timely reporting and updates, constructability feedback, and stakeholder contribution to schedule development.
Team	Relationship among project parties, skills, experience, and knowledge of those involved, vision and goal alignment, team members' ability to get along, engagement and active participation, motivation and incentives, guidance and workshops, training, and promotion of creativity.
Management	Stakeholder and management involvement, centralized workplace, management and sharing of risks/uncertainties, resource sharing, continuous focus on the customer, standardization of planning practices, joint problem-solving and decision-making, use of indicators, and identification and removal of constraints.
Technology	Efficient sharing of information and technology, BIM modeling for project understanding and implementation, and the use of tools and techniques, including visual signals, elimination of visual obstacles, and procedures to maintain a clean and organized workplace.
Contractual aspects	Definition and flexibility of scope/work packages, impact of project characteristics (type, size, and complexity), and effective conflict resolution.

RESEARCH METHOD

RESEARCH DESIGN

Case study was the research strategy adopted in this investigation, as it enables exploration of social-technical phenomena in real-world settings (Flyvbjerg, 2011). This study was carried out in a company involved in the delivery of modular construction projects, named Company A. The unit of analysis was the PP&C system developed in this company for managing site installation, which was strongly based on the Last Planner system. The research was divided into three phases: (i) understanding the problem and case study selection; (ii) collecting data on PP&C implementation; and (iii) cross analysis between PP&C practices and collaboration.

In the first stage, visits to the company and participant observation in planning meetings were conducted with the aim of understanding the context and complexity attributes of modular construction projects. At this stage, two projects (A and B) were chosen as case studies. The second stage consisted of collecting data on the development and implementation of a PP&C system for the selected projects. Initially, a production system design was carried out, followed by the development and implementation of the three planning and control levels, similar to the Last Planner System (LPS). Location-based planning was used at the long term planning level.

In stages 1 and 2, the sources of evidence used were: (i) participant observations of 58 medium-term meetings and 45 short-term meetings; (ii) direct observations at the construction sites, totalling 4 visits to the site of each project; (iii) semi-structured interviews with the project A and B engineer, planning coordinator, design manager, and manufacturing manager; (iv) workshops, comprising 2 Lean concepts training sessions and 5 Plan discussion workshops; and (v) document analysis such as Line of balance; Medium-term plans; and Short-term plans.

In phase 3, a list of PP&C practices was produced, including traditional LPS practices and also some additional ones that emerged along the implementation process, some of them necessary to deal with the complexity that exists in modular construction projects. Some of these practices were associated to different hierarchical levels, although some of them were related the PP&C as a whole. Each practice was then grouped into collaborative processes, such as meetings, technological tools for visualization and information exchange, as well as problem cause analysis processes. This organization of practices occurred because some of them do not directly involve collaboration but are integral parts of processes that promote collaboration. Thus, collaborative processes were analyzed in terms of categories of collaboration factors (Table 1), proposed by Elsayegh and El-Adaway (2021b). These categories were used to understand the role of collaboration in each process, enabling the evaluation of each based on the nature of collaboration. Data analysis was based on the subjective assessment of the degree to which the processes meet the collaboration factors of each category. Each collaborative process was assigned a weight corresponding to the degree to which it meets the factors, according to the following criteria:

- Weight 1.0: a process widely used in the company and strongly meets the category.
- Weight 0.5: a process is partially used in the company and partially meets the category.

For example, the process of analyzing the causes of non-compliance with work packages is a practice that the company implements; however, they analyze the causes superficially, without providing feedback or discussing action plan in meetings. Therefore, the process is carried out partially, involving only collaboration in identifying the cause, and not in the entire cycle of continuous improvement.

- Weight 0: a process that has no relation to any factor of the category. In this case, there is no evidence in the process that it is related to the analyzed category.

The result of the analysis stage consists of a table where the rows represent the PP&C practices and their respective collaborative processes, and the columns represent the categories of collaboration factors. By summing the weights assigned to each process, it was possible to analyze the practices with the highest degree of collaboration, as they address more categories, and also the categories most addressed by the implemented processes. With this tool, it was possible to analyze the relationship between the collaborative processes of PP&C and collaboration in modular construction projects, identifying opportunities for improvement. The authors assigned those weights based on their perceptions, using the data observed during the study to substantiate their decisions. The method proposed in this study can potentially be scaled to suit various projects, companies, and development stages within the modular construction industry. In phase 3, it is possible to select more practices according to the specific context of each project or company and group them in the same way in collaborative processes such as meetings, technological tools, information exchange and problem cause analysis. Those processes can then be evaluated according to categories of collaboration factors, previously established in the literature. The selection and evaluation of collaborative processes within different scenarios allows the method to be applicable to other contexts.

DESCRIPTION OF THE COMPANY AND PROJECTS

Company A has delivered modular construction projects since 2001. It has two main types of products: (i) heavy reinforce concrete modules used for penitentiaries; and (ii) steel chassis modules for other types of buildings, including schools and hospitals. The main reason for choosing this company is the fact that a Lean Production implementation program started in 2022, including all stages of project delivery: design, manufacturing, logistics and site installation. The two projects chosen for this investigation consisted of the construction of penitentiaries. The heavy modules used in this type of project is a patented solution, consisting of volumetric units arranged laterally to a central corridor, and above this, circulation through upper walkways for exclusive use by staff. The system involves two central elements: (i) cell-type module, and (ii) walkway-type module.

Project A involved the construction of a new prison complex (1650 vacancies), including prison areas (1884 vacancies), collective living spaces for inmates, administrative and technical areas, and infrastructure, summing up an area of 15,000 m². Different types of prefabricated components were used: 3 light modules, 240 heavy concrete modules, 120 walkway-type modules, and 566 W panels. The project duration was 12 months, starting in July 2022.

Project B consisted of a demolition of an existing penitentiary in two stages, and the construction of new cells, collective living spaces, administrative and technical areas, summing up 23,250 m². The construction stage started in July 2022. The main prefabricated elements were: 366 light modules, 220 heavy concrete modules, 110 walkway-type modules, and 798 W panels. During the first stage of the project B, part of the prison was in operation. Both projects had to be built in parallel, as the remaining prisoners from project B had to be transferred to Project A after it was concluded, This added some additional elements of complexity, the interdependence between the two projects, and the constraints for access of the construction site of Project B, due to the penitentiary in operation.

RESULTS

CHARACTERISTICS OF MODULAR CONSTRUCTION PROJECTS

Several complexity attributes of production systems in the company involved in the investigation:

(i) Large number of dynamic interactions between elements: This is mostly related to the interdependence between production units. The company has two manufacturing plants serving several construction projects. Individuals involved in factories, logistics operations, construction sites, design, and supplies are constantly interacting with each other. Additionally, these elements are strongly interconnected, meaning that the action of one sector directly impacts another due to the high degree of interdependence. Another important factor is that the company carries out design, fabrication, and assembly of various projects simultaneously, which become interdependent due to resources shared between them.

(ii) Wide diversity of elements: There were different hierarchical levels and disciplines involved, such as factory coordinators, project coordinators, architects, structural engineers, construction coordinators, engineers, workers, planning analysts, suppliers, logistics coordinators, etc.

(ii) Unforeseen variability: There was much uncertainty related to site conditions, fluctuations in demand, clients' requirements, and local regulations. The combination of variability and interdependences between production units tens to propagate variability.

(iv) Resilience: It refers to the system's ability to adjust its performance in the face of expected and unexpected conditions (Saurin; Gonzalez, 2013). This is a necessary attribute to be developed in the management system in order to cope with the existing complexity.

PP&C PRACTICES IMPLEMENTED

These are the main elements of the PP&C system: (i) Production System Design (PSD): it starts with the identification of requirements for the execution of this specific type of project (penitentiaries), which is based on the experience obtained by the company in previous projects, and also on the specific requirements of the projects A and B. Its scope involves the definition of a location system, layout, overall installation sequence, workflows, logistics flows, necessary capacity of the workforce and equipment, and 4D BIM simulation. Representatives from different sectors were involved in PSD: design, factory, construction site, material supply, logistics, planning, and contract management.

(ii) Long-term Planning: Based on the PSP, a location-based plan (line of balance) for the whole project, in which the main project milestones were defined. The final definition of the long-term plan was also developed in collaboration with different company sectors and made available online to all of them. Based on that plan a set of metrics based on the status of each location was defined, for controlling cycle time, work-in-progress, project progress, and batch completeness. The Production Status Matrix, which allows check-in and check-out in each location to be informed by each crew, plays a key role in the production of those metrics. This tool was only partially implemented, due to the lack of automated and user-friendly data collection tool.

(iii) Look-ahead Planning: Hybrid weekly meetings were carried out, considering a 6-week window, to allow the participation of representatives from different areas of the company. Both individuals in charge of identifying and removing constraints were involved. Those constraints were not limited to materials and labor, but also involved logistical and safety aspects. Responsibilities for eliminating these constraints were allocated among team members, each with a deadline for resolution. Due to the lack of effectiveness in removing constraints, an analysis of the causes for the non-removal of constraints was implemented. In this process, it was necessary to justify why constraints were not removed, and the group exchanged ideas on how to solve specific problems.

(iv) Short Term Planning*:* Weekly meetings were carried out on-site, in which work packages were assigned to each crew, specifying task content and location. Those meetings typically lasted for an hour, involving the site manager, engineering assistant, and crew leaders. An online spreadsheet was used to store and make available information to everyone. Site assembly activities were planned for a two-week horizon due to the need of the manufacturing plants planning process. Traditional LPS metrics were used, such as the Percent Plan Complete (PPC), and the causes for non-compliance.

(v) General PP&C practices*:* A set of additional practices related to the planning and control process as a whole was also implemented: digital dashboards with long, medium, and short-term metrics, weekly meetings for the joint analysis of medium and short-term indicators (involving top managers), and planning different types of slack at different planning levels. Additionally, there was a weekly planning alignment meeting, in which each sector (design, manufacturing and site installation) presented the existing plans, in order to align demands and identify the possibility of adding new projects or specific activities. Regarding Visual Management, besides the dashboards, and location-based plans, several visual devices were producing, including boards for displaying plans, constraints and metrics.

After multiple planning cycles, the need for load plans emerged, mainly to formalize the exchange of information between the sectors. Due to the existing uncertainty in the projects, issues on site installation were communicated to the manufacturing plant in order to confirm the capacity to meet project demands. This plan formalizes project needs, factory production, and logistics capacity, thus reducing the information conflict generated by informal communication, often conducted via WhatsApp. This tool was shared with the sectors involved, with the aim of increasing transparency and aligning everyone's demands.

ANALYSIS OF COLLABORATIVE PROCESS

In Table 2, the results of the analysis regarding the relationship of collaborative processes with the factors of collaboration categories are presented. Results in green correspond to processes that strongly adhere to the category, those in yellow represent processes that partially adhere, and those in white indicate processes in which none of the factors were observed.

Table 2 - Relationship between Collaborative Process and Collaboration Factor Categories

	PP&C practices	Collaborative Process	Collaboration categories: Behav	Commun	Team	Manag	Tech	Cont.	TOTAL
Production System Design	Identification of project requirements Definition of sequencing and batches Involvement of all sectors pre-project	Meetings at the beginning of the project	1	1	1	1	0	1	5
	4D BIM simulation	Technological tools	0	0	0	0	1	0	1
Long-term plan	Location-based plan Development of a visual long-term plan Indicators for assessing time deviation	Meeting at the beginning of the project, with different company sectors	1	1	1	1	0	1	5
	Production Status Matrix	Technological tools	0,5	0	0	0,5	0,5	0	1,5
Look-ahead Planning	Standardization (routine) Identification of constraints. Participatory decision-making	Meetings to identifying and removing constraints	1	1	1	1	0	0,5	4,5
	Non-removal of constraint	Analysis of the causes	1	0,5	0	0,5	0	0,5	2,5
	Online spreadsheet of constraints	Technological tools	0	0	0	0	1	0	1
Short Term planning	Standardization (routine) Definition of work packages Backlog of work packages Participation in decision-making. PPC Indicators	Meetings, involving the site manager, engineering assistant, and crew leaders.	1	1	1	1	0	0,5	5,5
	Implementation of corrective actions	Analysis of the causes of non-compliance	0,5	0,5	0	0,5	0	0,5	2
	Online spreadsheet shared data widely	Technological tools	0	0	0	0	1	0	1

Table 2 (continued) - Relationship between Collaborative Process and Collaboration Factor Categories

	PP&C practices	Collaborative Process	Collaboration categories: Behav	Commun	Team	Manag	Tech	Cont	TOTAL
General PP&C practices	Weekly alignment meetings of PP&Cs	Meetings in which each sector presented the existing plans	1	1	1	1	0	1	5
	Analysis of indicators with top management	Meetings for joint analysis of metrics.	1	1	1	1	0	1	5
	Set of interconnected dashboards for control	Technological tools	0	0	0	1	1	0	2
	Introduction of different types of slack	Information sharing between sectors and levels	0	0	0	0	0	1	1
	Load planning	Tool that allows information exchange	0	1	0	1	1	0	3
		TOTAL	8	9	6	9,5	5,5	7	

Collaborative processes related to meetings addressed the highest number of collaboration categories. This is because these practices are characterized by being formalized processes (management category) and involve several participants in the PP&C process. Members are expected to commit to plans (behaviour category), exchange information (communication category), align their objectives and goals, sharing risks and uncertainties (team category), and define procedures for conflict resolution (contractual aspects category). In a highly complex project, as it is typical of this modular construction system, addressing the highest number of collaboration factors contributes to improve to an effective coordination between sectors in order to achieve project objectives.

Processes linked to technological tools for visualization, information exchange, and shared understanding mostly addressed the technology category. The company invested in visual devices in planning to support project understanding and visualization of plans and metrics. These tools included planning spreadsheets, performance dashboards, and project activity warnings. All tools were made available online, and different stakeholders had access through the company server. Additionally, interactive screens and video calls were used to support planning routines. Therefore, the transfer and sharing of updated information among project stakeholders through involved different means, such as reports, spreadsheets, dashboards, and messages, with the aim of making everybody aware of the project process.

Another important factor concerns the complexity of the project. There was a formal process of using different types of slack in order to make project delivery more reliable, such as: (i) definition of alternative assembly flows (Project B), due to potential layout restrictions; (ii) possibility of producing some precast elements on-site, (iii) inventory of some standard small-size components at the manufacturing plants (e.g. furniture); (iv) spare formwork elements, among others. Slack planning was the result of information sharing between sectors and levels, either in formal meetings or informally, including brainstorm events to solve emerging situations, especially in the construction site. The most frequently used collaboration factor category in the collaborative processes was Management, justified by the operational nature of the practices included in this category, including participation in meetings, use of metrics that contributes to everyone's understanding. The least addressed category was related to Team, as these factors have a strong social character, such as team and stakeholders' skills, experiences, motivation, creativity, involvement and empathy. These competencies are related to each individual and the relationship among team members. These criteria are essential for collaboration, although not directly identified in processes. They must be present in the company and are not easy to develop in the short term. Therefore, a key topic for future research is to develop approaches for improving these competencies among stakeholders.

Two collaboration practices have been identified as only partially ineffective, and demand further attention: (i) the analysis of non-compliance problems with work packages, and (ii) the control of production status. In the former, although teams formally identified the causes of non-completion of work-packages, this process was done very superficially, and there was not enough effort to plan how to deal with the most frequent or severe problems. Regarding the latter, the company faced problems in implementing the production status matrix, such as poor definition of the location system, late updating of the matrix, and unreliable information. These two practices, besides promoting continuous improvement, also help understanding problems and monitoring the work-in-progress in other sectors of the company. These are necessary practices for collaboration and especially for integration among different sectors of the company.

CONCLUSIONS

This research presented a list of collaborative processes for planning and controlling modular construction projects. Each process was thoroughly evaluated across six categories of collaboration factors: behavior, communication, team, management, technology, and contractual aspects. It must be pointed out that some processes stand out for strongly promoting collaboration across multiple categories simultaneously, such as the use of PSP meetings, project kickoff meetings, look-ahead and short-term meetings, weekly PP&Cs alignment meetings among different sectors, and meetings for a joint analysis of metrics. Therefore, these processes need to be maintained and improved to promote collaboration.

However, evidence showed that although most practices address some collaboration factors, there are still areas that need to be improved to ensure more effective collaboration among stakeholders, especially the Team category. In this category, processes emphasizing motivation, engagement, and increasing team's sense of belonging need to be implemented.

This study is part of an ongoing doctoral thesis that will continue to delve into the analysis of collaboration factors in PP&C practices. One of the next steps in this investigation is to do and in-depth analysis of the 50 collaboration factors proposed by Elsayegh and El-Adaway (2021a), and understand the interactions between the categories. Regarding limitations of this investigation, it must be pointed out that this article has focused on formal collaboration practices implemented in a specific company. Further work is necessary to understand the role of informal practices that also contribute to foster collaboration. Additionally, the results reported are related to a single modular construction company. This study presents an analysis of collaborative processes in the early stages of implementation of a production planning and control model, based on LPS, and the results are limited to the specific context of that company. Therefore, the proposed recommendations are specific to this context, and cannot be generalized to the entire industry. Future studies must explore the context of other companies, considering other planning practices and collaborative processes.

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A CASE FOR LEAN-BASED GUIDELINES FOR CONSTRUCTION AND DEMOLITION WASTE MINIMIZATION IN ZIMBABWE

Kurauwone Maponga[1] and Fidelis Emuze[2]

ABSTRACT

Construction and Demolition Waste (CDW) significantly costs Zimbabwe, as most waste is directed to landfills, riverbanks, and open spaces. This has made construction practitioners call for efficient strategies such as lean construction (LC). LC could help minimize construction waste in on-site operations. It could reduce land and water pollution and the blockage of watercourses caused by CDW. Minimizing CDW creates cost savings and value for the construction project clients. Although LC has addressed CDW minimization in varying countries, this is not the case in Zimbabwe, where a pressing need for resource efficiency is urgent. Thus, this paper proposes a conceptual framework for evolving LC-based guidelines for minimizing CDW in Zimbabwe. A critical review of relevant literature was conducted to observe how LC tools are utilized to minimize CDW. Given that such a framework could limit the pollution of land and open spaces with CDW, which affects people and the built environment in general, the next phase of the doctoral study would be to test and modify it through mixed methods research empirically.

KEYWORDS

Lean construction, Demolition, Lean, Waste, Pollution, Construction projects, Zimbabwe

INTRODUCTION

According to the Lean Construction Institute (LCI) (2012), Lean Construction (LC) is a manufacturing and production management system that focuses on the elimination of all forms of waste and the creation of value for the client. The focus on LC is on both physical and process waste. The paper concerns physical waste, which is a harmful dilemma because construction and demolition activities are considered the highest waste generators globally (Karaz et al., 2021). The development of lean strategies to minimize CDW is a priority for some countries in the European Union (EU) (Karaz et al., 2021). According to Gálvez-Martos and Istrate (2020), the proper management of CDW is usually associated with high costs due to logistics and the relatively low benefit from its recovery and recycling. The EU has released incentives such as Directive Number 2008 /63/EC to reduce CO2 emissions, encourage recycling, and urge contractors and other professionals in construction to minimize the overuse of materials and the disposal of CDW to open areas and landfill and challenges are being addressed on how to incentivize contractors who comply (Karaz et al., 2021). However, Zimbabwe is lagging in

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CDW minimization techniques; hence, the guidelines provided by this study will act as an essential foundation for embracing lean construction.

According to Coşgun, Arslan, and Salgin (2012: 313), "the huge amount of construction waste streams in different countries has revealed the importance of local actions to manage, recycle and re-use the wastes generated through the lifecycle of buildings." Although the application of LC tools for the minimization of CDW has been investigated by several scholars who highlighted their potential (Gomez et al., 2018; Gutiérrez, 2020; Erazo-Rondinel & Huaman-Orosco, 2021; Orihuela et al., 2019; Erazo et al., 2020; Suarez et al., 2020; Ballard et al., 2009 and Ballard, Kim, Jang and Liu, 2007), in Zimbabwe such study is lacking. The construction sector worldwide faces severe challenges due to vast amounts of waste. Accordingly, the call for lean-based guidelines to minimize CDW cannot be overstated. The adoption of lean-based interventions has been shown to offer several benefits. According to Hamzeh and Albanna (2019: 179), "to reap the benefits of Lean Construction, construction companies should integrate, empower, and enable all personnel involved in the construction process whether on or off-site." Thus, in Peru, adopting lean-based guidelines achieved the following benefits: generating and adding value for the client, increasing productivity, reducing CDW, delivering the project on time, and improving communication (Erazo-Rondinel & Huaman-Orosco, 2021).

Despite the potential of lean-based interventions to minimize CDW, Zimbabwe still lags in embracing CDW minimization techniques. Accordingly, this study sought to develop guidelines to promote the adoption of lean-based interventions to improve construction and demolition waste minimization. The paper is part of a doctoral study that aims to develop guidelines for minimizing CDW in the Zimbabwean construction industry.

STATEMENT OF THE PROBLEM

CDW costs contractors and clients' money in Zimbabwe as most of the waste is directed to landfills, riverbanks, roads, and open spaces. In the country, 76% of the CDW produced is disposed of by open dumping, 7% is disposed of by burning, 10% is disposed of by a combination of open dumping and burning, 1% is disposed of by landfilling, and 5% is disposed of using other methods (Jerie, 2018). Limited or no recycling, reuse, or recovering techniques are employed to manage CDW. Figure 1 shows that CDW is often transported to landfills and dumped on roadsides, open spaces, and riverbanks. This leads to the pollution of watercourses and fertile lands. The lack of CDW minimization causes social, environmental, and economic problems. For instance, African countries are keen to overcome these challenges to meet their development and infrastructure needs for the 21st century. It is not news that Africa faces various problems in the construction industry that marginalize its ability to realize sustainable development goals (SDGs). Magadzire and Maseva (2006) suggest that Section 70(3) of the Environmental Management Act (2007) of Zimbabwe encourages the use of sustainable techniques for CDW management. The major hindrance is that the technology and knowledge needed to employ the techniques are unavailable. The Public Health Act (1996) of Zimbabwe stresses that the producers of waste should manage all forms of waste. The Act prohibits waste production and dumping on lands that the waste producers do not control. Waste producers are expected to transport and manage the waste; however, the Act is silent on the 3Rs: recycling, recovery and reuse, and lean construction techniques.

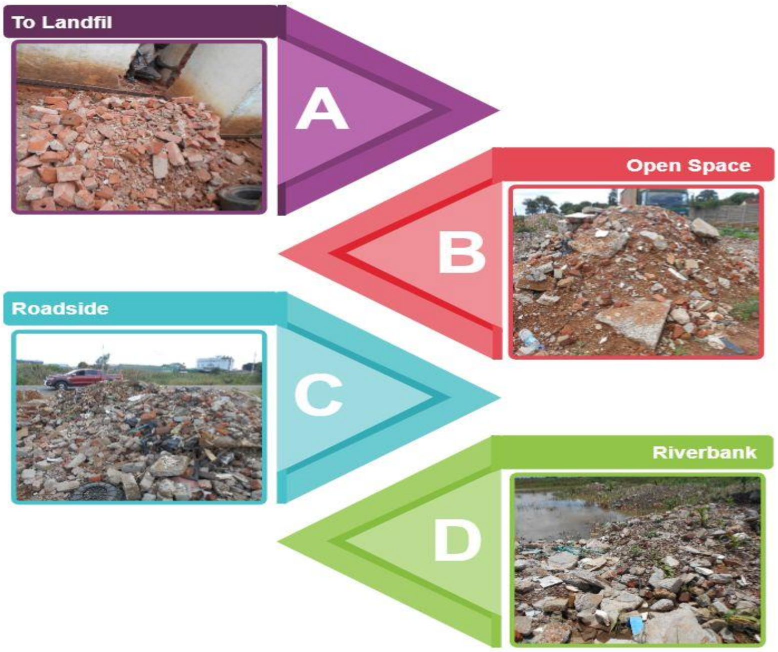

Figure 1: Disposal of construction and demolition wastes in Zimbabwe (Source: 2023 field survey of doctoral researcher)

According to the Environmental Management Act (2007) of Zimbabwe, a permit is supposed to be acquired for CDW disposal, fines are paid for illegal CDW disposal, and companies disposing hazardous waste into any waters or on the environment are made to remove their toxic waste and pay for environmental restoration. The Act also stipulated that a license should be acquired for transporting toxic waste, and construction sites generating CDW must minimize the CDW through treatment, reclamation, and recycling. Although some statutory instruments such as the Harare Waste Management by-law (SI 127 of 1981), Waste Management by-law (SI 477 of 1979) and (SI 185 of 1981) and other policies such as the Sustainable Strategy Policy and the Environmental Impact Policy exist, poor waste management of CDW in Zimbabwe persists because of lack of enforcement, lack of equipment and lack of expertise (Magadzire & Maseva, 2006).

The management of CDW in Zimbabwe can be improved by embracing several changes in design, communication, cost, scope, safety, and quality. Design aspects require changes to include more standardization, modularization, and modeling. The design must be done for CDW minimization to minimize offcuts, reworks, and defects. The design must include recyclable and reusable materials. Cost and scope aspects need to change to include more local and sustainable materials. The storage and transportation of CDW can cause cost aspects. Construction processes need to minimize the use of energy and environmental degradation. Safety and quality changes will help improve health and safety and reduce waste in materials, time, overproduction, delays, and unnecessary inventory. Legal and environmental constraints also come in, as CDW can cause pollution, and the Environmental Management Authority (EMA) can impose lawsuits. Communication and coordination will help minimize the time constraints for sorting and transporting CDW.

Tackling the poor handling and proliferation of CDW is one way to close this gap. The study thus sought responses to the following research questions:

- How will lean tools and techniques enhance CDW minimization practices in Zimbabwe?
- What lean-based guidelines would minimize the negative impacts of CDW in Zimbabwe?

Although exhaustive responses to these questions are beyond the scope of this conceptual paper, an attempt is made to present a framework that could aid the effort. The theoretical background of the framework is presented in the next section of the paper.

LEAN CONSTRUCTION AND CDW MINIMIZATION

According to Forbes and Ahmed (2020), LC is a technique used to design production and construction systems to minimize waste of time, materials, and effort to generate value for the client. Tommelein and Ballard (2016) define LC as applying lean thinking to the design and construction of construction projects. This means that effectively implementing LC tools and techniques will help minimize the materials used and save time. Salem et al. (2006) pointed out that the lean construction principles for the construction industry are transparency, process variability, continuous improvement, and flow variability.

Pedo et al. (2021) say that LC can enhance CDW minimization through early identification of requirements for process standardization and systematic waste analysis and offer accurate information regarding the materials and building systems, which allows stakeholders to decide on design early to provide reduced reworks, design iterations, and product visualization. Lean tools can help minimize CDW generation by allowing stakeholders to make critical decisions early, which helps minimize work variations, and reworks can be a source of CDW. According to Mawed et al. (2020), poor communication leads to project reworks, which generate CDW. Erazo-Rondinel and Huaman-Orosco (2021: 547), say "Even the construction industry in Peru is still working in silos, focusing objectively only on the project stage they oversee; however, client value mapping is still minimal." Employing lean-based CDW minimization techniques can help provide value for the client and reduce the amount of CDW produced on a construction site.

Najafpoor et al. (2014) stated that, in developed countries, 35 to 50% of the waste produced is CDW. Azmy and El-Gohry (2017) posit that one-third of domestic waste in Egypt is CDW. Elshaboury and Marzouk (2020) reported that CDW generated in the United States (US) amounts to 569 million tonnes, in Europe 330 million tonnes; in Germany 324.38 million tonnes; in Lebanon 9.6 million tonnes; and in Egypt 3.65 million tonnes. According to Huang et al. (2018), China produces an estimated CDW of 30-40% of the total waste. Ballard and Howell (2003) confirmed that 50% of construction waste goes to landfills, only 18% is recycled, and about 32% is reused. A case example will help to illustrate the CDW challenge in developing countries. In the example, Bajjou and Chafi (2018) note that poor project management and delivery in Egypt has caused CDW to proliferate, although there is a low level of use of LC in the sector. The use of LC would improve processes, project planning, inventory, time savings, health and safety, risk management, quality, and productivity, apart from customer value, improved decision-making, employee satisfaction, and better energy consumption (Shaqour, 2022). Reworks due to defects, material transportation, and overproduction caused a lot of CDW in the Egyptian construction industry, and the benefits of lean construction included reduced reworks and overproduction (Shaqour, 2022).

THEORY OF PLANNED BEHAVIOUR

The theory of planned behavior (TPB) was developed by social psychologists (Ajzen, 1991). The theory captures motivational factors influencing behavior. TPB expresses how hard people are willing to try to perform the behavior (Ajzen, 1991). In TPB, norms, attitudes, and perceived behavior control will have a physiological effect on workers' intended behavior in terms of the reuse, recovery, reduction, and recycling of materials (Ajzen, 2015 and 1991). The TPB postulates that project stakeholders' attitudes, CDW regulatory frameworks, CDW minimization techniques, and CDW project life cycle can lead to effective CDW management (Kabirifar et al., 2020). The most widely utilized CDW management technique encompasses reducing, reusing, and recycling strategies (Huang et al., 2018). CDW techniques involving reduce, reuse, and recycle strategies have been considered the most effective way to manage CDW (Kabirifar et al., 2020). Therefore, reducing, reusing, and recycling techniques will be a part of the Zimbabwean lean-based guidelines.

The application of lean-based CDW minimization is discussed based on best industrial practices from various countries. Kabirifar et al. (2020) developed a framework based on the TPB in Australia. The authors added that the regulatory frameworks involving rewards, incentive mechanisms, taxes on waste disposal and landfilling, and sustainable CDW management hierarchy are effective ways to manage CDW. According to Jahan et al. (2022), nearly 30% to 40% of total solid waste is generated globally, and in Australia, the amount of CDW increased by 61% from 2006 to 2017. They added that some Australian states achieved better CDW management from 2018–2019, where the State of Victoria and South Australia achieved 87% and 91.4% CDW recycling, respectively. Even with such efforts, 6.7 million tons of CDW went to landfills. Jahan et al. (2022) assert that prioritizing waste minimization and management are crucial to building a circular economy. The authors added that subjective attitudes and personal reluctance of designers and material suppliers to exercise waste mitigation techniques are crucial. Another effective CDW minimization strategy involves the designing out of the CDW; design for CDW minimization is also a practical approach to CDW minimization (Baldwin et al., 2009). The Australian government is emphasizing the use of BIM (Jahan et al., 2022). The industry lacks the utilization of BIM, CAD, and prefabrication because the effective utilization of prefabricated components could significantly minimize about 84.7% of construction waste (Jaillon et al., 2022).

RESEARCH METHODOLOGY

The paper is based on a literature review of LC principles. The conceptual framework was developed from working ideas in other countries. The literature was sourced from, Science Direct, LC textbooks, and the International Group of Lean Construction IGLC) conference papers. The keywords for the search included "lean construction", "lean-based CDW management", "lean tools", and "lean-based CDW case studies". An attempt was made to utilize the latest articles. Content analyses were utilized for conceptual framework development.

CONCEPTUAL FRAMEWORK

Figure 2 shows the proposed framework for the lean-based guidelines for minimizing CDW in Zimbabwe. The guidelines are hinged on CDW recycling, recovery and reuse, proper lean construction training, just-in-time deliveries, standardization of a worker rewards system, and proper regulatory frameworks. Achieving this helps come up with guidelines that can be utilized to minimize CDW on construction sites. The guidelines can aid in identifying further CDW issues as many huddle meetings, brainstorming, and planner systems will be used to gather feedback from workers; this can aid with continuous improvement.

The lean tools are implemented by the TPB stages of CDW stakeholders' attitude buy-in, CDW regulatory framework, utilized CDW tools, and CDW project life cycle standardization. The utilized CDW management lean tools will include the Last Planner System (LPS), Just-in-time (JIT), Continuous Improvement, 5S, and Flow Systems. The selected lean tools can be taught and adapted for utilization in developing countries. Stakeholders' buy-in and human resources training can be done through seminars, huddle meetings, and webinars. Stakeholders are essential because CDW minimization is a collective effort focused on reuse, reduce, and recycle techniques (Lu et al., 2015). CDW regulatory frameworks can be created by having rewards and incentives and lobbying for reduced taxes. The utilized on-site CDW minimization strategies will include reducing, recovering, reusing, and recycling. Last planner decisions on what to recycle will be used, the material will be delivered just in time (JIT), and there should be clear communication. The last stage of CDW project life cycle standardization will be standardizing a CDW process and rewarding practice. Lean CDW minimization should include all stakeholders because contractors and sub-contractors also affect the generation, recycling, reduction, and reuse of CDW through their attitudes (Saunders and Wynn, 2004).

The second column of the framework (Figure 2) shows the lean tools and activities utilized. The first stage of worker training uses seminars, huddle meetings, improved visualization, communication, and continuous improvement procedures. Training has benefits in column three, including improved communication, standardization, and reduced variability. The second stage of regulatory frameworks uses rewards, incentives, and lobbying for clear CDW policies on-site and in the country. Regulatory frameworks have the intended benefits of stakeholder buy-in, worker compliance, and waste stream identification. The utilized lean tools for CDW minimization in the next stage of the CDW minimization hierarchy include the LPS, which gives workers the autonomy to make decisions on CDW continual process improvements, reduced pollution, and reduced inventory. This helps minimize lawsuits caused by illegal CDW dumping. The last stage of the environmental life cycle will utilize 5S for site sorting, storage, and transfer of CDW. Information from the literature thus informed the proposed Lean CDW conceptual framework for Zimbabwe, as illustrated in Figure 2. Bajjou et al. (2018) stated that developing a lean-based conceptual framework helps show good practice and procedure. Figure 2 involves three main strands: TPB components, lean tools and activities, and client focus and benefits.

Theory of Planned Behaviour Components	LEAN TOOLS AND ACTIVITIES		CLIENT FOCUS AND BENEFITS
Norms and Worker Attitudes Stakeholder Engagement and buy-in 1	- Training	-Persuade management -Seminars, Improve CDW awareness -Webinars	• No variability • No miscommunication • Simplify CDW process • Simplify the training • Compress cycle times • Change acceptance
	- Improved communication	-Involve employees and open communication flow	
	- Huddle meetings - Weekly kaizen meetings	-Worker feedback -Educate all subcontractors	
Sustainability Frameworks Circular Economy 2	- JIT deliveries	-Procurement plan	• No inventories • Stakeholder buy-in • CDW quantification • Supplies done on time • Identification of CDW-producing streams
	- Value Stream Mapping	-Identify, understand current waste minimisation strategy	
	- Define-Measure-Analyse-Improve-Control (DMAIC)	-Define, Measure, Analyse, Improve and Control noting CDW problems	
CDW Hierarchy and Techniques Circular Economy 3	- Continuous improvement	-Brainstorm and refine procedures	• Last planner decisions by workers • Regulatory frameworks • Design for waste management
	- LPS	-Involve all workers	
	- BIM	-Build from BIM models	
	- 4Rs	-Recycle, Reduce, Reuse and Recover	
CDW Environmental Impact Life Cycle Assessment 4	- Standardisation of procedure	-Select on site CDW storage area -Select team, CDW sorting. Transfer. -CDW collection and transport -Rewards, incentives, taxes on waste disposal -Create continuous flow of work, refine procedure	• Increase customer value • Results analysis of recorded processes • Knowledge consolidation • Rewards and appraisals of workers who did well

Figure 2: Conceptual framework for lean-based guidelines for construction and demolition waste minimization in Zimbabwe (Source: Researcher's construct)

DISCUSSION

The guidelines target construction companies registered with the Construction Industry Federation of Zimbabwe. The construction project manager will spearhead implementing and managing the guides on the construction site. The skilled and semi-skilled workers will then implement the guidelines practically. Thus, an essential user guide is proposed to ensure effective implementation of the developed conceptual framework.

STEP 1: CONDITIONING OF WORKER NORMS AND BEHAVIOUR BY TRAINING

In step 1, training, huddle meetings, and improved communication will be utilized. Training employees in the organization and hiring new workers ensures the availability of the skills and expertise needed in the lean implementation phase (Watfa, and Sawalha, 2021). The project operation phase provides data and analysis, which creates a valuable database, which enhances learning capability (Moradi and Sormunen 2022). It is essential to document Lean guidelines, which specify the plan and scope of implementation (Watfa, and Sawalha, 2021). The conceptual framework provides a construction project lifecycle-based application of LC tools and techniques, which makes it easy to understand for project practitioners (Moradi and Sormunen 2022).

STEP 2: SUSTAINABILITY AND REGULATORY FRAMEWORKS

In step 2, the lean tools JIT, VSM, and DMAIC will be used to define and understand CDW generating streams. The second stage of regulatory frameworks uses rewards, incentives, and lobbying for clear CDW policies on-site and in the country. Regulatory frameworks have the intended benefits of stakeholder buy-in, worker compliance, and waste stream identification. A conceptual framework with sustainability frameworks has the advantage of mixing sustainability and LC for client value and delivery (Moradi and Sormunen 2022).

STEP 3: CDW MINIMIZATION HIERARCHY, TECHNIQUES

In step 3, CI, LPS, BIM, and 4Rs will be utilized as these tools can help with brainstorming, involving workers, modeling, and recycling of CDW. Engagement of all employees is a key element that supports and encourages management of resistance to change (Watfa, and Sawalha, 2021). Individual application of LC tools has fewer benefits and is more effective when integrated and used together (Moradi and Sormunen 2022). Karaz et al. (2021) defined LPS as collaboratively planning and controlling work processes. Supervisors and operatives are the last planners, as they are also involved in CDW minimization.

STEP 4: CDW ENVIRONMENTAL IMPACT LIFE CYCLE MANAGEMENT

Step 4 will involve mainly concretizing and standardizing perfect procedure. JIT is producing and delivering the right items at the right time in the right amounts and is used to reduce variation and waste (Ballard, 1995). Continuous Improvement (CI) is a procedure done by clearly documenting and constantly checking back to look for causes of CDW and find solutions (Marzouk et al., 2019). CI is an incremental, ongoing procedure to improve products, processes, and services (Imai, 1986). It is practically impossible to utilize all the discussed LC tools in this study as the resources required to do so may not be accessible. Table 1 gives the important lean implementation steps.

Studies by Bansal and Sing (2013), Akhtar and Ahmar (2018), Jin et al. (2019), Xing and Hao (2019), Shooshtarian et al. (2019), and Ghosh et al. (2020) have shown that standardization of 3D visualization and the 3Rs are the most common lean tools in CDW minimization cases. The cases given by the authors showed that LPS, GPS, GIS, BIM, CAD, daily huddle meetings, in-time inspections, incentives, and penalties utilized lean CDW minimization strategies. Clear policies, research, action cards, 5S system, clear communication, and pull planning were the third most effective techniques for CDW minimization. The last techniques that can be utilized are constraint analysis, prefabrication, clash detection, field software, and 5 WHYS.

Table 1: Application of the lean tools in the proposed framework

Lean Tools Applied	Important Implementation Steps	Source	Targeted Challenges
Value stream mapping (VSM)	Uses flow charts to depict every work process. Identify and monitor CDW-generating work areas.	Hamzeh and Albanna (2019)	Quality, Site organization, environmental and legal
Just-In-Time (JIT)	Procurement plan. Producing and delivering the right items at the right time in the right amounts	Karaz et al., (2021)	Reduced inventory
Six Sigma	Split smaller work processes and reduce the changeover of tasks.	Al-Aomar (2012)	Cost, legal, and environmental
Kanban	Card systems devised by the automotive industry produce or procure only parts needed at a particular time.	Marzouk et al., (2019)	Time and quality
Last Planner System, clear visualization, and 5S	Planning work collaboratively. Rules for workplace housekeeping. Include (Sort), (Set in order), (Shine), (Standardize), and (Sustain).	Enshassi and Zaiter (2014)	Clear communication, environmental sustainability
Continuous Improvement	Documenting and always checking back work for improvement.	Marzouk et al., (2019)	Communication, Time, and cost
BIM	Digital representation of the building. Models could be utilized.	Steel et al. (2012);Marte et al. (2012)	Scope design for CDW minimization.
Daily huddle meetings	Short everyday meetings focus on CDW-specific issues.	Memon et al. (2018).	Feedback meetings

CONCLUSION

The minimization of CDW in Zimbabwe has been an issue, as most of them are dumped on roadsides, watercourses, open spaces, and landfills. Some of the CDW is used for filing road potholes and as low-cost building hard cores, just improvisations of materials not intended for them. By applying lean-based CDW minimization guidelines, the contractors can minimize the environmental and health impacts of CDW, which are dumped everywhere. The guidelines can help minimize project reworks and work variability and increase customer value. In addition, Zimbabwean contractors can find the causes of CDW and develop more effective waste minimization techniques. The study, therefore, is just a preliminary step of a doctoral thesis; the study will provide further guidelines and recommendations from practicing construction industry professionals as more and more professionals will be consulted.

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PERFORMANCE MEASUREMENT FOR INFRASTRUCTURE PROJECT SUSTAINABILITY

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ABSTRACT

From a lean construction perspective, the role of a Public Roads Administration is to identify the value from the client's point of view and define the processes able to develop the value stream. In the long-run strategy, the public role is to be sustainable and apply the sustainability principle in the management of the portfolio of projects under the administration's control. This implies the development of a performance measurement system for sustainability. The case of the Norwegian Public Roads Administration is presented and analysed in the paper, as an example of an actor working on performance measurement for sustainability. The purpose is to evaluate the state of the art and use document study and literature to propose improvements. The research questions addressed in the paper are how sustainability is measured today for the construction portfolio in the Norwegian Public Road Administration and what are the pros and cons of the actual method (for measuring sustainability today). The proposal for improvements is made by comparing the state of the art with performance measurement theory.

KEYWORDS

Lean construction, sustainability, action research, performance measurement, and infrastructure projects.

INTRODUCTION

Among the roles of the project owner, understanding the value connected with a project is the first step to defining a committed process for managing the project with a clear vision (Fisher et al., 2017). From a public ownership perspective, the value must be identified from a societal point of view, as society is the direct client of the infrastructure work, in a lean construction perspective (Kalsaas 2017). Looking at the long-term perspective, sustainability is identified as a strategic goal for society (Samset, 2010) and it is towards this goal that the project and

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portfolio management must be evaluated. Evaluating sustainability has different implications, depending on the level of application of the requirement: a sustainable company must have a sustainable portfolio of projects, but a company with a sustainable portfolio is not necessarily a sustainable company. The focus of the paper is measuring sustainability at the project and portfolio levels. This is because having a single sustainable project could bring a not-sustainable portfolio: the investment, necessary to reach the goal at the single project level, could, for example, bring a lack of finance for other projects, already evaluated as necessary, with a consequent negative effect on society as a result for the whole portfolio. Before developing a performance measurement system for portfolio sustainability, it is necessary to understand how sustainability is measured for a single project.
The research questions addressed in the paper are

- how is sustainability measured today for the construction portfolio in the Norwegian Public Road Administration?
- what are the pros and cons of the actual method (for measuring sustainability today)?

The paper focuses on the case of the Norwegian Public Roads Administration (NPRA), as an example of a project owner with a large portfolio of projects dealing with the sustainability goal. The sustainability evaluation system used to define the construction portfolio for NPRA is compared with the chosen literature in terms of the choice of sustainability criteria. Pros and cons of the actual method are described and evaluated and a proposal for improvement is done using performance measurement theory, with a focus on sustainability performance measurement for the project portfolio.

LITERATURE REVIEW

The literature used for the article has three main branches. The first is dealing with the available literature on sustainability for infrastructure projects. In particular, the authors were investigating what the existing literature means with sustainability for infrastructure projects. The concept of sustainability is intended as a strategic measurement (Samset, 2010) for the long-term effect (Samset et al, 2022). But sustainability is also intended as the group of goals defined by the United Nations in the adoption of the Sustainable Development Goals (2015) built on the principles stated in the resolution "The Future We Want" (A/RES/66/288, 2012). These goals focus on the three pillars of economy, environment and society.

There are numerous scientific papers and publications on the sustainability topic (among 1'500'000 just in Google Scholar, searching for sustainability and infrastructures; over 2'300'000 searching for sustainability and roads), but few of them are focused on sustainability as set of criteria defined for a long-term goal. The sustainability criteria presented in the literature include economic criteria, environmental criteria, social criteria and a set of governance criteria, as for example time, innovation and seriousness of actors (Akomea-Frimpong 2022). Among the selected articles, some adopt the definition of the three pillars of sustainability (Faiz et al., 2012; Scope et al., 2021), while others investigate the sustainability topic in the infrastructure sector in a more holistic perspective (Corriere et al, 2012; Montgomery et al., 2015). Part of the investigated literature, nevertheless, especially if related to material development, limits the concept of sustainability to the environmental or climate topic (Hu et al., 2019). Like other actors operating in the infrastructure field, NPRA has adopted the broader definition, recognizing sustainability as a long-term value and building the strategy for the agency on 5 main goals that deal with the three sustainable pillars.

The second branch of the investigated literature deals with performance measurement and in particular with guidelines for performance measurement (Andersen et al., 2021). The available literature on performance measurement with a focus on sustainability is often an inherent production field (Qorri et al., 2018) and is almost always focused on the measurement of performance at the company level, even when related to public agencies (Adams et al., 2014). Interesting considerations can be made from the study of literature on performance measurement focused on sustainability applied in different fields from infrastructures (Warhurst, A., 2002), especially on the definition of the indicators and on the importance of stakeholders in the strategic focus of the company (Silva, 2019). The application of performance measurement guidelines to the sustainability measurement of the projects and portfolio of projects for a company is a necessary step towards the measurement of the sustainability of that company: to be a company focused on sustainability, the management of the portfolios and projects needs to be focused on sustainability (while the reverse is not automatic, as a company deals with additional activities outside the portfolios of projects). Developing a performance measurement for sustainability for the projects and the projects portfolios of a company is therefore a necessary step for a sustainable organization and the analysis of NPRA's methodology for performance measurement of projects and portfolio's sustainability will be the focus of the present paper.

Chosen literature on performance measurement theory (Andersen et al., 2021) and application (Andersen et al., 2021; Koho,2015) has been used to analyse the existing performance measurement method in NPRA and to suggest improvements.

Finally, the third branch of literature is related to sustainability and Lean. The connection between lean theory and sustainability performance is not new in the literature (Garza-Reyes, 2015; Martínez León, 2017), also in the engineering and construction field (Khodeir and Othman, 2018), but especially in the production field (Carvalho et al., 2011; Kofi et al, 2023; Mollenkopf et al, 2010). Since lean theory and the green concept have similar goals, the application of lean principles generally improves sustainability performance (Bhattacharya et al., 2019; Duarte and Cruz-Machado, 2015). The vice-versa effect is also supported in literature, since the explicit consideration of environmental sustainability, as the capacity to sustain the positive environmental effect gained in the long term (Samset, 2010), is seen as so effective from the lean perspective that sustainability is proposed by some literature (Fliedner, 2008) as an additional lean principle. Several aspects of sustainability are considered in lean literature, from the environmental to the social one (Duarte and Cruz-Machado, 2015). Nevertheless, there is no agreement in the literature on how sustainability is measured.

METHODOLOGY AND RESEARCH LIMITATIONS

The paper has two areas of the research design: the first is the case study analysis, with documents and programs study; the second is the document study of chosen literature.

The case study chosen is the Norwegian public roads administration, as a relevant example of actors dealing with sustainability in several phases of infrastructure projects. NPRA has published 5-top-goals for the strategy of the agency, together with the sustainability strategic areas (Figure 1). The status of portfolio management focusing on sustainability has been investigated (Minoretti et al, 2023) and specific documents and program studies have been performed. The documents analyzed have been suggested in information-gathering meetings with key informants from NPRA. Among the analyzed tools, the program used for suggesting the prioritization of the projects in the construction portfolio, called Effekt, has been studied. The program is used in the early-stage design and is evaluating each project's performance among societal, economic and environmental goals.

The system used today to measure sustainability in NPRA, for the specific application of the Effect program, is compared with chosen literature (Haavaldsenet al., 2012) and the pros and cons are investigated, in terms of indicators and in terms of process, using relevant literature on performance measurement (Andersen et al., 2001).

For the choice of the literature used in the study, a scoping literature review has been done on the topic of sustainability and infrastructures and on the topic of performance measurement systems. Google Scholar, Scopus and Research Rabbit are the chosen database. Using the keywords “sustainability”, “indicators”, “portfolio”, “selection”, “roads” and “projects”, no results are found in Scopus research database. The same combination allows us to find 20’900 results in Google Scholar. A systematic screening of the documents shows the scarce relevance of the literature for the research topic. Therefore, a partial combination of keywords is used and selected articles are inserted in Research Rabbit to increase the number of documents that could be interesting for the study. Finally, chosen relevant literature on the sustainability topic and on the performance measurement theory is selected from the search findings and used for the discussion.

The findings from the case study on NPRA, applying the results from the literature search, can be used to propose improvements in the performance measurement system for sustainability, both in terms of indicators and in terms of the process for evaluation. The study is used to understand the challenges in sustainability performance measurement for projects and portfolios of infrastructures, with a particular focus on the sustainability indicators used and on the process of measuring sustainability.

RESULTS

The present chapter describes how sustainability is measured today in NPRA and in the chosen literature, in terms of selected criteria and in terms of performance measurement, at the project and portfolio level. The strategic criteria for the organization are presented and a detailed description is done on the measurement and indicators used for the early phase of the investment (construction) portfolio. In particular, the tool ‘Effekt’ is taken into the analysis, since it is the only tool used by the agency to take care of the economy, environment and society in the sustainability measurement. The tool is used only in the early phase of the projects. The indicators are compared with the chosen literature and the general performance measurement system is described.

THE CHOSEN INDICATORS FOR SUSTAINABILITY

For each one of the three sustainability pillars, the specific department dealing with the concept phase for the project has defined a list of indicators that are used in a specific program called ‘EFFEKT’. The program, previously used for the analysis of the societal and economic impact, has been recently implemented to take care also of the environmental criteria.

As for the societal and economic indicators, for which the program allows to perform specific calculations and derive a defined measurable value, the climate impact has been implemented as one of the measurable indicators for the environmental impact analysis. On the contrary, other environmental indicators, for example, related to the evaluation of the impact on landscape, outdoor life, natural diversity and resources and cultural heritage, are considered separately in the evaluation and listed as non-numerical parameters. For them, an evaluation based on a level choice for the impact has been the chosen output and nine levels of consequence have been defined, from very negative to very positive.

For the priced themes (measured in money), the principles used in the evaluation are:

- utility about the benefits of a measure
- cost (or negative benefit) of disadvantages of a measure
- net benefit/net present value about the difference between benefit and costs
- socio-economic profitability (or positive net benefit/net present value) of measures where the benefits are calculated to be greater than the costs.

For the non-priced consequences (evaluated in a qualitative method), the principles used in the evaluation are positive consequences of the benefits of a measure or negative consequences of the disadvantages of a measure.

While the non-measurable indicators are listed, with the related evaluation, in a separate file, all the measurable indicators are returned in a monetary equivalent global evaluation. The evaluation is done for every proposed project and the program is used to compare the projects and to compile a list of suggested projects for prioritization. The indicators chosen in the Effekt program are listed in the following table (Table 1) and tentatively divided into the three sustainability pillars, showing the holistic perspective of the early-phase analysis that NPRA is performing.

In literature, considering the publications with a uniform concept of sustainability as based on the three pillars concept, it is possible to find a similar indicator list. The list stated in chosen literature is therefore selected (Haavaldsenet al., 2012), as specifically defined for investment projects and divided into the three sustainability pillars (Table 1). The indicators are listed in the table grouping them considering the similarity with the correspondent indicators defined by NPRA.

SUSTAINABILITY PERFORMANCE MEASUREMENT IN NPRA

NPRA is one of the actors dealing with different phases of a project, from the concept phase to the design, to the construction phase, until the use and maintenance of the infrastructure. The mentioned phases imply the involvement of different portfolios of projects internal to the organization. The concept phase may need a pre-involvement of the Research and Design portfolio of projects (not all the projects include necessarily an R&D phase). From the concept phase, the investment portfolio of projects flows to the design phase, then to the construction phase (after the necessary governmental approvals), and finally into the Maintenance portfolio.

The Public Road Administration has defined 5 strategic goals that are derived from the three sustainability pillars of economy, environment and society. The goals are: more value for money, efficient use of new technologies, contribution to Norway's fulfillment of its climate and environmental goals, vision zero -no fatalities or serious injuries-, and easier everyday mobility and increased competitiveness for business and industry. The Agency is supposed to measure its performance toward these goals, both at a company and at a portfolio level. For this purpose, a specific set of sustainability criteria has been defined by NPRA, especially tailored for the investment (construction) portfolio and the maintenance portfolio of the public administration (Figure 1).

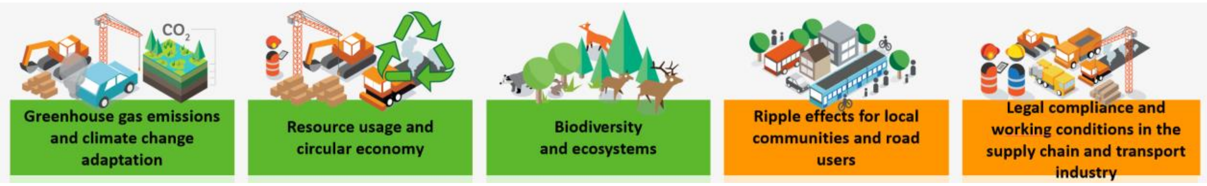

Figure 1: the five sustainable strategic goals in NPRA, Statens vegvesen (Statens vegvesen sin virksomhetsstrategi | Statens vegvesen, 2024)

Focusing on the sustainability measurement at the portfolio level of the organization, the study has investigated, through informal information gathering meetings and documental study, the way sustainability is measured along the project process and along the different portfolios, focusing on the investments (construction) portfolio. The construction portfolio is composed by project selected by the Government that are previously analysed and prioritized by the Agency on the base of sustainability criteria and indicators. This evaluation is done in the early stage of the project, considering the three dimensions of sustainability: economy, environment and society. The department taking care of this phase is using the specific tool Effekt, previously mentioned. After the government's choice of the projects to finance, other departments are taking care of the projects and, at the present moment, the work to define specific indicators or tools for the sustainability measurement is ongoing.

Table 1: Comparison of indicators used in NPRA (Effekt program) and in chosen literature (Haavaldsen et al., 2012); the NPRA's indicators are also specified if or not priced

Criteria	Priced/ Not Priced	Indicators from Effekt program (Handbook V712, NPRA)	Indicators from chosen literature (Haavaldsen et al., 2012)
ECONOMY	P	Operator benefit	
	P	Budget consequence for the public sector	Infrastructure costs
	P	Residual value	
	P	Tax cost	Consumer costs
	P	Road user and transport users benefit	Mobility barriers
	P	Traffic accidents	Damage by accidents
			Non-renewable resources
			Accessibility
			Traffic congestion
ENVIRONMENT	P	Noise and air pollution	Noise and noise control Air pollution
	P	Greenhouse gas emissions	Climate change
	NP	Natural diversity	
	NP	Natural resources	Non-renewable resources Water pollution Effects of water resources
			Housing and households
			Deterioration
SOCIETY	NP	Outdoor life/city and rural life	Living standard of the local society Effects on health Consequence for handicapped
	NP	Landscape picture	Aestetic
	NP	Cultural heritage	
			Equality Coexistence and discrimination
			Less expensive consumer products and services

The sustainability performance measurement method presented now has been evaluated in the next chapter using relevant chosen literature on guidelines for performance measurement (Andersen et al., 2021). The concepts described in the guideline to develop a performance measurement method toward a specific goal can be applied to the case of the sustainability performance measurement for the investment/construction portfolio of NPRA.

DISCUSSION

Using the principles described in performance measurement theory (Andersen et al., 2021), the NPRA's methodology for sustainability performance measurement in the early stage of the investment portfolio is analysed. In particular, the concepts of validity, reliability, completeness and coherence are discussed. The results are discussed in terms of pros and cons for both the indicators chosen and the process used to measure sustainability. Further work and improvements are proposed.

PROS AND CONS OF THE CHOSEN INDICATORS

The comparison between the indicators chosen by NPRA and the list of indicators shown in literature (Table 1), shows a discrepancy within each of the sustainability pillars. Even if both the methods shown are used within the same topic, that is infrastructures, there is no agreement on a unique set of indicators to measure the impact on each of the three criteria of economy, environment and society. This is clear also considering other literature sources from the same application field (Suprayoga,et al., 2020, Ugwu, et al., 2005).

From the perspective of measurement of performance, avoiding detailed evaluation of the specific measurement methodologies for every specific indicator and applying the general guideline considerations (Andersen et al., 2021), several considerations can be made.

The mentioned discrepancy in the indicators' list is somehow justified by the need of the actor to choose *valid* indicators. The validity of an indicator is connected to the ability of an indicator to "*correctly measure what it is supposed to measure"* (Andersen et al., 2021). Due to the different roles of the actors involved in a process and the possibility for them to gather and measure specific data, it is reasonable for them to choose indicators that they have the real possibility to control. In addition, it must be considered that the meaning of an indicator is specific for each company and specifically related to the company's activities. An example can be done also using an indicator whose use is very diffused and whose meaning has been generally agreed upon by the actors operating in the field, such as the indicator on *Emissions.* Depending on the specific role of the actor and on the data handled by the company, the same indicators could refer to different things, such as direct emissions, for example, produced by machinery, or indirect emissions, for example, related to the production of the material used, or third parties' emissions, dependent on the activities of third parties involved in the actor's activities.

The need for a specific choice for the indicators for each department has also been confirmed during the informal gathering meetings in NPRA and is traceable in the documents and tools used in the different phases of the projects. Furthermore, the literature review conducted shows that, in several fields of application, the preferred choice is to define a tailored list of sustainability indicators, especially to take into consideration the stakeholders' interest and to better support the company's approach towards sustainability (Warhurst, 2002).

This opens another consideration connected with the *reliability* of the chosen indicators, intended as "*the ability of an indicator to produce the correct value consistently over time*" (Andersen et al., 2021).

The specific departments need to define the specific indicators in the performance measurement, since these departments are connected, for example, with different phases of development of the same project, which means that, without a specific handling in the transition phases, it is not possible to check the same measurement in the next phase, characterized in practice by other defined indicators.

These specific departments' needs show a risk of compromising the reliability of the measurement along the process from the conceptual to the final stage of every single project. The possibility to transfer the measurement done on each specific indicator as an equivalent level for the related criteria in the phase stage could represent a solution for transferring the information on the expected performance (at the criteria level) in the transition phase stage. Looking at the strategic criteria defined for the Public Administration, the sustainability criteria specified and the list of indicators used in the early-stage analysis for the investment portfolio (Effekt tool), it is clear that a specific definition of the interdependencies among the different levels of criteria and with the specific indicators is a necessary further step for NPRA to guarantee not only the reliability of the performance measurement, considering the project process from evaluation to design, construction and maintenance, but also to perform control on coherence and alignment of the projects with the governance.

A process where the performance of every phase is measured in terms of the same criteria, but with specific-phase indicators, could represent a way to guarantee both the validity and the reliability of the performance measurement system along the project process.

Finally, the *completeness* of the indicators could be discussed, in terms of the presence of the three main pillars of sustainability (economy, environment and society) in performance evaluation. The investigated literature shows, for example, a lack of focus on societal indicators (Sierra Varela, 2017). Applied practice (NPRA), shows a not coherent development of the topic along the portfolio development: while in the early phase of the portfolio (analysis of projects for prioritizing, using the tool 'Effekt'), the three pillars are clearly all present in the indicators' list, at a later stage (construction, maintenance), sustainability is confined to specific areas of interest that are not clearly covering the whole spectrum of criteria. For this purpose, it has to be specified that the 'sustainability strategy' for NPRA is under development, so further specifications are expected. In addition, the topic of sustainability in the construction phase (after the approval of the financing) for the investment portfolio is additional to the previous main control criteria method, based on time, cost and quality. If we combine the set of main goals defined by the public Agency with the sustainability strategic goals (Figure 1) recently presented by NPRA, we see that the chosen global set of criteria is within the four areas of sustainable criteria defined in some literature for performance measurement of Public-Private Partnership (PPP) Projects (Akomea-Frimpong, 2022).

PROS AND CONS OF THE ACTUAL PROCESS: THE PORTFOLIO PERSPECTIVE

The process of developing a project in NPRA (Figure 2) includes several stages from the expression of the public need to the design phase, construction phase and it concludes with the realization of the effect (object) on the society. This includes the collaboration of Private and Public actors and a transversal coherent definition and control, along the process, for the chosen criteria. This is the actual challenge for NPRA.

In the development and implementation of ongoing processes, the application of standardized approaches, like for example the DMAIC (Define, Measure, Analyse, Improve, Control) approach, often used in performance improvement programs (Koho, 2015), could be helpful for the public Agency. The goal, from a strategic long-term perspective, would be to apply the approach at the portfolio level, following the whole process for the projects. An additional consideration could be done on the separate visualization of the priced and not-priced indicators, and this could be useful also to develop the potential of the measurement system in a portfolio perspective. The validity of a measurement system itself is also dependent on the ability of the system as a whole to perform the intended measurement. While the two groups of indicators could provide information on the single measurement and globally on the countable and not-countable groups of indicators, the measurement system remains incomplete in terms of providing a single evaluation for the measurement applied for example to two different projects in the portfolio. For this reason, a system to visualize globally the measurement of all the indicators is suggested. Applying a weighing system among the single indicators and among the criteria, to reflect the relative importance in the strategic perspective, it would be possible to use a spider diagram (Haavaldsen et al. 2012, Fischer et al., 2017) to show countable and non-countable indicators on the same graph.

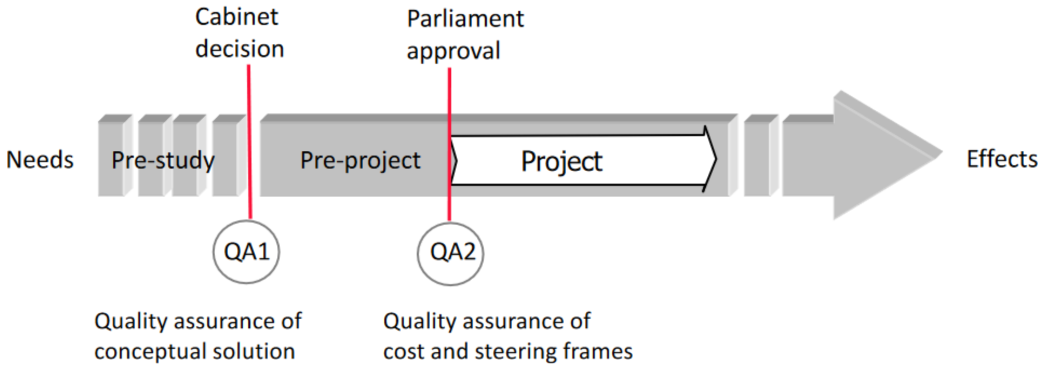

Figure 2: The Norwegian Quality Assurance regime for major public projects. Source: Norwegian Ministry of Finance. Samset and Volden (2016).

From a portfolio perspective, there is actually no consideration in the described tool of the eventual influences of a project on another. This means that there is no actual portfolio perspective, and it is therefore not possible to visualize eventual synergies for the global performance measurement in considering several projects together. Eventual synergies among different projects could give the possibility to enhance the performance of the whole portfolio for some specific criteria, always checking the effect on the global set of chosen performance criteria. A very practical example could be, for example, the possibility of treating the soil quantities in a project as a +/- requirement in a portfolio perspective: for a project that produces mass to disposal (from excavation, for example), another project could need soil for landfilling. The two parameters, that would score with a negative performance in a project perspective, would 'compensate' each other (in a simplified description of the topic) and not have a negative performance scoring for the environmental criteria in a portfolio perspective. The same example could be done on the possible positive consequence of different indicators if the portfolio perspective is used actively: a group of projects that could be realized with the same material would give the possibility, if managed in the same contract, to allow the market to offer a better economical offer for the same 'quality' (for example related to the CO2 reduction-goals connected with material production) of the material, thanks to the possibility to buy larger material quantities. A negative score on the economic criteria for a single project could therefore turn into a positive performance score if the same project is handled in a portfolio perspective.

The need of improvement for portfolio management should be highlighted also in a multiple portfolios perspective: the actual system of sustainability performance measurement is also not consider the possible influences of the choices done on a specific portfolio on the other portfolios of the agency. For example, the possible impact of the choices made for the investment/construction portfolio on the sustainability performance of the maintenance portfolio. Another example could be the consequences of the choices made for the R&D portfolio, in terms of projects financed, for example in the future alternatives for new materials available for the infrastructures, both for the construction and for the maintenance portfolios

The performance measurement system is part of a management system (Andersen et al., 2021) and it is necessary to follow it in the various management modes, such as the strategic level, the day-to-day management and the improvements that are emerging along the management practice. As the criteria and the indicators are usually connected to different levels of management, it is fundamental to draw the connections between the different criteria and the single indicators with the specific criteria they belong to and follow the dependencies in a coherent way along the process, especially in the transition phases where different departments or actors are involved. This is necessary also considering the timeline of a project development, to "*follow up in the whole process for the temporality of performance evaluation"* (Dalcher, 2012).

CONCLUSIONS AND FURTHER WORK

The paper is bounded on the case of NPRA as an organization focused on sustainability as strategic goal in the long-term-run. The chosen case study is one of the biggest actors in Norway, dealing with infrastructure management, involving different phases of the project development and from the concept to the design, construction and maintenance phase. Due to the long-term nature of the sustainable strategic goal, the importance of having an actor dealing with the whole project process and with an additional portfolio perspective, results in the possibility to investigate a perspective wide enough to generalize some of the conclusions. Nevertheless, additional data from similar organizations could give the opportunity to understand and share best practices, also in an international perspective.

The paper describes the sustainability performance measurement system, in terms of indicators and in terms of process, for the Norwegian Public Roads Administration, within the investment portfolio of projects, as an example of actor committed to develop the value stream in the long-term perspective. The performance measurement method applied for the construction projects and portfolio is therefore described and analyzed with respective to pros and cons, using relevant literature and performance measurement theory. The study shows that, at the present moment, the sustainability topic, as a combination of environmental, economic and social goal, is evaluated just in some phases for the project and just in a project perspective, missing possible synergies only possible in a portfolio level.

The study also highlights a lack of agreement in literature on the definition of sustainability in performance measurement. Specific focus on some of the sustainability pillars is underlined in part of the literature, while other publications adopt a more holistic perspective.

Using the findings from the performance measurement theory, applied to project and portfolio performance measurement focused on sustainability, further work is proposed for the improvement of the actual performance measurement system in NPRA. The actual choice of indicators in NPRA could be valid, reliable, and complete to measure sustainability, but the sustainability measurement is, by now, based on measurement done just in the early phase of a project and not followed up in a coherent way along the project development and construction. In addition, there is no portfolio perspective, so that all the possible synergies among the projects to enhance sustainability are lost. A general guideline could be helpful for the development of a specific performance measurement system for the infrastructure sector focused on sustainability. A dedicated tool could be designed and tested in the specific field applications, not only for the sustainability measurement of a single project but also to evaluate possible strategies in the portfolio management focused on optimizing the sustainability performance.

The challenges for the proposed improvements deserve a specific effort, especially in the general organization of the agency. To develop sustainable goals, it is necessary to implement the performance measurement system in a transversal way along the project process and in terms of portfolio management. Literature shows that the organizational structure has a great influence on the success in implementing the strategies in the portfolio (Petro, 2015). In addition, the perception of the organizational factors, in terms of transparency and performance measurement coherence and strategic alignment, is so important that can affect the performance of the agency's practitioners itself (Pellegrinelli et al., 2006), and therefore requires a dedicated endeavor.

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A COMPARATIVE ANALYSIS OF LEED AND GREEN GLOBES: A CASE STUDY APPROACH TO ENVIRONMENTAL PERFORMANCE ASSESSMENT OF AN EDUCATIONAL CAMPUS FACILITY

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ABSTRACT

The construction industry faces significant challenges in reducing energy consumption and achieving sustainability goals. Green building rating systems (GBRS) have been created to assess and confirm the effectiveness of sustainable construction practices. As buildings strive to reduce energy consumption, a holistic approach to building design, construction, and operation is necessary. The study aims to explore sustainable construction practices and their sustainability in high-performance green buildings (HPGB). The Georgia Tech Life Science Building (GTLSB), designed to serve the life science community in Metro Atlanta, is the chosen case study. Our research will involve (1) examining guidelines and standards for a sustainable building, (2) understanding the use of sustainable criteria, and (3) demonstrating technical expertise. Initially, we conducted a literature review of the current state of the GBRS and analyzed project information as a case study. Our analysis showcases an in-depth understanding of the technologies, methods, and resources required to produce and operate an HPGB. Our findings contribute to the knowledge of sustainable building and provide insights into the utilization of GBRS, focusing on two widely adopted systems, LEED and Green Globes (GG). The study's findings will help promote sustainable construction practices for professionals, policymakers, educators, and researchers and help achieve a more sustainable built environment.

KEYWORDS

Green building rating systems, LEED, Green Globes, Sustainable construction practices, High-Performance Green Building.

INTRODUCTION

The construction industry is one of the world's largest industrial sectors, accounting for about 10% of global GDP (Statista, 2024). However, it is responsible for approximately 40% of global

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energy consumption and carbon dioxide emissions. (*McKinsey,* 2023). As the world faces the effects of climate change, the construction industry has become an increasingly important focus for creating more sustainable and energy-efficient built environments. Green Building Rating Systems (GBRS) is a solution to promote sustainable building techniques by utilizing energy-efficient building materials (Doan et al., 2017), renewable energy sources, and sustainable construction practices, thus reducing the environmental impact of buildings in keeping with lean principles of efficient resource use (e.g., Antonio et al., 2019; Carniero et al., 2012, Holloway and Parrish, 2013; Parrish, 2012). GBRS accelerates the adoption of building practices that result in resource-efficient, healthier, and environmentally sustainable buildings (Matisoff & Noonan, 2022). These systems provide more affordable and realistic measurements than other sustainable building rating systems, which justifies a discussion to replace the term 'green' with 'sustainability.' (Berardi, 2013)

The benefits and challenges of sustainable building practices are essential for the construction industry to achieve a more sustainable built environment. For instance, according to a report Global Data (2022), the US green building market grew 8% between 2017 and 2021. However, the initial cost of constructing green buildings is increasing (Li et al., 2020) due to the changing nature of the construction industry with respect to the environment. Developers usually cover the design costs, which can be over 30%, and use the equity in the early stages of the project (Leskinen et al., 2020). Sustainable building developers also face longer construction times. This is because some eco-friendly materials used in construction have longer lead times than their conventional counterparts (Hayles & Kooloos, 2008). As a result, delays may occur, leading to a longer wait for positive cash flow (Jermak, 2023). A further obstacle to adopting sustainable practices is the need for more knowledge among construction professionals in designing and constructing. Also, building owners, architects, and contractors need more practical guidance on these practices. For instance, obtaining LEED certification can be expensive and time-consuming, which makes it challenging for smaller projects to achieve certification (Carneiro et al., 2012). On the other hand, GG offers a more affordable and practical measurement system than LEED, but it does not have the same level of recognition and market demand (Reed et al., 2009).

The industry increasingly focuses on sustainable and energy-efficient building design and operation, particularly Lean construction practices. To achieve these goals, current research evaluates and compares the assessment methods of GBRS. The objective is to improve our understanding of how LEED and GG systems can be utilized to promote environmentally responsible and energy-efficient practices. This research will be valuable to construction stakeholders seeking to implement sustainable building practices. Our paper proposes a method for analysing different GBRSs and acting as a green building consultant for the GTLSB project. We aim to evaluate the suitability of two assessment methods, LEED and GG, and suggest improvements to enhance the building's environmental performance. This study intends to answer the following research questions (RQs): RS1: What are the key differences between the LEED and GG certification systems, including their unique strengths and weaknesses? RS2: What are the specific sustainable criteria used in the project? RS3: Which rating system is more appropriate for the project? RS4: What are the potential credit points and strategies to improve the built environment and operational efficiency of the project?

The paper is organized into different sections. The first section introduces GBRS within the context of building construction. The second section is a literature review that describes two assessment methods, LEED and GG. It identifies the most suitable systems for application based on assessment criteria, potential credit points, and strategies to improve the built environment and operational efficiency. Section 3 defines the methodology used for the study. The following section presents data analysis and explores the case study of the GTLSB project.

The results and discussions suggest ways to improve the building's environmental performance. The paper concludes with the final sections: the conclusions and references.

BACKGROUND

COMPARATIVE ANALYSIS OF THE TWO GREEN BUILDING RATING SYSTEMS

The construction industry's sustainable practices have gained significant attention in recent years due to the increasing awareness of the environmental impact of buildings. As a result, two of the most widely recognized rating systems, namely LEED and GG, have emerged to assess a building's environmental performance. The Leadership in Energy and Environmental Design or LEED system, introduced by the United States, has become a widely adopted means of assessing the environmental impact of buildings. LEED is widely recognized and has a larger market share in the green building industry (Kibert, 2016), making it easier to find professionals familiar with the system (Peng et al., 2010). Other countries have created their systems based on LEED or adopted the approach. GG is a Green Building Initiative (GBI) certification program that improves a building's environmental performance. It offers a user-friendly and cost-effective alternative to other green building certification systems, focusing on practicality and flexibility. Recently, GG has evolved to include the latest sustainable building practices. According to Kibert's 2016 research, LEED and GG have strengths and limitations. Both systems share similar categories for evaluation, such as energy efficiency, water conservation, and indoor air quality. Despite their differences in certification approaches, the two approaches aim to promote sustainable and environmentally responsible practices. They provide frameworks for designing, constructing, and operating HPGB and have raised awareness about the importance of the environment in the industry.

To help those who use these rating systems better understand which system would work best for their project quickly, this research proposes a decision framework with ten criteria for comparative analysis. This framework expands upon the framework proposed by Reeder (2010). The selection criteria filter project characteristics, allowing researchers to analyse unique project features and decide which ones to include. These criteria, including Eligible Building Types, Brand Recognition, Rating Building Performance, Third-Party Verification, Ease of Use, Costs of Compliance, Professional Designation, Certification Process, Program Points, and Adaptability, will serve as attributes in a decision support framework that assists stakeholders in identifying the most relevant GBRS in construction projects. They need first to understand the fundamental differences between the two rating systems.

Firstly, both LEED and GG are voluntary certification programs developed by the U.S. Green Building Council (USGBC) and the Green Building Initiative, respectively, to assess the sustainability of High-Performance Green Buildings (HPGB). Both systems employ a point-based evaluation approach, covering categories such as sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, and innovation (*Green Building Initiative*, 2023). These systems offer various project types, like commercial, residential, etc., and online tools for project progress tracking. LEED's online certification platform encompasses new construction, major renovations, and continuous improvement of existing buildings, including commercial and multifamily residential projects. GG applies to similar project types, emphasizing an online self-assessment tool that allows users to evaluate projects based on available points, earning certification with a rating from 1 to 4 globes (*Green Building Initiative*, 2023; Reeder, 2010).

From another perspective, brand recognition is crucial for developers to highlight sustainability claims, attract tenants, and gain media attention. LEED, the older and more established system with over 150,000 certified projects worldwide, enjoys higher brand recognition than GG (*USGBC*, 2023; *Landscape Management*, 2015). Comparing their comprehensive performance targets, LEED and GG share similar sustainability goals but differ in their approaches. GG introduces the Project Management aspect, focusing on effective project team management. At the same time, LEED incorporates categories like Innovation in Design and Regional Priority to incentivize exceptional credit requirements and address regional priorities. In addition, GG provides a free Life cycle assessment (LCA) calculator tool, while LEED has a task force working on incorporating LCA into its system. Differences also exist in mandatory measures for certification: GG has none, while LEED has specific prerequisites (*Green Building Initiative*, 2023). Similarly, GG offers four paths for energy performance points and five certified wood options, while LEED provides two paths for energy performance points and only considers FSC-certified wood products. Third-party verification is also essential for green building certification. LEED includes design and construction phase reviews, and GG requires mandatory verification at the end of the design phase, followed by a site visit and additional documentation review.

Additionally, ease of use is a consideration when choosing a rating system. The LEED rating system provides several advantages over GG. For instance, LEED has a more detailed scoring system with certification levels ranging from Certified to Platinum *(Landscape Management*, 2015). However, GG is often considered more user-friendly and suitable for “do-it-yourselves” types due to its online application and self-assessment nature. Cost is another critical factor, and LEED costs are determined by project size and complexity. Implementation costs may vary based on the credits pursued, requiring staff time for learning, or hiring a consultant (*Green Building Initiative*, 2023). In contrast, GG is perceived as more cost-effective due to lower consultation fees and a fixed certification fee. Other aspects, such as professional designations like LEED Accredited Professional (LEED AP) and Green Globes Professional (GGP), demonstrate an individual's expertise in green building. Requirements for these designations include a minimum of years of experience and continuing education (*Green Building Initiative*, 2023; *USGBC*, 2023). The certification process involves project teams registering on online platforms (LEED Online for LEED, self-evaluation for GG), submitting documentation, and undergoing third-party verification.

Moreover, from a different standpoint, regarding program points, GG employs a 1,000-point scale compared to LEED's 110 points, with both systems prioritizing categories such as Energy, Water, Materials and Resources, and Indoor Environment. GG emphasizes project management by allocating a substantial percentage of points to progress meetings, coordination, benchmarking, commissioning, and documentation (Wu & Low, 2010). Predesign construction to post-construction stages are evaluated, and points are allocated for assessment (Peng et al., 2010). LEED and GG offer value when evaluating and certifying the sustainability of buildings. While LEED has distinct features and benefits, GG also boasts unique advantages. Ultimately, the decision to choose between the two depends on the specific goals and priorities of the project.

Table 1: Comparative Analysis of two green building rating systems

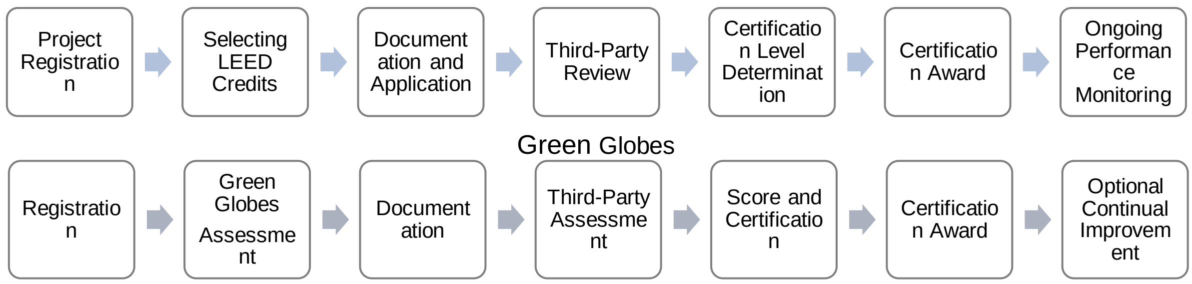
Criteria	LEED	Green Globes
Project Types Eligible for Certification		
Eligible Building Types	Commercial over 1,000 SF or over 250 SF for LEED-CI	Commercial & Multifamily Residential (4+ stories)
Prerequisites	Yes	No
New Construction/ Renovations	✓	✓
Existing Buildings	✓	✓
Market Penetration		
Year Launched	1998	2004
Number of Buildings Certified	105,000	3,223
Number of square feet Certified	12 billion square feet	600 million square feet
Category Types Considered in Rating Building Performance		
Site Selection & Development	✓	✓
Energy Efficiency	Two paths	Four paths
Water Conservation	✓	✓
Material & Resource Efficiency	✓	✓
Indoor Environmental Quality	✓	✓
Additional Categories	Innovation, Regional Priority	Project management
Forestry Certification	FSC Only	Five options
Point Systems		
Level of Certification	4	4
Total points available	110	1,000
Certification points minimum	Req. 40 pts + prerequisites	Project points: 35%.
Point Minimum or Partial Credit	No	Yes
The accessor visits a project.	Yes	No
Certified Levels	Certified 40 – 49 pts	1-globe 36 – 55%
	Silver 50 – 59 pts	2-globe 56 – 70%
	Gold 60 – 79 pts	3-globe 71 – 85%
	Platinum 80 – 110 pts	4-globe 86 – 100%

**Note*: Data and rates are from Feb. 2023 from the Green Building Initiative (2023) and USGBC (2023).*

Table 1 (continued): Comparative Analysis of two green building rating systems

Criteria	LEED	Green Globes
Registration and Certification Fees		
Registration Fee for each project	$1,200	$1,500
Assessment and Certification	New Construction: $2,500-$22,000 Existing Buildings: $1,750-$15,000 Consultant Fee: $10,000-$30,000 Testing & Verification: $1,000-$10,000	Pre-Design Review (NC): $3,000 - $12,500 Design Review (NC): $4,635 - $15,500 Final Certification: $4,120 - $15,500
Certification Process		

LEED



Program points

Rating systems	Categories	Points	Weight (%)
LEED BD+C	Integrated Process	1	0.91%
	Location & Transportation	16	14.55%
	Sustainable Sites	10	9.09%
	Water Efficiency	11	10%
	Energy & Atmosphere	33	30%
	Materials & Resources	13	11.82%
	Indoor Environment Quality	16	14.55%
	Innovation	6	5.45%
	Regional Priority	5	3.64%
	Total	*110*	*100 %*
Green Globes	Project Management	100	5 %
	Site	150	12 %
	Energy	260	39.5 %
	Water	190	11 %
	Materials & Resources	150	12.5 %
	Indoor Environment	150	15 %
	Total	*1,000*	*100 %*

**Note: Data and rates are from Feb. 2023 from the Green Building Initiative (2023) and USGBC (2023).*

Over the years, GBRS, including LEED and GG, have faced criticism and debates as they attempt to address sustainability in buildings. One of the reviews was the insufficient integration of LCA, which will be included in future rating system versions. Another criticism was that certification could be granted to buildings that were not necessarily energy-efficient, although this flaw was addressed in later LEED versions. To address the issue of energy efficiency further, LEED v4 now requires projects to provide actual energy and water usage performance data to the USGBC for at least the first five years of occupancy. This will allow the USGBC to compare actual building performance to a modeled performance, provide feedback about operations to owners, and potentially offer helpful feedback to design teams (Reeder, 2010). On the other hand, some judges claim that GG lacks transparency, while others argue that LEED is too prescriptive and inflexible. Also, there have been discussions about the minimum percentage of points required for each environmental assessment area that may not fully address all aspects of sustainability (Reeder, 2010). Apparently, the choice between LEED and other rating systems like GG depends on the specific needs and priorities of the building owner or developer, considering factors such as transparency, flexibility, and the level of detail desired in the certification process.

METHODOLOGY

The research project has begun with a literature review of the current state of Green Building Rating Systems (GBRS). This section involved examining the two assessment methods, LEED and GG. Google Scholar database was used to conduct literature research as it showcases a wide range of scholarly literature. Initially, the research used keywords in the 'Article title, Abstract, Keywords' field. The search was limited to articles and review papers, and the keywords used in the research field were "LEED," "Green Globes," "Green building rating systems," and "High-Performance green buildings." A total of 146 documents matching the keywords were obtained. Next, the 146 papers were thoroughly reviewed by evaluating the title and abstract to find relevant papers focusing on GBRS in building construction. The search included 94 publications containing critical terms in titles, author keywords, and abstracts. The full papers of the remaining 94 publications were carefully analysed in the last stage to fully comprehend the relevance of completing the research aim. As a result, 15 papers were identified as relevant for a detailed literature review.

In the Case Study analysis, a set of criteria for comparative analysis will be developed through a literature review to identify suitable systems for application. The chosen systems will be evaluated based on assessment criteria, potential credit points, and strategies to improve the built environment and operational efficiency. Research practices should be used to ensure the accuracy and reliability of findings to make informed decisions. The next step will use a case study research design focusing on three main aspects. Firstly, explore the sustainable criteria used in the Georgia Tech Science Square project and their contributions to sustainability. Secondly, it provides fragments of an in-depth understanding of the technologies, methods, and means required to produce and operate high-performance green buildings (HPGB) in the project. Lastly, we suggest improvements to enhance the building's environmental performance in the recommendation section. The study will utilize evidence from a literature review and a case study to address research questions and provide recommendations for utilizing GBRS and promoting sustainable construction practices.

CASE STUDY

To compare the effectiveness of different GBRS, we conducted a case study with the Life science building project. In this project, the authors intended to investigate the sustainability aspects of the building design and construction practices during the preconstruction and construction stages. The choice of a GBRS for a project depends on its specific needs and the stakeholders' preferences. This study uses the later Proposed Criteria (Table 3) to evaluate which systems are most suitable for project certification. The findings of this study will be helpful for construction professionals, policymakers, and researchers interested in promoting sustainable construction practices and achieving a more sustainable built environment.

PROJECT DESCRIPTION

Georgia Institute of Technology has announced its plans to apply for green building assessment and certification for the Science Square Building on North Avenue near Northside Drive. The building is part of a new development complex called Science Square at 387 Technology Circle NW, Atlanta, GA 30313. This 18-acre complex will comprise a mixed-use residential and commercial community. The community already has a few existing buildings, including the Biotech Innovation Lab and an office building constructed in the early 2000s. The development is a five-phase project expected to cost over a billion dollars. Phase 1A, the life science project, includes an office building, residential components, and a parking lot. The Science Square Building has a total square footage of 750,000, which includes 285 residential apartments and a six-floor, 1,000-spot parking deck. This combines the two buildings and provides parking for the district. The construction comprises all the MEPs, structure, skin, lobby, and core restrooms. The tenants occupying the space have design input on the interiors, and the owners will lend them a hand. This is known as the Core & Shell portion. The construction began in April 2022 and is expected to be completed by Fall 2024.

SPECIFIC SUSTAINABLE CRITERIA AND UNIQUE FEATURES USED IN THE PROJECT

Table 2: Comparison Table of Scorecard between LEED and Green Globes

Categories/ Sustainable Criteria	Life Science Building project - Unique Features	LEED	GG
	Project Management	1	98
Integrative Process	Contract type: Cost-plus		
	Collaboration with Perkins & Will for Green Certification		
	Accountability for Design and Construction elements		
	Location & Transportation	15	N/A
Location	Convenient location near Belt Line, Midtown, and Stations		
Transportation	Bicycle facilities, EV parking deck, charging stations		
	Sustainable Sites	4	86
Pollution Prevention	Maintain the record forms during construction.		
Habitat Protection	Consideration of preserved open space & rainwater Mngt.		
Bioretention Areas	Handling stormwater and preventing city line overload		
Existing Water Detention Vault	Reaching max capacity, requiring extra bioretention areas		
Rainwater Management	New construction requiring a new detention vault		

Table 2 (continued): Comparison Table of Scorecard between LEED and Green Globes

Categories/ Sustainable Criteria	Life Science Building project - Unique Features	LEED	GG
	Water Efficiency	4	113
Indoor Water Reuse	Lab Office building with three cooling towers		
HVAC System	Convective system for water recycling		
Plumbing Fixtures	Low-flow mechanisms, sustainable materials		
Hot Water System	Four boilers on the top meet specified criteria.		
	Energy and Atmosphere	20	124
Energy Metering System	Monitoring individual-level energy consumption		
Electrochromic Glazing	5,000 panels of smart glass for UV light control		
LEED Certification	Two-for-one deal with Electrochromic glazing		
Glass Control System	QR codes, low-voltage wires, EMS system control		
	Materials and Resources	5	56
Recycled Material	82% recycled content for LEED certification		
Construction Waste Mngt.	Professional handling of recycled materials		
Raw Material Sourcing	Meeting EPD standards, concrete mix design		
Raw Material Availability	Easy availability in Metro Atlanta's local market		
Carbon Emissions	Concrete usage remains despite LEED incompatibility.		
	Indoor Environmental Quality	7	84
Indoor Air Quality Mngt.	Blue cellophane wraps over ducts, post-installation cleaning.		
Daylight Improvement	Electrochromic glazing for better daylight		
Quality Views	Strategic placement of labs and offices		
Low-emitting Materials	Use of materials with low emissions		
Cleanable Surfaces	Polished concrete and cleanable walls instead of carpet		
	Innovation in Design	6	N/A
Innovative Features	Electrochromic glazing, convective mechanical system		
Certification	Pursuing LEED gold certification with a score of 64		
	Regional Priority	2	N/A
	Total	*64*	*561*

**Notes: Sustainable Criteria above are based on LEED and GG certification categories. The project achieved LEED Gold certification with 64 out of 110 points (58%), compared to achieving 2-Globe certification with 561 out of 1000 points (56%) for Green Globes.*

CRITERIA PROPOSAL

Each building has different characteristics that could influence the stakeholders' selection of different GBRSs. Based on a literature review of published studies, this research suggests ten criteria for comparative analysis (Table 3). Selection criteria were included to filter the project's attributes and help improve data analysis. The decision support framework uses these criteria to enable stakeholders to make transparent decisions when selecting Green Building Rating systems for construction projects. When evaluating green building assessment systems, there are several factors to consider. For example, eligible building types refer to buildings certified under a specific green building assessment system (Reeder, 2010). In addition, significant factors like market penetration, brand recognition, reputation, and credibility refer to people's awareness and familiarity with a particular brand or organization (Reeder, 2010; *Landscape Management*, 2015). Rating building performance involves evaluating its energy efficiency, water efficiency, indoor environmental quality, and other sustainability-related factors (Manoj Katiyar et al., 2020). Moreover, third-party verification is necessary for all green building rating systems to ensure that the certification process is objective and credible (Reeder, 2010). Ease of use, compliance costs, professional designation, certification process, program points, and adaptability are essential factors when selecting a green building assessment system. The research used the proposed criteria to compare two examples of GBRS, LEED and GG. A decision support framework was used to apply these criteria as a filter, which helps stakeholders select the most suitable green building assessment system for their project.

PROJECT CERTIFICATION SYSTEMS EVALUATION & RESULTS

Choosing the appropriate assessment system is a crucial first step in the green building assessment process. The choice should be based on the unique needs and objectives of the project, as well as the preferences of the building owner and design team. The choice of a green building assessment system for a project depends on its specific needs and the stakeholders' preferences. This study uses the Proposed Criteria to evaluate which systems are most suitable for project certification. Factors such as eligible building types, brand reputation, rating building performance, third-party verification, ease of use, compliance costs, professional designation, certification process, program points, and adaptability are considered when evaluating suitable systems for project certification. The project team will use the Proposed Criteria to make their evaluation correctly.

Table 3: Evaluate the suitable systems for project certification using Proposed Criteria

#	Criteria Analysis	LEED	Green Globes	Justifications (based on the GTLSB project)
1	Eligible Building Types	✓	✓	All building types.
2	Brand Recognition	✓		Widely used, with over 105,000 compared with 3,223 certified projects worldwide.
3	Rating Building Performance	✓	✓	LEED has a prescriptive approach, with specific requirements for each credit. GG offers flexibility and can choose strategies that best fit the project's goals.
4	Third-Party Verification	✓	✓	Both Required. GG: Site visit
5	Ease of Use		✓	LEED: This can be complex and time-consuming. GG: Easier to use and less time-consuming.
6	Costs of Compliance	✓		LEED: Structured based on project size and more complexity in cost.GG: More cost-effective in a less complex process.
7	Professional Designation	✓	✓	LEED Accredited Professional (LEED AP) Green Globes Professional (GGP)
8	Certification Process	✓	✓	LEED can take several months. GG can be completed in a shorter timeframe. GT is familiar with the LEED process.
9	Program Points	✓		Based on Scorecard, LEED gold compared with 2-Globe certified
10	Adaptability	✓	✓	LEED: Global, adaptable framework for sustainability. GG: Adaptable, user-friendly sustainability assessment.
	Total	*9*	*7*	

**Note: The number of remarks for each criterion shows how important they are for the proposed study. A higher number of remarks means that the chosen system is a better fit. The table shows LEED scored 9/10 points, while GG only scored 7/10 points.*

RESULTS, DISCUSSIONS, AND RECOMMENDATIONS

RESULTS ON SELECTING THE SUITABLE GREEN BUILDING RATING SYSTEMS

After analysing the criteria presented in Table 3, it was concluded that LEED is the most suitable choice for the project. This decision was made based on several key factors. LEED and GG were deemed eligible for all building types, but LEED stood out due to its widespread recognition, with over 150,000 certified projects worldwide compared to GG. Additionally, LEED's prescriptive approach with specific requirements for each credit aligned well with the project's goals and expectations. Both systems meet third-party verification requirements, but GG includes a site visit as part of its verification process, providing an additional layer of assurance. GG is considered more straightforward and less time-consuming than LEED, which may be crucial for a streamlined and user-friendly certification process. However, LEED's structured costs based on project size and complexity may impact the decision based on budget constraints. LEED outperforms GG in terms of program points, achieving a higher level of recognition with LEED Gold compared to 2-Globe certified for GG. The difference in recognition between the two rating systems can impact the decision-making process for building owners and developers. LEED's higher level of recognition might be a decisive factor in favor of selecting it over GG, especially if achieving a prestigious certification level is a priority. When considering these factors collectively, the overall recommendation for LEED is well-supported by its brand recognition, alignment with project goals, and professional designation, among other important considerations.

RECOMMENDATIONS FOR IMPROVING ENVIRONMENTAL PERFORMANCE

The project evaluated in Table 1 showed that several areas of environmental performance need improvement. The Sustainable Sites and Water Efficiency categories scored the lowest percentage from the total points available, receiving a 4/11 score (36%) each. The lack of on-site rainwater management, failure to protect or restore habitats, and limited heat island reduction measures were some of the most significant issues of environmental performance observed in the category. These issues resulted in zero on-site rainwater management and habitat protection points, while only one out of two points was awarded for heat island reduction measures. Additionally, no points were awarded for light pollution reduction.

To improve the project's environmental performance from a site perspective, incorporating a robust green roof could address almost all the issues in the Sustainable Sites category. Water-absorbent plants across the building's footprint can significantly reduce stormwater runoff. Creating habitats for animals such as bee hives, birdhouses, and bat boxes requires thorough planning, installation, and maintenance to ensure that they help to preserve biodiversity without causing any harm or inconvenience. If done correctly, these habitats can be integrated into green roofs, improving ecological performance and earning credits. A green roof can also contribute to reducing the heat island effect. However, practical concerns such as cooling towers, mechanical ventilation, and specialized exhaust systems must be integrated into the overall design to ensure they do not interfere with the green roof's functionality or harm the local ecosystem. The construction phase must consider weight loads by reinforcing the structure, but it is a viable option with a suitable investment. The only aspect of Sustainable Sites that a green roof would not overcome is light pollution reduction, which is caused by exterior lighting systems and affects wildlife and health (Kibert, 2016). However, one solution is to limit the opacity of electrochromic glazing after sunset or install light-reducing window coatings and shades to reduce night glow. Reducing light pollution in such an urban environment is less practical (given current technology and safety standards) than other options listed in this section.

The project receives partial credit in many areas in the LEED category of Water Efficiency. The project must reduce indoor and outdoor water usage to obtain high scores. Half of the points can be earned through reduced water use, while the other half is earned by optimizing water use processes. As such, the project can expand the planned greywater-recycling cooling towers and recycle water for additional cycles before using it to rinse green spaces and roofs. Low-flow water fixtures are installed; future tenants must agree to use similar fixtures to earn credits.

The project had un-awarded points in Energy and Atmosphere (E&A), 61% of the total points, and Materials and Resources, 36%. Some credits were partially awarded from the E&A category, but Advanced Energy Metering received no points. To address this issue, the owner can install more energy metering devices on the large lab equipment, fulfilling metering requirements and allowing more manageable maintenance and energy optimization. Additionally, windmills could be installed to complement the solar array on the roof, reducing the necessary space for solar panels and enhancing the ecological performance of the project.

The largest area of lost points in Materials and Resources was related to reducing the impact of the life cycle. While the proposals above could have partially focused on this issue, a more comprehensive LCA of all materials used in the project, especially the Sourcing Raw Materials, would have been necessary earlier in the construction phase. These points may be lost now, but undertaking these areas for future phases of Science Square is essential.

DISCUSSIONS

The research findings presented offer valuable insights into evaluating GBRS, explicitly focusing on comparing LEED and GG within HPGB. The study's project analysis provides a practical application of sustainable construction principles. It highlights the importance of integrating sustainable criteria, innovative technologies, and continuous improvement strategies in building design and operation. One key finding of the research is identifying areas for improvement in environmental performance within the project. By pinpointing inefficiencies, the study reveals that the Sustainable Sites and Water Efficiency categories scored the lowest percentage points, indicating opportunities to enhance on-site rainwater management, habitat protection, and heat island reduction measures.

Moreover, the research emphasizes the significance of practical considerations, such as cooling towers, mechanical ventilation, and structural reinforcement, in effectively implementing green roof systems. Addressing these technical challenges and ensuring compatibility with building systems and local ecosystems is crucial to optimizing environmental performance in HPGB projects. This finding underscores the need for a multidisciplinary approach to sustainable construction practices, requiring collaboration among architects, engineers, and environmental specialists.

Furthermore, Lean Construction principles focus on maximizing value and minimizing waste throughout the construction (Alarcón et al., 2013). This study contributes to Lean Construction by providing a comparative analysis of LEED and GG within the context of environmental performance assessment for an educational campus facility. This study emphasizes efficiency, sustainability, and continuous improvement in construction, aligning with Lean principles of optimizing resource utilization and enhancing project outcomes. The research suggests a sustainable framework integrating guidelines, standards, and technical expertise to achieve green building. Analyzing GG and LEED within environmental performance assessment allows construction stakeholders to select the most suitable GBRS that best aligns with project goals, sustainability objectives, and performance criteria.

CONCLUSIONS

The construction industry is transitioning towards sustainable building practices and reduced energy consumption. This shift is driven by various factors, including environmental concerns and the demand for more energy-efficient and environmentally friendly buildings. As the demand for sustainable buildings grows, sustainable building practices and rating systems like LEED and GG will become more important in promoting a sustainable environment for future generations. Our research contributes to the body of knowledge by providing an in-depth understanding of developing sustainable construction practices and the long-term sustainability of HPGB. Our study suggests that using GBRS and a comprehensive approach to building design, construction, and operation can help solve significant challenges the construction industry faces, such as energy consumption reduction and achieving sustainability goals. These approaches can promote a more sustainable built environment for future generations, benefiting both people and the planet. Our study proposes a sustainable decision framework that integrates guidelines and standards, sustainable criteria, and technical expertise, advancing prior works. The Georgia Tech Life Science Building is an excellent example of sustainable building practices, with its energy-efficient systems, natural light and ventilation, eco-friendly materials, and responsible waste management practices. Our study benefits professionals and academics by providing a valuable resource for comparative analysis and promoting the implementation of GBRS. Although there are some limitations, our findings are helpful to construction professionals, policymakers, and researchers interested in enhancing sustainable construction practices and achieving a more sustainable built environment.

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JET GROUTING: APPLYING LEAN PRINCIPLES IN GEOTECHNICAL ENGINEERING TO REDUCE WASTE

Björn Bernhard Vauk[1] and Dennis Dalchau[2]

ABSTRACT

Jet grouting is a widely used method for ground improvement and for sealing measures in geotechnical engineering. Due to the nature of the process, the material consumption of water-binder suspension is high. The objective of this research is to enable a more efficient use of resources by evaluating and reducing the waste of the resources used in the jet grouting process, taking lean principles into account.

The objective of this paper is to develop a production flow model for the jet grouting process. This is to enable a continuous improvement of the production processes and a reduction of the associated material consumption through recycling.

A production flow model is proposed to determine the amount of binder suspension required for production as a function of production time. The model presented will be used to control and continuously improve the production process and associated use of resources in future research. This will be done in accordance with the lean principles of customer value, value stream identification, flow, pull and striving for perfection.

KEYWORDS

Lean and Green, Sustainability, Waste, Production Pull

INTRODUCTION

The construction industry is currently facing the challenge of simultaneously achieving greater sustainability and enhancing efficiency. Sustainability and lean construction are increasingly becoming key topics in the german construction industry, with ecological responsibility and efficiency through the optimal use of resources taking centre stage. The objective of sustainability is to achieve long-term ecological, social and economic stability in order to meet the needs of the present without compromising the opportunities of future generations (Schlacke, 2023). This principle is also enshrined in Article 20a of the German Basic Law.

The objective of lean construction is to focus on effectiveness through customer orientation and to continuously improve efficiency by reducing waste. Waste can be classified into construction-specific categories (Koskela et al., 2013), which facilitates its identification. The five key principles of the Womack & Jones (2003) model must be considered in their entirety for the successful implementation of lean construction. Firstly, the principle of value specification defines the value of a service from the customer's perspective, which forms the basis for all subsequent steps. Subsequently, value stream identification leads to the analysis and optimisation of all necessary activities in the value chain. This involves the identification

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and elimination of cost-increasing activities (Muda Typ 2) and the reduction of (un)necessary activities that do not increase value (Muda Typ 1). The objective of the flow principle is to design all activities in a manner that ensures a continuous and uninterrupted process, with the aim of minimising cycle times. The pull principle means that production is controlled by actual demand, which enables agile and demand-oriented value creation. Finally, the principle of striving for perfection promotes a culture of continuous improvement by making incremental changes to get closer to an ideal state.

The jet grouting process is used in geotechnical engineering for the construction of auxiliary structures such as underpinning of buildings, horizontal sealing of excavations and ground improvement. Once the binder suspension mixed with the subsoil has hardened, a structurally stable and sealing earth mortar body is created.

The sequence of production processes in jet grouting can be identified using the value stream analysis method (Rother & Shook, 2003) and described quantitatively using a model to be developed. The erosion process begins after the borehole is drilled with the use of a high-energy hydraulic cutting jet, which consists of a binder suspension (1- and 2-phase system), to erode the existing soil structure and mix it with the binder suspension. The binder suspension, which has been mixed with the eroded soil structure, is returned via the borehole annulus as backflow suspension in accordance with the law of continuity and is then disposed of. In consideration of the lean principles, ideas are presented on how the backflow suspension from the production processes can be reused. In particular, the objective of this work is to contribute to the creation of a foundation for reducing the waste of finite resources through the production flow model presented and to promote the circular economy in geotechnical engineering. This will facilitate the transition towards more sustainable and efficient construction practices.

METHODOLOGY

The methodology describes the systematic methods used in the research to collect, analyse and interpret data. It includes both the theoretical foundation of the selected research approaches and the practical implementation of the study.

A comprehensive analysis of the process steps was carried out for the development of the production flow model of the jet grouting process. The key process steps were recorded directly on the construction site before and during production using value stream analysis and multi-moment recordings. These process steps were coordinated with the construction and project management teams to ensure precise documentation of the individual processes and their duration. The processing times of the rig were extracted from the machine data, which served as the basis for setting up the process model. Furthermore, the separation technology, consisting of screening systems and hydrocyclones, was carefully dimensioned. The adaptation was based on the expected geological conditions of the case studies, which were derived from the soil reports. The separation performance of the plant was determined in a systematic manner based on the density of the suspension and the remaining sand content of the backflow suspension.

A comprehensive literature review on the subjects of lean construction and jet grouting initially yielded no direct hits under the search terms used. This indicated a need to deepen the research and further elaborate the concepts of lean principles in the field of geotechnical engineering, in particular regarding the jet grouting method.

The investigation of the rheological properties of the suspension and the contents of water, cement and soil in the suspension is based on previous research by the authors. These previous studies form the basis for the current methodological orientation and future research activities based on them, which were also carried out by third parties (Thienert et al., 2017) on the basis of earlier investigations by the authors (Vauk, 2011).

JET GROUTING

SUSTAINABILITY CHALLENGES

Approximately 30 million tonnes of cement are consumed in Germany each year, resulting in an annual CO_2 equivalent of approximately 17 million tonnes (Verein Deutscher Zementwerke e.V., 2022, 2023). In the context of geotechnical engineering, the jet grouting process results in the disposal of approximately 50% of the approximately 220 to 350 thousand tonnes of cement used (Thienert et al., 2017).

"On average, 2,787 MJ of fuel energy and 113.1 kWh of electrical energy were used to produce one tonne of cement in Germany in 2022." (BVSE, 2022) The total energy consumption is thus approximately 887 kWh per tonne (0.2778 kWh/MJ). The operation of a separation plant as used in the case studies requires approximately 33 kWh of energy. This energy is used by two 2.3 kW screening plants and a hydrocyclone with a feed pump, which has an estimated energy consumption of around 25 kW, depending on the pump characteristic curve. The water requirement for the additional cleaning of the separation plant and the energy consumption of the separation process have already been amortised in terms of a positive ecological balance when processing 1 m³ of water-cement suspension (750 l/m³ water; 750 kg cement at w/c=1.0).

The DGNB certificate from Germany (DGNB, n.d.) or comparable certificates such as the LEED certificate from the USA (U.S. Green Building Council, n.d.) adopt a holistic approach to the sustainability of buildings, basing their assessments on defined criteria catalogues and usage profiles (Carneiro et al., 2012). The LC method value stream mapping enables the analysis of production processes from a sustainability perspective, identifying waste in the use of resources (Rosenbaum et al., 2012).

In the production process of the jet grouting method, the water-binder suspension required for the drilling and erosion processes is mixed and stored in the agitator regardless of the actual time-dependent demand (push). It is possible that the maximum processing time of the binder may be exceeded, resulting in the disposal of the fresh suspension unused, particularly in the event of high outside temperatures and production disruptions. If disposal is not carried out after the maximum possible processing time has been exceeded (hydratation), it is no longer possible to achieve the required final material strengths with certainty, which may result in defects (waste).

In the event that a mixed water-binder suspension is utilised during the maximum processing time, the suspension is utilised on a single occasion for the drilling and erosion processes. The water-binder suspension, which has been mixed with the eroded soil structure during the drilling and jet grouting processes, is returned via the borehole annulus as backflow suspension in accordance with the law of continuity (ratio 1:1 of water-binder suspension to backflow suspension). Subsequent to this, the volume of approximately 100% of the introduced suspension is disposed of, containing approximately 50 % of the introduced binder (waste).

USE OF EXCESS BACKFLOW SUSPENSION: FLOW CHART AND PULL CONTROL

Instead of disposal, the excess backflow suspension is to be treated and reused in order to prevent the waste of binder and water.

In instances where the actual demand for water-binder suspension can be determined by a production flow model based on time (depending on the process steps of moving the rig, setting up, drilling and erosion process), it can be mixed on demand (pull). Furthermore, the work content of the workers can be more evenly distributed according to the duration of the individual process steps, thereby increasing labour productivity.

Figure 1 shows the flow diagram of the suspension in the production process and the separation plant to be proposed. The requisite binder suspension, comprising water and cement, is combined in the mixer and previously stored in the agitator for delivery to the drilling rig. The drilling rig is supplied with the binder suspension via the high-pressure pump, and after the drilling and erosion process, it is pumped into disposal troughs or earth basins as backflow suspension via the return pump (1). After solidification, the backflow suspension is previously disposed of.

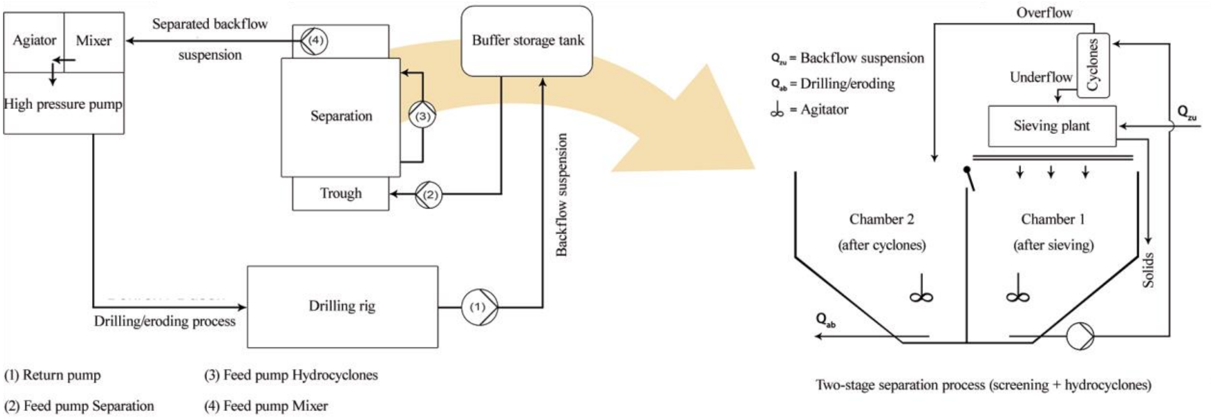

Figure 1: Flow diagram of the suspension and separation plant (Vauk, 2011)

The treatment of backflow suspension by separation is proposed. The use of a separation plant (two-stage separation consisting of screening and hydrocyclones) allows the backflow suspension to be treated for reuse. (Vauk, 2011) The separated backflow suspension is pumped to the mixing plant via the feed pump of the mixing plant (4), treated by the addition of binder and fed back into the production process.

In order to determine the time-dependent quantity of binder suspension required for the drilling and erosion process in accordance with demand, a production flow model is proposed. This model enables the time-dependent demand for binder suspension to be determined in advance, and the flow diagram to be designed in accordance with the lean principle of pull. The binder suspension required for the production process is drawn into production by the drilling rig from the high-pressure pump (pull). The separation plant is responsible for preparing the requisite quantity of binder suspension for production, with no excess. This is done according to demand. The proposed production flow model based on the pull principle ensures that the required quantity of binder suspension is known at all times. This allows the separation plant to be continuously improved in terms of its capacity (flow rate) and required separation performance (separation cut, screen area, mesh size of the screens, number of hydrocyclones, pressure of feed pump for hydrocyclones, etc.). This, in turn, enables the binder suspension to be recovered more economically.

In order to optimise the utilisation of the cement contained in the separated backflow suspension and thus reduce the need to add fresh cement, it is necessary to empirically test the effects of this reduction on the compressive strength of the elements produced from the suspension in the sense of a suitability test. In the authors' opinion, the addition of fresh cement should be gradually reduced, for example to 90 %, 80 % or 70 %. It is recommended that this test be conducted prior to any reduction in the addition of cement to the separated backflow suspension. Furthermore, it is essential to ensure that the cement already present in the suspension is processed before solidification commences.

PRODUCTION FLOW MODELLING FOR PULL CONTROL

In order to reuse the backflow suspension in the erosion process, it is necessary to determine the binder content that remains in the separated backflow suspension. In order to ensure that the static compressive strength of the jet grout body produced meets the required specifications, the missing binder content, which results from the water-binder value (target value) minus the remaining binder content, should be added.

Verification of the binder content after separation is not possible using electrometric, thermal and kaliometric methods (Vauk, 2011). As the solids properties change over time depending on the eroded subsoil (homogeneous areas), the time-dependent formation of the backflow suspension is to be described by the following production flow model.

The time required for the erosion process of a jet grouting element is dependent on the erosion performance of the subsoil in homogeneous areas:

$$t_j = \left(\frac{E}{\pi \cdot \left(\frac{d^2}{4} \right)} \right)^{-1}$$

with

t_j	Erosion time per metre [min/m]
E	Erosion rate (depending on the subsoil) [m³/min]
π	Constant
d	Diameter of the jet grouting element [m]

The suspension volume required for the erosion process for each homogeneous area is obtained from the erosion time t_j and the distance to be eroded l_j at a constant binder suspension flow rate of $Q_{j,min}$ per minute:

$$Q_j = Q_{j,\min} \times t_j \times l_j$$

with

Q_j	Suspension volume per homogeneous area (erosion process) [m³]
$Q_{j,min}$	Suspension volume per minute (erosion process) [m³/min]
t_j	Erosion time per metre [min/m]
l_j	Erosion distance per homogeneous area [m]

The suspension volume required for the drilling process for each homogeneous area is calculated from the drilling time t_d and the drilling distance l_d at a constant binder suspension flow rate of $Q_{d,min}$ per minute:

$$Q_d = Q_{d,\min} \times t_d \times l_d$$

with

Q_d	Suspension volume per homogeneous area (Drilling process) [m³]
$Q_{d,min}$	Suspension volume per minute (Drilling process) [m³/min]
t_d	Drilling time per metre [min/m]
l_d	Drilling distance per homogeneous area [m]

Depending on the geotechnical terrain model, a binder suspension requirement Q_E per jet grouting element results for n homogeneous areas:

$$Q_E = \sum_{i=1}^{n} (Q_{d,i} + Q_{j,i})$$

with

Q_E	Binder suspension requirement per jet grouting element [m³]
$Q_{d,i}$	Binder suspension requirement (drilling process) [m³]
$Q_{j,i}$	Binder suspension requirement (erosion process) [m³]
n	Number of homogeneous areas [-]

The production time t_E, in which the binder suspension Q_E is required, is calculated from the drilling time $t_{d,i}$ and the erosion time $t_{j,i}$ for n homogeneous areas:

$$t_E = \sum_{i=1}^{n} (t_{d,i} + t_{j,i})$$

with

t_E	Processing time (drilling process and erosion process) [min]
$t_{d,i}$	Drilling time [min]
$t_{j,i}$	Erosion time [min]
n	Number of homogeneous areas [-]

Taking into account the set-up time (moving and setting up the rig), the binder suspension requirement Q_E over time is calculated using the cycle time t_c per jet grouting element:

$$t_c = t_R + t_E$$

with

t_c	Cycle time (set-up time, processing time) [min]
t_R	Set-up time (moving and setting up the rig) [min]
t_E	Processing time (drilling process and erosion process) [min]

This results in the requisite binder suspension volume Q_E over the cycle time t_c, which is also produced as backflow suspension due to the volume balance (binder suspension to backflow suspension ratio of 1:1). The dilution of the backflow suspension (rinsing water) results in a dilution factor of 1.30 for cohesive homogeneous areas and 1.15 for rolling homogeneous areas. This indicates that 15 to 30% more backflow suspension is produced than the fresh suspension used (Vauk, 2011).

The time-dependent calculable binder suspension requirement Q_E over the cycle time t_c and the resulting backflow suspension quantity allows for the determination of the time-variable solids content of the suspension from the individual homogeneous areas with greater precision. The separation plant is to be dimensioned on the basis of the proposed production flow model, with regard to the required capacity according to the pull principle, and the achievable separation performance is to be continuously improved.

LEAN AND GREEN: ENVIRONMENTAL AND ECONOMIC BENEFITS

Taking In consideration of the principles of flow and pull as outlined in the LC methodology, the throughput time for the production of a jet grouting body comprising n jet grouting elements and the associated distribution of material consumption over the throughput time can be determined on the basis of the proposed production flow model. The throughput time is calculated as follows, taking into account the cycle time per jet grouting element:

$$TPT = \sum_{i=1}^{n} t_{c,i}$$

with

TPT	Throughput time for the production of the jet grouting body [min]
$t_{c,i}$	Cycle time per jet grouting element [min]
n	Number of jet grouting elements per jet grouting body [-]

The value stream analysis will facilitate a further reduction in throughput time by means of an analysis and optimisation of the processing and cycle times in accordance with the flow principle.

The implementation of the production flow model in the machine control of the jet grouting plant (drilling unit, high-pressure pump and peripherals) will also result in a continuous improvement of the production process in terms of labour productivity through automation. While manual operation of the mixing plant and the high-pressure pump currently utilises personnel capacity, the binder suspension required for production is to be automatically determined, mixed and drawn into the drilling and erosion process by the drilling rig according to the pull principle.

The solids properties of the backflow suspension should be able to be determined more precisely on the basis of the production flow model and the separation technology should be adjusted to this more efficiently. This would enhance the efficiency of the separation process, thereby increasing the recovery rate of the backflow suspension.

The required construction time should be estimated during construction based on the production flow model and the actual set-up times from the available machine data. Continuous construction time forecasting during construction would enable transport to be planned with greater precision in advance and transport costs to be reduced in a multi-project approach by sequentially linking construction sites.

The reduction of material stocks is to be achieved through the implementation of material requirement forecasts and needs-based material orders. In addition to the potential economic benefits, there is considerable ecological potential through the reduction of binder consumption as a result of a higher recovery rate of the binder suspension used and a resulting significant reduction in the amount of waste produced.

In light of the ecological objectives resulting from the ESG criteria (Environmental, Social, and Governance) and the obligation for companies to report on sustainability in accordance with the CSRD (Corporate Sustainability Reporting Directive) in the European Union, the necessity for improvement in production from a sustainability perspective is becoming increasingly important, regardless of economic interests (European Union, 2022).

CASE STUDIES: REPROCESSING OF EXCESS BACKFLOW SUSPENSION

The separation technology has already been successfully implemented on two construction sites in Germany (Figure 2). By separating the backflow suspension, the solids content could be largely separated from the water content of the backflow suspension and returned to the production process.

Figure 2: Schematic representation of the separation plant for processing the backflow suspension (Keller, n.d.a, n.d.b)

The savings at a construction site in Heidelberg, Germany, amount to 30% of the otherwise incurred disposal volume of the backflow suspension (Keller, n.d. a). The backflow suspension that was not disposed of could be reused for necessary drilling processes after separation.

The savings at a construction site in Dortmund, Germany, amount to 10% of the otherwise incurred disposal volume of the backflow suspension and 35% of the binder used. This is because the suspension at this construction site could also be partially processed for the erosion process (Keller, n.d. b).

CONCLUSIONS

The proposed production flow model enables the precise determination of the required amount of binder suspension and its time-dependent control in accordance with the lean principles of flow and pull. The parameterisation of the separation technology, adapted to the geological and process engineering conditions in accordance with the production flow model, can facilitate efficient reprocessing, taking into account relevant homogeneous areas. Potential secondary effects include increased labour productivity and reduced transport costs, as production times become more predictable and sites can be effectively sequenced.

The precise determination of the binder content in the separated return suspension represents a challenge that requires further research. The precise determination of the binder content is crucial for the further development of the sustainability and efficiency of the process, as it enables a more precise remixing of the required amount of binder.

Another field of research is the development of an advanced machine control system. A control system based on the pull principle has the potential to enhance labour productivity through automation and to improve the recovery rate of the backflow suspension by enabling the separation of the backflow suspension as required.

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LEAN CONSTRUCTION SUPPLY CHAIN: A TRANSPORT PERSPECTIVE

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ABSTRACT

The extensive and interdisciplinary construction supply chain is susceptible to inefficiencies at the interfaces of organisations. These inefficiencies are exacerbated by intricate logistics systems that operate among numerous stakeholders and actors, involving concurrent activities, processes, and on- and off-site systems. Transportation stands out as the most significant element within construction logistics. The fragmentation of the transport function stems from its intrinsic nature to every business, typically involving externalised asset ownership and deployment. Inefficiencies infiltrate the system due to isolated planning across different segments, gradually accumulating into macro-level visibility.

To optimise logistics, particularly the transport function, identified strategies involve reconfiguring activities, combining resources, and repositioning actors. This paper delves into the impact of vertically integrating distribution, implementing integrated planning for transport operations, and incorporating reverse logistics into operations on the transport function within a supply chain for manufactured construction products. The study evaluates sustainability impacts using transport efficiency metrics and domestically determined parameters to benchmark the 'leaning and greening' of the specific supply chain under consideration.

KEYWORDS

Construction transport, Construction logistics, Optimised transport, Lean construction supply chain.

INTRODUCTION

The construction sector, as a norm, makes up around 13% of the global Gross Domestic Product (GDP) (UNEP, 2020). This industry holds a crucial position in fostering job opportunities, advancing infrastructure, and supporting businesses, thereby contributing significantly to socio-economic progress. Despite its beneficial influence, construction is a noteworthy consumer of resources and a substantial emitter of carbon. Worldwide, it is responsible for about 36% of energy consumption and 39% of emissions (UNEP, 2020).

A typical construction project involves the amalgamation of numerous resources and materials sourced from various suppliers, resulting in a complex and distinctive end-product (Guerlain et al., 2019; Tetik et al., 2021). Logistics, encompassing transportation, warehousing, and inventory management, represents a crucial interdisciplinary aspect of construction supply chains (CSC). It exerts a significant impact on project management and costs (Ying & Tookey, 2014). In a fragmented supply chain (SC), inefficiencies in coordination and integration become

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apparent at organizational and operational boundaries (Alashwal & Fong, 2015). The subsequent increase in logistics process overheads gives rise to sustainability concerns.

Construction logistics undertake two primary roles: overseeing on-site logistics activities and facilitating the transportation of resources to and from construction sites (Ghanem et al., 2018). Approximately 60-80% of the total work conducted on a construction site revolves around the acquisition of materials and services (Sezer & Fredriksson, 2021). The intricacy of construction logistics arises from the adoption of customised procurement methodologies by the relevant stakeholders, coupled with the fragmented nature of the SC (Tetik et al., 2021).

Transportation constitutes the most substantial element of logistics, as most other logistics processes, other than warehousing, are categorised as business processes rather than physical ones (Szymonik, 2012). The characteristic of construction materials being of low value but high volume (Balm & van Amstel, 2018) can result in significant transportation needs, even for relatively modest projects. Consequently, transportation holds considerable importance in the realm of construction logistics.

Apart from energy consumption, emissions, and financial costs, transport comes with inherent externalities. These externalities may manifest directly, such as noise, air pollution, and congestion, or indirectly, e.g., disruptions in ecosystems, health impacts, and reduced quality of life (Chatziioannou et al., 2020). Issues related to transport in construction arise both within the construction site and beyond it, influenced by factors such as (Fredriksson et al., 2020):

- SC inefficiency, where lack of information and coordination leads to low delivery performance.
- Inefficiency of on-site logistics, leading to avoidable loss of resources, and therefore, higher inputs for maintaining delivery performance.
- Disjointed management of the construction site and the associated SC, with a distinct boundary between the two.

Given the projection that transport is expected to account for approximately 60% of global emissions by 2050 (Edenhofer, 2015), the diverse array of resulting impacts suggests the potential for enhanced sustainability outcomes through optimisation. In the construction industry, in particular, the primary rationale for pursuing optimisation is the improvement of workflow reliability (Perez et al., 2015; Tetik et al., 2021).

Every business inherently involves transportation, with asset ownership and deployment typically being outsourced. Consequently, from an SC standpoint, both strategic instruments and operational mechanisms serve as effective tools for optimising transport (Dhawan et al., 2022). However, the ability to make evidence-based decisions in the freight/logistics domain is hindered by a lack of pertinent data, as the available data usually pertains to individual journeys and lacks a comprehensive SC perspective (McKinnon, 2015).

In the context of New Zealand (NZ), approximately 93% of freight transportation relies on roads, with construction accounting for over 30% of this activity (Ministry of Transport New Zealand Government, 2020). The average truck's Gross Vehicle Mass (GVM) stands at around 22,500 kg (Wang et al., 2019), yet the average payload carried is only about 9.64 tonnes (Ernst & Young, 2021). These industry-wide figures, relevant to construction transport as well, underscore the immediate need and potential for optimising transportation, leading to improved sustainability.

The identified research gap pertains to using logistics planning as a means to achieve optimisation of transport at the strategic as well as operational levels. This study delves into the effectiveness of vertically integrated distribution, integrated transportation planning, and the integration of forward and reverse logistics as strategies to enhance efficiency and sustainability within a specific segment of the NZ CSC. The findings of this study indicate the potential applicability of these strategies across the broader spectrum of the CSC.

ANALYSIS BASELINES

The analysis baseline for this paper evolves along four directions: -

1. The problem of construction logistics.
2. A review of the construction materials SC.
3. Metrics for evaluating freight transport efficiency.
4. The resulting research questions.

THE CONSTRUCTION LOGISTICS PROBLEM

Construction logistics coordinate, control, and manage material flow from processing of raw material to final use in the construction process. Additionally, they include waste removal and disposal along the reverse route (Ying & Tookey, 2014). Stakeholders participate in various on- and off-site activities, which may be in the domains of planning/organising, transport, and activities related to construction on site (Janné, 2020). Key concerns include planning, designated spaces for loading/unloading, materials handling, storage, and linking actors and channels of the logistics system through transport (Janné & Fredriksson, 2019; Lange & Schilling, 2015).

The conventional perspective on construction logistics primarily centers around the main contractor's viewpoint, aiming to enhance on-site production efficiencies (Fredriksson et al., 2022). The management of suppliers and on-site deliveries is guided by the primary constraint of storage space (Lundesjö, 2015). The main contractor can effectively tackle both horizontal fragmentation issues (involving disaggregated skill sets/expertise) and vertical fragmentation issues (related to well-defined phases) due to the project-centric nature of construction delivery. However, concerns related to longitudinal fragmentation are overlooked, as suppliers and transporters operate independently and only collaborate for site-specific deliveries. The following major reasons for the differences between freight transport and construction transport (optimisation) are, therefore, inferred: -

- The distinctive characteristics of the CSC, marked by bespoke operations and a fragmented composition (Alashwal & Fong, 2015; Guerlain et al., 2019).
- Patterns of transport usage driven by project-centric delivery requirements (Sezer & Fredriksson, 2021).
- The widespread use of industry-specific equipment (Guerlain et al., 2019).
- Unlike city logistics, where responsibility lies with city managers, the construction industry bears the responsibility for construction logistics management (Janné & Fredriksson, 2021).

From the suppliers' standpoint, the fragmented logistics perspective undergoes a reversal. Deliveries managed by suppliers become effectively consolidated, showcasing greater efficiencies in comparison to the typical business-as-usual (BAU) approach (Dhawan, 2023).

THE CONSTRUCTION MATERIALS SUPPLY CHAIN

The construction materials SC is composed of three primary actors. The bulk suppliers and the construction site represent the two ends. The Builders' Merchants (BMs) and retailers are interposed between the two. The interposed actors provide interim storage and consolidation. The typical methodologies adopted for construction materials supply are illustrated in Table 1 (Commerce Commission New Zealand, 2022).

In the CSC, BMs play a crucial role as the primary economic stabilisers. They extend lines of credit to contractors and absorb market fluctuations by holding 'safety' stocks. BMs' inventory carrying costs can reach up to a fifth of the overall inventory costs (Vidalakis et al., 2011).

Table 1: Construction materials supply models (Commerce Commission New Zealand, 2022)

Model	Description	Typical supplies
Freight into Store (FIS)	Routing of bulk or retail quantities of materials through BMs, where bulk suppliers cannot manage retail quantities.	Aggregate, bricks, cement, fittings, plumbing, fixtures, heating supplies, tools
Specialist stockist sales	Marketing by manufacturers through their own subsidiaries.	Proprietary items
Direct to Site (DTS)	Material supplied directly at the construction site by the bulk supplier, where intermediaries are not required.	Steel framing

BMs operate nationally, regionally, and locally. Customer interaction invariably takes place through area specific depots, whose transport is driven by customer delivery demands. A small vehicle fleet caters to local customers. Delivery planning relies on staff knowledge of the local area layout (Dhawan, 2023).

Regional and national merchants centrally oversee their vehicle fleets, typically under the management of a transport professional. However, in the case of local BMs, the depot manager, who may lack transport expertise, is responsible for fleet management, prioritising customer service over transport efficiency. The order cycle is typically 24 hours, catering to the next day's tasks (Commerce Commission New Zealand, 2022). Inefficiencies are concealed within the seamless quantity take-off, representing 'hidden costs' of construction material (Balm & Ploos van Amstel, 2018; Verlinde, 2015; Ying & Tookey, 2014).

FREIGHT TRANSPORT EFFICIENCY METRICS

Freight transport system efficiency is a strategic measure of goods handling, whereas vehicle efficiency is operational/tactical (Pahlén & Börjesson, 2012). Vehicle efficiency revolves around 'filling rate,' - the ratio of actual loads transported to the maximum achievable with vehicles consistently loaded to their rated capacity (McKinnon, 1999). For trucks, vehicle efficiency - the ratio of utilised and available capacities - is expressed by five individual measures (McKinnon, 2010; Pahlén & Börjesson, 2012):

- **Level of empty running** Percentage of the distance travelled empty.
- **Weight-based loading factor** Ratio of the actual weight carried to the rated payload capacity.
- **Tonne-km loading factor** Ratio of the actual tonne-km (product of weight and distance) to the rated payload capacity-based tonne-km.
- **Volumetric loading factor** Percentage of the total vehicle cubic capacity occupied by the load.
- **Deck-area coverage** Percentage of the floor area of the vehicle covered by a load.

Measuring vehicle efficiency includes both onward and return trips. The construction sector faces difficulties in securing loads for return transport, turning what was once deemed empty running waste (Bølviken et al., 2014) into consideration through the sustainability lens (Kohn & Brodin, 2008). As a result, both policy and business perspectives prioritise minimising empty running in the pursuit of sustainable distribution strategies (McKinnon & Ge, 2006).

PROBLEM DESCRIPTION, DATA, AND RESEARCH QUESTIONS

The absence of pertinent data hampers evidence-based decision-making in the field of construction freight and logistics. The currently accessible data tends to focus on individual freight journeys without providing a comprehensive SC perspective (McKinnon, 2015). This poses a challenge when attempting to quantify efficiency improvements and analyse the potential for further enhancement resulting from implemented SC models and operational philosophies.

PROBLEM DESCRIPTION

The focus of the investigation is plasterboard supply in Auckland, NZ. The BAU scenario uses the FIS model for distribution through a disaggregated network having three key nodes: the manufacturing facility warehouse, BM establishments, and construction sites. Two links connect these nodes for both information and material flow (Bulk supplier – BM and BM – Construction Site), each emphasising storage as a primary function. This model aligns with the theoretical ‘Distributor storage with carrier delivery' logistics model (Chopra et al., 2013).

The modified (DTS) model integrates distribution and manufacturing vertically, outsourcing transport through second-party logistics (2PL). In contrast to the FIS model, this configuration includes three nodes and three links. Two of these are information links for invoicing and delivery (Contractor – BM, BM – Bulk Supplier), while the third (Bulk Supplier – Site) manages physical delivery. The manufacturer directly delivers materials invoiced by the BM to the site, exemplifying the 'Manufacturer storage with direct shipping' logistics model (Chopra et al., 2013).

DATA AVAILABILITY

This study examines three months’ truck movements data (October 2020 to December 2020) related to plasterboard delivery using the DTS model in Auckland, NZ. The data was obtained from the logistics department of NZ’s largest plasterboard manufacturer and supplier, who maintain a log of daily truck movements for plasterboard delivery. The dataset was obtained in two parts. The first part provided the details of trucks used for plasterboard delivery (i.e., manufacturer, model, rated payload, and Gross Vehicle Mass - GVM). The second part provided details of trips undertaken by these trucks daily for plasterboard delivery (i.e., truck ID, departure time, quantities of items in accounting units and weights, and delivery destinations for various consignments). The data pertained to 2762 trips across 58 days. Travel distances and drop sequences were, however, not available in the dataset. The following operational characteristics emerged from the dataset: -

- 26 trips with different rated payload undertaking 42 trips transporting an average of 330 tonnes of plasterboard daily.
- One to six drops associated with each truck trip.
- More than three drops were seen in less than 1% of the trips, hence ignored, being insignificant for analysis.
- Almost 75% of the trips were single-drop trips.
- Transport was procured on a per-tonne basis irrespective of distances involved.
- Diesel-powered flat-bed trucks comprising the fleet.

RESEARCH GAP AND QUESTIONS

The DTS solution appears to have provided greater service efficiency and customer satisfaction vis-à-vis the FIS model. However, improved transport efficiency has not been quantified. In the Lean philosophy context, this research gap prompted the following research questions: -

- **RQ1.** What is the improvement in transport efficiency in DTS deliveries compared to FIS deliveries.
- **RQ2.** What is the potential for further transport efficiency improvement and the potential means to achieve it?
- **RQ3.** What are the means available to integrate reverse logistics and what are the likely impacts of this integration on transporting efficiency?
- **RQ4.** How does the supply chain become Leaner as a result of the above?

TRANSPORT EFFICIENCY ANALYSIS

MEASURES SELECTED

The analysis focused on weight-based and tonne-km-based efficiencies, termed 'loading efficiency' and 'capacity utilisation,' respectively. Loading efficiency (static), is measured at dispatch, and does not consider transportation distance. Capacity utilisation (dynamic) factors both loads and distances. To introduce distances and drop sequences, 370 trips were selected as a statistically significant sample representative of the dataset (2762 trips), using random (probability) sampling (Krejcie & Morgan, 1970).

QUANTIFYING EFFICIENCY IMPROVEMENT OF DTS OVER FIS MODEL

Through vertical integration, the DTS model reduces one node and one link in the distribution transport network (Figure 2).

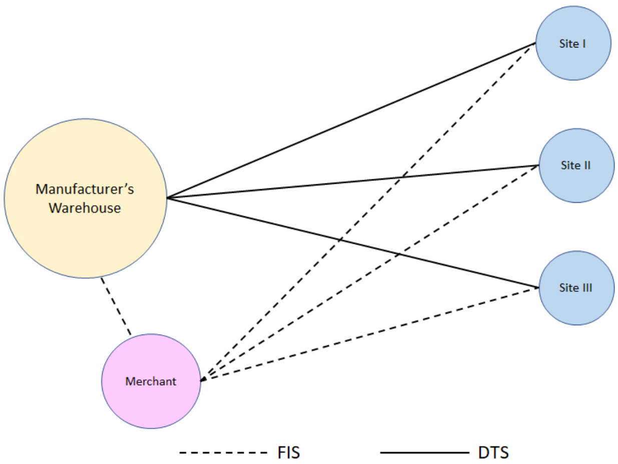

Figure 1: Transport network configurations for the DTS and FIS distribution models

Given that the three nodes connected by links form a triangle, any one link would always be shorter than the sum of the other two, unless all three are collinear – highly improbable in an urban setting. To estimate efficiency improvement through DTS rather than FIS deliveries each BM-destination pairing, the reduction in travelled distances served as a straightforward assessment parameter. A majority of the truck trips being single-drop (circa 75%) permitted considering individual BM-destination distances for the analysis. Inter-node distances were obtained from Google Maps. The analysis revealed a 30% reduction in distances travelled, equivalent to 11.1 km per trip, between the DTS and FIS models.

POTENTIAL FOR FURTHER EFFICIENCY IMPROVEMENT

The drop sequence was incorporated into the data sample (370 trips) from the 'Eroad' database (a NZ IT company providing GPS-enabled tracking services). Utilising inter-node distances, sequence of drops, loading efficiency, and individual destination loads, the analysis focused on tonne-km based capacity utilisation (Table 2).

The findings revealed a daily underutilisation of approximately 252 tonnes of truck payload, leading to non-utilisation of 72% tonne-km available. This highlights the necessity for enhanced planning strategies to decrease the number of daily truck trips while maintaining delivery output.

Table 2: Loading efficiency and capacity utilisation of trucks (DTS)

Drops	Trips	Loading Efficiency			Capacity Utilisation		
		Maximum	*Minimum*	*Average*	*Maximum*	*Minimum*	*Average*
1	261	99.21	4.31	55.89	49.61	2.16	27.99
2	81	99.77	6.45	57.08	55.79	3.33	27.84
3	28	90.33	14.99	60.53	42.11	4.93	24.82
Weighted Average (Fleetwide)				56.36			27.61

APPLICATION OF OPERATIONS RESEARCH

Transportation Problem

Logistics incorporates strategies and tools from various fields (Hrablik et al., 2015). In this case, the Transportation Model from operations research was explored as an optimisation tool. It typically involves a network with nodes representing sources and destinations connected by arcs representing routes, material quantities, and per unit shipping costs, with the objective of minimising costs while meeting destination requirements within the origins' supply capacity (Taha, 2013). The problem could not be transformed into a classical transportation problem due to a single origin and uniform channel costs. It was, therefore, reformulated as follows: -

- The sample dataset was disaggregated into daily operations' sub-datasets.
- The rated payload of each truck was considered an individual source (supply).
- Each delivery was considered an individual consumer (demand).
- The channel cost, being fixed, was considered unity.

The transportation problem was solved using MSExcel, which presented an upper limit of 200 objective co-efficients in the problem matrix. Being 'proof-of-concept' exercise, a truncated daily trip dataset while maintaining trip integrity, was used. The solution (decision variables - allocation of loads to trucks) are in Table 3.

Table 3: Transport optimisation (improved efficiency) using LP

Parameter	Manual truck allocation	LP based truck allocation	Improvement (%)	
			Absolute	*Over manual baseline*
Average loading efficiency	56.36%	92.89%	36.49%	64.81%
Daily truck trips	11	7	-	36.36%
Capacity utilisation (tonne-km)	27.61%	49.38%	21.77%	78.84%

The application of Linear Programming (LP) optimised the initial (truncated) 11 trips to 7. Extrapolating this to the actual baseline of 42 trips results in a daily reduction of 16 trips, without impacting delivery.

The Need for Integrated Planning

The application of LP highlighted the necessity for integrated planning between the transport contractor (supplier) and the bulk supplier/manufacturer of plasterboard (consumer). Currently, the manufacturer's priority is the daily transportation of ordered plasterboard quantities. The quantity of trucks employed, or the distances covered is not a consideration, given the 'per-tonne' pricing model. The transport contractor has the discretion of resource allocation. No resource-use analysis was considered essential as long as the daily tonnages are delivered.

Optimising transport becomes a necessity in two scenarios: when payments are distance-based (per-km) and when sustainability is integrated into the operational philosophy. The result is integrated planning, involving the manufacturer, even if only to monitor transport utilisation.

INTEGRATION OF REVERSE LOGISTICS

Truck capacity utilisation for a single-drop trip reaches a maximum of 50% (if fully loaded at the origin), and less than 50% for trips with more than one drop (Vrijhoef, 2015). Consecutive unloading at different drop points along the route creates capacity for backloads. This offers a potential opportunity to integrate reverse logistics with forward delivery, utilising waste backhauls on material delivery transport (Shakantu & Emuze, 2012). Considering estimates by Jacques (1999) and Nelson et al. (2022), approximately 20% plasterboard waste generation per site is considered a fair estimate.

Incorporating reverse logistics for removing plasterboard waste from construction sites relies on a comprehensive trip model, which includes the number of trips per truck site, load per trip segment, and the waste generated per site per truck. It considers average distances and loads from the sampled dataset, along with estimated plasterboard waste based on material delivery. Figure 2 illustrates the generalised trip model.

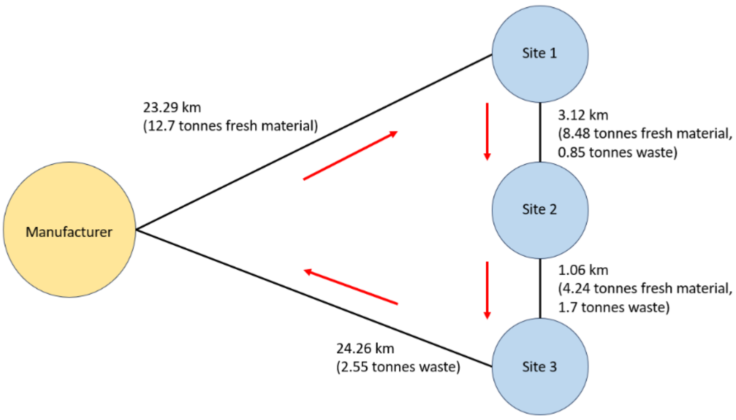

Figure 2: Generalised trip model

The incremental efficiency improvement utilises 326 tonne-km after LP application and 393 tonne-km with waste plasterboard backhauls, out of an available approximately 672 tonne-km per trip. This results in enhanced efficiencies of 49.38% and 58.04%, respectively, compared to the baseline of 27.61% (DTS).

LEANING THE SUPPLY CHAIN

THE LEAN PERSPECTIVE

The Lean perspective is discussed based on the three fundamental Lean construction principles, i.e., Respect for People, Continuous Improvement, and Maximising Value while Minimising Waste (Doan, 2022).

Philosophy 1: Respect for people

Respect for people extends to the environment. Thinking about the long-term environment, sustainability, and the impact of current actions on the planet and future generations (hidden stakeholders) forms an inseparable part of this philosophy (Doan, 2022). Table 3 brings out the reduction in vehicle-km and diesel consumption.

Table 3: Annual reduction in vehicle-km and fuel consumption

S. No.	Reason for improved transport efficiency	Impact parameters		Conversion based on
		Vehicle-km	*Fuel (litres)*	
1.	Adoption of DTS model over the FIS model	126,100	-	BAU truck GVM
2.	LP-based reduction in truck trips	207,600	-	
3.	LP-based improved capacity utilisation	-	35,500	Reduced truck GVM
4.	Integration of reverse logistics	-	19,674	

The impacts of these are reduction in emissions, pollution, carbon embodiment per-unit weight of plasterboard, noise, traffic congestion, disruption of ecosystems, negative health impacts from reduction of emissions due to optimised transport, and reduction in disposal to landfill and embodiment of resources due to re-cycling of waste plasterboard as raw material.

Philosophy 2: Continuous Improvement

Continuous improvement is illustrated by progressive application of tools and methodologies to scaffold improvements achieved. In the instant case, vertical integration, followed sequentially by application of operations research and integration of reverse logistics form the 'improvement staircase'. The progressive transport efficiency improvement is shown in Figure 3.

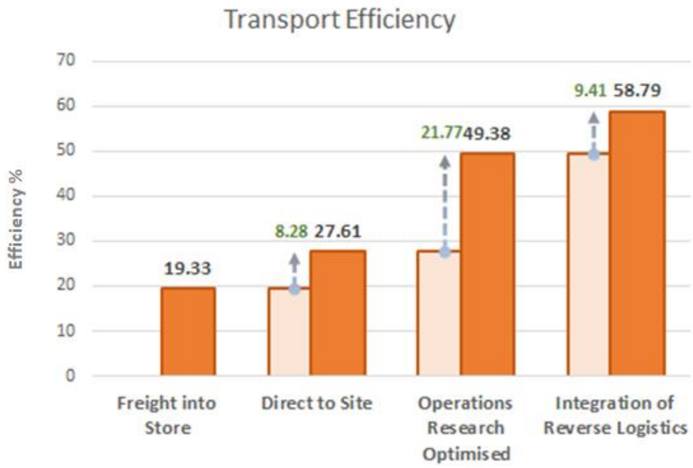

Figure 3: Progressive transport efficiency improvement

Philosophy 3: Maximising Value while Minimising Waste

Waste minimisation is achieved through i) Improved transport efficiency (reducing resource wastage); and ii) Utilisation of waste plasterboard as raw material for manufacture (Erbs et al., 2021) to the extent of approximately 10% to maintain quality, diverting it from landfill.

CONCLUSIONS

Logistics is multidisciplinary and does not have its 'own' tools and methodologies, adopting these from various domains. In answering the research questions, the initial analysis pertained to the quantification of transportation efficiencies achieved as a result of vertically integrating (Lidelöw & Simu, 2015) distribution with manufacture, from the Supply Chain Management domain. Next application of LP from the operations research/management domain was discussed as a tool for further optimisation. Integrated reverse logistics further improved transport efficiencies. The question of Leaning the SC was addressed by viewing the progressive improvement through the lens of fundamental Lean construction principles, i.e., Respect for People, Continuous Improvement, and Maximising Value while Minimising Waste.

The simple analysis leads to life cycle improvements in the SC, in addition to direct ones. It also points to further research directions such as quantification of reduced embodied resources, economic/cost implications of improved efficiency both within the CSC and economy-wide, issues of fleet management for improved operational sustainability, and the means for integrated planning.

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SMART HOMES AND WASTE REDUCTION

Samira Awwal[1], Patricia Tzortzopoulos[2], Mohammad Ruhail Gulzar[3], Rakesh Mishra[4], Leigh Fleming[5] and Scott Conor[6]

ABSTRACT

The concept of smart homes includes smart technologies, systems, and devices to facilitate efficiency, security, comfort, and overall management of the home environment. This paper presents the concept of smart homes and discusses how it relates to waste reduction, especially energy waste. As waste reduction is one of the key lean principles, the notion of a "smart home" and " waste reduction" can be connected to optimising efficiency and increasing the functionality of the home. An experiment was carried out in the Huddersfield smart house research facility for the optimisation of energy usage through smart home technologies and efficient appliances, resulting in lifecycle waste reduction. The investigation highlights the connection between Smart Home' and 'Lean Waste Principles' indicating how energy use in the building lifecycle is hidden in lean waste. This suggests a need for future empirical research to better understand how to reduce waste using smart home technology and provide solutions to resolve energy waste on a wider scale.

KEYWORDS

Smart Home, energy efficiency, waste reduction, comfort, lean waste

INTRODUCTION

In today's world, the rapid development of 'The Internet of Things' has led to the gradual integration of the concept of a 'Smart Home' into people's daily lives. Meanwhile, there is a worldwide increase in energy demand, resulting in negative environmental impacts. Buildings are one of the major contributors to rising energy consumption (Chenari et al., 2016). There are 29 million homes in the UK which use 14% of the UK's energy consumption (Pérez-Lombard et al., 2008) and the UK government aims to reduce 60% of these emissions by 2050 (Zala et al., 2017). This highlights the critical need for more effective strategies to manage energy consumption (Hakawati et al., 2024).

Efficient waste elimination is crucial to address the stated problem (Nižetić et al., 2019). One of the key Lean principles is waste reduction (Koskela et al., 2013). Seven types of waste are found in lean literature i.e. transport, inventory, motion, waiting, overprocessing, overproduction, and defects, and the eighth waste, making-do (Koskela et al., 2013). This paper will focus on waste in use, as opposed to production waste, i.e. wasted energy due to the

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inefficiency of buildings; and defects- appliance inefficiency in the home during a building's lifecycle, emphasising energy-efficient living environments. In a lifecycle analysis, five stages are typically recognised in the life cycle of infrastructure: material manufacturing, construction, maintenance, operation, and end-of-life (Liljenström et al., 2022). This study focuses on the operation stage of the building lifecycle.

Andrade et al., (2022) highlights that the integration of smart technologies expedited by the Internet of Things (IoT) has a pivotal role in reducing energy usage and enhancing user comfort. Monitoring energy consumption and improving efficiency through computational solutions can be achieved through smart homes, equipped with technologies for customised services.

The notion of Smart home technology and energy usage in the built environment is not novel. However, fewer evidence is found on waste reduction through energy efficiency from a lean construction lens. This paper discusses the concept of a 'Smart Home' and waste reduction from a lean construction perspective, for instance, energy optimisation using energy management systems, appliance efficiency, home automation, scheduling thermostats to reduce energy usage, and renewable energy integration. The main aim of the paper is to link smart homes to Lean from the context of lifecycle waste reduction. An experiment in the smart house research facility (Huddersfield Smart House Research Facility-HSHRF; see link here: Smart House - University of Huddersfield) is presented to support the findings.

RESEARCH METHOD

The research method included three steps; (i) a bibliometric analysis of Scopus-indexed papers; (ii) a review of relevant topics, and (iii) an experimental case study in the Smart House research facility at the University of Huddersfield.

The bibliographic analysis was conducted to understand the connection among Smart homes/ intelligent buildings, energy utilisation, and waste reduction. The following keywords are used: {smart AND home AND waste AND management AND energy AND efficiency} (See Figure 1). 36 Scopus-indexed journals were used as a database to generate the co-occurrence of topics and create a network of visualisation.

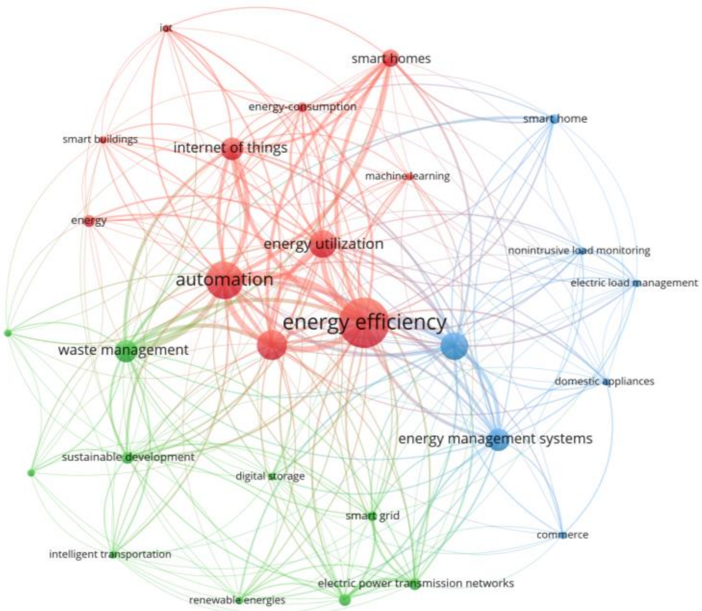

Figure 1 Bibliographic Analysis- Network visualisation of papers' keywords

It is observed in Figure 1 that effective energy efficiency is intrinsically connected to certain keywords, such as energy management, waste reduction, smart home, IoT, renewable energies, and energy consumption. After identifying keywords from the co-occurrence network, a related relevant topic is selected for the review of the literature.

A case study experiment conducted at Huddersfield Smart House Research Facility (HSHRF) is presented to support the findings. The HSHRF is a house built within a building, which has a number of sensors, as well as a digital twin, and it's used for testing is used for various physical testing purposes. The experiment explored a smart radiator in the HSHRF to observe the energy usage through a period of 24 hours and evaluate optimisation of energy in smart home environments.

LITERATURE REVIEW

CONCEPT OF SMART HOME

A smart home is supplied with a high-tech network connecting sensors and home devices, which can be remotely accessed, monitored or controlled (Wu et al., 2023). The 'original' concept of a smart home is an integrated home with various services interconnected by a single communication system (Lutolf, 1992; Aldrich, 2003). In a regular home environment (i.e., not smart), residents operate home appliances and devices individually and separately. Appliances and lighting are individually controlled by occupants rather than a centralised control system. However, network devices have proliferated in the environment of ubiquitous computer technology. As a result, in the last decade, the "smart home" concept has received considerable attention in the built environment (Yang et al., 2017). There are various definitions of a Smart Home in the literature, as shown in Table 1.

Table 1 Definition of Smart Home

Author	Year	Description of Smart Home
American Association of House Builders	1984	In the early 1960s, the concept of smart homes was called 'Wired Homes', built by hobbyists.
(Lutolf, 1992)	1992	A Smart Home is known as a network of home electronic devices and attributes linked to the internet.
(Aldrich, 2003)	2003	A "smart home" is a residence installed with computing and information technology that senses and reacts to the needs of the residents, aiming to enhance comfort, security, and entertainment through technology management.
(Lertlakkhanakul et al., 2008)	2008	smart home can be regarded as a 'smarter' version of home automation with integrated technological systems
(Albany et al., 2022)	2022	A smart home is a group of connected IoT devices that can be controlled remotely using a smartphone or computer.
(Munirathinam, 2020)	2020	Smart home technology, is defined as home automation, providing homeowners security, comfort, convenience, and energy efficiency by allowing them to control smart devices.
(Basarir-Ozel et al., 2023)	2023	A smart home represents smart devices and sensors, integrated into an intelligent home network, offering control, monitoring, and support services to satisfy user needs.

Smart home technology can be used primarily in two ways: (i) to ensure the occupants safety, health and comfort and (ii) to facilitate household operations, especially reduce energy costs (Schieweck et al., 2018). A smart home is connected with cutting-edge technologies for automation of functionalities, household appliances, and electronics for communication and entertainment (Lertlakkhanakul et al., 2008; Schieweck et al., 2018; Albany et al., 2022). In summary, the concept of the 'Smart Home' has been proposed to increase the building's efficiency and performance, enabled through the rapid development of artificial intelligence (Zhang et al., 2023); and integrated smart systems play a role through IoT technology (Huang et al., 2018).

CONCEPT OF WASTE IN LEAN

A core principle of Lean is to eliminate waste with the aim to increase performance (Aisyah et al., 2023) and as a driver for improvement (Tzortzopoulos et al., 2020). Seven lean waste types are:1. Transport: redundant and unproductive flow of information or materials; 2. Inventory: information or materials waiting to be processed; 3. Motion: Employee performed activities associated in the workflow; 4. Waiting: waiting for information or inputs; 5. Overprocessing: Associated with the processor (conversion) operation, which can possibly be prevented; 6. Overproduction: Producing more than is needed for immediate use; 7. Defects: accusation, untrustworthy or miscoded data, documentation and transcription errors, unauthorised procedures (Koskela et al., 2013; Owais et al., 2023; Sutherland & Bennett, 2007). Energy usage reduction is often concealed in lean wastes. EPA, (2007) highlight energy impacts associated with wastes targeted by lean. Table 2 provides an overview of lean waste types, lean waste in production, and energy use hidden in lean waste by (EPA, 2007; Owais et al., 2023; Sutherland & Bennett, 2007).

Table 2 Lean Waste in production and energy use hidden in lean wastes

Waste Type	Lean Waste in production	Energy Usage
Overproduction	Connected to a larger volume of production than requested or desired	Unnecessary energy used in operating equipment
Inventory	Pertaining to material waste caused by overstocks or unused stockpiles	Additional energy required to heat, cool, and light inventory storage and warehouse
Transport	Avoidable movement of products, materials, or information.	Additional energy used for transport
Defects	It occurs when the result fails to fulfil the quality standards.	Energy consumed in making defective products-, increasing lighting, heating, and cooling demand and energy consumption
Motion	Unnecessary movement of people, such as walking, reaching and stretching	Deals with activities performed by users
Over-processing	Associated with the processor (conversion) operation, which can possibly be prevented	More energy consumed in operating equipment due to unnecessary processing
Waiting/Delays	Any delay between the end of one process and the start of the next activity	Wasted energy during production downtime from heating, cooling, and lighting

In addition to the above wastes, the eighth category of waste is conceptualised by (Koskela, 2004). Making-do occurs where a task is initiated without all standard inputs, especially in production where there are multiple uncertain inflows to the tasks. The inputs can be materials, machinery, tools, personnel, external conditions, instructions, etc. Waste by making do can occur in different ways, for example, efficiency syndrome- the urge to maximise resource utilisation; pressure for an immediate response- situation of incomplete inputs and unreliable inflows of the production system (Koskela, 2004).

Buildings contribute significantly to the depletion of natural resources and emissions to the environment during its lifecycle. Buildings generate manufacturing waste, transportation of materials waste, construction waste, operation/use waste, and deconstruction/end-of-life waste. As the building industry is shifting its focus to sustainable development, the consideration of these waste factors is crucial to ensure waste reduction (Hossain & Thomas, 2019). The following section discusses the notion of smart home technology in waste reduction from the building use/operation point, especially in energy waste.

WASTE REDUCTION THROUGH SMART HOME

The evolution of smart home is transitioning from the initial emphasis on occupants' comfort to the development of innovative solutions aimed at effective and efficient control of the infrastructure (Murty & Kumar, 2020). A smart home can significantly influence waste reduction through the integration of multiple technologies and smart systems, resulting in reducing environmental pollution, and thus increasing the degree of environmental health (Škulj et al., 2019). The deployment of smart meters and controls, and the emergence of smart appliances and their inclusion in home networks allow energy consumers to benefit from a more comfortable, and healthier living environment, while consuming less energy thus reducing waste (European Commission et al., 2017).

There are multiple aspects connecting the smart home with energy waste reduction among which the paper reviews the following topics: (i) Energy monitoring and optimisation; (ii) Smart appliance efficiency; (iii) Home automation; and (iv) Renewable energy integration and smart home energy storage.

Energy Monitoring and optimisation

Smart monitoring systems can play a crucial role in integrating energy management and monitoring control systems through IoT technology (Huang et al., 2018). 'Smart Sensors' can be defined as sensors using semiconductor technology to join output power devices with control circuitry (Naidu, 1998). The smart home comprises of sensors that are wirelessly connected and dedicated to measuring physical quantities, such as various environmental characteristics- temperature, sound, light intensity, humidity, force, and pressure (Chakraborty et al., 2023; Chauhan et al., 2022). Additionally, smart home wireless sensors can detect smoke, gas, and temperature and alarm early fire in a smart home environment.

Optimisation of energy can be achieved through a smart energy management system for residential buildings (Essa, 2019). The energy management system prioritises energy conservation, expenditure reduction, safety improvement, and easy maintenance (Li et al., 2020). Efficient energy management systems reduce energy consumption, waste, and costs, help conserve fossil fuel resources, and increase occupant comfort. For instance, if Matsui, (2018)'s home energy management systems (HEMS) are installed in smart homes, they can predict the indoor comfort level, reduce 5.15% electricity consumption, and increase the comfort level by 16.4% for occupants. Another example is IoT-based smart sensors through energy-applied load monitoring (ALM) systems can be explored to predict energy consumption through smart data collection. Users are then informed by the total energy usage from several sensors connected to home devices; and take corrective actions to optimise consumption (Oudat et al., 2019).

Appliance Efficiency

Smart home appliances constitute multiple devices and applications such as smart washing machines, smart kettles, smart dishwashers, stoves, and smart refrigerators among others. Smart appliances can be remotely accessed, controlled, and monitored by the occupants (Balta-Ozkan et al., 2013). In a smart home environment, various devices can be remotely controlled through mobile terminals such as smartphones (Ma et al., 2023). One of the essential benefits of smart home appliances is the potential for energy reduction by both smart appliances themselves and (in)direct feedback options to the user (Du et al., 2023). For instance, smart lighting integration contributes to energy efficiency when combined the required lighting with natural lighting. User requirements are calculated and the lighting system can be adjusted using automation or task/user-based lighting to reduce the waste of energy (Vijayan et al., 2020).On the other hand Paul et al., (2022) argue, that the older version of the same appliance consumes more energy, than the newer ones. It is better to determine the economic and energetic replacement time of the appliances for the customer thus impacting the overall economic impact. In summary, smart appliances when appropriately installed and replaced in a timely manner, can optimise resources more efficiently, improving equipment utilisation and reducing waste.

Home Automation

Automation is defined as the capacity of technology to carry out functions in an autonomous mode with the least possible human interaction (Wong et al., 2017). An automation system is at the core of the concept of a Smart home, consisting of multiple systems in a home, for instance, control of HVAC systems, lighting control, energy management, security systems, and entertainment in home environments (Asadullah & Raza, 2016), designed for user comfort and energy efficiency. Automation allows better utilisation of advanced technologies and conservation of energy to be prioritised through smart homes that are inbuilt with communicative and innovative technologies (Vijayan et al., 2020). The development of automation can act as a key factor in resolving the issues of energy poverty (Niu et al., 2024). Specifically, automated processes improve to streamline operations, minimise energy wastage, and optimise resource utilisation, resulting in energy supply increase (Farzaneh et al., 2021)

Renewable Energy Integration and Storage

To support a cleaner environment, there is a shift toward the integration of smart meters, renewable energy resources (RERs), smart sensors, and energy storage systems (Nie et al., 2023). Renewable systems are equipped with a fully automated energy system, photovoltaic panels, and battery-electric storage systems (Nakıp et al., 2023). For instance, Nezhad et al., (2022)'s paper discusses the smart home with solar power generation through a rooftop PV panel. The solar power generation is forecasted and scheduling can be organised to minimising the operational cost, for example using the energy for a home appliance load. Essa (2019) presents a home energy management strategy that adjusts electricity generation and consumption based on the operating parameters of photovoltaic battery systems and thermostatically controlled loads. Battery energy storage and renewable generation in Smart homes will therefore optimise energy and further contribute to emission waste reduction.

DISCUSSION

Building components consisting of individual autonomous behaviours, to be controlled by a level of central control is considered smart and lean (Chien, 2013). From the theoretical point, there is not enough existing empirical evidence to consider smart house waste reduction from a lean point of view, especially, how the energy use in the building lifecycle hidden in lean waste relates to lean waste principles. From a practical point of view, it is observed that there is a gap in the interoperability of smart home technologies within the lean construction framework. Albeit both concepts prioritise efficiency and optimisation, integrating smart home systems without standard protocol requires careful consideration. The data exchange poses a threat to safeguarding information resulting in resistance to smart home technology installation (Yang et al., 2017). Furthermore, there is a gap in knowledge and expertise within the construction industry (Pavlou et al., 2007) to implement smart home technologies which will require a collaborative approach among construction firms, technology providers, and regulatory bodies to overcome these challenges.

CASE STUDY EXPERIMENT

EXPERIMENT DESIGN AT THE HUDDERSFIELD SMART HOUSE

An experiment was carried out in the Huddersfield Smart House research facility (HSHRF), which is a physical house providing a collaborative hub to accelerate research and development for energy efficiency in the built environment.

The HSHRF is a fully monitored physical smart house with real-time data over 48 wireless sensors to analyse temperature, humidity, CO2, and particulate matter. All the sensors are connected to a cloud-based system, called ‘iMonnit’. iMonnit refers to a cloud-based mobile internet platform and a central hub to manage iMonnit and ALTA products. All data is secured on dedicated servers operating Microsoft SQL Server (See Figure 3). The sensors installed in the smart house are constantly collecting real-time data, and they can be analysed and optimised through a digital simulation of the building.

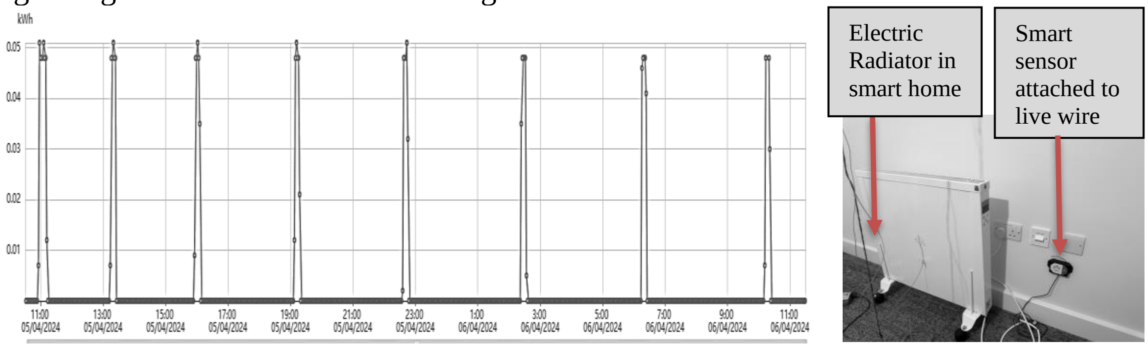

Figure 2 Experiment of Optimisation in Energy Consumption; Left: The usage of energy; Right: The experiment set up in HSHRF

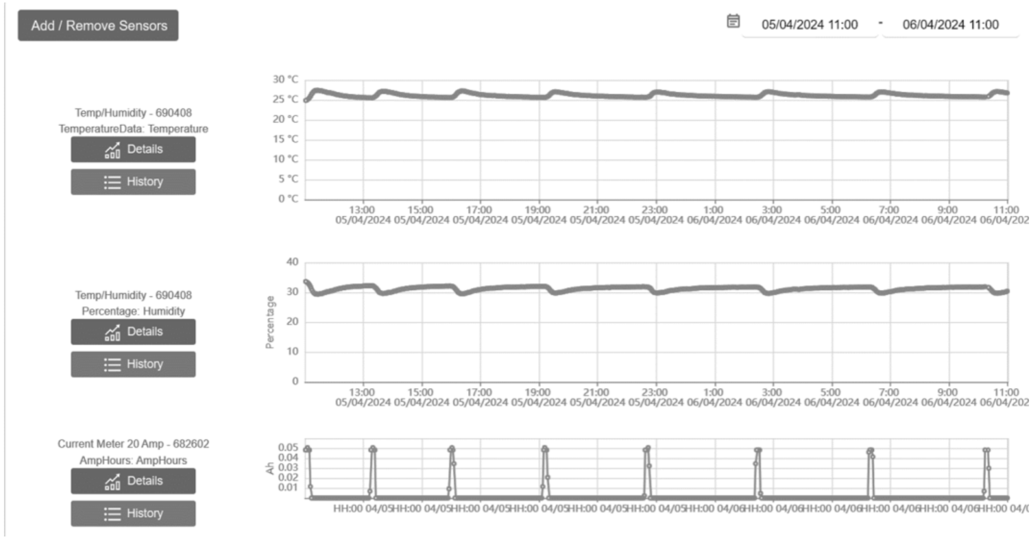

Figure 3 iMonnit chart- Monitors in Huddersfield Smart House research facility

The experiment was set up to validate energy optimisation through smart appliances, and smart sensors in a smart home environment (See Figure 2). The experiment was conducted to evaluate energy optimisation through a smart sensor and an electric radiator and generate an optimal temperature and humidity for the users. Electric radiators are becoming popular due to the government's green schemes for new-build housing (Zala et al., 2017). The data collection sensor is attached to the live wire, sending real-time data through the iMonnit cloud-based database system. The smart radiator was used to observe the energy usage over a period of 24 hours and evaluate optimisation. It should be noted the Smart house has installed external insulation properties such as external cavity walls and triple-glazed windows and acts as an energy-efficient experimental testbed.

RESULTS

The American society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) has established guidelines for thermal comfort, recommending a range of 20 °C to 23.88 °C for temperature and 30-60 % for relative humidity. At the start of the experiment, the base temperature for the experiment room was 24°C. The smart house is built within a building and not exposed to outdoor environmental parameters, which is a limitation. However, this provides accurate data due to the repeatability of the testbed; results are consistent.

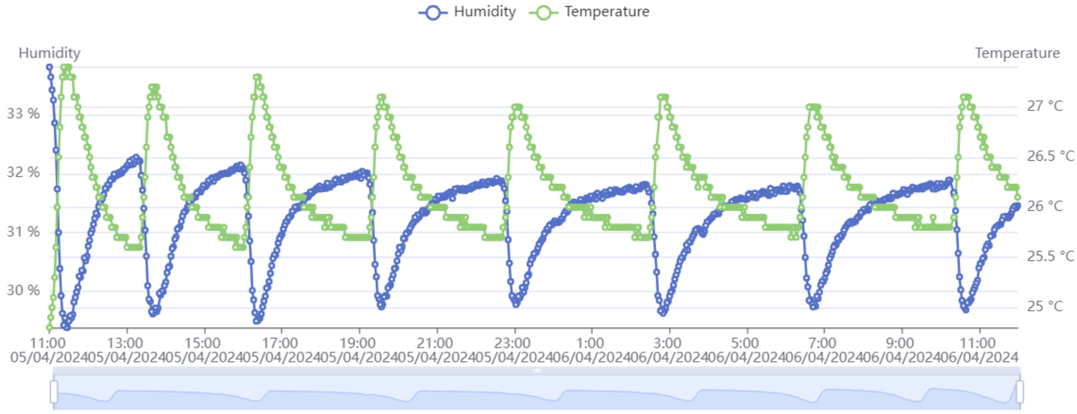

Figure 4 iMonnit chart- Temperature and Humidity graph

It is observed that this electric radiator consumed 1.90 kWh during a 24-hour test period (See Figure 3). After achieving the desired temperature, the radiator remained switched on for 1 hour and 20 minutes out of 24 hours, accounting for 8.3 % of the total time, indicating its ability to maintain room temperature effectively without constant energy consumption. This indicates that the appliance can maintain the optimal room temperature and minimise energy usage in an insulated smart home (See Figure 3). It effectively raised the room temperature from 24 °C to 27 °C during the 24 hours, with humidity levels ranging from 33% to 30%, indicating its ability to control humidity and create a comfortable living environment for occupants (See Figure 3). Figure 4 illustrates that when the temperature is high, the humidity is low, and vice versa, illustrating the temperature-humidity interrelationship in the living environment. As mentioned above, the experimental temperature is at a high range due to the limitations of the testbed. Nevertheless, as the Smart House is well insulated, the smart appliance successfully optimises energy usage and uses negligible energy when reaches the desired optimum temperature in a smart environment. This can be observed in Figure 3 through the smart charts derived from the collected real-time data.

CLOSING REMARKS

Smart home technologies are essential for improved energy energy, resulting in reducing carbon footprints. The household conditions can significantly improve with the deployment of smart technologies (Ehsanifar et al., 2023), and health and well-being can be improved through better management of internal environments, safety, and security. From the experiment, it is shown that the use of efficient appliances in a sensor-controlled energy-efficient smart home environment creates a comfortable living environment for the occupants with low energy consumption. The energy-efficient testbed successfully optimised the energy usage when reached the desired optimum temperature according to AHSRAE guidelines. The use of smart sensors contributes to real-time data and allows continuous improvement in smart product development. Furszyfer Del Rio et al. (2021) describe the potential sustainability benefits of smart home technologies that can support cost benefits and contribute to social and environmental impacts.

The waste reduction through smart homes can be directly connected to lean in the context of energy efficiency, energy waste reduction, data-driven decision-making, and improving user functionality. The review shows that Smart homes relate to increased capacity, better tracking, improvements in equipment utilisation, streamlined operations, and lower emissions.

Smart homes allow waste reduction through increasing efficiency, appraising user control in a home environment, and inducing continuous improvement. A summary of how the notion of smart home addresses lean principles is presented in Table 3. The findings presented in Table 3 are consistent with some synergies identified in Table 2, adapted from Awwal et al. (2023).

Table 3 Lean principles and Smart Home in waste reduction

Lean Waste	**Energy Usage (EPA, 2007)**	**Synergies with Smart Home**
Overproduction & Over processing	Additional energy consumed in operating equipment and more energy consumed due to unnecessary processing	A smart home allows energy efficiency through smart appliances, smart monitors and controls, and the integration of renewable technologies
Defects	Energy consumed in making defective products-, increasing lighting, heating, and cooling demand and energy consumption	A smart home allows the monitoring of real-time data and enables determining when there is a need for product replacement (e.g. Building materials and appliances) during the lifecycle of the building
Waiting/Delays	Streamlining operations	-Automation in smart homes allows streamlining daily operations and reduce waste

Table 3 depicts that the adoption of smart home technologies allows waste reduction/elimination during a building's lifecycle. The contributions were categorised into three groups: Overproduction and overprocessing-where smart home can minimise energy usage through better tracking and optimisation; Defects- Smart home allows real-time data collection; it can offer information on building deterioration over time, for example, if the humidity level is continuously high, measures can be taken to improve the condition, or if the appliances are older and consuming more energy, a replacement can be considered through smart data observation and waiting/delays- automation in a smart home can streamline operations which can result into increasing energy efficiency, especially in a well-insulated smart home which can retail heat for a longer time.

It should be noted that Table 2 is limited to the conceptual analysis presented in the paper. which needs further empirical data. The paper is limiting the study to a specific element of the smart system (e.g. radiator) and a case study in terms of building envelop (HSHRF). The smart house as an experimental testbed has some limitation, for instance, the building does not have a direct connection with the outdoor environment, which impacts independent variables such as temperature, precipitation, humidity etc. The experiment applied in this research is small, and not applied in a larger case study; further research is needed to assess the applicability.

Despite the limitations, this paper points out that Smart Home' connects to a 'Lean' perspective from an efficiency and operations point of view. It is evident that energy-efficient devices and systems, such as smart thermostats, lighting controls, and energy monitoring systems, contribute to reducing overall energy consumption in a smart house. Thus, smart homes could be explored further as an improved approach to promote energy efficiency and a better lifestyle for the building occupants and contribute to sustainability development goals. Energy consumption is a pressing concern worldwide. Smart home through lean construction allows optimisation, streamline workflows, and maximise efficiency which supports several SDGs for instance SDG-7 Affordable and Clean Energy; SDG-11- Sustainable Cities and Communities; SDG-12 Responsible Consumption and Production and SDG 13- Climate Action. In conclusion, the deployment of smart home technologies from a lean construction point of view offers valuable insights into energy waste on a larger scale and provides guidance for future research on informed regulatory decisions toward a more sustainable built environment.

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AN INTEGRATED FRAMEWORK FOR PRODUCTION AND ENVIRONMENTAL WASTE MANAGEMENT IN CONSTRUCTION

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ABSTRACT

Lean construction has successfully developed and utilised several tools to minimise production waste generation in construction projects. In addition, sustainability research has contributed to improving the environmental performance of the construction industry by managing the impact of construction waste on the environment. Research on construction sustainability has been utilising some of the capabilities of lean construction tools to address environmental-related issues that are difficult to tackle using conventional approaches. Even though research in the Lean-Sustainability area has progressed over the last two decades, knowledge of Lean-Sustainability applications is still limited amongst industrial practitioners. A potential reason is the lack of an integrated approach combining lean principles and sustainability for construction applications. To address this limitation, this paper proposes a management framework that deals with both production and environmental wastes concurrently. The framework is developed by combining a lean process improvement method with an environmental management system approach. The framework is validated through interviews with experts in lean construction and sustainability to establish its theoretical contribution and practical applicability. Through this integrated waste management framework, this study contributes to the efforts of managing production and environmental wastes to deliver more efficient and environmentally friendly projects in the construction industry.

KEYWORDS

Sustainability, Lean Construction, Value Stream, Production waste, Environmental waste

INTRODUCTION

There have been growing concerns about the adverse environmental impact of the construction industry over recent decades (Li et al., 2022). Extensive research efforts have been dedicated to investigating the environmental issues associated with construction activities, including greenhouse gas emissions and the depletion of natural resources (Dräger

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& Letmathe, 2022; Farias et al., 2019; Kosasih et al., 2023). Many studies have been conducted to propose concepts and practices to enhance the environmental performance of construction projects, but there remains to be a gap in translating existing research recommendations into practical implementation. A potential explanation for this shortage in knowledge lies in the current industry focus on managing waste based on its consequences rather than addressing its root causes (Farias et al., 2019; Kosasih et al., 2023; Poshdar et al., 2022). Furthermore, prevailing sustainability practices tend to concentrate primarily on the design phase of construction projects, often neglecting process wastes and the interrelationship between design and construction (Rosenbaum et al., 2014).

To bridge these gaps, lean construction research has sought to address these limitations by emphasising the interrelationship between production and environmental waste in construction. This shift in focus can potentially overcome the constraints of managing production and environmental wastes separately (Arroyo & Gonzalez, 2016). Therefore, integrating lean and sustainability principles presents an opportunity to tackle different types of waste at different production levels (Khodeir & Othman, 2018).

In response to the existing gaps in construction waste management, this paper introduces a novel management framework that integrates lean and sustainability concepts. Adopting a constructive research methodology, this study identifies a practical problem within the existing body of knowledge and introduces a new construct to address it. By combining elements from lean and sustainability approaches and considering all production planning levels (strategic, tactical, and operational), the proposed framework ensures the visibility of all waste types, effectively addressing the challenge of invisible waste, as highlighted by Koskela (2004).

BACKGROUND

The environmental repercussions of construction activities rank among the key concerns within the industry (Araujo et al., 2020). The magnitude of construction-related waste generation remains alarmingly high in both developed and developing countries. For instance, in 2018, the United States produced over 600 million tons of construction-related waste, surpassing the municipal solid waste generated in the country (US Environmental Protection Agency, 2020). Similarly, the Gulf Cooperation Countries (GCC) produces a staggering 120 million tons of construction and demolition waste annually (Ouda et al., 2018). This surge in construction waste has substantial consequences, impacting production costs (Formoso et al., 2020) and depleting natural resources (Pradhan et al., 2017). Consequently, global awareness regarding the magnitude of construction waste and its environmental impact has grown, leading to an increased focus on waste minimisation in the construction domain (Ajayi et al., 2017).

Waste has been a central theme in the field of lean construction. From a lean perspective, production waste arises from non-value-adding (NVA) activities, which represent processes that consume resources without contributing value to the final product or end-user. Examples of NVA activities include over-production, waiting, and unnecessary motion (Ohno, 1988). Ohno initially defined seven categories of NVA within the manufacturing industry, a classification subsequently adopted by lean construction, which expanded to include additional categories (see Table 1).

Research has established that NVA activities can exert adverse effects on the environment (Banawi & Bilec, 2014; Belayutham et al., 2016). Therefore, the elimination or minimisation of waste, particularly NVA activities, has been proposed as a mechanism to enhance both process flow and the environmental performance of construction projects (Formoso et al., 2020; Sarhan et al., 2019). Despite the growing interest in advancing sustainability in construction through waste minimisation approaches, current waste management practices often lack practical applicability in the industry (Ajayi et al., 2017; Sarhan and Pretlove, 2021). This limited adoption of current practices can be attributed to their reactive nature, as they tend to address wasteful processes and their root causes after they have occurred. Additionally, these practices frequently treat production and environmental waste as separate entities (Kabirifar et al., 2020), indicating a lack of recognition of their interconnectedness within construction projects. Interested readers on the interrelated connections and trade-offs between Lean and Sustainability are referred to the systematic review by Sarhan et al., (2019).

Table 1: Construction Waste Categories

Waste Categories	Definition	Reference
Motion	Equipment or people moving more than necessary	(Ohno, 1988)
Waiting	Time lost in between steps in production	
Transportation	Moving products that do not need to be moved	
Inventory	Work and finished work not being processed	
Over-Processing	Poor use of tools and in the production of the goods that the customers do not need	
Overproduction	Production moves ahead of demand	
Defects	Extra effort involved in fixing problems	
Making- do	It refers to a situation where a task is started without all its standard inputs, or the execution of a task is continued although the availability of at least one standard input has ceased.	(Koskela, 2004)
Work in progress	Working on relatively small tasks left from the previous plan	(Hopp & Spearman, 2011)
Unfinished work	It includes rework and small finishing tasks that are left over after a crew leaves a workstation.	(Fireman & Formoso, 2013)
Waste of human potential	For example, not speaking and not listening. It also includes late or lack of involvement of contractors and specialist subcontractors in design and planning stages	(Macomber and Howell, 2004)
Institutional waste	Systems, norms, and routines, which are taken for granted and impede efficiency and improvement efforts in construction	Sarhan et al (2014)

RESEARCH METHODOLOGY

This research is conducted over five phases following the constructive research approach, which is centred around developing innovative solutions to practical problems that have research potential (Kasanen et al., 1993). The first phase included an examination of the body of knowledge to identify the gap related to the lack of a practical framework for the integrated management of production and environmental waste in construction. Subsequently, the second phase focused on obtaining a comprehensive understanding of the identified problem through a thorough literature review on the topics of lean construction and environmental waste management. In the third phase, a solution is proposed by integrating lean process improvement techniques with an environmental management system to develop a conceptual framework. The framework was validated in the fourth phase through expert interviews (refer to Table 4 for further details). Also, a case example is presented to demonstrate the framework's applicability in actual construction piling operations. Finally, insights for the successful implementation of the framework are presented based on the lessons learned from the validation exercise and the case-example demonstration. The final stage aims to establish the theoretical and practical contribution of the proposed solution as per the requirements of the constructive research approach.

PRODUCTION AND ENVIRONMENTAL WASTES IN CONSTRUCTION: A MANAGEMENT FRAMEWORK

DEVELOPMENT OF THE FRAMEWORK

Traditional practices for waste management in construction usually tackle production and environmental waste separately. This paper suggests a way to combine the two by integrating principles from lean and sustainability research. The proposed framework combines a lean-six Sigma improvement model and an environmental management system by integrating the DMAIC (Define, Measure, Analyse, Improve, and Control) with the Aspect and Impact Analysis (AIA).

DMAIC is a data-driven model that guides the process of gathering information and optimising production processes (Banawi & Bilec, 2014). In this context, DMAIC is employed in the framework to define and measure wastes, analyse and manage their root causes, and enhance overall process performance. It also helps control the proposed actions and establish procedures for future improvements. On the other hand, AIA is an environmental management system that focuses on improving environmental performance (International Organization for Standardization, 2015). In the scope of this research, AIA is utilised to identify NVA activities contributing to environmental waste, find their root causes, prioritise them based on impact level, and suggest suitable actions to address these causes and impacts. The integrated framework is structured into six stages as illustrated in Figure 1.

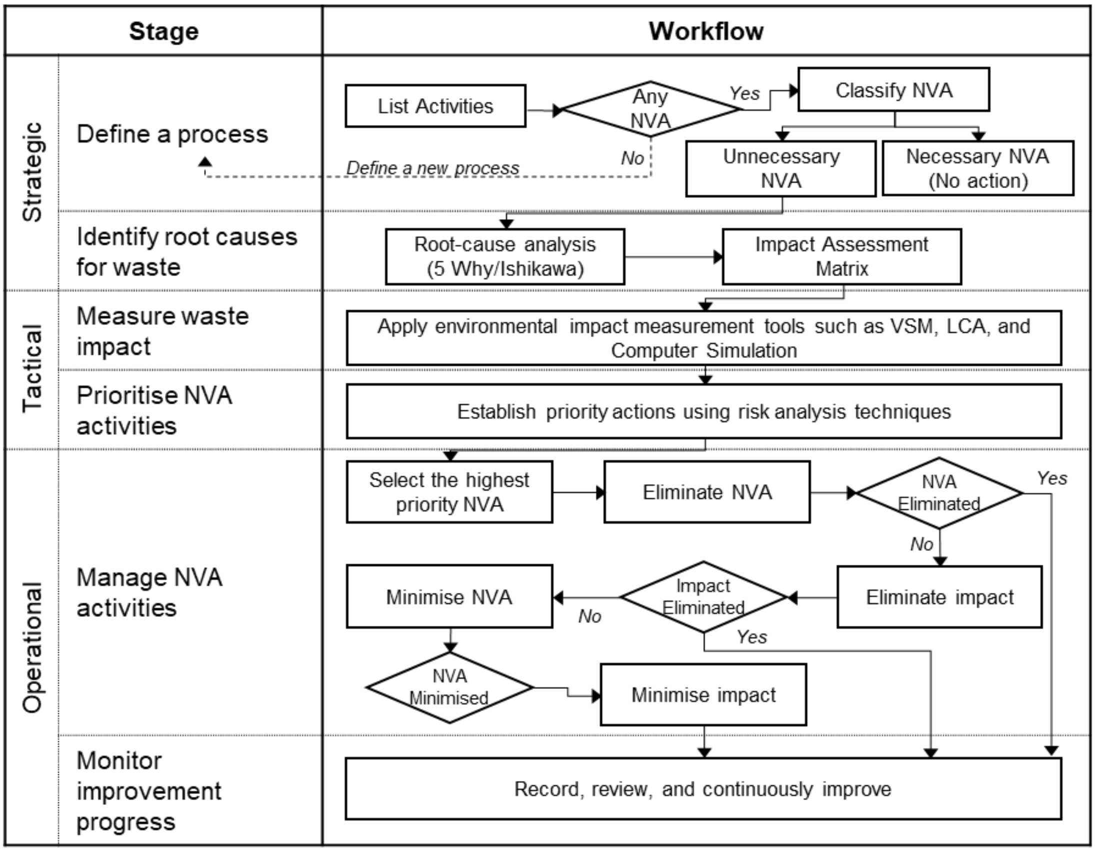

Figure 1: The Proposed Framework Stages and Workflow

The framework flow is designed in a straightforward approach to provide clear guidance to industry practitioners on production and environmental waste management in construction projects. The main aim of the framework is to capture NVA activities and recognise their impact across three production levels: strategic, tactical, and operational. However, it is essential to realise that some NVA activities are unavoidable in construction and that aiming to eliminate them completely is unrealistic. Therefore, the aim should be focused on minimising their existence or mitigating their impact as much as possible. The framework should be implemented iteratively to ensure that all NVA activities are identified and dealt with.

CASE EXAMPLE

To illustrate the application of the framework, a case example of the construction of cast-in-place reinforced concrete piles will be utilised. Piles are crucial structural elements in various construction projects. Piling operations are chosen for this example due to their complexity as they involve interrelated activities that require different materials and machinery. In addition, external factors, such as groundwater level, space constraints, and soil profile, can all contribute to the complexity of operations. This aligns with the findings of Banawi and Bilec (2014), who demonstrated the use of a Lean, Green, and Six Sigma (LG6) model on pile cap operations. Their study found that lean implementation in the construction of piling caps can reduce costs by 1% and environmental waste by 9%.

The case example is a retrospective study based on the construction project of an educational building in Auckland, New Zealand. The project faced several challenges as it was in a busy area with proximity to a hospital and residential buildings. Therefore, constraints on machinery types and numbers necessitated careful planning to ensure undisrupted production. The piling process involved seven main activities: site preparation, land survey, pile drilling, dewatering, steel cage insertion, concrete pour, and excavated soil removal. Additionally, two activities were required for the constant supply of steel cages and fresh concrete. The following subsections provide a detailed overview of each stage of the framework, followed by a demonstration of how these stages can be implemented in the case example.

STAGE 1: DEFINE A PROCESS

This stage of the framework aims to identify wastes generated during the construction phase, where their root causes will be investigated in the following stages. It begins by selecting a production process or sub-process in a construction operation to explore the reasons behind waste generation within the process. In this step, it is essential to assess the current state of the chosen process by identifying all activities and categorising them into Value-Adding (VA) or NVA. NVA activities should then be categorised into necessary and unnecessary. Necessary NVAs are unavoidable and integral to the production process, while unnecessary ones consume resources without directly contributing value to the final product. The primary focus of the framework is on addressing unnecessary NVA (i.e. waste). It is essential to indicate that activities like necessary NVA and VA can have environmental impacts. However, addressing them requires separate methods and falls outside the scope of the proposed framework.

Table 2 illustrates the analysis of the seven activities for the case example of piling operations. As can be seen, three activities are classified as VA, three as necessary NVA, and one as unnecessary NVA. It is important to highlight that this analysis depends on the project requirements, complexity, and circumstances. Thus, these activities can be classified differently in other contexts.

Table 2: VA and NVA activities for the construction of cast-in-place concrete piles

Piling activities	VA	Necessary NVA	Unnecessary NVA	Explanation
Site preparation		✓		Although this process does not directly contribute to pile production, it is necessary to allow piling machinery to operate within the pile location.
Land survey	✓			Land survey is classified as VA as any mistakes in pile locations might diminish the operational value of the pile to support the building structure.
Drilling	✓			Piles can not be constructed without displacing the soil in the pile location to allow for the steel and concrete to be inserted.
Dewatering		✓		Dewatering is a necessary NVA due to the negative effect of water on the quality of the pile materials. It is not VA as the pile can still be produced underwater using special tools and materials if necessary.
Steel cage insertion	✓			Steel is a critical structural component of reinforced concrete piles, so it has to be inserted into the piling location.
Concrete pouring	✓			Concrete is a critical structural component of reinforced concrete piles, so it has to be poured into the piling location.
Excavated soil removal			✓	The process of drilling produces soil from the pile location. The removal of this soil does not add value to the production of piles. This soil type was found to be suitable for recycling in any future construction operations and thus was unnecessary to be removed from the site.

STAGE 2: IDENTIFY ROOT CAUSES FOR WASTE

To address waste at its origin, it is essential to identify its root causes. Accordingly, this stage aims to identify the root causes of NVA activities and their impacts. It is proposed to utilise the 5-Whys technique developed by Sakichi Toyoda (Ohno, 1988) and Ishikawa diagram, also known as the fishbone diagram (Ishikawa, 1982). The 5-Whys technique is helpful in uncovering the origins of waste in the process. On the other hand, the Ishikawa diagram is effective in illustrating the cause-and-effect relationships among different causes of waste and their impacts. The outcome of this stage can be presented in a matrix that shows the connections between identified root causes and their potential impacts. The role of this stage is to ensure that the root causes and impacts of each identified NVA activity are transparent to facilitate actionable waste management strategies in the following stages.

For the case example, the Ishikawa diagram method was utilised to identify the following root causes for the soil removal activity:

- Excessive drilling leading to excavated soil surplus
- Incorrect geotechnical information leading to unnecessary excavation
- Poor maintenance of machinery leading to contaminated soil
- Lack of expertise in investigating soil types for recycling purposes

Table 3 illustrates the relationship and impact that the identified NVA for the case example could have on production and environmental waste generation during the construction process.

Soil removal may generate production and environmental waste due to the use of transportation within the construction site and outside to the dumping site. The removal of soil requires excessive movement of excavators to move the soil to a stocking area. In addition, it involves haul trucks to transport the soil from the construction site to the dumping station. These machines consume energy, generate pollutants, and create dust. Moreover, the use of heavy machinery increases the risk of hazardous material leakage and soil pollution.

Table 3: Impacts of NVA

NVA	Production waste											Environmental waste								
												Excessive Consumption				Excessive Emission				
	Transportation	Inventory	Motion	Waiting	Over-processing	Overproduction	Defect	Making – do	Rework	Work in progress	Unfinished work	Material	Energy	Water	Land	Air pollution	Solid Waste	Hazardous Materials	Water	Soil
Soil removal	✓	✓	✓	✓	✓							✓	✓		✓	✓	✓	✓		✓

STAGE 3: MEASURE WASTE IMPACT

This stage is designed to explore the environmental impact of NVA activities. Traditional lean practices primarily focus on enhancing productivity, time, and cost performance with less focus on the environmental impact (Teixeira et al., 2021). However, studies suggest that lean principles can be extended to include environmental measures (Arroyo and Gonzalez, 2016; Kosasih et al., 2023). To strengthen the environmental aspect of lean, the framework recommends employing process analysis techniques, such as Value Stream Mapping (VSM) (Weinheimer et al. 2017), Life Cycle Assessment (LCA) (Farias et al., 2019), and Simulation modelling (Golzarpoor et al., 2017), to measure the environmental impact of targeted NVA. The selection of analysis techniques can vary depending on the types of waste and the available information and are within the discretion of the framework user. As the case example was a retrospective study, waste impact of soil removal activities was not measured. However, we envisage that the use of a simulation model can be very effective in facilitating impact measurement.

STAGE 4: PRIORITISE NVA ACTIVITIES

This stage operates at the tactical level of the framework. The identified NVA activities should be assessed using a risk assessment rating system (e.g., probability and impact matrix). Then, the risk matrix can be utilised to determine which NVA has a low, medium, or high risk in terms of both production and environmental waste. This prioritisation process helps to focus attention and resources on addressing the riskiest NVA activities to aid the following stages of defining a strategic and efficient approach to waste management.

For the case example, as illustrated in Table 2, three NVA activities were identified. Soil removal is the only unnecessary NVA, so it is the highest priority for management intervention. As illustrated in the next stage, other NVA activities should also be dealt with. Although site preparation and dewatering are assessed as necessary for the process, they should be further analysed to reduce the need for such NVA or minimise their impact on production and environmental wastes.

Stage 5: Manage NVA activities

This stage provides a series of tools and procedures to address NVA activities and their environmental impact. It begins by selecting the top prioritised NVA activities and proposing actions for their management. The ideal goal is to eliminate NVA activities to prevent the generation of environmental waste. If elimination is not feasible, alternative measures are taken to reduce the impact on the production and environmental waste of the process. To manage NVA activities and their impacts, the framework suggests using the following steps in the designated order to ensure a strategic and efficient approach to managing NVA and minimising their impact.

- Eliminating NVA activities in the currently selected process to address the problem at its root cause.
- Eliminating impact by focusing on immediate measures to prevent waste generation in the process.
- Minimising NVA activities by redesigning production operations to avoid unnecessary NVA activities.
- Minimising impact by utilising approaches to control waste generation in the process.

In the case example, it was found that soil removal can be partially eliminated as some of the excavated soil was unsuitable for other construction operations. A mitigation strategy was to re-examine the geotechnical report and update it based on the accurate information from the site, to avoid future errors. Also, the additional soil can be used as a temporary protective layer under heavy machinery and be removed by the foundation contractor as part of their site excavation activities to avoid the production and environmental wastes associated with the removal of the small amount of soil only excavated from piling operations.

Stage 6: Monitor improvement progress

In the last stage, the framework focuses on tracking the performance of the framework. Also, it aims to capture any new wastes that might emerge from the strategies implemented in the previous stage. To ensure continuous improvement, it is essential to maintain a record of current challenges and the decisions or solutions applied. These records can be used as lessons learned to facilitate knowledge retention and transfer to enhance the effectiveness of the proposed framework over time.

FRAMEWORK VALIDATION

Expert validation

The proposed framework was validated through input from academic and industry experts in the field of lean construction and sustainability. Expert validation is an exploratory qualitative method, which is a common practice for validating conceptual models and frameworks (Hancock et al., 2001). In this study, a sample of 10 participants was initially formed based on their extensive academic and/or industry experience in both lean construction and sustainability. Six experts from both academic and industry backgrounds agreed to participate. The demographic details of the participants are outlined in Table 4.

Table 4. Demographic details of participant

Interview Reference	Title of Interviewee	Education	Country	Years of experience in lean and/or sustainability	Experience
VAL01	Researcher/ Academic	Doctoral	USA	Over 15 years	Academic+ Practical
VAL02	Researcher/ Academic	Doctoral	Chile	Over 15 years	Academic + Practical
VAL03	Researcher/ Academic	Doctoral	Turkey	Over 15 years	Academic + Practical
VAL04	Researcher/ Academic	Doctoral	Malaysia	five to ten years	Academic + Practical
VAL05	Project Manager	Master	Saudi Arabia	five to ten years	Practical
VAL06	Construction Manager	Bachelor	New Zealand	Five years	Practical

Semi-structured interviews were conducted via Zoom with a focus on how to ensure the framework's alignment with advanced research outcomes and industrial best practices. The interview covered four key themes, and content analysis was performed to extract insights on these themes from the participants' responses. The following subsections cover the results of the expert validation process. Based on the outcomes of these interviews, the developed framework underwent refinement to incorporate feedback and recommended modifications.

GENERAL OVERVIEW OF THE FRAMEWORK

The initial part of the interview focused on obtaining the overall impressions of participants about the framework. The aim was to ensure the clarity, ease of understanding, and its effectiveness. Prior to the interview, the framework was shared with the participants for review. All six experts confirmed that the framework was well-structured, easy to follow, and has the potential to enhance waste management in construction projects. The following statements from experts affirmed this sentiment:

"It looks well organised. It looks relatively, going to be easy to follow…The flow of the framework is clear, easy to follow." (AVL02)

"I found your framework very useful, and it's a good idea to combine lean and sustainable concepts every time, in my opinion." (AVL03)

"The framework looks well-structured to me. It is good to have a framework that can manage waste and assist us to achieve sustainability at the same time." (AVL05)

The second question in the validation process investigated the framework's efficiency, with responses provided below:

"It can eliminate the non-value adding activities...It has the potential to reduce schedule for sure, environmental impact in terms of emission from the construction phase." (AVL01)

"The framework consists of strategic, tactical, and operational levels...This will help in LEED accreditation...I notice that in your framework." (AVL02)

"This framework could definitely improve the efficiency of construction, provided the users could properly conduct and understand the impact measurement well." (AVL04)

APPLICABILITY OF THE FRAMEWORK

The next question aimed to explore the practical application of the framework to identify potential issues or limitations that could impede its implementation in real construction projects. Participants expressed confidence in the applicability in actual construction projects. They highlighted the ease of practical implementation and reported no significant impediments. Examples of participants' responses include:

> *"Yes, in my opinion, you can apply it to a real construction project." (VAL03)*

> *"Absolutely yes...I would apply it straight away as we are suffering from a lack of attention in waste management." (VAL05)*

BENEFITS AND DRAWBACKS OF IMPLEMENTING THE FRAMEWORK

To assess the practicality of the framework, the next question examined both the benefits and drawbacks associated with its implementation. The reported drawbacks were generally around the time and costs associated with implementing such a management intervention. Additionally, Expert VAL01 noted that *"Measuring NVA can be hard but depends on NVA types."* On the positive side, the participants found potential benefits for the framework in construction projects. These include a reduction in both production and environmental waste. Also, the framework can enhance productivity and improve time and cost performance. Moreover, the experts indicated that the framework can foster increased awareness about environmental waste and improve understanding of the relationship between lean and sustainability concepts.

CHALLENGES OF IMPLEMENTATION

While there was a consensus about the applicability of the framework, the experts raised awareness of potential challenges during implementation. Resistance to change was reported as a critical barrier. Another identified barrier was the lack of knowledge about lean and sustainability concepts among construction practitioners. Differences in regulations across countries also posed a challenge. Furthermore, the scope of implementation was considered, with a suggestion to apply the framework initially in smaller pilot projects before addressing entire projects. The experts highlighted the need for well-designed guidelines and clear demonstrations of the framework's benefits to overcome these challenges.

CONCLUSION

This study underscores the critical interplay between production and environmental waste in construction projects, emphasising the urgent need for a comprehensive waste management approach. The developed framework uniquely integrates lean and sustainability principles by addressing waste at strategic, tactical, and operational levels. Unlike previous studies that primarily focused on specific site operations, this framework systematically tracks waste's root causes and potential impacts across various production stages.

The application of lean concepts in construction offers a promising avenue for the simultaneous reduction of production and environmental waste. The framework equips construction organisations with the means to enhance operational efficiency while adopting environmentally friendly strategies. Practitioners can leverage this tool to identify and rectify inefficiencies in construction processes to enhance the overall performance of the industry in terms of cost, time, and environmental sustainability.

This paper has the following limitations. First, the proposed framework is limited to addressing unnecessary NVA. However, it is important to recognise that necessary NVA as well as VA can be sources for waste in construction operations. Addressing such activities requires redefining engineering methods to embed sustainability into the design of construction operations (and potentially the asset itself) to avoid any waste generation during the construction and operation of the asset. Another limitation is the use of a simple case example to illustrate the application of the framework, which might not represent the overall picture of real-life implementation. To address these limitations, further refinement of the framework will be conducted in future research. These refinements include the development of a holistic framework covering all lifecycle phases of construction projects and investigating the incorporation of cause-effect relationships between different waste types. The evaluation of the applicability of the framework and its impact in a real construction project is also recommended to validate its effectiveness in practical settings. Through these initiatives, ongoing advancements can be made to revolutionise waste management practices in the construction industry.

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EVALUATING THE AWARENESS OF DESIGNING OUT WASTE IN CONSTRUCTION: A LEAN–GREEN SYNERGY

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ABSTRACT

The construction industry generates millions of tons of material waste annually throughout a project's life cycle. In Lebanon, one million tons of Construction and Demolition Waste were generated during the years 2009 and 2010. To support organizations in enhancing their environmental efficiency, the Green paradigm has emerged. Such a paradigm can be complemented with the Lean management approach paving the way for a Lean-Green synergy. This synergy is based on the alignment of the two approaches on the need to minimize waste, in its different forms, as well as maximize stakeholder value; the client, and the environment. As such, this paper introduces the concept of the Design out Waste (DoW) approach. This approach aims to improve the sustainability aspect of a project, throughout its lifecycle and starting from the early design phase, supported by Lean tools and principles. Specifically, the aim of this paper is to investigate the current state and examine the level of awareness of implementing DoW principles in the Lebanese construction industry through conducting surveys. The survey results showed a low level of awareness of the DoW approach among practitioners in Lebanon with little attention given to waste minimization when making decisions.

KEYWORDS

Lean construction, Green construction, sustainability, Lean-Green synergy, waste minimization

INTRODUCTION

Each year, the construction industry generates millions of tons of material waste across the different stages of a project's life cycle (Wang et al., 2014). Estimates also show that 30% of the materials brought to a typical construction site go to waste (Osmani, 2011). More specifically, the construction industry in Lebanon has generated one million tons of Construction and Demolition Waste (CDW) during the years 2009 and 2010 as per the latest available studies (Tamraz et al., 2012). With the absence of a proper regulatory framework to

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manage solid wastes in Lebanon, including CDW, the waste issue has become more critical to handle (Tamraz et al., 2012).

With the increasing cost overruns, clients are requesting a further reduction of waste in the projects (Akintoye, 1995). This can be due to the high proportion of materials cost that amounts to 50%-60% of the project's cost (Polat & Ballard, 2004) . Therefore, any reduction in material waste can lead to substantial cost savings (Polat & Ballard, 2004). Additionally, research shows that failing to apply waste reduction measures in the design phase of a construction project could result in an estimated 33% of the total waste generated on-site (EPA, 2015).

Given the environmental and economic concerns with the large amounts of CDW waste generated each year (Wang et al., 2014) and the clients' need to reduce waste on their projects (Akintoye, 1995)., it is essential to consider sustainable construction (Polat & Ballard, 2004). The Green paradigm has emerged as an approach to support organizations in enhancing their environmental efficiency (Garza-Reyes, 2015). To support the implementation of Green initiatives in construction projects and to maximize value to the client and the environment, Green approaches can leverage the use of tools and principles developed by the Lean community (Huovila & Koskela, 1998).

Lean has initially emerged as a management approach to designing production systems with the aim of maximizing customer value and minimizing waste in its different forms (Koskela et al., 2007). It is governed by a set of 14 principles adopted from the Toyota Production System (TPS) that cover 4 aspects: 1) "Philosophy" which focuses on long-term thinking as opposed to short-term wins, 2) "Process" which focuses on leveraging lean tools and techniques to eliminate any form of waste in the production process, 3) "People and Partners" that focuses on respecting and challenging the people in the organization as well as other stakeholders, such as suppliers, to understand the organization's philosophy and to help them improve and finally 4) "Problem-solving" which aims to solve problems by identifying the root cause in the pursuit of continuous improvement (Liker, 2004). Additionally, Taichi Ohno identified 7 categories of waste that need to be eliminated from any production process. These include (Polat & Ballard, 2004):

1. Product defects
2. Overproduction
3. Inventory
4. Unnecessary processing
5. Unnecessary movement
6. Unnecessary transportation
7. Workers waiting on work

LITERATURE REVIEW

Although the foundation of the Lean philosophy is rooted in the manufacturing industry, the construction industry has been witnessing a successful implementation of the Lean management approach (Singh & Kumar, 2020). Specifically, Lean in construction emphasizes the need to reduce different types of waste that are present throughout the different phases of a project's lifecycle (Horman et al., 2004). Among the common tools and techniques used in construction are the 5S, visual management, standardization, big room, and continuous improvement along with many others (Liker, 2004). The successful implementation has been reflected in terms of customer satisfaction, waste reduction, cost reduction, and timely project delivery (Singh & Kumar, 2020).

The success of Lean implementation has also been witnessed in the Lebanese construction industry in particular. To start with, Kallasy and Hamzeh (2021) developed a "Lean Culture

Index" to assess the readiness of construction companies in Lebanon to apply Lean tools and principles. The developed index covered all the aspects of the 4Ps: philosophy, process, people and partners, and problem-solving. The authors also proposed practical recommendations to guide practitioners in Lebanon on Lean implementation. Moreover, Hamzeh et al. (2016) analyzed a large-scale construction project case study regarding its first intensive implementation of Lean tools and the Last Planner System (LPS) in Lebanon. The project team witnessed improvements upon implementation including improved performance visualization, better communication among engineers and the foremen, and better linkage of the main project metrics on time, cost, and quality to the principles of the TPS. In another study, Awada et. Al (2016) evaluated the potential of adopting Lean tools and concepts to reduce safety-related incidents in the Lebanese construction industry. The study showed that practitioners understand the benefits associated with such Lean tools to enhance safety management in construction.

Lean and Green approaches align well with the idea of waste elimination, in its different forms, and with the idea of maximizing stakeholder value; the customer stakeholder and the environment stakeholder. As such, a Lean–Green synergy can be considered where the two approaches complement one another. This synergy has become practically possible in construction given that the Lean construction community has shown the potential of considering the environment as a customer (Huovila & Koskela, 1998).

The aforementioned synergy allows for a smooth implementation of Lean tools and principles to achieve - on top of customer satisfaction - environmental benefits in the construction industry. For example, Vieira and Cachadinha (2011) showed that the use of the 5S Lean tool helped maintain a clean and organized site by placing waste containers in the immediate vicinity of the generated material waste as well as sending material waste to their identified locations. The case study presented by Valente et al. (2013) utilized the Gemba Lean practice on a monthly basis to monitor and document the requirements needed to apply for LEED certification. Moreover, just-in-time (JIT) material delivery and Kanban systems were utilized to improve the flow of material on-site (Rosenbaum et al., 2012). In another study, Abou Dargham et al. (Abou Dargham et al., 2019) showed that adopting a pull material delivery system ensured a more efficient use of the material delivery trucks.

Although the integration of Lean and Green approaches has been successful, previous studies mostly address the construction phase of the project as opposed to the different stages of the lifecycle. To spread awareness of the benefits of Lean to improve projects' sustainability aspect during their lifecycle, the Designing out Waste (DoW) paradigm is introduced.

The guidelines of DoW were developed in the year 2000 by the Waste and Resource Action Programme (WRAP) to promote sustainable waste management (WRAP, n.d.-a). It is a methodology implemented from the design phase to control, monitor, and eliminate waste in construction projects. It consists of identifying key waste reduction opportunities, investigating the promising ones further, and implementing the most practical option (WRAP, n.d.-b). The DoW process has presented five key principles described below (WRAP, n.d.-b):

1. *Design for waste efficient procurement:* requires an agreement between the suppliers and project teams to provide only the needed quantity of material at the right time as opposed to batch delivery. The aim is to avoid the storage of excess material on site. Accordingly, this will also reduce potential material damage and thus the need to order new batches (WRAP, n.d.-b). The Lean concepts of the JIT delivery system and the pull approach can be utilized to support a waste-efficient procurement (Abou Dargham et al., 2019) thus reducing excess inventory and potential defects (Polat & Ballard, 2004). As such, this principle aligns well with the following Lean principles of the TPS: "Use pull systems to avoid overproduction" and "Respect your extended network of partners and suppliers by challenging them and helping them improve" (Liker, 2004).

2. *Design for off-site construction:* is based on fabricating construction elements in a controlled factory environment and then shipping them to the site for assembly (WRAP, n.d.-b). It is a method well accepted by the Lean community to efficiently reduce construction waste (Polat & Ballard, 2006). Being in a factory setting, off-site construction entails a production line approach similar to that adopted in the manufacturing industry. In this case, the tasks performed at each workstation are standardized to a certain extent. This must be accompanied by levelling the workload among the different stations to reduce waste in the process. Waste here covers a variety of aspects including inventory, work waiting on workers, and workers waiting on work. Moreover, value stream mapping acts as an effective Lean tool to help identify different types of waste in the production process and thus propose opportunities for improvement (kaizen) (El Sakka et al., 2016). So, this principle aligns with the following principles from TPS: "Standardized tasks are the foundation for continuous improvement and employee empowerment" and "Level out the workload" (Liker, 2004).
3. *Design for materials optimization:* tackles design approaches that consider efficient use of resources without affecting the quality or the design (WRAP, n.d.-b). This can be achieved by minimizing the amount of materials incorporated in the design through value engineering to reduce waste production in the construction phase (WRAP, nd). It can also be achieved by standardizing the materials and components used as much as possible (WRAP, n.d.-b). This principle aligns with Lean thinking by eliminating Muda; waste in its different forms, and using only what is required of the resources (Polat & Ballard, 2004). Additionally, standardizing the materials and components used allows for a smoother standardization of the construction processes which is a core Lean concept as well (Liker, 2004). As such, this principle aligns well with the following principles from the TPS: "Standardized tasks are the foundation for continuous improvement and employee empowerment" (Liker, 2004).
4. *Design for reuse and recovery:* considers the entire life of the materials used on site. Material reuse allows the reduction of the consumption of new raw resources by exploiting materials and the facilities present originally on-site to their fullest capacity before considering new resources (WRAP, n.d.-b). From a Lean perspective, designing projects in a way that allows material reuse requires pulling information from the client in the early design stages (Elmaraghy et al., 2018). Additionally, implementing this principle supports the elimination of Muda by reusing existing materials as opposed to transforming them to waste and using new materials (Polat & Ballard, 2004). In order to effectively design for material reuse and recovery, the project stakeholders need to focus on longer-term goals as opposed to short-term gains. In other words, it might require more effort and some additional costs to reuse and recover existing materials as opposed to ordering new materials. However, in the long run, this will reduce the overall waste generated and will add value to the customer and the environment. So, the principle is rooted in the following Lean principle of the TPS: "Base your management decisions on a long-term philosophy" (Liker, 2004).
5. *Design for deconstruction and flexibility:* considers the recovery and the deconstruction stages of materials by incorporating methods that facilitate their maintenance and reprocessing (WRAP, n.d.-b). Lean principles can be applied to plan for deconstruction by pulling information from the clients to meet their needs and expectations thus increasing client value (Elmaraghy et al., 2018). Developing a deconstruction plan requires the project stakeholders, including the client, to think about the long term as opposed to focusing on short-term gains. Although this requires additional planning, effort, and potential cost at the early stages of the project design, however, on the long term this is expected to reduce the total waste generated and will add value to the customer and the environment. As such, this principle is rooted in the following Lean principle of the TPS: "Base your management decisions on a long-term philosophy" (Liker, 2004).

Implementing each principle requires effective coordination between the teams of the project: clients, designers, contractors, and subcontractors, from the preliminary design phase (WRAP, n.d.-b). Therefore, following an integrated approach to enhance effective communication starting from the design phase could help avoid several construction problems (Emmitt et al., 2004). From a Lean perspective, following such an approach can practically be achieved by adopting an Integrated Project Delivery (IPD) method (Ballard et al., 2011).

The literature shows the benefits of the DoW approach accompanied by integrated practices in minimizing the waste generated during a construction project's lifecycle which then saves on cost and time and increases stakeholders' value (the client and the environment). Additionally, the urging needs to handle the CDW in Lebanon calls for leveraging the described Lean-Green synergy whereby Lean tools and principles smoothly support the implementation of Green initiatives. As such, this paper aims to study the current state and examine the level of awareness of implementing DoW through integrated practices in the Lebanese construction industry. The specific research questions that this study aims to answer are as follows: 1) What is the level of awareness of the construction industry in Beirut, Lebanon regarding each of the DoW principles? 2) What is the level of integration between the client, designer, and contractor in the early stages of the construction project? and 3) What is the relative importance of time, cost, and waste aspects in construction projects? The study outcomes will act as a baseline for construction practitioners and researchers to identify opportunities for improvement related to implementing Green initiatives backed up by Lean thinking.

METHODOLOGY

To examine the current practices and the level of awareness of implementing DoW methods through an integrated approach in the construction industry in the city of Beirut in Lebanon, a qualitative approach using questionnaire surveys was followed in this study. Survey-based research can help researchers collect information from a certain group of individuals based on the responses they provide to a pre-defined set of questions (Ponto, 2015). Generally, the researchers start by formulating a set of questions that can help them understand certain preferences or behaviours of the population (Ponto, 2015). Specifically, the Likert scale can be used to measure the attitudes of the individual to identify the degree to which they agree or disagree with a certain statement (Likert, 1932). As it is not possible to collect data from an entire population, a sample of the population is often selected to estimate how the responses of the population (Ponto, 2015). As such, researchers would try as much as possible to select a sample of individuals that have characteristics similar to the population (Ponto, 2015).

The developed questionnaire was based on key findings from the literature regarding the five principles of DoW and integrated practices in construction as well as the synergy with Lean practices. It was divided into two main sections: section one tackled the DoW principles, while section two focused on the integrated approach.

In the first section of the survey, when addressing the first principle, design for waste-efficient procurement, the survey tackled the concept of JIT ordering, supplier cooperation in delivering the needed quantities, the extent of buffers allowed when ordering materials, and the flexibility in the choice of material. The second principle, design for off-site construction, was approached by investigating the reason behind using off-site construction methods and whether the contractor was involved in making such a decision in the design phase. The third principle, design for materials optimization, tested if the designer involves the contractor in the design phase to find solutions for constructability issues and whether the contractor raises such concerns to the designer during construction. In addition, this principle addressed the purpose behind minimizing material cut-offs. The fourth principle, design for reuse and recovery, was studied by examining the use of recyclable and reusable materials in construction projects. The fifth principle, design for deconstruction and flexibility, was addressed by checking if the design accounts for potential future changes and for developing a deconstruction plan.

The second section of the survey targeted the implementation of DoW from the design phase through an integrated approach. The questions addressed the extent to which regular follow-up meetings take place between designers, clients, and contractors and the contractor's involvement in the design phase regarding the construction methods and constructability issues.

Two formats of the survey questions were produced; one for the designers and one for the contractors. Both surveys had the same content. However, the formulation of the questions was slightly modified so that each respondent could better relate to it given their background. The surveys were filled by professionals in the construction field through interactive interviews ensuring the reliability of the collected data.

To measure the different degrees of attitudes and opinions of the respondents, the five-point Likert scale was used (Likert, 1932). An answer of "1" stands for "strongly disagree", an answer of "3" indicates a "neutral" opinion, whereas an answer of "5" means "strongly agree". The awareness level was then measured from the mean score (MS) of each topic under study. In other words, an MS of less than 3 indicates a low level of awareness, whereas an MS of more than 3 indicates a high level of awareness. Questions were formulated in both positive and negative senses to ensure unbiased feedback thus increasing the trustworthiness of the results. Throughout all the survey questions, the relative importance of time, cost, and waste in the project delivery process was measured.

A total of 33 valid surveys were completed upon interviewing professionals in the Lebanese construction industry, specifically in the city of Beirut. The sample of respondents included architects, engineers from different disciplines, contractors, and consultants with an experience range of one to thirty years in the Lebanese construction industry. Specifically, 20 of the surveys were completed by professionals on the designers' teams with experience ranging between 1 and 30 years and an average of 10 years of experience. As for the remaining 13 surveys, they were completed by professionals on the contractors' teams with experience ranging also between 1 and 30 years with an average of 9 years of experience. The responses were collected from a total of 7 organizations; 4 engineering companies and 3 contracting companies.

The collected data were sorted and analyzed using descriptive statistics and a one-sample T-test. Then, recommendations for implementing DoW in Lebanon, with the support of Lean tools and principles, are suggested.

RESULTS AND ANALYSIS

Table 1 shows the level of awareness of the survey respondents along with the mean and standard deviation on the following items: each of the DoW principles, the integrated approach, and the overall DoW approach. Moreover, Figure 1 shows the corresponding box plots. The results obtained are then analyzed to understand the current construction practices.

Table 1: Level of awareness summary

Section	< 3	= 3	> 3	Mean	Standard Deviation
Principle 1	51.92%	21.15%	26.92%	2.8	0.7
Principle 2	53.54%	19.19%	27.27%	2.6	0.6
Principle 3	55.70%	17.72%	26.58%	2.8	0.5
Principle 4	68.18%	21.21%	10.61%	2.2	0.3
Principle 5	57.50%	15.00%	27.50%	2.7	0.65
Integrated approach	58.18%	19.39%	22.42%	2.6	0.7
DoW	57.50%	18.95%	23.55%	2.5	0.6

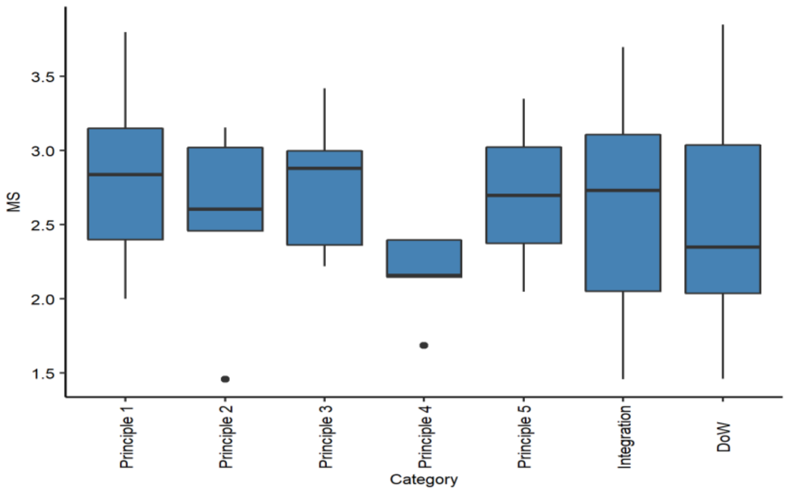

Figure 1: Level of awareness box plots

PRINCIPLE 1: DESIGN FOR WASTE-EFFICIENT PROCUREMENT

Table 1 shows the relative frequency of the respondents who answered less than 3 (52%), 3 (21%), and greater than 3 (27%) on the questions related to the 1st principle. The box plot in Figure 1 confirms the results by having more than half of the data scoring below 3. The MS of the data turned out to be 2.8 with a standard deviation of 0.7 reflecting a low level of awareness on this principle.

Most of the interviewed contractors order materials in batches and store them on-site as opposed to adopting JIT procurement methods. Their point of view was that ordering in batches helps them save on transportation costs and get better deals from suppliers. Moreover, based on the professionals' answers, the suppliers showed little cooperation in delivering materials in small quantities when needed because it would cost them more. In addition, excess material buffers were often used to account for variability that takes place on-site including material damage, loss, or delayed delivery. Moreover, little flexibility was shown in changing the materials being used to ones that generate less waste.

PRINCIPLE 2: DESIGN FOR OFF-SITE CONSTRUCTION

Table 1 shows the relative frequency of the respondents who answered less than 3 (54 %), 3 (19%), and greater than 3 (27%) on the questions related to the 2nd principle. The MS of the data turned out to be 2.6 with a standard deviation of 0.6. The box plot in Figure 1 shows that the median is below 3, which means more than half of the scores are below 3. This can be explained by the current practices that follow traditional contractual relations prohibiting the early engagement of the contractor. Hence, the results indicate a low awareness regarding designing for off-site construction.

The results confirm that off-site construction methods were used for the sake of reducing the construction time and getting better quality instead of the purpose of reducing waste in its different forms. In addition, the decision to use such methods was mostly taken in the early design phase without the involvement of the builders, thus increasing the chances of conflicts during construction. As such, current practices have not prioritized maximizing value to both the client and the environmental stakeholders.

PRINCIPLE 3: DESIGN FOR MATERIALS OPTIMIZATION

Table 1 shows the relative frequency of the respondents who answered less than 3 (56%), 3 (18%), and greater than 3 (26%) on the questions that tested the 3rd principle. The box plot in Figure 1 shows that the median is slightly below 3, which means more than half of the scores are below 3. The MS of the data turned out to be 2.8 with a standard deviation of 0.5, reflecting a low level of awareness regarding designing for material optimization.

The results indicate that most of the targeted practitioners do not consider standardizing the design to reduce the material cut-off generated during construction. In addition, contractors seemed to be hesitant about raising related constructability issues with the designers since they believe that they are two independent entities. On the other hand, designers do not consider addressing contractors about the feasibility of constructing the generated design for the same purpose.

PRINCIPLE 4: DESIGN FOR REUSE AND RECOVERY

Table 1 shows the relative frequency of the respondents who answered less than 3 (68 %), 3 (21%), and greater than 3 (11%) on the questions related to the 4th principle. The MS of the data turned out to be 2.2 with a standard deviation of 0.3. Similarly, the box plot in Figure 1 shows that the median is below 3 which also confirms that more than half of the data is below 3. Hence, this indicates a low awareness regarding designing for reuse and recovery.

It can be inferred from the results that most of the respondents do not incorporate materials that have a percentage of recyclable content throughout the projects. The clients' perspective on this matter was sought based on the information shared by the respondents. Clients are not aware that they could save on the cost of dumping the materials in landfills by recycling them, which could increase their profit. Additionally, clients might not have a thorough background on the associated environmental value of material reuse and recovery. In addition, choosing materials that can be reused later for a purpose it is suited for, whether on the same project or a new one, is not taken into consideration either. In this case, the old material will be considered unnecessary waste (Muda). Moreover, the project stakeholders might not find it financially feasible to recover and re-use existing material as this would require a certain up-front cost regardless of the long-term benefits. Stakeholders also find it challenging to re-use and recover material between different projects as each project is likely to be handled by a different team. As such, more planning is required between the teams to support a smooth transition of material reuse and recovery.

PRINCIPLE 5: DESIGN FOR DECONSTRUCTION AND FLEXIBILITY

Table 1 shows the relative frequency of the respondents who answered less than 3 (55 %), 3 (16%), and greater than 3 (29%) on the questions related to the 5th principle. The box plot in Figure 1 shows that the median is below 3 which also confirms that more than half of the data is below 3. The MS of the data turned out to be 2.7 with a standard deviation of 0.65. This indicates a low awareness of designing for deconstruction and flexibility.

The results reveal that most designers do not account for potential future changes in the project during design. Also, most of the contractors do not consider developing a deconstruction plan in the design phase to deal with the CDW generated. This can be explained by their lack of awareness about the cost savings, environmental benefits, and added client value upon reusing and recycling materials as stated in the previous principle.

INTEGRATED APPROACH

Table 1 shows the relative frequency of the respondents who answered less than 3 (56%), 3 (19%), and greater than 3 (22%) on the questions related to following an integrated approach. The box plot in Figure 1 shows that the median is below 3 which also confirms that more than half of the data is below 3. The MS of the data turned out to be 2.7 with a standard deviation of 0.7.

It could be concluded that there is minimal integration between the client, designer, and contractor altogether in the early design phase to develop strategies to design out waste. Results show that meetings do take place between clients and designers or between clients and contractors. However, these meetings are held further into the project construction phase as opposed to the early stages of design. These meetings often address general updates on the progress of the project, issues faced -if any -, time delays, and cost overruns.

LEVEL OF AWARENESS OF DESIGN OUT WASTE

Table 1 shows the relative frequency of the respondents who answered less than 3 (59%), 3 (18%), and greater than 3 (23%) on the questions related to DoW: the five principles and the integrated approach. The box plot in Figure 1 shows that the median is below 3, which means more than half of the scores are below 3. The MS of the data turned out to be 2.5 with a standard deviation of 0.6. Hence, this indicates a low awareness of DoW through integrated approaches in the construction industry in Beirut, Lebanon.

The normality of the collected data was confirmed using the Shapiro test with a confidence level of 95%. The PDF of the data is plotted in Figure 2 showing a symmetric distribution. The graph shows that there is a probability of 78.9% of having a low level of awareness (less than 3).

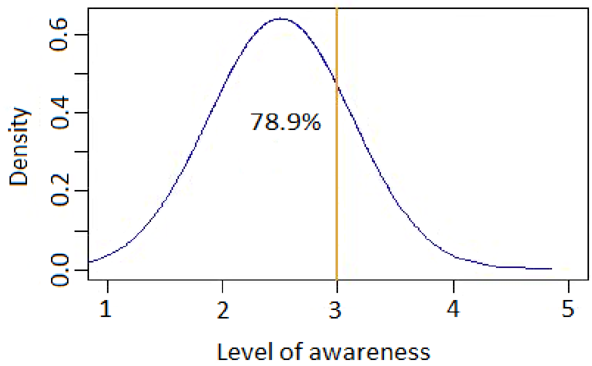

Figure 2: PDF of Level of Awareness of DoW

It was possible to conduct a one-sample T-test since the data was normal to check whether the MS of the survey questions addressing DoW through integrated practices (2.5) is statistically significant from the neutral MS (3). The null hypothesis states that the data is not statistically different from 3 and the alternative hypothesis states that the data is statistically different from 3. The resulting p-value was equal to 0.0002343 which is less than 0.05. Thus, the null hypothesis can be rejected meaning that the data is statistically significant with a 95% confidence level.

IMPORTANCE LEVEL OF DIFFERENT FACTORS

The survey questionnaire included certain questions that reflect how important the factors of time, cost, and waste are important to the respondent. The results revealed that the most important factors that practitioners take into consideration when delivering a construction project are time followed by cost as Figure 3 shows. The time factor had an MS of 4.1 while the cost factor with an MS equivalent to 3.8. However, the importance of considering waste showed an MS lower than both of the latter (2.5). This shows that professionals focus on time and cost while making decisions. However, they are not aware that the waste factor indirectly affects the other two; investing more in adopting methods that generate less waste will save time and cost in the long run. Additionally, it would increase value to both the client and the environment which is the ultimate goal of the DoW approaches.

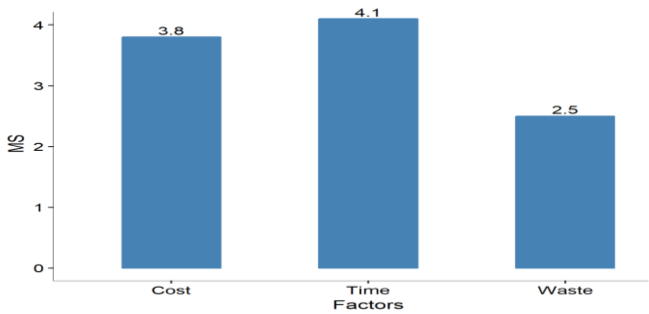

Figure 3: Results for the importance level of the different factors in project delivery

CONCLUSIONS AND RECOMMENDATIONS

DoW is a strategy that aims at minimizing waste by following five main principles: design for waste-efficient procurement, design for off-site construction, design for materials optimization, design for reuse and recovery, and design for deconstruction and flexibility. It requires the integration between the project stakeholders from the beginning of the project. Lean tools and principles, on the other hand, help support the implementation of the DoW principles in construction projects. As such, the Lean–Green synergy in construction was introduced in this paper. This study also showed how the DoW principles and Lean TPS principles go hand-in-hand with a focus on the 4Ps model: philosophy, process, people and partners, and problem-solving. A questionnaire conducted among professionals in the construction industry in Beirut, Lebanon, given the high numbers related to CDW waste in the country, revealed a low level of awareness regarding DoW. Also, results showed that professionals' focus in project delivery is the direct time and cost savings disregarding the benefits of minimizing waste to ultimately add value to the client and the environment.

Given the study outcomes, the Lebanese construction industry can benefit from a set of recommendations to support the implementation of DoW accompanied by the corresponding Lean tools and principles. To start with, construction companies need to thrive to build a Lean culture in the organization which would act as the foundation for continuous improvement in the different aspects. Second, construction companies should invest in training employees on the benefits of implementing the different Lean tools and principles to reduce waste and maximize value. Third, the companies should carry on training on the benefits of leveraging these Lean tools in implementing DoW principles to further maximize value to the environment. Fourth, companies also need to guide owners on how they can better define their value while maximizing value to the environment. Finally, it is recommended to implement the DoW along with the necessary Lean tools and TPS principles on a pilot project in an attempt to showcase the potential benefits of minimizing waste, and maximizing the client and environmental value.

Future research should further examine the level of awareness of clients regarding DoW approaches supported by Lean tools and techniques to obtain an overall awareness. Another direction for future research is to investigate, based on a case study analysis, the benefits of implementing DoW principles supported with Lean tools and principles. Finally, the authors will be working on expanding the study by increasing the sample size of the respondents to get a better representation of the current state in Beirut, Lebanon. Additionally, a larger geographical context in Lebanon will be considered. This would help ensure a better representation of the population in the Lebanese construction industry.

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EVALUATION OF THE LITERATURE SYNTHESES ON LEAN CONSTRUCTION CONTRIBUTIONS TO SUSTAINABILITY

Müge Tetik[1], Lauri Koskela[2], Ergo Pikas[3] and Kädi-Riin Vendel[4]

ABSTRACT

In the last ten years, the interest in the question on how lean construction could contribute to sustainability has considerably increased. This is reflected in the rapidly growing number of publications addressing this question. Especially systematic literature reviews have been popular. In this explorative paper, such reviews are critically evaluated. A synthesis of findings about the conceptual framework of the relation between lean and sustainability is provided. Based on the findings, we determine the missing topics in the available literature reviews. For example, target value design and takt production have not been gaining attention on reviews focusing on lean and sustainability relationship compared to other lean methods. We present suggestions for future research as well as a conceptual framework for contributions of lean construction on sustainability.

KEYWORDS

Lean construction, sustainability, critical evaluation, target value design.

INTRODUCTION

Sustainable development initiatives have been significantly impacting the building lifecycle phases already for the last three decades (Kibert, 2022). In the same period, another initiative for improving construction, namely lean construction, has been evolving. In the community of sustainable construction, there has not been much interest in lean construction. For example, the thorough book by Kibert (2022) mentions lean construction only twice and does not go into much detail. In the community of lean construction, there has been more interest in sustainability, but still that topic has been somewhat in the periphery.

Sustainability is defined as a long-term strategy where economic growth, social coherence and environmental protection are closely associated and are jointly supporting (European Comission, 2024). Lean contributes to sustainability, for example, through reduced waste and resource consumption, and improved safety (Solaimani & Sedighi, 2020). The idea of a relation between lean construction and sustainability has been raised already in 1998 by Huovila and Koskela. After that, the interest into this topic has increased dramatically (Fig. 1). Examples of current studies exploring the connection between lean construction and sustainabilityare provided by Moradi & Sormunen (2023) and, Le & Nguyen (2024). Thus, the topic is

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contemporary and continues to attract attention. The wider topic of the relation between lean and sustainability has experienced a similar pattern of increased popularity (Fig. 1s).

What can we learn from this considerable literature about the possible contribution of lean construction to sustainability? Because this question triggered the publication of many literature reviews (many are systematic), we choose to critically evaluate them. A specific topic is to make a synthesis of findings regarding the conceptual framework of the relation between lean and sustainability. Our method to achieve this is the critical evaluation of systematic literature reviews.

The underlying research has been done in two stages. First, a number of the most cited papers looking at the contributions of lean construction to sustainability were analyzed. Based on findings, a few topics for critical evaluation were determined. In the critical evaluation, when relevant, more papers were taken to be scrutinized. After critically evaluating the available literature, missing topics in the reviews have been determined. Then we discuss the conceptual relationship between lean and sustainability, ways to scale up its sustainability benefits and the methodological limitations of literature reviews.

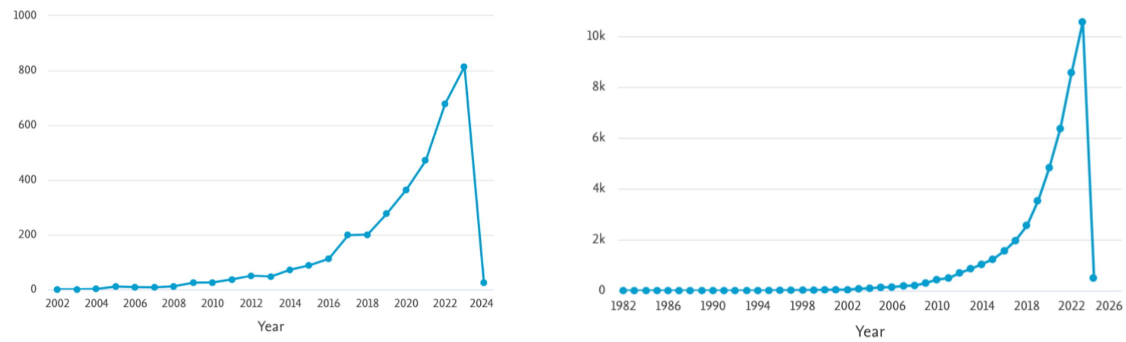

Figure 1. Number of documents found in Scopus database illustrated by year for "lean construction AND sustainability", and the number of documents found in Scopus database illustrated by year for "lean AND sustainability" (taken from scopus.com).

RESULTS OF THE PRELIMINARY STUDY

Among the 20 most cited papers which match the "lean construction AND sustainability" query in Scopus database, a classification of the nature of papers was done. The existing literature mostly consists of literature reviews, and conceptual frameworks to integrate sustainability and lean construction. Examining and trying to use the proposed frameworks, especially with utilizing case studies, as well as implementing more real-life cases would crystallize the findings obtained from the current studies. Among the most-cited 20 papers, the systematic literature reviews (SLR) were selected and more SLRs were added when found relevant. Table 1 summarizes the contents of the selected articles.

Table 1. Synthesis table of the selected articles

Paper	Scope, sample	Key findings
Rosenbaum et al., (2014)	Structural concrete work phase, medical center project in Chile	Reports a value stream mapping (VSM) application case study as a lean approach in a hospital project to improve its environmental and production performance
de Carvalho et al., (2017)	Building sector, 46 papers	The literature review determines synergies between lean thinking and sustainability and provides a conceptual framework depicting their integration
Erdil et al., (2018)	4 cases from healthcare, manufacturing, construction	Proposes a framework to integrate sustainability into improvement initiatives with a DMAIC process
Khodeir & Othman (2018)	Design and construction management, 16 company reports in 11 countries	Provides guidelines for firms through a correlation matrix for applying integrated lean and sustainability principles on design and construction management
Carvajal-Arango et al., (2019)	Construction phase, 117 papers	Reveals that prefabrication, VSM and Kaizen lead to the most sustainability benefits. The social aspect of sustainability is the least addressed by researchers
Solaimani & Sedighi, (2020)	Different construction phases, 118 papers	The current literature focuses more on the economic values than social and environmental aspects, provides a holistic, multi-dimensional framework toward sustainability
Mellado & Lou (2020)	Building lifecycle, 215 papers	Suggests an integrated framework based on theoretical elements. The analysis reveals that the focus is on waste reduction regarding the interactions between BIM and lean
Li et al., (2020)	Structural construction, MEP installation in 6 high-rise projects in China	A conceptual framework of the on-site industrialization method developed; it is suggested to be a cleaner and more sustainable industrial construction method
Dehdasht et al., (2020)	Survey of 23 construction professionals, case study in Malaysia	The empirical study determines the key drivers for successful and sustainable lean construction implementations

A few preliminary observations can be made based on the analysis conducted on the selected 9 papers. The case studies focus only on a specific phase of construction projects such as Rosenbaum et al., (2014) and Li et al., (2020), lacking the whole lifecycle perspective while literature reviews try to have a more comprehensive and holistic perspective such as in De Carvalho et al., (2017), Soleimani and Sedighi (2020), Mellado and Lou (2020) and Khodeir and Othman (2018). While most papers try to focus on all three aspects of sustainability, the social side was found to be under emphasized such as in Erdil et al., (2018) and Carvajal-Arango et al., (2019) and limited to only intra-company interactions in especially case studies such as in Mellado and Lou (2020).

However, when engaging with this small sample of papers, a number of such observations were made which indicate that another tack than systematic literature review as such had to be taken in our research. One such observation was that the share of systematic literature reviews was surprisingly high; what is the reason for this? Another finding was that it is difficult to compare the papers as the results were presented in different ways, i.e., some proposing theoretical frameworks and some listing mere findings. Furthermore, it was spotted that there are three times as many papers on lean and sustainability in comparison to lean construction and sustainability. Probably many conclusions from this more general literature are valid or interesting for construction, too. How to take this wider literature on board? Thus, it was decided to continue towards a critical evaluation of the literature syntheses on lean construction contributions to sustainability.

CRITICAL EVALUATION OF THE METHODOLOGY IN PRIOR REVIEWS

SYSTEMATIC LITERATURE REVIEWS: CRITIQUE

The problems of systematic literature reviews may be visible in many papers. First, a general term, such as lean, does not necessarily catch all activity which could be termed lean but is not. An important example is provided by value engineering/management/methodology (Musa, Pasquire & Hurst, 2016), which exists as an independent method but is also used, at least informally, in lean efforts (especially Target Value Design). Terminology problems exist also on the sustainability side, for example, the terms green and sustainability are used interchangeably. Thus, Garza-Reyes (2015) is using the term green as a synonym for sustainability, more or less.

Second, it might be also argued that SLRs have been partially misunderstood; having a well-documented and disciplined way of finding literature is not always that important; especially when the intention is to have as comprehensive a picture on the phenomenon as possible.

Third, the SLRs have been mostly conducted with a focus on the quantitative aspects such as lists of cited works, classification of papers based on the publisher, or number of hits in databases, rather than considering the qualitative aspects in depth.

Fourth, contextual and historical awareness would be needed. The method of Integrated Project Delivery, now a common lean method, was originally developed in Canada in the framework of sustainability efforts (Kibert, 2022). This is rarely mentioned in the literature reviews.

ABUNDANCE OF LITERATURE REVIEWS

The somewhat strange abundance of literature reviews on lean and sustainability deserves a comment. Taşdemir and Gazo (2018) are among the few authors (of literature reviews on lean/lean construction and sustainability) who have analysed past literature reviews on this topic.They found 35 of them. Consequently, the authors present thinly veiled criticism on this situation:

> *Researchers are expending substantial effort to discover the path to "true sustainability" by re-visiting findings and proposals of their colleagues who approached the situation from various perspectives.*

Aligned with this, these authors proposed that the research must focus on new actionable methods for promoting sustainability:

> *Researchers and professionals should channel their concentration on the development of new methodologies, frameworks, and tools that could help with the achievement of truly sustainable organizations and supply chains compliant with the proposed ultimate objective concept.*

One can ask what the reasons for this inflated interest towards literature reviews on lean and sustainability are. One basic reason of course is that there **is** an ample stock of recent papers to review. Another might be that both topics, lean and sustainability seem extensive and amorphous, and thus a literature review seems a good way to create some basic order and understanding and to start research in this area. Often, when reading a literature review, one gets the impression that the authors have scarce familiarity with either lean or sustainability.

CRITICAL EVALUATION OF SUBSTANTIAL FINDINGS IN PRIOR REVIEWS

SYNTHESES OF FINDINGS

Most review papers present a synthesis of the findings as a conceptual framework. In fact, a considerable variety of conceptual frameworks are presented in the papers:

- Simple diagram showing that lean-green and sustainability tools are contributing to economic growth, environmental integrity and social accountability (Carvajal-Arango et al., 2019)
- Overlap of Lean and Green presented as a Venn diagram (Mellado & Lou, 2020)
- A pie chart for Lean principles and practices for sustainable construction (Solaimani & Sedighi, 2020)
- Conceptual map: Common features of lean and green, moderated by contingencies, lead to triple bottom line results (de Carvalho et al., 2017)
- Causal-loop diagram (Forrester-style) of Lean management in sustainable construction (Solaimani & Sedighi, 2020)
- Concept map of the lean and green literature review showing the different research streams identified (Garza-Reyes, 2015)
- Sustainability additions to DMAIC (Erdil et al., 2018)
- *Affects* and *Effects* between lean and sustainability from the environmental perspective (León & Calvo-Amodio, 2017)

It is evident that the conceptual frameworks presented are largely incommensurable, and this makes it difficult, but not impossible, to compare the results of different papers. Especially, in this case, this problem is alleviated by the fact that the findings are relatively straightforward (as discussed below).

Besides conceptual frameworks, review findings are usefully presented in the form of

- Types of related literature (Garza-Reyes, 2015)
- Questions for future research (Garza-Reyes, 2015)
- Propositions (León & Calvo-Amodio, 2017)

The distinctions between different types of papers will not necessarily surface in conventional systematic literature review, however, these may throw illuminating light on the research activities. Questions for future studies reveal gaps in current knowledge. In turn, propositions contain broad, preliminary conclusions which attract validation in future research.

RELEVANCE OF LEAN AND ITS PRINCIPLES TO SUSTAINABILITY

Lean and lean construction are overwhelmingly found to produce benefits, rather than disbenefits, from the sustainability viewpoint. Thus, Solaimani and Sedighi (2020) write:

> *[…] that almost all the Lean principles and techniques seem to have a positive impact (or a 'reinforcing' effect) on triple bottom line across the construction process.*

Further:

> *…the Lean principles and practices are useful in largely all the facets of construction process, across various phases and stakeholders.*

Carvajal-Arango et al., (2017) similarly claim:

> *Implementation of lean construction practices during the construction project generates positive effects on the three dimensions of sustainability, namely, economic, social, and environmental, in the construction phase."*

It is noteworthy that if (almost) all the Lean principles and techniques contribute to sustainability, one of the central justifications for literature reviews drops out, namely responding to the question whether such a contribution exist. Koskela (2020) has claimed that lean construction is the best available (although constantly evolving), theory-based method to manage construction towards the goals set by the client. If we accept this, then, of course, lean construction should be used in sustainability efforts. Then, it is not an optional or niche approach, and the focus should be turned away from whether it can contribute, and which are the impacts, etc., to how it can best contribute.

ARE THE FINDINGS RELEVANT?

The typical result of a literature review has the following form: Lean method X, when applied in construction project phase Y, brings benefits to environmental (or social or economic) sustainability. The number of lean methods covered is typically large, 50 – 100. As stated above, most lean methods are found to contribute to sustainability. It can be asked whether these results are relevant?

Those results can be considered relevant in a situation where the relation between lean and sustainability is not well known. Such a situation indeed prevailed 5 – 10 years ago. However, today, such results lack academic novelty and industrial relevance.

What, then, would be industrially relevant knowledge? While determining industrial knowledge needs is a fertile research topic as such, we posit that there are two obvious directions for relevant research, both geared towards narrowing the gap between lean and sustainability. First, it is probably worthwhile to augment lean methods so that sustainability aspects are taken into consideration. There are already excellent examples on this, such as sus-VSM, and takt production. The purpose is to extend the lean construction toolbox to be fully able to promote sustainability targets. Second, the current methodologies for sustainable construction could be looked at and the opportunities for added efficiency through lean methods could be suggested.

MISSING TOPICS IN PRIOR REVIEWS

The literature mostly focuses on lean construction and sustainability integration (de Carvalho et al., 2017) as well as lean practices applications such as VSM (Carvajal-Arango et al., 2019; Rosenbaum et al., 2014). Takt production, TVD and value engineering have high potential for sustainability aspects. Based on our review of the previous synthesis literature, the relation and interaction of TVD, value engineering and takt production with sustainability have not gained much attention. Thus, it is deserved to outline possible sustainability connections regarding these three approaches.

TARGET VALUE DESIGN/DELIVERY

Target Value Design (TVD) is an important lean methodology for sustainability because it is possible to achieve all three aspects of sustainability through TVD (Olender & Rosen, 2023; Russel-Smith et al., (2015). Decreasing the environmental impacts of buildings is possible by establishing sustainability targets in the design stage of the building projects. Sustainability values are required to be clearly communicated to obtain a shared view (Novak, 2014). Silveira and Alves (2018) mention that TVD inspired practices such as involving the users and owners in the process, pull design, transparency, and creating a clear vision leads to environmentally friendly buildings. Iteratively utilizing sustainable design targets during the design phase is proven to decrease the environmental impact of buildings throughout the life cycle, especially reducing the energy consumption during the use phase of the buildings (Russel-Smith et al., 2015). Thus, taking sustainability aspects earlier into account in building projects enhances sustainability performance.

TAKT PRODUCTION

Takt production in relation to sustainability aspects has gained limited attention. An exception is provided by Slosharek et al. (2021) who develop a conceptual framework to evaluate environmental performance using the takt production method. Both qualitative and quantitative environmental impacts were examined. Takt production has considerable potential for sustainability. It decreases process waste and shortens lead times (Frandson et al., 2013; Heinonen & Seppänen, 2016), improves control and flow of the construction processes (Lehtovaara, 2023), increases transparency (Kujansuu et al., 2020) and enforces the production schedule (Tetik et al., 2019). Increased transparency and control enable workers to focus on the tasks without losing time due to uncertainty over processes. Takt production also decreases material waste (Chauhan et al., 2021), thus contributing to the environmental performance of construction projects. Moreover, improving the flow of the production reduces the energy consumption on site (Maraqa et al., 2023). However, more case studies are needed to concretize the impacts of takt production in sustainability on construction industry.

VALUE ENGINEERING/MANAGEMENT/METHOD

Value engineering/management has the potential to benefit sustainability in construction by addressing environmental concerns in the early project stages. Yet, its focus has often been predominantly on cost reduction (Zainul Abidin & Pasquire, 2005). Integrating sustainability into the VE/VM job plan is significantly influenced by clients' priorities, often conflicting with sustainability objectives, especially in terms of first cost (Wao et al., 2016). To encourage the consideration of sustainability in proposals, VE/VM facilitators must establish connections between sustainability and other value drivers, align these goals with ongoing activities, and showcase potential monetary benefits to create real incentive (Abidin & Pasquire, 2007). A paradigm shift is necessary from the traditional approach of VE, which assesses cost-worth primarily in terms of initial expenses, towards a performance-worth VE that seeks optimal value for the lowest economic investment throughout the entire building life cycle (Wao et al., 2016). Still, further research is needed to validate proposed methods and explore additional approaches to adapt the VE/VM practice to sustainability.

DISCUSSION

HOW IS LEAN CONCEPTUALLY RELATED TO SUSTAINABILITY?

That lean can contribute to sustainability is thus widely agreed in the literature examined, however this conceptual linkage is variably presented. We contend that little new has been forwarded in comparison to the scheme presented already in 1998 by Huovila and Koskela. Basically:

- Lean and sustainability are aligned by their purpose; specifically, the lean purpose of waste reduction/elimination aligns with the general sustainability purpose of reduction of the use of material resources. In this angle, the contribution of lean to sustainability is broad and diffuse.
- Lean, through its methods for increasing value, is instrumental in achieving sustainability purposes and the contributions of lean to sustainability are related to specific sustainability purposes.

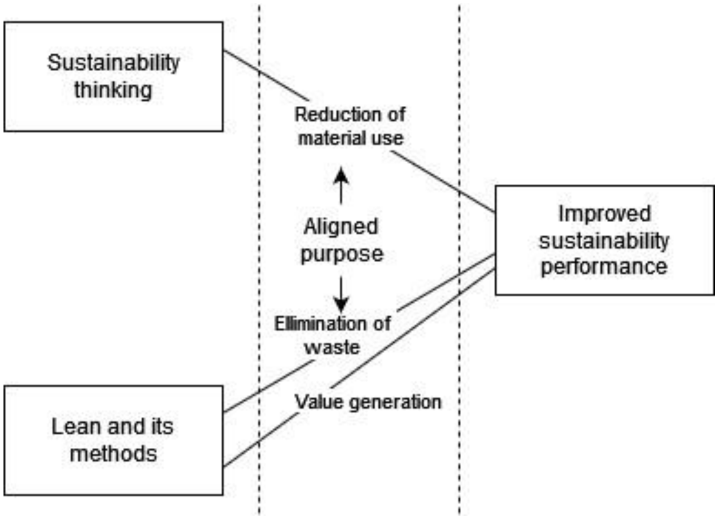

Figure 3. Conceptual relationship between lean and sustainability

SCALING LEAN UP

Lean construction has been thus far utilized in individual projects and mega-projects (Leth et al., 2019; Evans et al., 2021). Scaling lean application beyond single projects to neighbourhoods can scale up the sustainability contributions especially for the social and environmental aspect of sustainability. Moreover, since almost all lean practices seem to contribute to sustainability in construction industry, there is value in incorporating lean principles into policy making to reap more benefits for all sustainability aspects. For instance, it was suggested that efforts for trainings and spreading knowledge in collaboration with policy makers would improve the practical impact of using lean construction practices on regional level through the industry, specifically for small and medium sized enterprises (Tezel et al., 2019). Involving policy makers for adopting lean practices due to their contribution to sustainability would enhance the contribution to sustainability to a larger scale.

To determine the highest sustainability performance and low-cost solutions, algorithmic optimization methods have been developed for urban scale (Kämpf & Robinson, 2009). Several methods exist utilizing design automation, such as computational design for assessing sustainability of design solutions (Shahi et al., 2021). Simulations can be run to assess and determine the design options with higher sustainability performance (Østergård, Jensen & Maagaard, 2022). Utilization of these solutions are limited to specific instances and application in larger scale is needed.

METHODOLOGICAL PROBLEMS

The systematic literature reviews seem to suffer from two specific methodological problems: lack of criticality regarding systematic literature reviews and loose definition of the notion of conceptual framework. Both problems may have been inherited from the weaknesses of more general management literature.

Systematic literature review (SLR), as a methodology, originates in medicine and healthcare, representing settled disciplines with stable terminology. Later, SLR has started to be used in many other disciples, such as management and information technology. However, this methodology has also attracted critical views. For example, Boell and Cecez-Kecmanovic (2014) argue that SLR as a general approach to conducting literature reviews is highly questionable, concealing significant perils and caution that SLR could undermine critical engagement with literature. In the case of lean contributions to sustainability, the risk that seems to have been unnoticed or underestimated by authors is related to the still evolving terminology and scope of both areas, namely lean and sustainability.

Thus, when trying to create a literature overview on a selected topic, it is clearly advisable to critically approach the available methodological choices. Especially, an integrative literature review (Torraco, 2016) offers itself as a methodological alternative where active engagement of the researcher with the literature is supported. As discussed above, there is considerable looseness regarding the notion of conceptual frameworks. Van de Veldt (2020) states that there is evidently no clear-cut definition and application model for conceptual frameworks. This lack of unity has clearly created the impractical manifold of different understandings of conceptual frameworks in the SLR papers reviewed. It would be advisable to consult some of the few guidebooks covering how to define and prepare a conceptual framework (for instance, Ravitch & Riggany, 2016).

CONCLUSIONS

The interest into lean/sustainability topic has grown exponentially. The many literature reviews have been instrumental in showing that the general question whether lean can contribute to sustainability has already been solved: it definitely can. It must be concluded now that research efforts should be directed elsewhere. Now, it is time to focus on relevant topics and target actionable outcomes. We propose especially the following for further research:

- Critical case studies on implementation of lean/sustainability programmes in companies and projects.
- Augmenting existing lean methods with sustainability add-ons.
- Using value generation methods for sustainability purposes (especially Target value Design and Value engineering).
- Developing lean support for methods aligned with sustainability but usually not covered from the lean viewpoint, especially Circular design and production.
- Possible contributions of lean towards developing renovation policies at national and urban level must be explored.
- Identifying how lean can best contribute to sustainability.

The limitation of this study is that the analysis covered only some of the most cited “sustainability and lean construction” related papers.

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COUPLING DEMAND RESPONSE AND PDCA TO LEAN BUILDING OPERATIONS: A PROOF-OF-CONCEPT

Abdulmhseen Shaibh[1] and Kristen Parrish[2]

ABSTRACT

The Plan-Do-Check-Act (PDCA) approach allows stakeholders to identify potential changes and measure their impacts on a small scale prior to making a larger investment in such a change. One change that could be evaluated through PDCA is the installation or implementation of energy efficiency measures (EEMs). Building owners may be reticent to implement energy efficiency measures (EEMs) without fully understanding their costs and benefits. A PDCA approach coupled with demand response (DR) – whereby building owners reduce electricity consumption during periods of peak electricity demand in exchange for incentive payments – allows owners to assess EEM performance in a pilot study prior to making a larger investment in the EEM. Various EEMs can help building owners and operators shift their energy consumption to off-peak hours to earn DR incentives, e.g., reducing lighting power via controls, precooling a building prior to the peak hours. This paper documents how one building owner, Arizona State University, leveraged PDCA to identify DR strategies for a campus building and then used results from the DR event to identify permanent EEMs for the building. This case study serves as a proof of concept that indicates that a PDCA approach that leverages DR implementation supports identification of EEMs for permanent installation.

KEYWORDS

PDCA, energy management, lean operations.

INTRODUCTION

This paper crosswalks the lean concept of PDCA with energy management. This paper explores, through case study, how participation in a Demand Response (DR) program can serve as a first run study and inform future energy management efforts in a building.

PLAN DO CHECK ACT (PDCA)

Shewhart (1939) and Deming (1986; 2000) discuss the plan-do-check-act (PDCA) cycle that supports continuous process improvement. In the buildings industry, this cycle can be implemented in support of lean design, construction, and operations processes. Implementation of PDCA for improving the building design and construction process is well-documented (e.g., (Hassan 2006; Sobek II and Smalley 2008; Parrish et al. 2009; Zhichun and Yuejun 2011). In the operations phase, research documents how PDCA can be used to improve work processes, not necessarily to improve energy performance (Smith and Hawkins 2004; Ishikawa et al. 2012). Literature also documents how PDCA can be used to reduce building energy consumption (ISO

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2011; Parrish et al. 2012; Parrish and Whelton 2013). In this paper, we explore how participation in DR programs serves as a first run of PDCA for energy management, through the application of PDCA on a case study project.

DEMAND RESPONSE

Demand Response (DR) is generally defined as a measure to decrease energy demand in a building to alleviate the strain on the grid during peak hours (FERC 2019). DR programs involve a contractual commitment for demand reduction and agree to an incentive payment for said reduction (Motegi et al. 2007). Utility providers often activate their DR programs, or call a DR event, to manage demand based on forecasted energy prices and weather (Henríquez et al. 2018; Abapour et al. 2020; Gerke et al. 2020; Liu et al. 2022). DR supports reliability in that it can reduce demand, in turn reducing the need for brownouts or blackouts within the utility service territory. Weather forecasting allows for reasonable prediction of the demand and also allows utilities to determine the value of demand reduction (i.e., if DR incentive payments [$/kWh avoided] to customers are the most cost-effective means of reducing demand on a given day). Customers opt in or out of a DR event and then reduce their demand in accordance with the commitments outlined in the agreement with the utility. In some cases, customers implement DR strategies in house, while in other cases, an outside contractor will implement building controls to achieve load reduction during an event. For example, a building owner precool a building to reduce the need for air conditioning, and therefore, reduce energy demand, during a DR event. To do so, an owern may set their thermostats to temperatures below comfort levels prior to the period of peak demand, and then allow the temperature to “float” to a temperature at the high end of the comfortable range during the DR event (e.g., (Yin et al. 2010; Sun et al. 2012; Arababadi and Parrish 2016; Arababadi et al. 2017; Arababadi and Parrish 2017). According to Gerke et al., approximately 9% of commercial buildings in the United States participated in DR programs as of 2018 (2020).

RESEARCH OBJECTIVE

The authors’ objective is to develop a PDCA process that leverages DR to support assessment of DR strategies for permanent EEM installation. This is paper documents such a process and presents results from an implementation at Arizona State University (ASU).

LITERATURE REVIEW

Literature (Assimakopoulos et al. 2020; Moran et al. 2020; Qu et al. 2020; Rau et al. 2020; Uidhir et al. 2020; Coyne and Denny 2021; Li et al. 2021) supports that addressing energy management holistically, e.g., through implementation of a certified energy management system (ISO 2011; Parrish and Whelton 2013), is a best practice. Indeed, Moran et al. (2020) discuss the benefits of coupling building envelope retrofits with heating system retrofits. This allows building owners to reduce their heating demand (through increasing insulation in the envelope) and install a smaller heating system when they replace their original heating system with a heat pump. Similarly, Li et al. (2021) discuss the ability to reduce the air conditioning load in a school building when daylighting is used in lieu of artificial lighting – the need for air conditioning decreases due to the fact that the daylighting does not generate as much heat as the artificial light. Finally, Qu et al. (2020) discuss the energy and carbon reduction benefits of coupling passive and active energy efficiency measures with renewable energy production in Norwegian apartment buildings; their work illustrates that a holistic approach yields 66% more savings than an approach that only installs passive efficiency measures.

While a holistic approach that leverages the synergies between building systems is effective, this approach may represent too significant of an investment for many building owners or operators, who may not be able to justify the capital expense of EEM implementation without knowing how the EEM(s) will perform in their particular building and in their particular climate. PDCA allows building owners and operators to first test EEM performance prior to investing in the EEM installation throughout the building, using the DR event as the "Do" phase of the PDCA cycle and evaluating EEM performance through the "Check" phase prior to implementing the EEM in the building in the "Act" phase. Given that DR participation involves an incentive payment, leveraging PDCA to identify DR (and subsequent EEM) strategies and their performance represents a lower-cost opportunity for owners to reduce energy consumption.

METHODS

This research began by documenting how the PDCA process could be used to identify DR strategies, as well as for evaluating their implementation. To assess whether this proposed process would be feasible, the authors conducted an interview with the energy manager responsible for implementing DR at Arizona State University to determine whether a PDCA approach could be used to identify and evaluate DR opportunities on campus. Finally, the authors present energy data from DR implementation to serve as a proof of concept and illustrate the efficacy of using PDCA to identify DR strategies and evaluate whether these strategies show promise for EEM implementation throughout the building(s).

DEVELOPMENT OF PDCA APPROACH THAT LEVERAGES DR

The authors began with the PDCA process and added DR implementation to it as a proposed process for identifying EEMs, where DR implementation serves as a first run study.

INTERVIEW PROTOCOL

The authors developed the interview protocol (Table 1) to assess the feasibility of implementing the proposed PDCA process at ASU. As such, the questions focus on whether or not, and how, ASU currently completes PDCA to identify DR strategies (questions 1 and 2). The authors also sought to understand how ASU's DR participation impacted the selection of EEMs for campus buildings (questions 3 and 4). The authors conducted the interview in November 2022 with the energy manager responsible for DR implementation on ASU's Polytechnic campus; he has over 20 years of experience in facilities and energy management in higher education. Given that this paper documents a proof-of-concept for a single building owner, the authors interviewed the one energy manager that makes decisions about DR and EEM implementation on the campus. The authors did not code the interview responses, as three of the four questions had straightforward responses. Question 2 asked the energy manager to share a process, this was documented by the authors as the interviewee described it.

Table 1: Interview Protocol

Question	Response Options
How much load do you commit to DR?	kW committed
How do you currently determine strategies to implement to achieve load shift or shed during a DR event?	Process for selecting DR strategies
Do results of DR implementation help to identify potential investments in long-term energy efficiency measures?	Yes or No
Do you consider permanently implementing the successful DR strategies for sustained energy savings?	Yes or No

RESULTS

PROPOSED PDCA APPROACH FOR SELECTING EEMS BASED ON DR RESULTS

Figure 1 documents the proposed PDCA approach for selecting EEMs based on DR implementation.

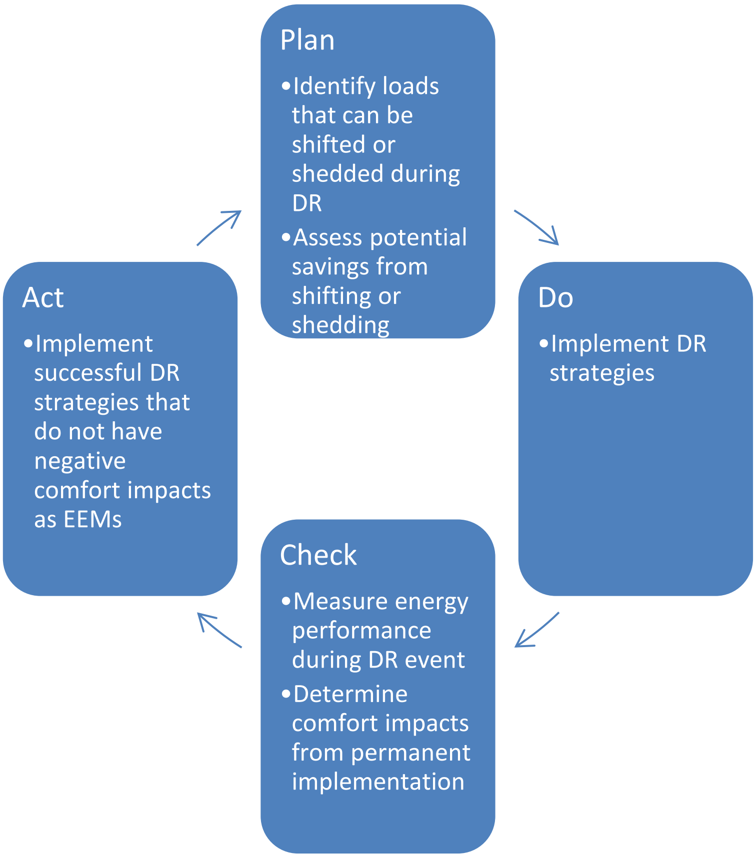

Figure 1: Proposed PDCA Approach for Selecting EEMs based on DR Implementation

The Plan phase requires that energy managers consider the energy consumption and demand of their building(s) and identify loads that may be able to be shifted, e.g., through precooling a facility (Yin et al. 2010) or shed, e.g., turning lights off, during a DR event. The Plan phase also requires that the energy manager estimate the potential reduction in demand to ensure that the DR strategies being considered provide sufficient demand reduction to secure the incentive payment associated with the DR program. During this phase, the energy manager(s) may generate several alternative DR strategies that satisfy the demand reduction commitment; if this is the case, the authors suggest using Choosing by Advantages, or CBA (Suhr 1999; Parrish and Tommelein 2009; Arroyo et al. 2015), to select the most advantageous set of DR measures to implement during a DR event.

The Do phase is when energy managers implement DR strategies, either via building controls or through manually adjusting building operations.

The Check phase requires energy managers review the impact of the DR strategies on demand reduction and energy consumption. At this stage, energy managers also need to evaluate whether DR strategies led to increased complaints from building occupants about thermal or visual comfort. For example, did occupants complain that the building was too hot or too cold during the DR event?

Finally, the Act phase requires energy managers determine which DR strategies have most promise for permanent implementation as EEMs. Research documents several examples where building owners and operators have implemented DR strategies on a permanent basis to realize those energy savings consistently (Mathieu et al. 2013; Arababadi et al. 2017).

INTERVIEW RESULTS

Following the implementation of DR strategies in the summer of 2022, the authors interviewed the energy manager at ASU to determine whether the proposed process (Figure 1) would be a viable approach for ASU to identify EEMs. The energy manager indicated that a formalized process for permanently implementing successful DR strategies would be helpful. Further, they indicated that, to date, the review of DR implementation was generally done to determine what DR strategies would be repeated in the future without considering which DR strategies may be strong candidates for permanent installation as EEMs.

PROOF OF CONCEPT: ASU ENERGY DATA REVIEW

Plan

In 2020, ASU participated in a DR program for the first time. To prepare, the campus energy manager reviewed energy consumption across campus in the campus' energy information system (Figure 2) and took the following approach during the "Plan" phase:

1. Review the metered electrical usage data for campus buildings and identify anything with at least one 15-minute demand interval larger than 500kW, i.e., the campus' largest loads.
2. Look for buildings that had at least one 15-minute demand interval larger than 150kW, i.e., medium-sized loads.
3. Examine the total kW and kWh of the buildings with "large" demand (those from Step 1) or "medium" demand (those from Step 2) over the course of the previous fiscal year to create a list of candidates based on the percentage of demand intervals that were over the targets listed above.
4. Work with the campus Facilities Management team to discuss recommendations and refine the list based on "boots on the ground" knowledge.
5. Finalize the list of buildings for participation in the DR program.

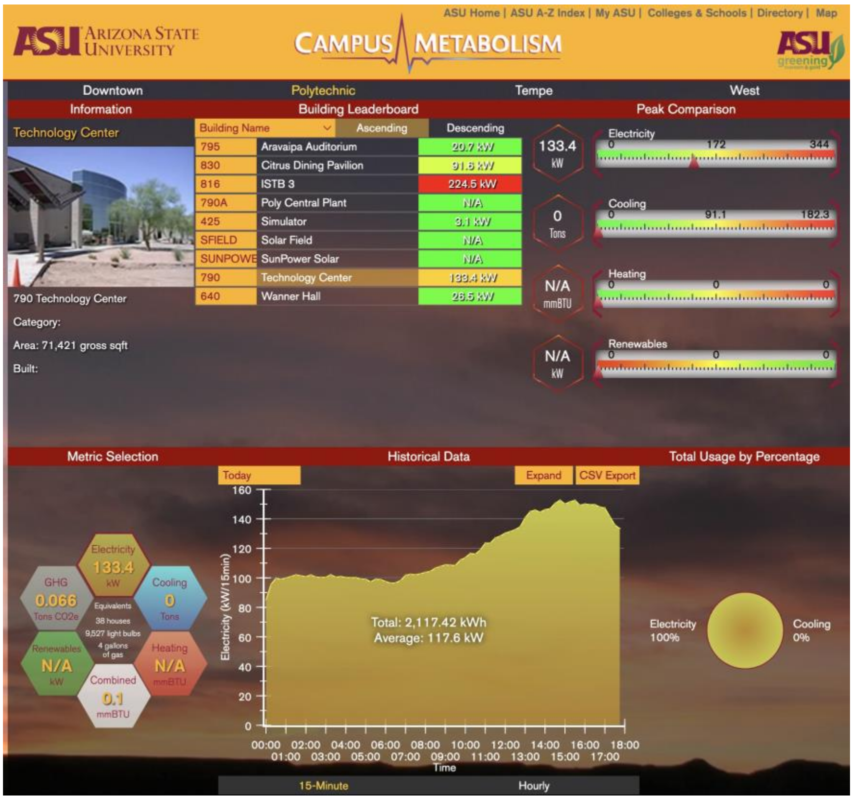

Figure 2: ASU's Energy Information System, Campus Metabolism, helps to identify buildings that may be good candidates for DR (screenshot from K. Parrish on 17 April 2024)

Once the list of buildings was finalized, the campus energy management team worked to identify specific measures to take in each of the facilities to reduce demand. They considered "typical" DR strategies like dimming lights and changing temperature setpoints (Gerke et al. 2020). Unfortunately, due to the operating requirements for classrooms and offices on campus (ASU 2024), these 'traditional' DR strategies were not feasible for ASU. Thus, the Facilities Management and Energy Management teams worked to identify customized DR strategies, including changing fan operations, increasing the temperature in the book storage facility, and dimming the lights at the Fitness Centre. The variables considered when evaluating potential DR strategies were demand reduction, in kW, where more reduction was preferred, and human comfort, where more comfort was also preferred. The energy management team avoided any DR strategies that violated ASU's operating requirements for classrooms and offices on campus, which limited their number of feasible DR strategies such that leveraging multi-criteria decision-making was not required. In fact, the energy management team initially struggled to develop feasible DR strategies that would yield the demand reductions necessary to earn the incentive payments.

Do

During the summer of 2020, ASU implemented the strategies outlined above in fifteen (15) buildings measured in eleven (11) meters and saved ~620kW per DR event.

Check

Following the implementation in the summer of 2020, the campus energy and facilities teams reviewed their success in the DR program to determine how they could increase their DR commitment in the summer of 2021, thereby increasing their incentive payment. They determined that several DR strategies implemented negatively impacted occupant comfort. For example, when classroom temperatures were set to 25.5C (the high end of the allowable operating temperature range in classrooms) during the summer at 15:00 (the start of the DR event), the classrooms quickly became uncomfortable as students released sensible and latent heat when they entered the classroom warm from an outdoor walk (outdoor temperatures in Arizona are approximately 40C during DR events). Thus, strategies that increased classroom temperatures were determined unfit for future DR seasons.

The energy and facilities teams also identified DR strategies that showed promise for future implementation, including shutting down the air handler to the book storage facility, which had sufficient thermal mass to maintain safe temperatures throughout the three-hour DR event, even when the air conditioning to the facility was shut off. Similarly, the light dimming in unoccupied areas of the Student Fitness Centre showed promise for future implementation.

Act

In 2020, this phase consisted of documenting the DR strategies that could be implemented in future DR events, in 2021 and thereafter. Indeed, reflecting on the successes and challenges associated with DR implementation provided valuable insights for future DR enrolment. By 2023, ASU had increased its DR commitment to over 1MW, and was able to secure increasing incentive payments each year.

In 2022, the authors presented the Energy Manager with the proposed PDCA approach for selecting EEMs. At this point, the conversation following DR implementation expanded to include an agenda item for identifying DR strategies that could be permanently implemented, i.e., those strategies that could serve as EEMs rather than simply DR strategies. The energy and facilities teams highlighted that the automated light dimming in unoccupied areas of the gym was a strategy they would like to implement year-round. The teams also identified other DR strategies they would consider as EEMs, like precooling classrooms and automated light dimming across campus. Importantly, the teams also highlighted those DR strategies that could not be permanently implemented, like shutting down the air handler that served the book storage facility.

DISCUSSION AND RECOMMENDATIONS

The authors discuss herein how the PDCA approach described above can support identification of potential EEMs, thereby reducing the investment cost and minimizing the risk that the EEM does not yield the expected energy savings.

EVALUATING ALTERNATIVE DR STRATEGIES IN THE "PLAN" PHASE

At ASU, the set of feasible DR strategies was limited due to the campus' strict operating guidelines for classrooms and offices. The operating guidelines made light dimming and temperature setpoint adjustments greater than 2.25C infeasible. However, other commercial building owners and operators may find that they have a large set of feasible DR strategies that they can evaluate during the "Plan" phase. When owners and operators are faced with large sets of feasible alternatives, the authors suggest using CBA to select from among alternatives. As at ASU, the factors to consider when evaluating potential DR strategies would be demand reduction, in kW, where more reduction is preferred, and human comfort, where more comfort is also preferred. Building owners and operators will also need to explicitly state 'must' criteria for CBA, e.g., "The building must provide light and conditioned air that supports productive work throughout the DR event" that ensure that DR strategies do not render the building uncomfortable or impossible to work in.

LEVERAGING THE ACT PHASE TO IDENTIFY EEMS

While ASU did not refer to their DR commitment process as a PDCA effort, their process was essentially a PDCA process, even prior to the authors' engagement with the energy management and facilities management teams. Indeed, the teams had a standardized process for planning, doing, and checking. The teams used that knowledge to act on future DR commitments. The authors' engagement in this process added a new dimension to the "Act" phase, whereby the teams identified DR strategies that could be implemented permanently alongside those that showed promise for future years' DR events. While this change was relatively small for ASU, the entire process (Figure 1) may be unfamiliar to other building owners or operators. Thus, the authors recommend that all building owners and operators consider implementing PDCA to identify DR strategies and then explicitly identify the subset of DR strategies that show promise as EEMs during the Act phase.

CONTINUOUSLY IMPROVE THE "CHECK" PHASE TO SUPPORT EEM SELECTION

EEMs perform differently in different environments. For example, at ASU, light dimming yielded savings in the Fitness Centre, but not in the classrooms due to differing occupancy patterns. The "check" phase of the proposed PDCA process offers an opportunity to align evaluation criteria to evolving goals. For instance, building owners and operators may want to add criteria about consistency of energy savings during DR events to their reviews; this way, prior to investing in a permanent installation, owners and operators can be assured they will achieve the savings they expect. (Typically, energy savings for EEMs are determined via spreadsheet calculation for technology changes like ballast replacements or via energy modelling for, e.g., new building control sequences.)

Building owners and operators may consider a set-based design approach (e.g., (Ward et al. 1995; Sobek et al. 1999; Rekuc 2005; Parrish et al. 2007; Parrish et al. 2008a; Parrish et al. 2008b; Parrish 2009) when selecting potential EEMs based on DR implementation. Set-based design allows project teams to consider multiple design options longer than would be typical in a point-based design scenario. For EEMs selection from the proposed PDCA process, set-based design may involve considering certain DR strategies for multiple years before deciding to implement those strategies as EEMs. This allows project teams to consider various DR strategies and explore their fitness for the building at hand and ensure that these EEMs make financial sense for the building owner and operator, given that EEMs cannot be used for collecting DR incentives once they are part of daily operations. (This is because once installed, EEMs will reduce the baseline energy demand, and DR requires reductions from **actual** demand, rather than from a baseline demand in a prior year.) Once DR strategies that could transition into EEMs are understood, project teams can make data-driven decisions about which to install permanently using Choosing By Advantages (e.g., (Suhr 1999; Parrish and Tommelein 2009; Arroyo et al. 2015). Energy demand reductions can be expressed as a 'must' or a 'want' criterion for either DR implementation or EEM installation at the owner's discretion.

BROADER CONTEXT: EXISTING BUILDING RETROFITS

This paper explores the transition from DR strategy to EEM, and how a PDCA approach could support this transition. As decarbonization and energy efficiency policies begin to be implemented (e.g., (State of California 2018; New York City 2019), building owners may need to retrofit their facilities. A PDCA approach is demonstrated to support building energy retrofits (ISO 2011; Parrish and Whelton 2013), and this paper builds on these existing processes by highlighting how DR can be used to earn money while testing potential EEMs in actual facilities.

CONCLUSIONS

This paper explored, though case study, how a PDCA approach can be implemented alongside participation in a DR program to support selection of EEMs for building energy retrofits. The authors proposed a PDCA approach and illustrated its potential via a proof-of-concept at Arizona State University. This proposed process allows building owners and operators to understand how potential EEMs will perform in their building(s) prior to investing in EEM installation. The authors discuss how PDCA, and lean tools like set-based design and Choosing By Advantages, can help building owners and operators reduce energy demand and consumption, in turn supporting decarbonization of the building sector.

The authors note that the sample size for this work is small, so this paper only illustrates a possible process for transitioning DR strategies into EEMs. Future work may present the proposed process to other higher education institutions, and other DR program participants, to evaluate the feasibility and efficacy of the proposed process in a new context. Such efforts would be welcome in future research by the IGLC community.

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INSIGHTS ON SUSTAINABILITY IN INDUSTRIALIZED CONSTRUCTION IN EUROPE AND THE UNITED STATES

Giulia Scagliotti[1], Jerker Lessing[2] and Martin Fischer[3]

ABSTRACT

Embracing lean philosophy, which emphasizes waste reduction and resource efficiency, is a pre-condition to improving the environmental impact of a building but is not sufficient to produce a sustainable building. To increase the environmental sustainability of their products, industrialized construction (IC) companies need to understand the constraints of the location where they operate, and best practices applied by leading IC companies. To delve into constraints and best practices, we interviewed sustainability leaders of six IC companies at the forefront of sustainability practices in Europe and the United States. The purpose of each interview was to highlight the challenges and opportunities caused by external factors that companies are experiencing, and the advancements that other companies could replicate. Based on comparative analysis, our results show stricter sustainability regulations and a collaborative stakeholders' network with similar sustainability goals in Europe compared to the US. These factors seem to favor 1) a careful evaluation of tradeoffs when considering technical solutions; 2) the adoption of disassembly, adaptability, and circularity principles; 3) the development of new business models; and 4) companies developing new rating systems to capture their advanced product sustainability. Our results can inform lagging IC companies to adopt the most advanced sustainability practices.

KEYWORDS

Lean Construction, Lean and Green, Sustainability, Industrialized Construction, Off-site Construction

INTRODUCTION

Improving the efficiency of construction processes and minimizing waste, as embraced by lean philosophy, has been widely recognized for its economic benefits (Poppendieck, 2011). Beyond the economic advantages of reducing waste, some studies highlight the positive relationship between lean philosophy and environmental sustainability (Solaimani & Sedighi, 2020; Johnsen & Drevland, 2016; Galeazzo et al., 2014; Carneiro et al., 2012). Specifically, the lean philosophy holds promise in reducing the environmental impact of construction (Degani & Cardoso, 2002; Ghosh et al., 2014). In addition to following lean philosophy, the application of industrialized construction (IC) methods generates several environmental benefits over the entire building life cycle if compared to conventional construction methods (Kedir & Hall, 2021;

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Sotorrío Ortega et al., 2023). Companies that adopt industrialized construction methods design their buildings using a product-oriented approach based on predefined solutions structured in platforms, which are used project after project and are essential for continuous improvement and systematic management of knowledge. IC companies can be more efficient in material estimation and acquisition (Banawi & Bilec, 2014), can control the source of energy to power their factories and their means of transportation (Quale et al., 2012), and achieve sophisticated buildings with consistent quality that support energy-efficient solutions (Podder et al., 2020).

However, achieving the environmental sustainability of a building involves multifaceted considerations beyond applying lean principles and industrialized construction methods (Tasdemir & Gazo, 2018). These additional considerations depend on the location in which each company operates and include, for example, the possibility of innovating product design, regulatory compliance, and stakeholders' engagement to create a more environmentally sustainable building product. With new IC companies emerging in different countries around the world (Pullen et al., 2019; Wuni et al., 2022; Malmgren, 2014) and the increasing pressure to create sustainable products (Dutil et al., 2011), it becomes critical to identify how external factors differ depending on the country and what their impacts are on the sustainability of a product. The goal is to raise awareness among companies and policymakers about regulations and stakeholder's engagement that foster sustainability in different countries and highlight the best sustainability practices adopted by leading IC companies.

This work shows initial findings of the external factors relevant to the advancements of sustainability practices and the impact they have on final building products and the structure of IC companies. We hope this work enables emerging or lagging IC companies to replicate the identified sustainability approaches and new policies that will favor sustainability practices.

METHODOLOGY

In this work, we chose a multiple case study method to enable a broad understanding of the sustainability approaches taken by six different industrialized construction companies in the US and Europe. Over four months in 2023, we researched all six companies and interviewed them to collect information and data. Our data collection followed the same pattern and included the following three steps:

- Analyze the company's public stance on sustainability as expressed on the company's website.
- Conduct a 1-hour semi-structured video interview with the sustainability manager or CEO of each company.
- Review additional documents shared directly by the company (e.g., pilot study results and projects in collaboration with universities).

COMPANY SELECTION

We chose six companies based on the following four primary criteria:

- Categorized as working with industrialized construction methods according to Lessing's framework for industrialized construction (Lessing, 2015).
- Produce wood based modular residential buildings.
- Companies are based in different countries, including Europe and the US, and at different maturity stages, including well-established and recently started companies.
- Companies are at the forefront of sustainability practices in their country.

We selected six IC companies: four in Europe, specifically two in Sweden, one based both in Denmark and the Netherlands, one in Switzerland, and two in the US, one in Pennsylvania and one in California. Among the companies selected in Europe, two were newly established startups (Group A), and the other two were well-established Swedish IC companies (Group B). The two companies selected in the US (Group C) were established about ten years ago. Each company is briefly described in the following section, and all companies' names have been anonymized.

Group A: European IC Startups

Company A1 is a non-traditional real estate startup established in 2021 with operations in Denmark and the Netherlands and a team of about 25 people. Their main goal is developing urban communities that are inclusive, livable, and sustainable. They recently partnered with a construction company to build their first residential project, which has a minimal carbon footprint. They are using modular timber construction, have developed material passports, and are applying circular economy principles.

Company A2 is a Swiss startup established in 2021 that designs and develops reusable and re-adaptable buildings for real estate owners and investors and has a team of about 10 people. The company aims to help cities become more dynamic and fulfill changing users' needs through their future-proof circular building products. Their products are manufactured as a standardized modular kit of components and designed to maintain value over multiple life cycles since they can be quickly readapted or relocated to minimize their environmental impact.

Group B: Swedish Family-owned IC Companies

Company B1 is a well-established family-owned Swedish wood company with over 2,000 employees. They act as suppliers of wood materials and components but also as manufacturers and developers of wood volumetric modular multifamily houses. Environmental consciousness is one of their core values. They source raw materials from forests and replace the trees removed with new trees. They build climate-smart and energy-efficient homes with the goal of creating sustainable communities.

Company B2 is a well-established family-owned Swedish company with about 150 employees that builds wood volumetric modular multi-story dwellings. About 70% of their production is offered to external customers, whereas the remaining 30% is used by their own real estate company. They consider sustainability from an ecological, social, and economic perspective, looking at the entire life cycle, and have the goal of developing long-lasting communities.

Group C: United States IC Companies

Company C1 is a vertically integrated wood volumetric modular construction company established nearly ten years ago with factories in Pennsylvania and California and about 300 employees. It is focused on providing multifamily affordable housing that is resilient and environmentally friendly and invests in sustainability on many fronts, from using clean energy to power factories to reusing and recycling materials.

Company C2 is a California-based company that produces wood panelized components that can be assembled into volumetric modules. Launched in 2016, the company has about 100 employees. Their goal is addressing the housing shortage in California while supporting people and the planet. They have had carbon-neutral operations since 2020 and are working to further reduce emissions throughout their value chain, reducing waste, and selecting sustainable materials.

Data Collection and Execution

We developed interview questions about sustainability to better understand the company's motivation, technical advancements, challenges, future vision and whether they use Whole Building Life Cycle Assessment (WBLCA) on their products, track their direct and indirect environmental impact, and collaborate with their stakeholders to improve the product sustainability. We also asked additional questions about circularity, e.g., whether they apply circular principles in their product development or plan to include them in the future. The interviews were 1-hour long, semi-structured, and via video with the sustainability manager or CEO of each company. They were conducted by the same interviewer who asked open-ended questions that encouraged a conversation. Once the information was collected, our analysis followed a qualitative approach using qualitative coding to systematically categorize the excerpts to find themes and patterns and qualitative synthesis to pool data and draw conclusions. The study revealed similarities and differences between the six companies, which are reported in the next section.

RESULTS AND DISCUSSION

All the IC companies in this study see lean principles and industrialized construction methods as advantageous to achieving a more sustainable building product. In this section, we show how, in the last decade, the IC companies interviewed similarly developed buildings that can support energy-efficient solutions and are now shifting towards lowering the embodied carbon emissions of their building products. We also illustrate that finding sustainable technical solutions is not their main challenge. Conversely, cost, industry resistance to change, and regulation play a greater role in hindering their ability to make their final product more sustainable. These factors are common in both Europe and US based companies though in some countries in Europe, the establishment of a network of stakeholders interested in improving sustainability and stricter building regulations that promote sustainability seem to have accelerated the continuous improvement of more sustainable products. Indeed, only the European companies interviewed evaluate tradeoffs between operational and embodied carbon impact; consider products' disassembly, adaptability, and circularity while developing their technical solutions; and look beyond typically adopted business models and rating systems.

SUSTAINABLE TECHNICAL SYSTEMS

All companies interviewed have focused on achieving energy efficiency for both their factories and the final products they offer. All companies' factories are partially or totally powered by solar energy, reducing the environmental impact of the production and assembly phases of the building life cycle. In the last decade, all the companies put substantial effort into reducing operational carbon and developing an energy-efficient building product. They offer buildings powered by electricity generated by solar energy or geothermal energy, heat pumps, and wastewater recycling systems to treat and reuse water. These options are available to customers and could be easily implemented in the final building product. After focusing on energy efficiency and achieving products that generate low operational carbon during their lives, all the IC companies interviewed are now switching their interests towards reducing the embodied carbon of their products. These companies are now experimenting and testing new bio-based materials to substitute materials commonly used in construction and lower the initial carbon footprint of their building product. For example, company B1 is trying to replace mineral wool with cellulose to insulate buildings and company C1 is testing bamboo as a replacement for lumber. Given the high embodied carbon of traditional concrete foundations, companies are exploring alternatives such as using cross laminated timber (CLT) or steel for the foundations and bedframes of their buildings. This work of lowering embodied carbon emissions is quite challenging since the companies must triangulate their sustainability goals with financial constraints and current regulations.

BARRIERS AND CHALLENGES TO IMPROVING SUSTAINABILITY

Although innovating technical systems can present challenges, none of the interviewed companies explicitly mentioned technical issues among the main barriers and challenges they face while improving the sustainability of their products. Conversely, all the interviewed companies identified financial issues, their industry's resistance to change, and regulation and compliance requirements among the challenges preventing the wide adoption of the most sustainable solutions, as summarized below.

High Initial Cost

The IC companies interviewed shared that the most sustainable option, on average, is not yet cost effective and that bio-based choices on the market are more expensive. This represents a barrier for them to improving the sustainability of the baseline product. Although they see a growing interest in sustainability, only a few customers choose the most sustainable option available since they need to pay a premium for it. In addition, progress in building sustainability requires increasing investment by IC companies. However, it is hard for them to prioritize sustainability when the building sector is struggling, and they find it challenging to be profitable and guarantee fast product delivery.

Resistance to Change

The IC companies interviewed note a general resistance to change from their stakeholders. For example, suppliers would need to change how they produce materials and use cleaner energy instead, customers would need to change their approach and consider the entire building life cycle and opt for the most sustainable option. The adoption of sustainable options is still quite limited and to expand it, we need a change of mindset that prioritizes sustainability as a factor that matters when evaluating a final product.

Regulation

The IC companies interviewed believe regulatory infrastructure is quite fixed and difficult to change. It is often challenging for them to bring new sustainable products into the market because of compliance issues. It is difficult to meet fire, acoustic, and structural requirements with new sustainable products. Doing so would require them to do more testing and larger investments of money and time in mockups. In the US, building codes are fragmented because it is a large country with different needs (seismic, hurricane, etc.). Therefore, it is difficult to broadly adopt certain technologies and methodologies.

DIFFERENCES: EUROPE VS UNITED STATES

All European and American IC companies face similar challenges and barriers to achieving a more sustainable product. However, different regulations and business norms create differences in how European and American companies address these challenges and barriers. In this section, we will present two external factors that favor sustainability advancements in Europe: the presence of stricter regulation and a stronger network of stakeholders to collaborate with. We highlight factors that are indicative of the progress of the European IC companies interviewed that can be taken as models of how to achieve further sustainability: evaluating tradeoffs between operational and embodied carbon emissions when choosing a technical solution; considering disassembly, adaptability, and circularity of the final product; and developing new business models and sustainability rating systems.

Regulations and Life Cycle Assessment Requirements

External factors that exist in Europe and not in the United States yet are regulations that mandate reporting the environmental impact of a company (Directive 2022/2464) and a maximum carbon footprint for projects (One Click LCA, 2022). In the European Union (EU), in addition to reporting Scope 1 emissions, which are direct emissions that occur from sources controlled or owned by a company, and Scope 2 emissions, which are indirect emissions from the generation of purchased electricity consumed by the company, companies must report Scope 3 emissions, which are indirect emissions from upstream and downstream activities in the value chain (Bhatia & Ranganathan, 2004). As of 2024, large companies are reporting Scope 1, 2, and 3 emissions, whereas small and medium-sized companies will start in 2026 (Directive 2022/2464). This also means that IC companies in the EU will soon need to report the environmental impact of purchased materials; upstream and downstream transportation and distribution; waste generated; processing, use, and end-of-life treatment of their sold products (in this case buildings); employee commuting and business travels; etc. In the US, only public companies need to disclose greenhouse gas emissions. Starting in 2026 (Scope 1 and 2) and 2027 (Scope 3), the State of California (S.B. 253, 2023) will mandate disclosure of GHG emissions to public and private companies, but only if operating with over 1$ billion in revenue.

Besides the mandated reporting of companies' environmental impact, in recent years, several North European countries such as Denmark, Finland, France, Netherlands, and Sweden, put in place mandatory regulations for Life Cycle Assessments (LCA) of all newly constructed buildings including residential, whereas in the UK, Germany, and Switzerland, similar requirements exist for public buildings only (One Click LCA, 2022). Regulations setting limit values for the carbon footprint of buildings will be further revised in the upcoming years to progressively reduce the environmental impact of new buildings. The European IC companies interviewed are in the countries with the most advanced mandatory legislation to lower the carbon footprint of new buildings. The life cycle stages and building components and systems required to be included in the calculation of the LCA differ depending on the regulations in each country, and details are reported in Table 1 (One Click LCA, 2022). In the United States, no requirements around the carbon footprint of buildings are yet enforced, although there are programs to support green buildings and initial work to require embodied carbon considerations in new construction and major renovation projects. With CALGreen, starting in July 2024, the State of California will require LCA calculation for certain projects, but this does not apply to residential buildings (California Building Standards Commission, 2010).

Table 1: Mandatory regulations for the LCA of newly constructed buildings in each of the country where the companies interviewed are based (One Click LCA, 2022).

Country	Buildings	Year	Limit value	Future plan	Stage LCA	Components required for LCA
Denmark	All new buildings >1000m^2	2023	Yes	All new buildings in 2025	A1 to A5, B4, B6, C3, C4, D	All except for MEP, furniture, and appliances.
Netherlands	Offices >100m^2 and residential	2018	Yes	To be determined	All except for B6 and B7	All except for external work, furniture, and appliances.
Sweden	All new buildings >100m^2	2022	Not yet	Mandatory limit value in 2025	A1 to A5	All except for floor and wall finishes, external work, MEP, furniture, and appliances.
United States (California)	Office and schools	2024	Not yet	To be determined	To be determined	To be determined

Although limit values enforced today are not yet strict, the European IC companies interviewed envision their path ahead and the need to become more sustainable year after year to comply with more stringent rules in the future. They have already started the journey to lower the carbon footprint of their final product. On the other side, the American IC companies interviewed are still in an experimental phase, since their initiatives to lower the carbon footprint of their product are taken on a voluntary basis and not because of pressing regulations or the belief that rules will be stricter in the years to come. They have assessed the building life cycle environmental impact only on specific projects or when the client asks for it, whereas the European IC companies interviewed do it routinely because of regulations that enforce it.

Network of Stakeholders with Similar Sustainability Goals

Besides the presence of a different regulatory infrastructure, we found that the network around IC companies in Europe is more supportive of and interested in sustainability than the network present in the United States. Swedish IC companies collaborate with stakeholders on sustainability throughout the entire product value chain (Fig. 1). Customers, municipalities, architects and engineers, facility managers, construction companies, suppliers, subcontractors, and waste management companies share their perspectives and tackle sustainability from different angles, enriching the discussion and proposing solutions to technical and commercial issues. In addition, academia is involved in the discussions within this large network of stakeholders and acts as an independent and impartial entity. Even financial institutions and insurance companies are part of this large network. The former offers advantageous loans to customers that invest in a more sustainable project, creating a virtuous loop; the latter is working to provide insurance for buildings made of reused materials, increasing the expansion opportunities of this nascent market.

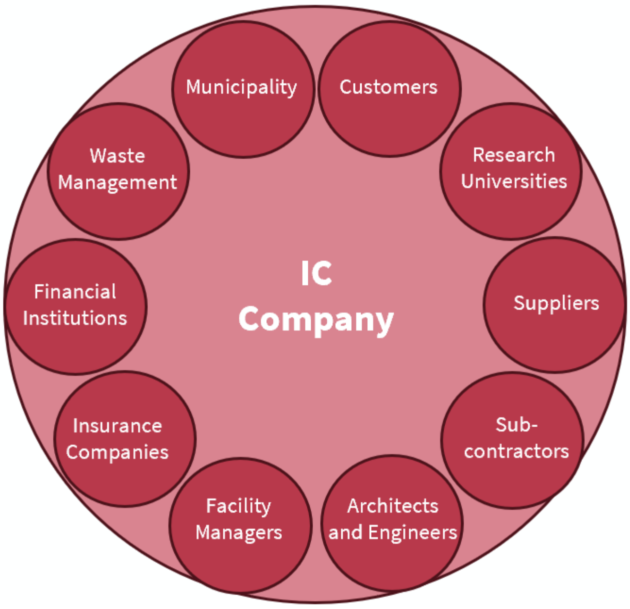

Figure 1: Network of stakeholders in Europe supporting sustainability efforts throughout the product value chain.

Like Swedish companies, company A1 based in the Netherlands and Denmark has created an online platform to engage the entire industry in the sustainability and circularity journey. This platform offers a place to connect many stakeholders but also serves educational purposes. European IC companies interviewed have a collaborative approach and work on advanced topics related to the sustainability of their product even with direct competitors, understanding that the journey towards achieving sustainability cannot be undertaken alone.

Although willing to cooperate with stakeholders, the companies interviewed in the US find challenges on the supplier and developer sides. For example, company C1 aspires to have a consortium of all stakeholders in the market with a third party, whether academia or government, to get more attention from all the players in the construction market on sustainability topics and foster the circularity of their final product. Unfortunately, such a consortium has not yet been established, and today it is rare for individual suppliers to be willing to address IC companies' concerns around embodied carbon emissions and modify or adapt their production to satisfy the request of only one IC company. Startups offering more sustainable materials are emerging, but often can't satisfy the large demands required to complete a building project. For example, company C2 identified a potential supplier of an innovative sustainable material that could be used in buildings. However, the supplier did not have the capacity to supply enough material for their entire building project. In addition, developers typically flip the project after a short period of time, which results, with rare exceptions, in no investment in durable materials and no consideration of the usage and end-of-life stages of the project. Moreover, customers generally don't choose the most sustainable option among the many available on the market because of the high initial cost of the most sustainable option and the lack of financial incentives.

Evaluation of Tradeoffs of Technical Solutions

From the interviews conducted, a factor that is indicative of the advancements in European IC companies is the evaluation of tradeoffs when opting for one technical solution or another, including variables such as embodied carbon, operational carbon, the source of energy for building operations, cost, and estimated building life in the decision-making process. Our analysis indicates that two practices enable evaluation tradeoffs: the habit of analyzing the entire life cycle of a building, partially due to the new regulations in force, and the developer's interest in keeping the building in their portfolio for a long time instead of flipping the project soon after construction. We report some examples that companies shared with us below.

1. **Wall Thickness**

   About 15 years ago, Swedish company B1 developed a new wall system that was much thicker than the typical one with the belief that it could be a more sustainable solution in the future and reduce operational carbon emissions. However, this solution was expensive and could not reduce the energy consumption enough to balance the high cost and higher carbon footprint generated by the extra layers. Therefore, the company did not adopt the thicker wall and concluded that increasing the thickness of the wall to achieve better performance during building use does not always represent the best sustainable option when we also account for the embodied carbon and the life cycle costs.

2. **Envelope Material**

   Swedish company B1 offers multi-story residential buildings with wood-cladding façades. This type of façade needs to be repainted every 12-15 years for maintenance. Company B1's clients prefer a brick or glass façade to reduce maintenance costs and time. However, a brick or glass façade would cost much more than a wood façade and have a higher carbon footprint. Repainting the wood façade every 12-15 years is cheaper and results in a lower carbon footprint for the envelope. Although offering the option of a brick or glass façade, company B1 recommends clients to choose a wood-cladding façade if sustainability is among their priorities.

3. **Triple Glazing**

   Company A1 explored to what extent they need to insulate a building. The building code forced them to use triple glazing to have a better insulated building and decrease the operational energy use. However, after carrying out an analysis, the company discovered that the production of the glass for the extra panel would require more energy than the energy saved by having triple glazing in the building. Therefore, the savings in operational carbon would not balance the higher embodied carbon of the extra glass panel and the company recognized triple glazing is counterproductive in the project examined.

These examples reveal that a company needs to make decisions looking beyond the initial cost, and considering the entire building life cycle with a clear understanding of all the factors that play a role in the decision. The most sustainable option sometimes is not the most obvious or the one desired by other stakeholders.

Consideration of Disassembly, Adaptability, and Circularity

Another difference that emerges when comparing companies, not only between Europe and the United States but also considering their maturity stage, is the attention to disassembly, adaptability, and circularity.

European IC startups (Group A) are placing these future-proof concepts at the core of their business. For example, company A1 offers adaptable buildings with large apartment units that can be subdivided into smaller units in the future, if necessary, as the trend indicates that families are decreasing in size on average. They also design their buildings for disassembly and embed circularity into the product from the beginning with the idea of reusing their buildings at the highest possible value once they reach their end of life. Similarly, company A2 designs its products to be reusable, embedding specific technical characteristics that make the building circular, enabling disassembly and re-assembly an infinite number of times. Their buildings are also adaptable and flexible: the floor area or number of floors can be increased, and elevator shafts can be added.

Although companies B1 and B2 are well established and much more mature than companies A1 and A2, they are considering future-proof concepts as well, evaluating how to modify their products step by step to increase the disassembly, adaptability, and circularity potential. In collaboration with a Swedish university, company B2 performed a WBLCA on one of their projects to understand whether and how a more flexible and adaptable product could reduce their life cycle environmental impact. During a workshop organized by the same university, Group B companies developed their disassembly instruction manuals as a first step towards increasing the disassembly potential of their buildings. They recognize the challenges of disassembly in practice, as the guidelines would only apply if the assembly was carried out following precise instructions, i.e., without adding additional nails or not-tracked elements to the product during construction. The wood volumetric modules can be disassembled because each module is attached to another through dry connections only. Conversely, disassembling the module itself would be challenging, especially because the mechanical, electrical, and plumping (MEP) system is not designed to be easily disassembled and glue and adhesive are used within each module. Moreover, the market value of an assembled module would be higher than the total value of each detached single component within the module. For now, companies B1 and B2 have difficulties imagining how to solve the commercial aspects of disassembly and reuse, but both foresee the importance of circularity in the future.

Group C companies do not have disassembly, adaptability, and circularity on their roadmap or among their priorities. However, company C1 considers product sustainability during design, using a scorecard system to assess the end-of-life treatment of the materials chosen: whether they are reusable, recyclable, intended for landfill, or hazardous. Company C2 is focused on increasing the quality of assembly to be able to easily replace components in the future.

Beyond Commonly Used Business Models

IC companies have different business models than traditional construction companies (Lessing & Brege, 2018). These business models are structured based on continuity and are more suitable to improving the sustainability of their product and achieving full product circularity (Berglund-Brown et al., 2022). Startups that design their business models based on industrialized construction principles have beneficial conditions to fully embrace circularity principles and translate them into practice. For instance, company A1 invested a lot of time in developing its business model. As developers, they intend to keep each building in their portfolio throughout their life to maximize the benefits of including disassembly, adaptability, and circularity. They have developed material passports since they see their buildings as a temporary deposit of materials. In this way, materials will have a retained value and investing in the sustainability and circularity of the product becomes much more attractive from an economic standpoint. Although a company changing their business model requires much effort and risk taking, especially by well-established companies, mature companies in Europe are starting to think about new business models to enable circularity. For example, company B2 envisions keeping material ownership of their buildings during their lives as a good opportunity to better control the end-of-life phase of the building and reuse its components and materials.

Beyond Commonly Used Sustainability Rating Systems

In recent years, many rating systems to assess the environmental impact of buildings have been established (Bernardi et al., 2017). Commonly available rating systems, such as the Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) and the Leadership in Energy and Environmental Design (LEED), provide a framework with precise criteria for assessing different categories of a building's environmental impact, such as materials, water efficiency, and indoor environmental quality. The IC companies interviewed use these systems to benchmark their products and gain certification, which they use to market their products to customers. However, the different companies had different opinions of the commonly used sustainability rating systems and how useful they are, mostly depending on the level of maturity of the company. Group A startups criticized the commonly available rating systems because they find them too limited to capture the entire value of their innovative product. Company A1 shared that companies using these systems can achieve very good ratings with traditional approaches and materials without necessarily rethinking their methods and without creating a truly more sustainable and circular building. As an example, company A1 shared that a project with 11 $kgCO_2/m^2$/year, which is not a difficult target to achieve, can earn a good rating such as a gold certification using DGNB, whereas they are already offering their first product at 5.3 $kgCO_2/m^2$/year, but can't reference a commonly used sustainability rating system that fully captures the additional value of substantially reducing the environmental impact of their product. Therefore, company A1 started to explore methods to capture this additional value, by developing their own tracking and rating system. Company A2 made similar criticisms of the commonly available rating systems, explaining that they also developed their own tool to capture the benefits of their product spanning multiple building life cycles and show the environmental impacts and costs since there were none available. Conversely, Group B and Group C companies still measure the sustainability of their product relying on commonly used rating systems, showing that their product can reach good ratings such as Gold certification with DGNB and LEED and find that currently sufficient.

CONCLUSION

Our goal was to raise awareness among companies and policymakers by analyzing the context and the best sustainability practices adopted by leading IC companies in the US and Europe. Based on our analysis of six IC companies at the forefront of sustainability practices, we conclude that the presence of strict regulations that enforce sustainability and the collaborative approach of stakeholders play important roles in developing an environmentally sustainable final product, as demonstrated by the European IC companies analyzed. They show more advancements in sustainability than US companies because they tend to 1) evaluate tradeoffs when considering technical solutions; 2) consider disassembly, adaptability, and circularity principles; 3) adopt new business models; and 4) develop new sustainability rating systems.

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CARBON EMISSIONS OF CONSTRUCTION OPERATIONS IN A COLD CLIMATE

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TABSTRACT

This study focuses on the energy use of construction operations and explores the associated greenhouse gas (GHG) emissions. The case study methodology is used in this exploratory investigation to assess the energy consumption and GHG of eight construction projects in Estonia. The findings highlight the need to account for heating and illumination emissions, underlining the importance of including construction phase emissions in building lifecycle carbon assessments. No strong correlation between building size and energy consumption is found, but there seems to be a connection between project duration, use function, and emissions. It suggests that addressing the embodied carbon of construction operations, particularly when heating is required, is crucial for reducing the overall carbon footprint. This study develops and invites the lean community to establish a baseline for construction operations' energy use and related GHG emissions. A baseline is needed to facilitate the continuous improvement of construction processes from the sustainability viewpoint.

KEYWORDS

Sustainable construction, energy consumption of construction operations, greenhouse gas emissions, winter heating and illumination.

INTRODUCTION

The need to address the effects of climate change has highlighted the urgency of reducing carbon emissions globally (European Commission 2020a). The United Nations Environment Programme estimated that the greenhouse gases (GHG) from construction materials and operational energy emissions of buildings constituted 37% of worldwide emissions (United Nations Environment Programme 2022). Addressing the construction sector and the built environment emissions is deemed a key strategy for decarbonizing the European economy by 2050 (European Commission 2020b).

However, the construction and built environment status report published in 2022 revealed that the gap between actual and target performance is growing (United Nations Environment Programme 2022). The building and construction industry is behind in its efforts to meet the 2050 decarbonization target, which is the key objective of the Paris Agreement (Paris Agreement 2015). It is becoming clear that incremental changes are insufficient; substantial

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strategic and structural reforms are necessary to face the escalating challenge of realizing a net-zero-carbon built environment (Council of the European Union 2023; Kibert 2022).

Thus far, the focus has been on reducing operational emissions from buildings, but emissions from construction operations remain underexplored (Tang et al. 2013; Weigert et al. 2022). The whole life cycle approach is needed (Kibert 2022). All embodied carbon emissions associated with construction products, transportation, and processes must be tackled to avoid undermining the carbon reductions achieved from energy efficiency and saving measures. The construction phase is expected to become increasingly significant as operational carbon emissions decrease due to enhanced energy efficiency in both new and existing buildings (Bahramian and Yetilmezsoy 2020). However, the baseline for construction operations' energy use and related GHG emissions is not well established.

This research addresses the greenhouse gas emissions associated with construction site processes and activities, with a specific focus on the energy use of construction operations during winter and summer seasons. The case study methodology is used for this exploratory investigation (Yin 2018). Data from eight construction projects of an Estonian building company were gathered, analyzed, and compared. Finally, ideas to reduce the emissions of construction operations are discussed.

RESEARCH BACKGROUND

Lean construction focuses on improving construction processes by eliminating or reducing waste (Koskela 2020), including among others unnecessary consumption of material and energy resources. Systematic literature reviews (e.g., (Moradi and Sormunen 2023)) and detailed studies (Osorio-Gómez et al. 2020; Wandahl et al. 2021) on synergies between lean construction (and lean in general) and sustainability have been conducted.

Osorio-Gómez et al. (2020) evaluated the influence of Lean Construction techniques on the environmental footprint of construction projects through a comparative case study of two projects, one employing Lean principles and the other using traditional methods. The study highlighted an 18–24% reduction in categories like acidification, ecotoxicity, eutrophication, global warming, and ozone depletion for the Lean Construction project. Wandahl et al. (2021) explored the impact of Construction Labour Productivity (CLP) improvements by adopting Lean tools and methods on the EU's renovation wave's energy efficiency targets. The study demonstrated a link between construction process improvement and reduced energy consumption.

While these studies present evidence of the direct relationship between Lean process improvement and environmental impact, most building codes and regulations tend to address operational energy carbon for heating, cooling, and lighting the indoor environment but do not account sufficiently for embodied carbon (United Nations Environment Programme 2022). The studies that address embodied carbon tend to be limited to the extraction, manufacturing, and transportation of construction products, emphasizing the design phase, including selection, methods, and tools (Joseph and Mustaffa 2021), and neglecting construction operations related emissions (Weigert et al. 2022).

A recent comprehensive systematic literature review on carbon assessment of construction operations identified the following themes as significant when considering construction-phase carbon emissions: (1) time and country trends, (2) carbon assessment methods, (3) construction stage-related carbon factors, (4) construction equipment classification, and (5) recommendations for reducing carbon emissions (Joseph and Mustaffa 2021).

Three research focus periods for carbon assessment were identified (Joseph and Mustaffa 2021). In the first period before 2010, there were a few studies focused on isolated aspects of buildings and carbon-related emissions. In the second period between 2010 and 2015, different Life Cycle Assessment (LCA) methods surfaced, including additional aspects and factors of carbon emissions. However, the scope and system boundaries for assessment varied significantly (Tang et al. 2013). That is, no standardized method was used for the LCA (Mastrucci et al. 2017). In the third period after 2015, standardized LCA methods and phases based on the ISO14040 began to be used (Arvanitoyannis 2008), including the different types of construction projects, phases, and construction methods (e.g., prefabricated versus on-site construction) (Bahramian and Yetilmezsoy 2020). This phase also incorporated modeling, simulation, and sensitivity analysis (Joseph and Mustaffa 2021).

The same studies revealed that the carbon emissions of construction operations are typically assessed using (1) LCA, (2) optimization method (3), simulation, and (4) on-site observations (Joseph and Mustaffa 2021). The two main approaches for LCA include the process-based LCA (the bottom-up approach) and input-output-based (I-O) LCA (the top-down approach) (Mastrucci et al. 2017). The selection of the LCA method depended on the main aim of the research (Mastrucci et al. 2017). Optimization methods focus on maximizing or minimizing the chosen function or parameter, such as the carbon impact of construction equipment or selecting the most appropriate construction method (Avetisyan et al. 2012; Szamocki et al. 2019). In simulation-based studies, discrete event simulation, for example, has been used to model and analyze construction operations (Liu et al. 2021). On-site field studies/observations are used to collect emissions data and to study carbon emissions management practices (Joseph and Mustaffa 2021). Also, remote monitoring to measure construction equipment emissions has become more broadly used.

The embodied construction phase-related assessment of different sources of carbon emissions typically includes (1) materials (including also auxiliary products), (2) transportation to and on the site, (3) machinery and equipment, (4) site accommodation and welfare, (5) building operation or energy use, and (6) construction waste (Joseph and Mustaffa 2021). Most studies have focused on construction machinery and equipment, materials, and transportation (Joseph and Mustaffa 2021), which comprise the largest proportion of embodied carbon (Weigert et al. 2022). Regarding construction equipment, the following are typically addressed (Joseph and Mustaffa 2021): (1) lifting and transportation machinery, (2) earthwork machinery, (3) concrete and mortar machinery, (4) processing machinery, (5) piling machinery, (6) welding machinery, (7) road construction machinery, and (8) pump machinery.

The LCA calculation in Europe follows the standard EN 15978:2011 (Van Gulck et al. 2022). In the A5 “construction phase”, all carbon emission sources need to be considered. In addition to the carbon sources listed above, the standard includes also heating and cooling of temporary spaces and the building during construction activities (e.g., during cast-in-place concrete or interior works), auxiliary works, materials and products, re-work, and water requirements on the construction site. However, these aspects are often neglected in the LCA studies (Joseph and Mustaffa 2021) or are addressed to a limited extent.

Estonia is situated in a cold climate zone, which means that construction operations carried out in the winter require heating and additional illumination. However, studies addressing the impact of construction operations that need heating and illumination during the winter period could not be found. This gap will be addressed in this study.

RESEARCH METHOD

This exploratory case study research aims to determine the carbon footprint of the energy consumption of construction site operations. The EN 15978:2011 standard was followed and the 2022 CO_2 emissions data for Estonian electricity production was used for all sites to ensure a common basis for comparison.

INITIAL DATA AND LCA CALCULATIONS

While EN 15978:2011 for LCA helps to classify life cycle phases and to categorize carbon emission sources, there is no detailed method for scoping (system boundary) and calculating the carbon footprint of construction operations. This has been addressed differently in various studies utilizing LCA calculations. In this study, for comparing different construction projects, the energy consumption of construction operations was converted into carbon footprint equivalent (kgCO_2e), and the total carbon footprint of energy consumption was divided by building net area (kgCO_2e/m^2).

For calculating the electricity consumption and district heating carbon emissions, the GHG factor 0.636 (kgCO_2e /kWh) for 2022 from the main Estonian utility company (Elering 2024) and the Estonian Environmental Research Centre (Eesti Keskkonnauuringute Keskus 2024) were used. For district heating, the district heating factor 0.200 (kgCO_2e/kWh) from the Estonian Environmental Research Centre (Eesti Keskkonnauuringute Keskus 2024) was used. The carbon emissions for the combustion of fuels for heat energy are calculated by multiplying the burned fuel volume with the fuel factor (kgCO_2e/kWh). For the comparison of electricity and heating energy intensity of different construction sites, the diesel and natural gas/propane energy density factors were also used. For the natural gas/propane, the average of the two was used in calculations. The initial values for calculations are summarized in Table 1.

Table 1. Carbon emission factors for the Estonian energy carriers in 2022 (Elering 2024; European Environment Agency 2023).

Energy Carriers/Sources	CO_2e Factor	Energy Density
Electricity (Estonia)	0.636 (kgCO_2/kWh)	
Diesel	0.250 (kgCO_2/kWh)	10.74 (kWh/l)
Natural Gas/Propane (Gas)	0.140 (kgCO_2e/kWh)	15.4/13.8 (kWh/kg) (average 14.6)
District Heating (DH)	0.200 (kgCO_2e/kWh)	

SELECTED CASE PROJECTS

The study included construction projects conducted between 2015 and 2023 where energy consumed during construction activities was available. Data on eight construction projects of an Estonian private sector building company were collected. All investigated sites were managed by different site teams and were organized according to ISO 9001, 14001, and 45001 requirements.

The electricity consumption data were obtained in two ways, including (1) monthly electricity meter data, and (2) the recordings of the initial and final meter readings. Meter data on electricity consumption came from the meters installed by the general contractor. For heating in the winter period, the fuel or district heating supplied by the general contractor was considered. Consumption data for the fuel and district heating energy were collected from invoices. Fuels consumed by subcontractors for construction machinery and equipment were excluded from the study.

Table 2 summarizes the main information about construction projects, including the project number (PR), building use function, net area of the building, construction start and end months and years, the duration of the construction project, and consumption of electricity, fuels, and district heating. On projects PR 1 – 3, no heating during construction was used. Different sources for heating were used on PR 4-8. For diesel and natural gas/propane, two energy consumption values are presented, including the natural unit and the equivalent in kWh. Most observed projects were industrial or office buildings, including the residential and warehouse buildings as exceptions. The building sites under investigation varied in size, ranging from 500 to 9000 m², and in construction durations ranging from 4 to 19 months.

Table 2. Information on selected construction sites (* the intended use is not available).

PR	Building Use Function	Net Area (m²)	Construction Duration: Start and End	Electricity (kWh)	Diesel (liters/kWh)	Gas (kg)	District Heating (kWh)
PR 1	Industrial Building; Office Building	1430	6 Months: July 2022 -January 2023	7278			
PR 2	Other Industrial Building; Office Building	500	4 Months: July – November 2022	3896			
PR 3	Other Warehouse Building	2170	10 Months: September 2021 – July 2022	25016			
PR 4	Other Industrial Building	1900	5 Months: October 2022 – March 2023	29894	2842/ 30535		
PR 5	Office Building	9000	9 Months: September 2015 – June 2016	133566	24000/ 257861		
PR 6	Other Industrial Building	1380	7 Months: December 2020 – June 2021	25721		731/ 10673	
PR 7	Residential Building with Three or More Apartments; Office Building	8150	19 Months: September 2020 – April 2022	161845		11551/ 168645	
PR 8	*	1280	15 Months: November 2020 – February 2022	29434			56280

RESULTS

In this section, the energy consumption and carbon emissions for construction operations with and without heating are presented. In the last subsection, the impact of future decarbonization scenarios for electricity and district heating production on construction operations is discussed.

ENERGY CONSUMPTION IN CONSTRUCTION PROJECTS

Table 3 depicts the electricity and heating energy consumption for the studied projects in kWh. The average electricity consumption for projects without heating was 12 063 (kWh), for projects with heating 76 092 (kWh), and across both categories 52 081 (kWh). The average heating energy consumption was 104 799 (kWh). When normalized by net area, the electricity across all sites was 14.56 (kWh/m^2) and heating 23.42 (kWh/m^2), which are 38% and 62% of the total energy consumption, respectively. The overall average per net area for projects without heating is 8.14 (kWh/m^2) and for projects with electricity and heating 41.84 (kWh/m^2).

The best-fit linear regression trendlines were calculated for the building size and energy consumption and between project duration and energy consumption. The trendline y=0.0024x+21.495 for the building size and energy consumption is characterized by a small slope (0.0024) and an R^2 value of 0.1429. This suggests a weak positive correlation, indicating a limited predictive capacity of the linear model. In contrast, the trendline y=2.6177x+4.6584 for the project duration and energy consumption exhibits a steeper slope (2.6177) with a moderate R^2 value of 0.4162, reflecting a stronger relationship and a moderate explanatory power. That is, while the connection between building size and energy consumption is minimal, there is a moderate relationship between project duration and energy consumption. The reason could be that projects with longer duration typically have higher construction scope and likely involve works in the winter season that may need heating. This requires further validation.

Projects with heating have a larger share of electricity consumption per net area. This could be because of the building use functions (see Table 2). Projects PR 4-8 with heating are buildings with residential and office functions, while projects PR 1-3 are mainly industrial. When compared to industrial buildings, residential and office buildings have a higher share of construction operations, mainly interior works, which typically require more electrical machinery, equipment, and heating.

Table 3. Energy consumption on construction projects by energy type.

PR	Net Area (m^2)	Duration (months)	Electricity (kWh)	Heating (kWh)	Electricity (kWh/m^2)	Heating (kWh/m^2)	Average per Category (kWh/m^2)
PR 1	1430	6	7278		5.09		
PR 2	500	4	3896		7.79		8.14
PR 3	2170	10	25016		11.53		
PR 4	1900	5	29894	30535	15.73	16.07	
PR 5	9000	9	133566	257861	14.84	28.65	
PR 6	1380	7	25721	10673	18.64	7.73	41.84
PR 7	8150	19	161845	168645	19.86	20.69	
PR 8	1280	15	29434	56280	23.00	43.97	
AVERAGE	3226	9	52081	104799	14.56	23.42	24.99

CO_2 EMISSIONS IN CONSTRUCTION PROJECTS

Table 4 depicts GHG emissions of consumed energy during construction operations for the studied projects. The average GHG emissions for projects without heating was 7 672 ($kgCO_2e$) and for projects with heating 26 646 ($kgCO_2e$). The average electricity emissions across all projects was 33 124 ($kgCO_2e$) and the average heating emissions across all fuels was 19 953 ($kgCO_2e$), which make up 62% and 38% of carbon emissions respectively. The largest share of carbon emissions comes from electricity consumption in construction projects. This high carbon footprint from electricity consumption is because electricity is the primary energy source on construction sites and Estonian electricity has high carbon intensity when compared to the other EU countries (European Environment Agency 2023). Results are in alignment with the carbon emission factors for the Estonian energy carriers in Table 1.

Table 4. CO_2 emissions of construction sites with and without heating.

PR	Net Area (m^2)	Electricity ($kgCO_2e$)	Diesel ($kgCO_2e$)	Natural Gas/Propane ($kgCO_2e$)	District Heating ($kgCO_2e$)	Total Emissions ($kgCO_2e$)	Average Emissions ($kgCO_2e$)	Average Emissions ($kgCO_2e/m^2$)
PR 1	1430	4629				4629		3.2
PR 2	500	2478				2478	7672.3	5.0
PR 3	2170	15910				15910		7.3
PR 4	1900	19013	7634			26646		14.0
PR 5	9000	84948	64465			149413		16.6
PR 6	1380	16359		1494		17853	26646.3	13.0
PR 7	8150	102933		23610		126544		15.5
PR 8	1280	18720			11256	29976		23.4
AVERAGE	3226	33124	36049	12552	11256	53076	17159	16.5

Figure 1 presents the GHG footprint per net area. The emissions are divided into two categories, including electricity (blue bars) and heating (red bars) emissions (CO_2e kg/m^2). Total carbon emissions per net area range from 3.2 to 23.4 ($kgCO_2e/m^2$), with an average of 5.2 ($kgCO_2e/m^2$) for projects without heating and 16.5 ($kgCO_2e/m^2$) for project with heating. The values for electricity emissions vary across different projects, ranging from as low as 3.2 ($kgCO_2e/m^2$) to as high as 14.6 ($kgCO_2e/m^2$). The heating emissions are lower than the electricity emissions, with values from 1.1 to 8.8 ($kgCO_2e/m^2$).

The chart also depicts an "AVERAGE" column for construction sites with electricity only and sites with electricity in addition to heating emissions, showing the average electricity and heating emissions per net area. For sites with electricity only, the average electricity emissions are 5.2 ($kgCO_2e/m^2$). For sites with electricity and heating consumption, the average electricity emissions are 11.7 ($kgCO_2e/m^2$) and the average for heating emissions is 4.8 ($kgCO_2e/m^2$). Again, these results seem to align with the observations above that building projects with longer duration and use functions related to more interior works tend to have much higher energy consumption. Also, electricity usage is responsible for most of the emissions on construction projects when compared to heating, with electricity making up 66% and heating 34% of the total construction operation emissions.

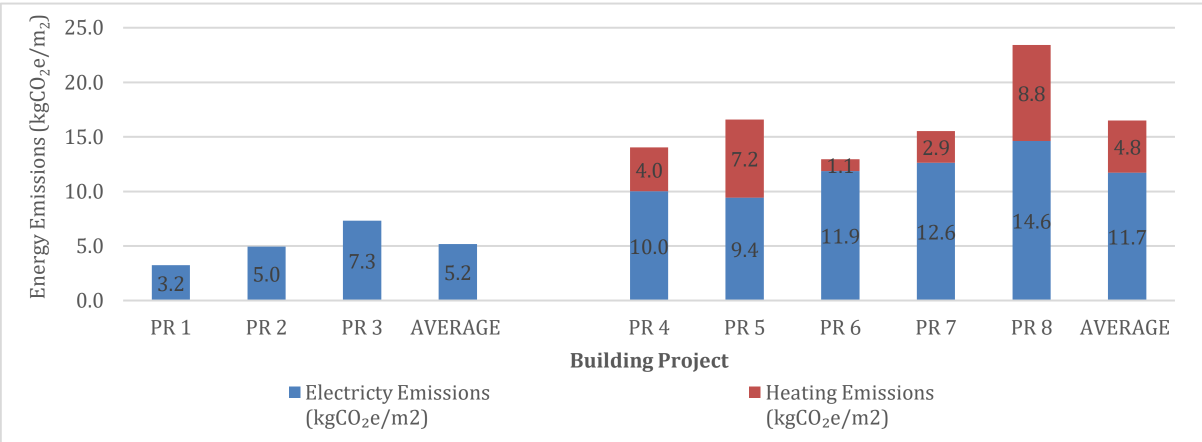

Figure 1. Electricity and heating energy consumption emissions per net area.

IMPACT OF ENERGY DECARBONIZATION ON CONSTRUCTION OPERATIONS

The European energy sector is expected to be the main contributor to the decarbonization of the European economy by 2050 (European Commission 2020a). The Estonian Ministry of Climate has developed a decarbonization strategy for the Estonian energy sector and the Estonian Environmental Research Centre (Eesti Keskkonnauuringute Keskus 2024) has estimated the projected GHG factors for electricity and district heating. In Table 5, the electricity and district heating emission factors are presented for the period from 2024 until 2050 with higher frequency in the early years.

Table 5. Future decarbonization scenarios for the construction operations.

Description	2024	2025	2026	2027	2028	2029	2030	2035	2040	2045	2050
Electricity Emission Factors (kgCO2e/kWh)	0.56	0.55	0.47	0.39	0.31	0.22	0.14	0.06	0.05	0.00	0.00
District Heating Emission Factors (kgCO2e/kWh)	0.10	0.09	0.09	0.08	0.08	0.07	0.07	0.06	0.05	0.04	0.04

Based on the new emission factors, the average electricity 14.56 (kWh/m^2) and heating 23.42 (kWh/m^2) emissions per net area, and average net building area 3226 (m^2) of the projects studied above, three future scenarios for carbon emissions of construction operations were generated: (1) electricity emissions + heating emissions with 25% share of district heating; (2) electricity emissions + heating emissions with 50% share of district heating; and (3) electricity emissions + heating emissions with 75% share of district heating. Different proportions of district heating are used to visualize the potential impact of heating sites with the combustion of fossil fuels versus district heating.

Figure 2 presents the three scenarios for construction operations with electricity emissions and the district heating share of 25%, 50%, and 75% of total heating. Currently, the electricity carbon emissions dominate. This is because Estonian electricity production has one of the highest carbon intensities in Europe (European Environment Agency 2023). However, if the national electricity decarbonization strategy goes as planned, the heating carbon emissions of construction operations become equal to electricity emissions around 2030 and continue to dominate afterward. From thereon, the combustion of fossil fuels becomes dominant, influencing the embodied carbon of buildings. For example, by 2050, in the scenario of a construction site, where half of the heating comes from the combustion of fossil fuels and the other half from district heating, the heating emission with 50% district heating is expected to be around 2.76 (kgCO_2e/m^2), while electricity emissions will be near carbon neutral.

This shows that when electricity production and operational carbon are reduced due to the increased renewable energy sources and energy efficiency of new and existing buildings (Bahramian and Yetilmezsoy 2020), the construction phase is expected to start playing a more important role. The execution of construction operations requiring heating and illumination in the winter season could become a major factor influencing the embodied carbon of buildings in the Estonian cold climate.

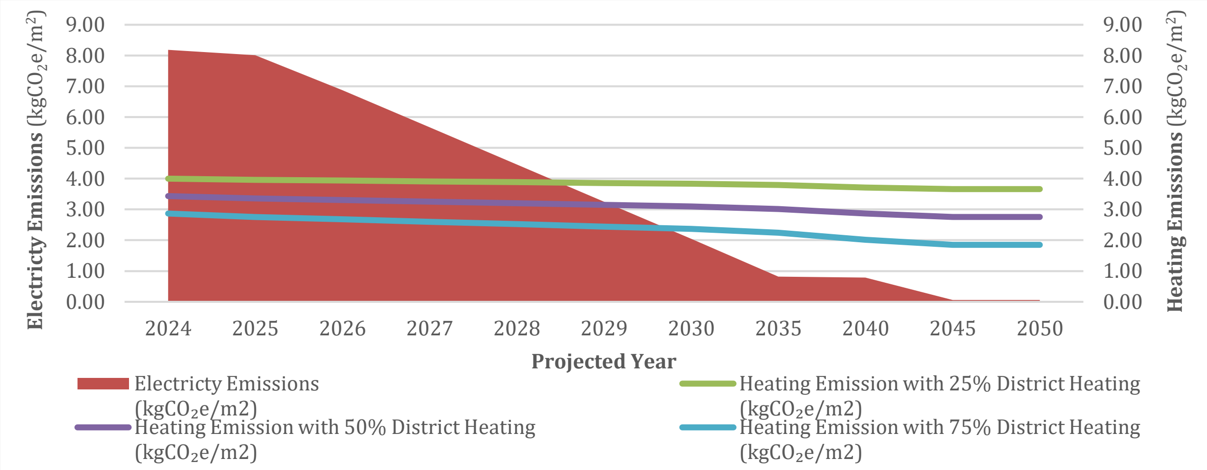

Figure 2. Electricity and heating emission scenarios.

DISCUSSION

To meet global climate objectives, it is necessary to decarbonize the construction and built environment sectors. The construction industry is lagging behind its climate goals. Much emphasis has been placed on enhancing the energy efficiency of buildings, considering the substantial carbon footprint of electricity and heating over their 50 to 60-year lifespan (Joseph and Mustaffa 2021; Weigert et al. 2022). This study highlights the importance of addressing the carbon emissions of construction operations, especially given the illumination and heating demands of winter months in Estonia.

While no direct correlation could be observed between a building's size and construction operations' energy consumption and GHG, a relationship seems to exist between the project's duration, its use function, and its energy consumption and emissions. Industrial projects without additional heating averaged electricity emissions at 5.2 $kgCO_2e/m^2$, while those with extensive interior work and additional heating saw a substantial increase, with average electricity emissions at 11.7 $kgCO_2e/m^2$ and heating emissions at 4.8 $kgCO_2e/m^2$. This means a threefold increase in total emissions, provided that in Estonia, electricity and heating are emissions-intensive.

This study, although limited to one company, offers insights that could contribute to the development of a more generalized approach. Findings demonstrate the great impact of the winter period on the carbon emissions of construction operations, especially regarding heating and illumination during colder months. This becomes increasingly crucial as Estonia moves towards decarbonizing its energy sector. A baseline and parameters for such assessments need to be established and standardized to consider and plan alternative improvement scenarios.

For a thorough assessment of construction activities' carbon footprint, more detailed case studies need to be made, looking at energy use in different types of work. Furthermore, action research for project-wise reduction of construction carbon emissions, as well as for continuous improvement at the construction company level, is needed. Establishing industry-wide methods and developing practical guidelines for reducing carbon emissions in construction operations across different climates and building types are important steps forward.

CONCLUSIONS

This study on carbon emissions from construction operations in Estonia's cold climate has demonstrated that winter demands for heating and illumination significantly contribute to GHG, with heating-required projects averaging 16.5 $kgCO_2e/m^2$ in emissions versus 5.2 $kgCO_2e/m^2$

for those without. While no strong correlation between building size and energy consumption was identified, a connection between project duration and emissions was observed. This emphasizes that it is important not to neglect the embodied carbon of construction operations in lifecycle assessments. The research suggests that significant emission reductions can be achieved through targeted improvements in construction processes, particularly in projects necessitating heating. The implementation of lean principles – prioritizing process improvement and waste reduction – emerges as a natural strategy in the pursuit of carbon footprint reduction in construction as well as of the broader objectives of sustainable construction.

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ASSESSING ENVIRONMENTAL IMPACTS: A CASE STUDY OF CIRCULAR ECONOMY ON CONSTRUCTION MATERIALS

Michelle Diaz[1], Mauricio Neyra[2] and Sulyn Gomez [3]

ABSTRACT

The construction sector is a major contributor to environmental degradation, accounting for a significant portion of global energy-related carbon dioxide emissions. The traditional linear construction practices follow a "take-make-dispose" model, which entail the extraction of raw materials, manufacturing of construction products, their use in building projects, and ultimately the disposal of waste generated throughout construction projects. Both Lean and Circular Economy (CE) are philosophies that seek to minimize waste. While Lean promotes value through the reduction of production waste during design and construction, CE proposes the reduction of material waste by promoting closed-loop material flows throughout the construction lifecycle. Applying Lean and CE principles to construction waste management shows promise in reducing negative environmental impacts.

Despite increasing interest, a comprehensive assessment of CE's impact in this context has not been thoroughly presented yet. This study aims to close this gap by analyzing the environmental performance within a case adopting CE principles using Life Cycle Assessment information. Results indicate significant reductions in Global Warming and Ecotoxicity using CE. Meanwhile, Lean provides another approach to waste reduction by avoiding the generation of environmental waste through production control. This research underscores CE's efficacy in mitigating negative environmental impacts while identifying areas for further optimization.

KEYWORDS

Lean, Circular Economy, Life Cycle Assessment, Environmental Impact, Waste.

INTRODUCTION

The construction industry serves as both a vital component of global economic growth and a significant contributor to environmental degradation. According to the World Green Building Council (WGBC), construction activities contribute substantially to the waste stream and accounts for approximately 39% of global energy-related carbon dioxide (CO2) emissions during building construction and operation (WGBC, 2019). Traditional linear construction practices follow a "take-make-dispose" model, involving the extraction of raw materials, manufacturing of construction products, their utilization in building projects, and ultimately, the disposal of resulting waste (Ellen MacArthur Foundation, 2013). Due to the substantial waste generated, construction stands out prominently, making it a prime target for innovation within the framework of Circular Economy (CE) (Benachio et al., 2020). CE is diverse in its

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existing definitions, and includes all activities carried out in a society.. A holistic approach with the construction of circular loops of material, energy, and waste flows embracing all society activities is the main feature of a CE, setting it apart from other attempts to minimize energy and material consumption (Masi et al., 2018).

While CE literature is relatively novel, it has deep roots in green production literature (Vargas & Medrano, 2020). The development of a green production philosophy revealed the benefits of lean manufacturing in reducing waste and its negative environmental effects (Huovila & Koskela, 1998). Green manufacturing has gained traction with Lean approaches of value promotion as a deeper treatment of waste beyond the boundaries of construction and design phases in the form of product life cycles (Salibi et al., 2022) Concurrently, CE has garnered comparable attention for its efficacy in curbing waste across the economic supply chain (Adams et al., 2017).

Lean's focus on process waste reduction complements CE's closed-loop approach to waste reduction and recovery from various materials (Johns et al., 2023). Numerous studies have highlighted the potential advantages of CE in the building industry by drawing parallels between its waste reduction focus and the Lean philosophy (Chen et al., 2021; Schmitt et al., 2021; Johns et al., 2023). For instance, Chen et al. (2021) proposed that Lean approaches can complement CE efforts during the construction phase by minimizing waste generated in the execution of construction processes. Similarly, Johns et al. (2023) identified beneficial overlaps between the tactics used in the design and production (i.e., construction) stages.

A study by El Machi, A., & Hakkou, R. (2024) demonstrated that adopting CE practices in construction can lead to significant reductions in resource consumption and waste generation. However, despite the growing interest in exploring and applying CE principles within the construction industry, there remains a pressing need for a comprehensive evaluation of the tangible environmental impact reductions achieved through CE implementation for the management of construction waste. This study aims to start closing this gap by presenting the results of a thorough analysis of the environmental performance of a case study in construction adopting CE principles. To achieve this, a collaborative research project was carried out with a company leading the business of CE in Peru to assess the environmental impact changes when applying CE.

LITERATURE REVIEW

WASTE IN CONSTRUCTION PROJECTS

Waste, from the Lean perspective, can be understood as any "activity that takes time, resources or space but does not add value" (Koskela, 1992). Ohno (1978) identified seven types of production waste (or *muda*): overproduction, time on hand (waiting), transportation, processing, stock on hand (inventory), movement, and making defective products. With the application of Lean in the construction industry, additional proposals for an eighth type of waste have been introduced, such as Making-Do (Koskela, 2004). Womack & Jones (1996) further categorized waste into necessary waste, which supports value-adding activities but can be minimized, and unnecessary waste, which can be entirely eliminated.

Environmental waste is closely linked to production waste, encompassing the environmental impacts stemming from production waste activities such as increased energy usage for transportation, waste from deteriorating or damaged inventory, energy wastage during production downtime, disposal of obsolete products, unnecessary processing leading to increased energy consumption and emissions, and disposal of defective components (U.S. EPA, 2007). However, integrating environmental waste into traditional lean management practices presents challenges due to the primary focus on productivity improvement rather than environmental impact reduction (Belayutham & Gonzalez, 2013). In that sense, environmental waste is regarded as a distinct category, moving away from the activity-centered concept of production waste but keeping its core concept of non-value addition, and encompassing environmental-related waste types such as emissions, solid and liquid waste, and energy consumption, among others (Arroyo & Gonzales, 2016).

CIRCULAR ECONOMY

Circular Economy (CE) aims to reduce waste throughout a product's lifecycle by increasing value and decreasing waste (Geisendorf & Pietrulla, 2018). To do this, a pull system must be established, and linear waste that lowers system value must be closed off. CE principles such as the 3Rs (reduce, reuse, recycle), 6Rs, and 12Rs delineate the objectives of CE, minimizing resource consumption, repurposing goods, and parts, and ultimately recycling waste back into the system to optimize resource value (MacArthur, 2013). Refuse, reduce, repair, reuse, repurpose, regenerate, rethink, remanufacture, recycle, recover, rot, and re-evaluate are the extra details found in the 6Rs and 12Rs, which expand on the 3Rs (MacArthur, 2013).

The adoption of CE within the construction industry is still relatively young (Adams et al., 2017). However, given the significant waste generated in construction, this industry is a prime candidate for CE innovation. CE strives toward waste-reducing or waste-eliminating product designs (Caceido, 2017). According to Balboa and Domínguez (2014), CE is a framework for eco-design that is inspired by living things. It aims to shift from a linear economy (produce, use, and discard) that is becoming harder to implement due to resource depletion to a circular and regenerative model. The concept by Balboa and Dominguez (2014) is intriguing because they highlight it as a potential solution to the resource shortage issue.

CIRCULAR-LEAN SYNERGIES

Although the Lean and CE philosophies are well developed in their respective fields, the synergies among the two philosophies are not widely studied in the construction industry (Benachio et al, 2021). Common strategies between the two philosophies, particularly in waste reduction principles, have been identified, including a focus on consumer-driven value creation, waste reduction, process simplification, long-term orientation, and continuous improvement (Johns et al, 2023). However, their approach for value promotion and waste reduction is slightly different.

Both Lean and CE aim to reduce resource consumption. Johns et al (2023) suggests that the overall similarities of the strategies are vast enough to be used complimentary to each other. Moreover, Schmitt et al (2021) studied the potential of the interdependencies between Lean and CE. Lean is focused mainly on product and process level, and CE is more focused to the system level, showing that these three levels are interdependent, and there is a great potential for the use of Lean and CE together (Schmitt et al, 2021). According to Chen et al. (2021), integrating Lean principles with CE can extend efforts, particularly during the construction phase, by reducing waste generated from activities and processes.

Schmitt et al (2021) stated that there is yet a current need of a research path to understand the complementarities and conflicts between "lean" and "circularity". Lean is a concept that has been widely accepted within the construction industry practitioners improving its productivity and sustainability profiles (Babalola et al, 2019). Meanwhile, CE adoption in construction industry still faces cultural barriers that are entrenched to their historical linear economy nature (Hart et al, 2019). Some of the cultural barriers for linear production to prevail over CE are the lack of collaboration between business, business functions, and the lack of engagement throughout the supply chain (Hart et al, 2019). Although this is the common trend, much research has evolved over the advantages of working with both Lean and CE (Johns et al, 2023) Many authors agreed that the combination of lean and circularity could lead to significant improvements (Johns et al., 2023; Benachio et al, 2020; Schmitt, 2021).

LIFE CYCLE ASSESSMENT

The use of Life Cycle Assessment (LCA) as a systematic methodology for evaluating the environmental effects of the built environment is growing in acceptance. Although the building industry depends on LCA to address social and environmental issues associated with construction, some barriers prevent LCA from being broadly and confidently embraced in the industry (Ingrao et al., 2018). For instance, completing an LCA research based on primary data is challenging due to several factors, including the laborious inventory procedure that needs an abundance of data as input for the analysis (Hetherington et al., 2014). Another major barrier is the complexity of LCA results that makes it difficult for stakeholders in the construction industry to apply them to improve their environmental performance. (World Business Council for Sustainable Development, 2016).

ISO 14044 presented four steps that must be followed to evaluate the environmental loads of processes and products over the course of their life cycle as presented in Table 1.

Table 1: Life Cycle Assessment (ISO 14044)

Process	Description
Goal and Scope Definition	Define the purpose, objectives, functional unit, and system boundaries
Life Cycle Inventory (LCI)	Gather, describe, and verify all data pertaining to inputs, processes, emissions, and other aspects of the entire life cycle
Life Cycle Impact Assessment (LCIA)	Quantify the environmental consequences and resources used. Three mandatory components make up this step: • Assigning LCI results to the impact categories that have been chosen based on goal and scope parameters. • Calculating category indicators (characterization) • Selecting impact categories based on those parameters. ISO 14044 describes Normalization and Weighting as two additional possible steps in the LCIA process.
Interpretation	Analyse the findings

Although many construction companies are adopting the Lean principles in their projects (Babalola et al,2019), some studies have shown that there is still cultural resistance within the implementation of CE principles (Hart et al, 2019). Many theoretical studies have been framed to show the mutual advantage of Lean and CE when implemented together (Johns et al., 2023; Benachio et al, 2020; Schmitt, 2021). Therefore, more quantitative research in the construction industry is needed to support the benefits of working with Lean and CE principles together. The presented research gives a quantitative approach to understanding the environmental impacts that are avoided when implementing a CE approach.

RESEARCH METHODOLOGY

This research adopted a quantitative approach based on a single case study, in collaboration with Company A, a Peruvian company known by its focus on Circular Economy (CE). According to Yin (2009), case studies are particularly suited for investigating "how" or "why" questions within real-life contexts where the boundaries between the context and phenomenon are not clearly defined. This paper explores the connection between CE principles and the environmental impacts of resources (i.e., materials and equipment) from construction projects.

The methodology employed encompasses the logic of design, data collection techniques, and specific approaches to data analysis (Stoecker, 1991). Yin (2009) identifies six crucial sources of evidence, each offering complementary insights and commonly utilized in well-executed case studies. This research used three of the primary sources of evidence that were identified by Yin (2009), including:

- Documentation such as reports of CO2 emissions avoided from 2019 to 2022.
- Archival records such as the clients served from 2019 to 2022 and the worker energy consumption for their time frame.
- Interviews with stakeholders to better understand the data and processes involved.

After the data gathering from Company A, the emissions reported by Vahidi et al (2016) on pipe materials were used for the PVC pipes emission factor using the UCEPA TRACI methodology. The emissions of transportation were obtained from EcoTransIT software showing results for complimentary impact categories. Finally, the energy emission factors were considered from the results of Santoyo-Castelazo et al (2011) who used the ISO 14040 guidelines to inform the emissions generated by hydroelectric power plants.

CASE OVERVIEW

The case study addresses the interaction between company A, company E1, and company E2 within two different scenarios S1and S2.

Company A works as an online commercial platform that sells the disused goods of large corporations to avoid CO2 emissions from the production of more goods of the same category. Company E1 is a construction company that has finished its construction process. This company has used all the materials that it needed, and it has surplus materials (PVC pipes) that will typically go to storage over a big period. Company E2 is a Company that has started its construction process. This company is looking for materials (among them, PVC pipes) to enter their construction process.

Figure 1 shows the two scenarios that are discussed in this research to understand the environmental indicators that might be changed by company A's approach of CE. In Scenario 1, base scenario, material, equipment, and resources entered company E1's construction phase. Once their construction phase is finished, some good materials are left and normally disposed of in storage or landfills. In Scenario 2, materials left from company E1 are transported into a second company E2 whose construction process is still ongoing. Both Scenarios considered transport emissions. However, material production emissions are only included in scenario 1, and energy consumption emissions are only considered in scenario 2 from company A's activities.

Input data for our analysis include a carbon footprint analysis commissioned by a consultant for sustainability and climate change. The data from Company A's 2019-2022 carbon footprint report was used. Additionally, interviews with Company A's CEO were carried out to understand the life cycle of the materials and equipment they typically process.

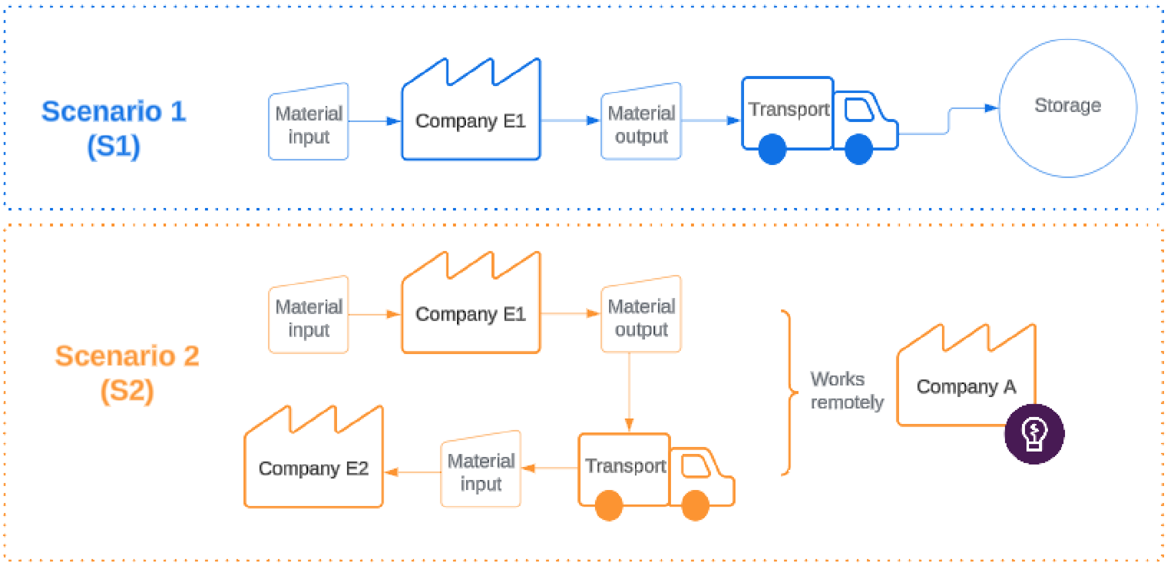

Figure 1: Scenarios with (S2) and without (S1) Circular Economy.

For over four years (2019-2022), Company A has worked with 33 companies, providing a recovery equivalent to 3006.6 ton of materials, including:

- Inoperative equipment (tractors, excavators, trucks, mining truck tires, telehandlers, cranes, mobile cranes),
- Damaged materials (industrial materials, paint, cement, iron rods, glue, personal protective equipment, pipe paint, pipe coating materials),
- Damaged equipment and minor tools (grinders, rotary hammers, drills, vibro-rammers, small equipment used for construction),
- Spare parts for inoperative equipment, computer equipment (laptops, computers), inoperative vehicles (trucks, cars),
- Furniture (office furniture, desks, campsites, containers, portable toilets).

This study scope is limited to the materials recovery analysis of one of Company A's clients. Table 2 shows the scope of materials that this client reported as residue, which is analysed in this case.

Table 2: Case Study Scope Description

Item	Description	Ton	Initial Location	Destination with Company A	Destination without Company A
Material	PVC Pipe	10	Arequipa	Lima	Lima

In the context of LCA, "end of life" refers to the final stage of a product's life cycle. It encompasses the product's disposal, recycling, or any other fate after it has reached the end of its useful life (Sandin, 2014). Since the case study is based on the final stage of the PVC pipes in company E1, the results were based on an "End of Life" approach for the analysis.

In this research, LCA analysis from other authors (Vahidi et al, 2016, Santoyo-Castelazo et al, 2011) were introduced in the results to compare which of the two scenarios S1, S2 has a better environmental performance.

RESULTS

LIFE CYCLE ASSESSMENT

Goal and scope definition

According to Hauschild (2018), goal definition sets the context for the LCA assessment and provides the basis of the scope. Table 3 frames the goal and scope of our case:

Table 3: Goal and Scope Definition

Goal/Purpose	Evaluate LCA comparing environmental impacts of the management of Materials from the construction stage
Application	Basis for decision on recovering Materials from the construction stage
Functional Unit	Three functional units were taken into consideration as a unit of measurement that serves as the basis for comparing different alternatives: • Transportation emissions, km is the functional unit. • Emissions related to waste (such us materials and equipment), ton is the functional unit. • Emissions related to storage area, m2 is the functional unit.
System Boundary	The following considerations were taken to define the boundaries of our analysis: • Materials (PVC Pipes) that are covered by Company A from the construction stages from 2021. • All processes contributing significantly to the life cycle impacts are considered. • In S2, there is no more raw material extraction emissions since they use material from S1. • There are transportation emissions in both scenarios S1 and S2. Both are considered to have the same results since their destination are near each other.

A thorough analysis of the "End of Life" phase of residual materials is used to determine environmental impacts in two different scenarios, as depicted in Figure 1. One basic scenario S1 in which Company A is not involved, and a second scenario S2 in which Company A participates and applies their CE approach.

Figure 1 shows Product System of S1 that consists of two main processes which are production of PVC pipes, and transportation of residual pipes from company E1 to their storage. While information for the transportation system and its relating input-output data was gathered from EcoTransIT software. Information for the PVC pipe input-output data was gathered from Vahidi (2016) who explained the main materials and processes that are considered in a LCA of PVC pipe production. Product System of S2 consists of another two main processes which are transportation of residual pipes from company E1 to E2, energy usage of Company A's workers to manage construction materials. The values and processes for electricity were considered to come from a hydroelectric source. In 2020 in Peru, electricity generation from hydroelectric plants increased their participation to 59.6%. Although electricity generation has year to year variations in the contribution of renewable energy sources (RESs), hydroelectric plants have been consistently producing around half of Peru's electricity over the past years (Campodonico, 2022).

Inventory Analysis

The inventory analysis collects information about the flows of input-output of resources, materials, and energy. The inventory data consists of Company A emission reports from 2019-

2022. Table 4 shows a summary of the main inputs and outputs considered in the analysis for both scenarios.

Table 4: Input-Output flows from S1 and S2

Flows	S1	S2
Input Flows	Pipe Production (Vahidi et al, 2016)	Electricity (Santoyo-Castelazo et al, 2011)
	Transportation (EcoTransIT)	Transportation (EcoTransIT)
Output Flows	M&E transported (Company A reports)	M&E transported (Company A reports)

Impact Assessment

Life Cycle Impact Assessment methodology was studied to evaluate and quantify the environmental performance across two different scenarios for the End of Life of construction materials (pipe production). The UCEPA TRACI methodology was developed for the pipe production (Vahidi et al, 2016). The ISO 14040 was used to delve into the emissions of energy consumption from hydroelectric sources (Santoyo-Castelazo et al, 2011).

The UCEPA TRACI methodology included the impact categories of ozone depletion (kg CFC-11 eq), global warming (kg CO2 eq), smog (kg O3 eq), acidification (kg SO2 eq), eutrophication (kg N eq), carcinogenics (CTUh), non carcinogenics (CTUh), respiratory effects (kg PM2.5 eq), ecotoxicity (CTUe), and fossil fuel depletion (MJ surplus).

The LCA results from ISO 1404 showed results for global warming (kg CO2 eq), (CH4), terrestrial acidification (kg SO2 eq), ozone formation (kg NOx eq), respiratory effects (kg PM2.5 eq).

The emissions of transportation were obtained from EcoTransIT software showing results for respiratory effects (kg PM2.5 eq), global warming (kg CO2 eq), terrestrial acidification (kg SO2 eq), ozone formation (kg NOx eq).

Table 5 shows the results of Company A's avoided emissions and produced emissions from S1 and S2 respectively. For this results, two Life Cycle Assessment studies were considered, their resulting emission factors were multiplied by the activity level from both scenarios (Vahidi et al, 2016, Santoyo-Castelazo et al, 2011).

Twelve environmental impact categories were identified in this analysis. The second scenario S2 showed better or equal performance on all of the environmental indicators, but Global warming and Ecotoxicity. Smog, Acidification, Eutrophication, Respiratory effects, Fossil fuel depletion, Ozone depletion, Carcinogenic, Non-Carcinogenic, Ozone formation and Air pollution showed similar results for both scenarios.

The CO2 emissions for S1 is approximately higher by three times compared to S2, showing that the CO2 emissions related to PVC pipe production are greater than CO2 emissions from company A´s energy consumption. Greenhouse gases are contributors to global warming and climate change, CO2 is one of the most relevant in this matter (Yoro et al, 2020). Although, the pandemic has slowdown the expected increase of CO2 emissions, the UNEP Emissions Gap Report 2020 shows that this will be an insignificant reduction of 0.01ºC by 2050 if the international community doesn't prioritize green recovery. There are many opportunities that have been increasingly more visible to the construction sector that recycling construction waste and applying it to new construction sites will reduce carbon emissions and its impact to global warming (Yang et al, 2023).

Table 5: Life Cycle Assessment results for S1 and S2

Impact Category	Reference Unit	S1	S2
Ozone depletion	kgCFC-11 eq	2.79E-05	0
Global warming	kg CO2 eq	2.45E+03	8.30E+02
Smog	kg O3 eq	2.90	0
Acidification	kg SO2 eq	9.27	3.13
Eutrophication	kg N eq	1.81	0
Carcinogenic	kg 1,4-DCB	9.75E-05	0
Non carcinogenic	kg 1,4-DCB	2.4E-04	0
Respiratory effects	kg PM2.5 eq	0.77	0.19
Ecotoxicity	kg 1,4-DCB	6.890E+03	5.9E-06
Fossil fuel depletion	MJ	1.70E+04	1.27E+04
Ozone formation	kg NOx eq	8.40	8.40
Air pollution	kg NMVOCx eq	0.53	0.53

Ecotoxicity was a major environmental impact by S1. The production of PVC can contribute to ecotoxicity because of the chemical composition of toxic vinyl chloride monomers, and other additives such as pigments to improve its performance (Bidoki & Wittlinger, 2010). Pigments and other additives or stabilizers such as lead compounds in PVC pipes can be toxic and harm aquatic life if released into the environment (Bidoki & Wittlinger, 2010). Additionally, the production of PVC involves energy-intensive processes such as manufacturing, polymerization, and manufacturing which would eventually affect the ecotoxicity indicator by the energy consumption emissions.

This result adds to the body of knowledge of the well-known benefits of recycled materials in a context of construction companies applying principles to manage more efficiently their waste. Although these results are only based on the impacts of one company (company E1) recycling it PVC pipes, it should be highlighted that company A has worked with 33 different companies (including company E1) in over three years. Further research should explain the overall impact of more environmental indicators that are related to the manufacturing of other materials.

CONCLUSIONS

The construction industry's significant environmental footprint necessitates urgent measures to reduce waste and mitigate environmental impacts. This paper examines the application of Circular Economy (CE) principles in construction waste management, aiming to evaluate its effectiveness in minimizing environmental degradation. By leveraging a case study approach and employing Life Cycle Assessment (LCA), the study provides valuable insights into the environmental performance of CE implementation within the construction sector. Our findings underscore the potential of CE to reduce environmental impacts associated with construction. Through the analysis of environmental indicators using different Life Cycle Assessment studies, it was evident that CE adoption led to notable reductions in various impact categories, aligning with the principles of waste reduction, resource optimization, and closed-loop material flows inherent in CE. Despite the promising results, our study highlights the need for further optimization and refinement of CE practices within the construction sector. Addressing regional energy sources and enhancing material recovery processes could further enhance CE's efficacy in mitigating environmental impacts.

In this study, data from the specific construction processes that produced the material wastes was not available. However, through diligent application, Lean principles provide an approach to reduce material waste before they are generated due to production wastes of inventory, overproduction, and rework from defective products. Therefore, the synergies between Lean and CE philosophies further amplify the potential for waste reduction and resource optimization within the construction industry. While Lean emphasizes process waste reduction, CE focuses on material waste throughout the lifecycle, offering complementary strategies for minimizing environmental impacts.

This study contributes to the growing body of knowledge on CE implementation in construction waste management, providing valuable insights for policymakers, industry practitioners, and researchers. By embracing CE principles and leveraging synergies with Lean methodologies, the construction industry can move towards a more sustainable and environmentally responsible future.

LIMITATIONS AND FUTURE RESEARCH

Despite the contributions of this study, several limitations should be acknowledged. First, while this case study provides in-depth insights into a specific context, generalizing findings to broader populations or contexts may be limited. Future research could complement the analysis with large-scale empirical studies to enhance the robustness and generalizability of findings. Second, the availability and reliability of data can pose challenges for conducting comprehensive assessments, such as the necessary for addressing material waste generation from the Lean perspective (production management) and CE perspective (construction life cycle). Future research can explore ways to improve data quality and accessibility. Third, certain assumptions and simplifications were made in the analysis, such as uniform transportation emissions and energy sources. Future research could consider certain nuances in the assessment. Fourth, this study was limited to a specific period, potentially overlooking long-term trends and changes in environmental performance. Future research could extend the analysis over longer durations to capture temporal variations and assess the durability of CE practices. By addressing these limitations, scholars and practitioners can continue to advance our understanding of CE implementation in construction waste management and contribute to the development of more sustainable construction practices.

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TRANSITION TO A LEAN MINDSET THROUGH THE "HERO'S JOURNEY"

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ABSTRACT

Transitioning from a conventional, established, and familiar project mindset to a Lean mindset has proved challenging and is a barrier to implementing Lean Construction. It has been argued that shifting from traditional management thinking to a Lean mindset can be considered a paradigm shift. Such substantial changes will require overcoming innate resistance and adjusting ingrained habits to become progressive and open-minded to the potential benefits of new ideas. This conceptual paper investigates how the potentially demanding change from a traditional mindset to a Lean mindset can be dealt with by employing Joseph Campbell's "Hero's Journey" framework. The Hero's Journey describes a generic journey about overcoming challenges met when facing unfamiliar territory. It is found in antique stories but is also applicable in life. A way to tackle the challenging task of adjusting to the ongoing change in the construction industry using the Hero's Journey is proposed in this paper. The research shows that applying the Hero's Journey framework in a construction context can be valuable for making the transition to a Lean mindset less daunting for practitioners.

KEYWORDS

Lean construction, Hero's journey, Collaboration, Storytelling, Change

INTRODUCTION

The construction industry meets increasing demands for innovation to improve value delivery. However, the industry's characteristics appear to detain the innovation process. Development can be divided into two categories: innovation related to production or processes. Product innovation incorporates adding new materials or components into physical products. On the other hand, process innovation, representing a variety of management challenges, focuses on developing new organizational structures, management techniques, and other methods to enhance business processes and competitiveness (De Valence, 2010).

This paper relates to innovation – and changes. Implementing Lean Construction (LC) often requires a shift in organizational culture and structure (Nesensohn et al., 2012). Doubt or resistance to change are common challenges to implementing LC in construction projects. Porwal et al. (2010) write that one of the challenges of implementing the Last Planner® System (LPS) is organizational opposition through a "This is how I've always done it" attitude. Through a comprehensive literature review, Wandahl (2014) found that the most common barriers to LC implementation were insufficient knowledge about the LC approach, lack of training, and general maturity. Similarly, Albalkhy and Sweis (2021) identified 29 barriers to LC implementation, and among them were *management resistance to change, lack of adequate lean awareness and understanding, employees' resistance to change and fear of unfamiliar*

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practices, and *insufficient training for workers.* All these relate to the challenges of embracing unfamiliar territories that require a change in mindset.

In traditional project delivery methods, the delivering parties are often incentivized to concentrate on their interests rather than owners and public project objectives. Due to the isolated organizational structure, the project actors' diverse interests may sometimes align or sometimes oppose. According to Ballard et al. (2014), maintaining scope stability is key to successfully applying traditional, non-lean project management methods. Korb and Ballard (2018) argue that transitioning from traditional management thinking to Lean thinking can be considered a paradigm shift, suggesting that adopting Lean requires considerable effort. Further, they encourage the LC community to address the challenges posed by the paradigm shift by presenting innovative measures and strategies to advance the progression of LC.

There is a lack of research addressing the challenges mentioned above regarding changing and transitioning to LC. Searching for "transition" or "change" on iglc.net only gives one hit (Riekki et al. (2023) suggest using takt production as a driver for the implementation of LC principles). This paper seeks to respond to this knowledge gap by addressing resistance to change during the introduction of an unfamiliar practice, such as applying a Lean mindset to a construction project. We explore strategies to enhance the transition from a traditional project management mindset to a Lean mindset, employing the narrative effectiveness of storytelling.

The "Hero's Journey" was introduced by Campbell (1949) and popularized by Vogler (1992). It is a narrative framework that outlines the typical stages a hero typically undergoes in a story. The framework has since been used as an illustrative metaphor in many fields. Williams (2019) writes that the Hero's Journey can be used as a comprehensive guide for individuals who willingly embrace or are forced to undergo change. Recognizing life as a "mudmap" with distinct phases and various substages enables life's chaos and challenging aspects to possess order and purpose. This paper has taken a conceptual approach. Supported by the narrative structure of the Hero's Journey framework, this study seeks to provide valuable insights and guidance for navigating and overcoming obstacles in the evolving landscape of construction practices. Thus, through the framework of the Hero's Journey, we aim to address the following research question: *"Can the Hero's Journey work as a tool for a successful transition from a traditional mindset to a Lean mindset in construction projects?"*

METHOD

This paper takes a conceptual approach to building theory. Conceptual papers are effective for theory-building (Cropanzano, 2009; Jaakkola, 2020). A conceptual paper does not have empirical data. According to Gilson and Goldberg (2015, p. 128), conceptual papers do not need to present new theories but rather "bridge existing theories in interesting ways, link work across disciplines, provide multi-level insights, and broaden the scope of our thinking."

Jaakkola (2020) presents four types of research design for conceptual papers: theory synthesis, theory adaptation, typology, and model. This paper has the theory adaptation design. Papers focused on theory adaptation aim to incorporate insights from other theories to improve an existing theory. This study employs theoretical insights from human storytelling, notably exemplified by the Hero's Journey, to enhance strategies for addressing the challenges of implementing LC posed by the paradigm shift in the construction industry. This paper utilizes the Hero's Journey framework of mythologist Joseph Campbell to illustrate how construction industry practitioners can move from a traditional mindset to a Lean mindset. Two books have been vital as core literature in this research. First, the third edition of Joseph Campbell's book from 1949, *The Hero with a Thousand Faces* (Campbell, 2008). Secondly, the popular screenwriter textbook *The Writer's Journey,* where Vogler puts Campbell's original work into a movie screenwriter context (Vogler, 1992). A literature study in the Google Scholar and Scopus databases was conducted for social sciences literature by searching for literature on words such as: "curiosity," "storytelling," "narrative," and "myth." Furthermore, we have looked at research examples where the Hero's Journey has been applied in various academic fields in the same databases. Also, since the Hero's Journey has been placed in the context of LC and collaborative project delivery, a literature review on these topics has been conducted for the research.

STORYTELLING AND NARRATIVE

According to Polletta et al. (2011), a *narrative* is a sequential account of events meant to convey a point, and they usually involve characters, often human or human-like, fostering audience empathy. McAdams (2019) writes about how storytelling creates the essential tools for *narrative identity*: constructing a self-defined life narrative that explains how a person has become who they are. This is because storytelling is a fundamental human characteristic. Lewis (2011, p. 505) writes, *"Humans are drawn to a story through our residence in narrative life."* Storytelling is a cornerstone of the teaching profession, with great teachers such as Homer, Plato, Jesus, and Gandhi using stories, myths, and personal history to instruct. Stories make information more believable and easier to remember (Zabel, 1991).

Stories are powerful means for communicating values, ideas, and norms, often proving to be more impactful tools than statistical data (Morgan & Dennehy, 1997). Campbell (2008, pp. 197-198) wrote: "We may doubt whether a scene ever actually took place. But that would not help us any; for we are concerned, at present, with problems of symbolism, not historicity. We do not particularly care whether Rip van Winkle, Kamar al-Zaman, or Jesus Christ ever actually lived. Their stories are what concerns us, and these stories are so widely distributed over the world - attached to various heroes in various lands - that the question of whether this or that local carrier of the universal theme may or may not have been a historical, living man can be of only secondary moment." Ideas embedded in mythology resonate with psychological truth, and the universal power of mythological ideas renders them applicable to comprehending almost every human challenge (Vogler, 1992). Stories want to teach you a lesson disguised as entertainment.

THE HERO'S JOURNEY

The hero's story is always a journey that can appear in many variations. The hero leaves his own well-known, familiar, and comfortable surroundings to venture on an inward journey (of the mind) or outward journey (physically). The Hero's Journey was introduced by Joseph Campbell (1949). Campbell showed how the standard path of the mythological adventure of the hero follows the same formula with three stages and associated sub-stages: 1) Separation/Departure, 2) Initiation, and 3) Return. Campbell named these three symbolic transitions the *nuclear unit of the monomyth.* Campbell contended that "whether presented in the vast, almost oceanic images of the Orient, the rigorous narratives of the Greeks, or in the majestic legends of the Bible, the adventure of the hero normally follows the pattern of the nuclear unit … a separation from the world, a penetration to some source of power, and a life-enhancing return" (Campbell, 2008, pp. 27-28).

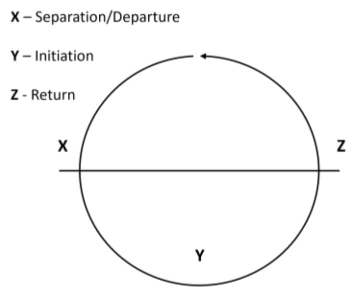

Figure 1: The nuclear unit of the monomyth (Campbell, 2008).

EXAMPLES OF THE HERO'S JOURNEY IN VARIOUS DISCIPLINES

The Hero's Journey is an illustrative metaphor in various fields, showcasing its diverse applications. Below, a selection of these disciplines will be listed to highlight the range and variety of contexts where the Hero's Journey finds relevance. As we can see from Table 1, there are many different segments where the Hero's Journey has been applied, and the list goes on.

Table 1: The Hero's Journey applied in different academic fields.

Author (year)	Area of Study	Summary
Vogler (1992)	Screenwriting	Adapted Campbell's work for screenwriting, using familiar Hollywood narratives like Star Wars.
Osland (2000)	Human Recourses	Applies HJ to expatriate experiences to aid the Hero's Journey professionals and individuals living abroad.
Senn (2002)	Religious Education	Discusses the Hero's Journey in the context of religious education.
Smith (2002)	Nursing	Examines myths in nursing, linking health and healing literature to the Hero's Journey.
Goldstein (2005)	Education/Teaching	Uses the Hero's Journey as a metaphor for managing stress in student teaching.
Ip (2011)	Video Games	Evaluate the Hero's Journey in narrative structures of video games.
Kelsey (2016)	Journalism	Investigate the Mail Online's articles about whether the former leader of the UK Independence Party, Nigel Farage, was portrayed in a heroic light through the ideological mechanisms of populist discourse.
Robledo and Batle (2017)	Tourism	Relates transformational tourism to the Hero's Journey as an archetypical transformation journey.
Williams (2019)	Humanistic Psychology	Proposes the Hero's Journey as a guide for personal change.
Moin et al. (2020)	Marketing	Argue for using the Hero's Journey in promotional videos for marketing.
Rogers et al. (2023)	Sociopsychology	Analyses the Hero's Journey in a socio-psychological context, discussing its impact on life's meaning.

STEPS OF THE HERO'S JOURNEY

In this paper, we will adopt Vogler's 12-step Hero's Journey (Vogler, 2007). The reason we prefer Vogler's journey is that it is simpler. Campbell's journey dives deep into ancient myths, folktales, and legends and uses a language that is harder to follow, while Vogler's version is more accessible and easier to communicate. It should be noted that Vogler's version is wholly based on Campbell's original journey, and scholars from different research areas have embraced both journeys. A detailed examination of the 12 steps will ensue as we discuss them in an LC context later in the paper. For now, we will settle by presenting the steps chronologically, as illustrated in Table 2.

Table 2: The Hero's Journey (Vogler, 2007, p. 205).

Character arc	Step of the Journey
Limited awareness of a problem	Heroes are introduced in the ORDINARY WORLD, where…
Increased awareness	They receive the CALL TO ADVENTURE.
Reluctance to change	They are RELUCTANT at first or REFUSE THE CALL, but…
Overcoming reluctance	Are encouraged by a MENTOR to…
Committing to change	CROSS THE FIRST THRESHOLD and enter the Special World, where…
Experimenting to change	They encounter TESTS, ALLIES, AND ENEMIES.
Preparing for a significant change	They APPROACH THE INMOST CAVE, crossing a second threshold…
Attempting a big change	Where they endure the SUPREME ORDEAL.
Consequences of the attempt (improvements and setbacks)	They take possession of their REWARD and…
Rededication to change	Are pursued on THE ROAD BACK to the Ordinary World.
Final attempt at a significant change	They cross the third threshold, experience a RESURRECTION, and are transformed by the experience.
Final mastery of the problem	They RETURN WITH THE ELIXIR, a boon or treasure, to benefit the Ordinary World.

LC AND COLLABORATIVE PROJECT DELIVERY

PROJECT DELIVERY METHODS

Numerous strategies have been developed over the years to ensure the successful completion of projects. These strategies are encapsulated in project delivery methods, which define how to achieve project objectives. Miller et al. (2000, p. 59) describe it as a "system for organizing and financing design, construction, operations and maintenance activities that facilitates the delivery of a good or service," while Love et al. (1998) define it as an organizational system that allocates specific responsibilities and authorities to individuals and organizations and outlines the different components in constructing a project. Furthermore, many different categories, or classes, of project delivery methods exist. Some scholars use a continuum ranging from separated to integrated (see Miller et al. (2000)). Others use the terminology of traditional (discrete) and collaborative (relational) (Ballard & Howell, 2005).

As Ian MacNeil outlines, the concept of relational contracts positions contracts on a spectrum from discrete to relational. He proposed that while some forms of contract are discrete, other forms of contract are relational in their conception and are, in many instances, a reflection of societal customs and norms (MacNeil, 1985). Relational contracting is a term used for transactions or agreements designed to acknowledge the partnership between contracting parties formally. The contract places greater emphasis on the relationship, with delivery mechanisms prioritizing trust and partnership (Colledge, 2005). In construction, integration of delivery evaluates how project components like planning, design, construction, and operation are combined throughout the production cycle, while separated-focused methods distinctly divide design and construction activities (Miller et al., 2000). Integration-focused methods merge design and construction responsibilities, rely on inter-organizational collaboration, and potentially offer competitive pricing through the contractor's market expertise and purchasing power (Davis et al., 2008).

LEAN CONSTRUCTION

Research in organizational behavior and psychology indicates that to implement new managerial practices successfully, there must be corresponding shifts in the culture or social relationship structure (Blader et al., 2015; Collins & Smith, 2006). LC represents a divergence from traditional managerial practices and culture. Scholars refer to Lean as a philosophy that requires a 'paradigm shift' so that practitioners adopt the 'lean thinking' mindset (Tommelein, 2015). To explain what constitutes a Lean mindset, we will refer to prior literature on the subject recognized and well-known for Lean practitioners.

Womack and Jones (2010) presented five principles of Lean: 1) The customer defines value, 2) A value stream creates value, 3) Make the value stream flow, 4) Use "pull" to drive flow, and 5) Continuous pursuit of perfection. Lean Project Consulting, Inc. presented the “Five Big Ideas that are Reshaping the Design and Delivery of Capital Projects” at a Sutter Health conference in 2004. The five ideas can be considered as a basis for shaping a Lean organization culture, and they are as follows (Macomber, 2004): 1) Collaborate, really collaborate, throughout design, planning, and execution; 2) Optimize the whole; 3) Tightly couple learning with action, 4) Projects are single-purpose networks of commitments, and 5) Intentionally build relationships on projects. Lastly, Lean Construction Institute (2024) has introduced the "Six Tenets of Lean": 1) Respect for people, 2) Optimize the whole, 3) Removal of waste, 4) Focus on process and flow, 5) Generation of value, and 6) Continuous improvement.

If we summarize these principles, the general purpose of Lean seems to be collaboration to generate value for customers while respecting all people. It also removes wasteful activities and increases process flow by optimizing the whole. In addition, it's essential to couple learning with action so you can learn from the process and continuously pursue improvement and perfection.

LEAN CONSTRUCTION IN THE HERO’S JOURNEY

For our purpose, the Hero's Journey is about transitioning from one mindset to another and can be regarded as an inward journey (transitioning from a traditional PM mindset to a Lean mindset). It will also arguably be a physical change in the workplace. However, due to limitations in the paper format, we choose to only reflect on the inward journey and change of mindset.

The steps associated with the hero’s story are symbols of universal life experiences and can be applicable to a simple comic book story or the most sophisticated drama (Vogler, 1992). The Hero's Journey is a structure that does not necessarily need to be followed precisely. Although all the stages in the framework are usually evident in any story, the order of the stages can be shuffled and come in different variations. Stages can also be deleted or added without losing their power. Therefore, the Hero’s Journey has endless flexibility, accommodating myriads of variations without compromising its features. In the following, we will use the Hero’s Journey as explained by Vogler (2007) and put it in a context where someone (e.g., an individual practitioner or organization) must switch from a traditional mindset to a Lean mindset.

Ordinary World

Most stories take the hero into a new, unexploited “special” world. To illustrate the new world, it is first necessary to show the hero in his comfortable surroundings, the “ordinary world.”

In our example, the ordinary world is a well-known work environment with familiar tried-and-tested techniques that fit a traditional mindset in the construction industry. However, the organization realizes the inefficiencies and waste in current methods and acknowledges the potential benefits of LC, which calls for adventure.

Call to Adventure

The hero is presented with a problem, challenge, or adventure. Once he or she is presented with the "call to adventure," the hero can no longer remain in the comfortable zone of the ordinary world.

In our example, the call to adventure can be the recognition of a need to change in the construction process. Or, as Korb and Ballard (2018) call it, a paradigm shift. A new strategy that relies more on interdisciplinary collaboration requires a Lean mindset. For our hero, accustomed to the comfort of doing things the old way, adjusting to this new, unfamiliar way of thinking is challenging. However, whether the new strategy is embraced or resisted, the situation requires a change, which is the call to adventure that represents our hero's challenge.

Refusal of the Call

At this point, the hero is normally reluctant to the expected change. Refusal of the call is usually tied to the fear of change. The hero is not fully committed to what's happening at this journey stage.

In our example, resistance to change might be due to the comfort of existing practices, skepticism about new methods, or fear of the unknown. As mentioned in the Introduction section, reluctance to change is one of the top barriers to LC implementation (Albalkhy & Sweis, 2021; Wandahl, 2014). Some kind of encouragement or change in circumstances might be helpful for the hero. For instance, some calming words from a person with LC experience (a *mentor*) can be encouraging.

Meeting with the Mentor

At this stage in the journey, most stories have introduced the mentor, which often comes in the form of a wise old man or woman (Gandalf in The Lord of the Rings, Prof. Dumbledore in Harry Potter, the Fairy Godmother in Cinderella). Still, they can come in different shapes (e.g., Aslan in Narnia or Rafiki in The Lion King). The relationship between hero and mentor is among the richest in symbolic value, as it represents the bond between parent/child, teacher/student, role model/protégé, etc.

In our LC example, the mentor could come in different shapes, from forward-leaning companies leading down to individual Lean champions. For instance, Raghavan et al. (2017) found that the drive by the top management, coupled with efforts from Lean champions in the project team, was essential for transitioning from a conventional project delivery method to an LC method. These mentors provide training, resources, and support to understand and implement Lean principles. They can typically be represented by the project manager or someone with experience and knowledge of LC or change management. However, the mentor can only go so far with the hero. Eventually, the hero must embrace and be open to the task himself. The hero must *want to* go through the change to a Lean mindset.

Crossing the First Threshold

Now, the hero commits to the adventure fully and enters the new special world for the first time by crossing the first threshold. Vogler (2007) writes that movies are built in three acts: 1) the hero's decision to act, 2) the action itself, and 3) the consequences of the action. The first threshold indicates the point of no return between acts 1 and 2. It's not always the hero's decision to act.

In a construction project, crossing the first threshold may be when a project commits to an LC approach. It can be at the start of a project where the involved are going into the uncharted territory of interdisciplinary and collaborative methods for the first time. It can also be a pilot project or an initial implementation phase where the LC principles are applied on a small scale.

Tests, Allies and Enemies

The first threshold is crossed, and the hero is now in the unfamiliar territory of the “special world.” The hero will now encounter new challenges, make allies and enemies, and start to learn the norms and expectations in the new environment. This is a stage where the hero usually can undergo stressful situations, but the hero gains a lot of experience. The challenges can be both inward and outward.

Challenges arise as the organization starts applying Lean principles. Wandahl (2014) found that mis-conceptualization and mis-implementation of LC, particularly the Last Planner System, are significant issues, with the consequence that benefits are not being realized, with inadequate knowledge, education, and communication identified as key contributing factors—other issues like adapting to new workflows, resistance from employees, or logistical challenges. Interdisciplinary collaboration, resources, unexpected events, etc., are challenges that make the transition to an LC approach difficult. There can also be inward challenges, such as a lack of understanding of the concept and its benefits or a transition to a Lean mindset during a stressful period at work. Our heroes might feel angry or frustrated at being outside their comfort zone. Luckily, the mentors are there to help, and after a while, people will steadily improve their understanding and mastery of the approach.

Approach to the Inmost Cave

The hero approaches the edge of "the inmost cave," which is a place where the object of the quest can be found. The inmost cave is usually the most dangerous place in the special world. Typically, this can be the enemy’s headquarters or where the object of special value is hidden. The approach covers all preparations to enter the innermost cave, where death or supreme danger can be expected. This is the second significant threshold in the journey.

As challenges are identified, the project organization needs to refine its approach. This might involve more training, better communication, or adjusting strategies to fit the context better. The *inmost cave* can, for example, be the construction phase. In the construction phase, you will determine if everything is going according to plan and how the new LC approach works. The planning phase can be considered as the *approach*, as this is where all the preparations for the “dangers” of the construction phase occur. Furthermore, research has stated that successful implementation follows the line from top organizational management down to its divisions and into construction projects, becoming embedded in the organization (Torp et al., 2018).

Supreme Ordeal

In this pivotal moment, the hero experiences a battle with his greatest fears. Faced with the possibility of death (figuratively), he is pushed to the edge in a fierce confrontation with a hostile force. In movies, the supreme ordeal serves as a “black moment” for the audience, leaving us uncertain about whether the hero will succeed or succumb to the challenges. This is a critical moment in any story. The hero must die or appear to die so he can be reborn.

Theoretically, this is the decisive moment for all organizational change processes. Despite the potential benefits, change is not easy to achieve in practice, and some have even stated that up to 70 % of change processes fail (Higgs & Rowland, 2000). In a construction project context, the supreme ordeal might be when our hero meets challenges that make him question the new approach. This is a critical point where the organization faces significant challenges that test its commitment to LC. This could be financial constraints, communication issues, opportunism, unforeseen events, different perspectives, external issues, etc. How our heroes confront these challenges and overcome the urge to return to safe traditional methods is vital and can be considered the supreme ordeal.

Reward

The hero can celebrate overcoming the supreme ordeal (slaying the dragon, finding the holy grail, finding love, etc.). The hero now takes possession of the treasure he was seeking, the reward. The reward comes in various shapes, either by tangible items or increased knowledge or experience. The hero may also become more attractive after surviving the supreme ordeal.

In our example, the reward is increased knowledge, experience, and understanding of how the Lean mindset works after overcoming major challenges in the construction phase. The organization started seeing the benefits of LC – improved efficiency, reduced waste, higher quality, and better interdisciplinary collaboration (Ashcraft, 2022; Cheng & Johnson, 2016). Additional long-term benefits may include an improved project outcome or the acquisition of expertise that will appeal to future projects intending to employ the LC approach.

The Road Back

However, the journey has yet to be finished. On the road back, we are crossing the third threshold as the hero deals with the consequences of confronting the dark forces of the supreme ordeal. The hostile forces are pursuing the hero after he seizes his reward.

Our heroes have survived the biggest challenge by gaining knowledge, understanding, and experience about the LC approach. However, unforeseen events can still occur, and they will be put to the test again. Aligned with the Kaizen philosophy (continuous improvement), often expressed with the PDCA cycle (Plan-Do-Check-Act) (Kunz & Fischer, 2020), lessons are applied to refine processes in the organization further.

Resurrection

The hero must be reborn and cleansed in one last ordeal and resurrection before returning to the ordinary world. This is the final exam, where the hero will be tested to see if he has learned his lessons.

In our example, this might be to ensure that the experience and insight from the project are saved and can be utilized in future work. LC becomes ingrained in the organization's culture. It's not just a set of practices but a way of thinking and working. Our heroes should be able to deal with unforeseen troubles using new tools, knowledge, and experience acquired during the LC journey.

Return with the Elixir

The hero returns to the ordinary world and brings back an "elixir," a treasure or lesson from the special world. This elixir can be both tangible and intangible. The hero is doomed to repeat the adventure if nothing is brought back from the special world to the ordinary world. But usually, the hero returns with increased experience and knowledge, which can hugely benefit the ordinary world.

In our example, the elixir will be the increased knowledge of LC, which will help us overcome the transition from a traditional mindset to a lean mindset. Our heroes have not forgotten the ways of the ordinary world but are now equipped with the knowledge to also handle the Lean mindset. Our heroes have now conquered the fear of change from the comfort of the old mindset, and this is no longer a barrier to future LC projects. The knowledge and experience gained can be shared with others in the industry, contributing to broader change.

CONCLUSIONS

We set out to answer if the Hero's Journey can work as a tool for a successful transition from a traditional mindset to a Lean mindset. Employing the Hero's Journey in a construction context can make the transition to a Lean mindset less overwhelming for practitioners. Going through each stage of the Hero's Journey, we have shown that it can easily be applicable in an LC context and work as a “mudmap” for change. Another interesting observation is how Joseph Campbell’s iterative cycle of the monomyth resembles the iterative process of continuous improvement in Lean.

Table 2 summarizes the Hero’s Journey for LC, drawing parallels between each step and the corresponding stage in the Lord of the Rings films. This approach provides a familiar comparison from the movie world, intending to enhance the reader’s understanding of the Hero’s Journey and how it can be applied. The steps proposed for LC are illustrative examples, and journeys might differ depending on the practitioner's or the organization’s purpose.

Table 2: A Hero’s Journey: Lean Construction versus the Lord of the Rings films.

Step of the Journey	Lord of the Rings	Lean Construction
Ordinary World	The Shire	A traditional PM mindset
Call to Adventure	Gandalf entrusts Frodo with the ring	Transition from a traditional mindset to a Lean mindset
Refusal of the Call	Frodo refuses that he, a simple hobbit, can be entrusted with such a task	Hesitation to change something well-known and comfortable
Meeting with the Mentor	Aragorn and Gandalf function as mentors	A project manager or an LC expert/consultant
Crossing the First Threshold	The hobbits leave the Shire	Committing to an LC approach or the start of an LC project
Tests, Allies and Enemies	The fellowship of the ring, Sauron, Gollum, trolls, orcs, the ring itself	Frustration, unexpected events, resistance from employees, trouble adapting to the approach
Approach to the Inmost Cave	Frodo and Sam’s journey through the pass of Cirith Ungol and into Mordor	Preparations for the construction phase
Supreme Ordeal	Frodo and Sam face Gollum, Sauron, and finally, Frodo’s own hesitation	The construction phase
Reward	The hobbits seize the reward of destroying Sauron to save Middle Earth	Increased knowledge, experience, and understanding of LC
The Road Back	The ring is destroyed, and the volcano erupts. The eagles rescue Frodo and Sam.	Dealing with new challenges by continuously improving the process
Resurrection	Frodo heals from the strains of destroying the ring. The hobbits are praised and honored for their contributions.	Making sure the new knowledge is saved for the future. LC is ingrained in the organization's culture.
Return with the Elixir	The hobbits return to the Shire scarred but wiser, wealthier, confident, and with peace.	The hero is now equipped with a Lean mindset and has conquered their fear of change.

PRACTICAL SIGNIFICANCE, LIMITATIONS, AND FURTHER WORK

The practical usage of the LC Journey depends on the user’s imagination. The framework’s flexibility makes it adaptable to various contexts. One possible area of use is within teaching, where the framework can describe the benefits of LC and how the Lean mindset differs from traditional management thinking. Another area can be at the start of a project where it is decided to implement LC principles or at any arena to present LC engagingly. A limitation of the research is that the study did not examine how the framework applies to a diverse range of projects. The framework has yet to be tested on people without LC knowledge, so further work on this topic might be done to design a journey for a selected purpose within LC and test the framework. Furthermore, looking deeper into how Campbell's monomyth can be used to demonstrate continuous improvement is possible.

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MAGICAL VS METHODICAL: CHOOSING BY ADVANTAGES AS ANTIDOTE TO THE PLANNING FALLACY

Eran Haronian[1] and Samuel Korb[2]

ABSTRACT

Cost and schedule overruns are the bane of construction projects, in part due to overly optimistic predictions of project progression. This "optimism bias" is called the planning fallacy, a form of "magical thinking" where planners convince themselves that their project will be different (and better) than others. "Choosing by Advantages" (CBA) is a methodical approach for decision-making. By engaging "slow thinking" at the organizational level, CBA can help counteract the tendency to default to best-case scenarios when selecting among designs and production methods, even in the middle of a project. In this paper, a case study of a Pumped Hydroelectric Energy Storage facility that had to choose between a bottom-up raise boring and a top-down shaft sinking construction method for the vertical shaft connecting the reservoirs is presented. The paper then examines how CBA helped shift the thinking of the project team away from fallacious planning and overcome the sunk-cost fallacy.

KEYWORDS

Choosing by Advantages, Optimism Bias, Planning Fallacy, Risk Management, Monte Carlo

INTRODUCTION

The planning of a construction project is a process that involves making a number of assumptions (Gao et al., 2014). While construction professionals draw on their knowledge and experience, as well as the use of computer simulations and archived data, there comes a time when the humans involved with the planning are making their best assumptions: assumptions about durations of project tasks, likely contingences and how to react to them, and – if the project involves any excavation – what lies beneath the surface of the construction site. Again, these assumptions may be informed guesses that rely on models and empirical evidence like core sampling (in the case of the ground substrate), but until the project is underway there is no way of knowing exactly what the truth may be.

Thus, human psychology comes into play in the planning of any construction project. Humans are prone to some illogical thought patterns, including the optimism bias (Weinstein, 1980), which is a tendency to assume the best case scenario when considering future events. It is likely in part due to this tendency that construction projects experience a mismatch between how they are planned to be carried out versus the reality of their implementation, leading to the budget overruns and schedule delays that plague the industry (Egan, 1998).

During tendering (especially in tenders that put most of the weight on price) owners and contractors often have a tendency to take an optimistic approach (Chadee et al., 2021; Son & Rojas, 2011), which allows a lump sum fixed price to be reached. But once construction begins,

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it may turn out that risks have been underestimated, and assumptions regarding various aspects – including the construction methods selected to complete the project – must be re-examined. The question at this point is what do they do – continue as planned or re-think? Here too, human psychology comes into play, as there is a tendency to want to continue an earlier-planned course despite new information coming to light. This is referred to as escalation of commitment (Staw, 1981) or the sunk cost fallacy (Arkes & Blumer, 1985). Overcoming these innate tendencies is difficult in practice, and again runs into the optimism bias. Project personnel tend to want to project an aura of competence and project optimism, not wanting to expose bad news that could make them, or the project, look bad.

One way to combat these fallacious approaches is to institute rigorous approaches to decision making. The Choosing by Advantages (CBA) method (Suhr, 1999) is a systematic decision-making strategy that can help to confront hard truths. When implemented in a project, it can assist in addressing issues more effectively at an earlier stage, rather than "kicking the can down the road" due to the combined forces of the optimism bias and the sunk cost fallacy. The CBA method is transparent, which helps in communicating the issues across the project organization and building consensus. And yet, the existing literature has not explicitly used CBA to address the planning fallacy.

In this paper, we attempt to close that knowledge gap by presenting a case study of an infrastructure construction project which encountered the issues described above. After planning the project for a "best case" scenario, upon commencing the project it was discovered that the reality of the implementation did not meet the assumptions. CBA was used to assist a mid-course correction, selecting a construction method that, while costing more in the short term, would lead to the best outcome for the project. We present the issues at play in the project and how CBA helped address them, showing that methodical approaches like CBA can serve as an "antidote" to tendencies like optimism bias.

LITERATURE REVIEW

CHOOSING BY ADVANTAGES

CBA is a Multi-Criteria Decision Making (MCDM) system (Köksalan et al., 2011), developed by Suhr (1999), and applicable for a wide range of decisions, from mundane daily individual-personal decisions through strategic-organizational-collaborative decisions. Though CBA is a relatively new approach in the MCDM field, it has been widely implemented by academic and industry practitioners, assisting project teams in building consensus that includes different perspectives and addresses sometimes-conflicting interests (Arroyo et al., 2022; Arroyo & Long, 2018; Martinez et al., 2016; Parrish & Tommelein, 2009; Schöttle et al., 2019; Schöttle & Arroyo, 2017). Successful applications of CBA can be found regarding design alternatives (Arroyo et al., 2012; Arroyo & Long, 2018; Kpamma et al., 2017; Parrish & Tommelein, 2009) or for operational decisions (Martinez et al., 2016). Arroyo et al. (2012) describe the "Lean" properties of CBA that include: a systemic multidisciplinary approach for global optimization, enhanced involvement of stakeholders, consideration of cost only at the last phase of the process once an objective basis has been established, and good visualization of the process and the outcome which enables transparency and collaboration.

In CBA, it is important to document assumptions (and the thought processes that led to them) for decisions, so they can be revised later in the project when new considerations arise (Parrish & Tommelein, 2009). This becomes even more valid in high-risk projects, as decision makers must re-evaluate their decision as the project progresses. Additionally, CBA may assist in making "difficult" long-term decisions that need to be transparent across the organization in order to be approved by stakeholders (Schöttle et al., 2023).

The seven steps of CBA (Arroyo, 2014; Suhr, 1999) were followed in this project, where the "factors" are the decision criteria for all options whereas "attributes" are the ways in which an individual option realizes a particular criterion:

1. Identify alternatives
2. Define factors
3. Define criteria for each factor
4. Evaluate attributes for each alternative
5. Decide the advantages for each alternative
6. Decide the importance of each advantage
7. Evaluate cost data.

OPTIMISM BIAS AND THE PLANNING FALLACY

Optimism bias is the tendency for people to overestimate the likelihood of positive future outcomes and/or underestimate the likelihood of negative future outcomes (Sharot, 2011). The term was coined by Weinstein (1980) and has repeatedly been documented in a variety of settings (Klein & Helweg-Larsen, 2002). Optimism bias is somewhat insidious in that it resists efforts to "inoculate" people to its effects; efforts to do so can actually increase the amount of optimism bias displayed (Weinstein & Klein, 2002). Since optimism bias reflects a divergence between thought processes/assumptions and objective reality, it constitutes a form of "magical thinking", which entails drawing correlations not based on evidence (Hutson, 2013).

The application of optimism bias to project planning has been called "the planning fallacy" by Kahneman and Tversky (1977). This refers to the tendency to assume only the best-case scenarios when laying out the plan for a project (Buehler et al., 2010), which is reflected in unrealistic project timelines. Planning fallacy contributes to projects costing more and taking more time than expected (Flyvbjerg, 2011). Kahneman (2011) has suggested that while humans have a default thinking mode that is more fallible, deliberate thinking can help arrive at more logical conclusion; these two modes are referred to as "fast thinking" and "slow thinking" respectively. In the realm of Lean Construction, Senior (2012) has looked at documented psychological biases and suggested that Lean Construction techniques such as Last Planner (Ballard, 2000) can combat some of the biases that are inherent to human psychology leading to overly-optimistic planning. Roch et al. (2022) have suggested that cognitive biases like the planning fallacy are an obstacle to the introduction of the Lean concept of "flow" in the construction industry, as human brains have been shown to struggle with internalizing (and exploiting) stochastic and statistical realities.

CASE STUDY: SHAFT CONSTRUCTION METHOD FOR PUMPED-STORAGE HYDROELECTRIC FACILITY

The project in this case study, where CBA was successfully applied to combat the tendency towards optimism bias, is a Pumped Hydroelectric Energy Storage (PHES) facility. PHES is a method of storing excess electricity generation (Rehman et al., 2015) when demand and supply levels are out of sync. In times of excess supply, energy is used to pump water "uphill" from a lower water reservoir to an upper reservoir. In times of excess electricity demand, the flow of water is reversed, with the water from the top reservoir driving generators to put energy back into the grid. An "engineering, procurement, and construction" (EPC) contracting method (Carrillo, 2005) was used, with the PHES project structured as a turnkey project where the General Contractor was responsible for design, procurement, construction, and commissioning.

Within the scope of the PHES facility, the main focus of this case study is the construction of the underground chambers that would connect between the upper and lower reservoirs. The main components of a PHES facility are shown in Figure 1.

The following components of the PHES facility appear in this figure:

1. Upper and lower reservoirs, that contain the bulk water storage.
2. Power House (PH), in which the pumps/generators/turbines are located.
3. Horizontal tunnel, which connects between the lower reservoir, the PH, and the bottom of the shaft.
4. Vertical shaft, which connects between the elevations of the upper reservoir and the lower reservoir, horizontal tunnels, and the PH

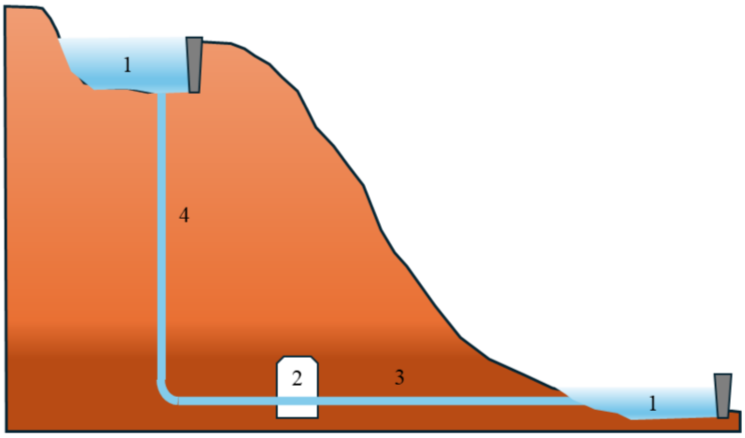

Figure 1: Cross-section of the PHES facility

The main focus of this case-study is on the selection of the construction method that was used to excavate the 700-meter vertical shaft as well as the interplay between the timing of digging the tunnel and the shaft.

Background

For this project, two options were considered for the method of excavating the vertical shaft, as shown in Figure 2.

The following sections describe these two methods of drilling, as well as their impact on the project's critical path.

Raise Boring

Raise Boring (RB) is referred to as a "bottom up" method of drilling (Liu & Meng, 2015), and it requires access to the bottom of the shaft for most of the work. A small-diameter pilot hole is sunk from the top of the shaft, just wide enough to accommodate a drill string. Then a large-diameter reamer head is attached to the drill string at the bottom of the shaft (i.e. via the tunnel in this case study). The reamer head is then raised back towards the top of the shaft, which means the drill face for the shaft is oriented towards the bottom of the shaft. The material dislodged by the reamer head falls down the shaft to the bottom (the tunnel) via gravity, where it can be collected and removed with loaders and dump trucks.

Shaft Sinking

Shaft Sinking (SS), by contrast, is a "top down" method of drilling, where the entire excavation takes place from the top side of the shaft (Lashgari et al., 2011). It can be based on conventional "drill and blast" excavation or mechanical equipment, but both the equipment for extraction and the excavated debris enter and exit through the top opening of the shaft. As a safety feature preventing loose or unstable soil or rock from falling into the shaft, the sides of the shaft are supported with shotcrete as the shaft is excavated.

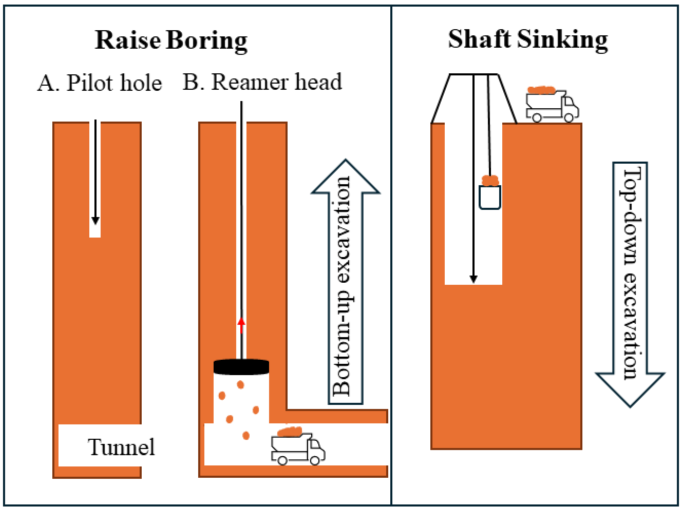

Figure 2: Raise Boring vs Shaft Sinking, for excavating the vertical shaft

Project Timeline and Critical Path

Due to the fact that in RB, the reamer head has to be installed from the bottom of the shaft, in this approach the shaft can only be dug once there is access to the lower level of the shaft. In this case, this meant after the tunnel was completed. Likewise, the rubble that the reamer dislodges must be extracted via the tunnel, which further increases the dependence of RB on tunnel completion. While it is possible to sink the pilot hole prior to tunnel completion, this is a relatively minor component of RB and thus does not effectively decouple the two steps.

SS does not have the same constraint, as the top of the shaft is used exclusively for entry and exit of both equipment and excavated materials. Thus in terms of the project steps, SS can take place in parallel with tunneling – a potential time savings for the project – whereas RB is in series with tunneling. After the tunnel and shaft are completed, the project can progress to testing and commissioning. The two options are portrayed in Figure 3.

The tunneling was found to be on the critical path for the overall project, which means that RB would also be on the critical path, if selected, whereas SS would not be on the critical path as it takes place in parallel with tunneling.

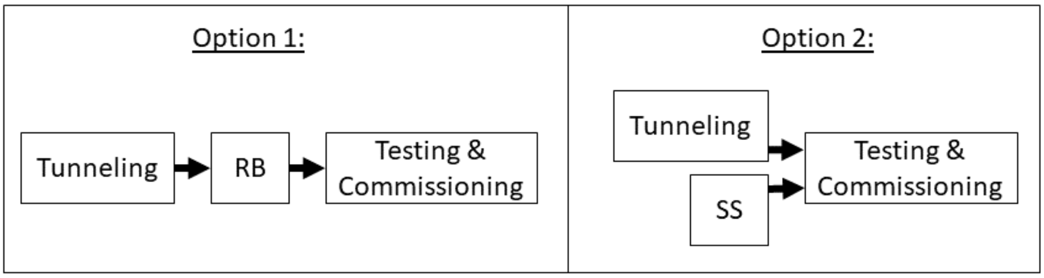

Figure 3: Impact of RB vs SS on project process flow

Before Applying CBA

Prior to project commencement, the project team was faced with the decision about whether to choose RB or SS as the method of digging the vertical shaft for the PHES facility. While CBA (or any other systematic decision-making approach) was not employed, this does not mean that the subject was not given some thought.

The major factor that contributed to the decision was cost. RB is a more "technically advanced" method of shaft digging, requiring less human input, which brings down costs. Removing the excavated material is logistically less complex since it uses loaders and dump trucks running on the effectively-flat tunnel floor. SS, on the other hand, is a more "basic/traditional" method that requires the ground excavated to be removed through the top of the shaft (which becomes progressively further from the drill face as the shaft progresses) as well as shotcrete along the sides of the excavation.

The duration of each alternative also played a part in the initial selection of RB; it was estimated to take 14 months versus 24 months for SS. Finally, the impact of each option on other steps in the project process was a factor, with RB having less impact and SS having more of an impact. This was due to the fact that SS required more logistical work in and around the upper reservoir, which also was undergoing construction (including drill and blast excavation) at the time same time.

Though at the time of the decision to use RB these factors were not formally tabularized, we have done so in this paper to sum up the considerations, as shown in Table 1.

Table 1: Factors leading to the selection of RB prior to applying CBA

Factor	RB	SS
Price	Lower	Higher
Sophistication/ Resources	High: advanced equipment, low labor input	Low/Traditional: basic equipment, extensive labor input required
Duration	14 months	24 months
Impact on other works	Low	High
Logistics	Low complexity	High complexity

For all these reasons, and mostly due to the cost, the choice that seemed obvious was to select RB, and that was what was indeed done on the eve of commencing the project.

APPLYING CBA

Soon after the project got underway, it became clear that certain assumptions that had been made during the project planning phase might not be correct. In particular, the ground consistency was not in line with the statistical assumptions that had been made regarding the geological condition of the site. The excavation method, equipment, and required levels of support for the tunnel/shaft, were planned according to the Geological Base Report (GBR), which reflects statistical analysis of field investigations for the soil classification.

However, once construction of the tunnel commenced, the project began to encounter unpredictable and problematic ground conditions that differed from the initial assumptions, instabilities potentially leading to cave-ins. The worse-than-expected ground conditions significantly affected the tunneling works, as much greater support levels were required than what was planned, causing schedule delays, cost overruns, and unexpected safety hazards. As a result, questions arose regarding the construction method for the vertical shaft: was the execution method that was initially selected suitable for the latent ground conditions? Was it reasonable to rely on a construction method that required the completion of the lower tunnels to begin the work on the vertical shaft? Given the developments with the ground conditions, risk considerations rose to a more prominent position in terms of project attention, so it was decided to reexamine the alternatives for the vertical shaft.

A team was assembled that consisted of six engineers (with professional experience that ranged from 15 to 40 years each): the Project Manager, the Construction Manager, the Head

Tunneling Engineer, the Head Civil Engineer, the Project Geologist, and the Planner (also the first author of this paper). The team was tasked with re-evaluating the construction method for the shaft in light of the difficulties encountered during the tunneling. In order to work as methodically as possible, and make sure decisions made sense to both members of the committee and the ownership of the construction company, the decision was made to work according to CBA.

It was at this time that the factors listed in Table 1 were formally codified. Three additional risk factors were recognized and added to the analysis: schedule risk, soil stability risk, and safety risk.

Schedule Risk

With the tunneling works delayed, the start of RB would also be delayed. Likewise, the ground instability that plagued the tunneling could possibly delay the RB progress. As these both were on the critical chain if RB was selected, a much more detailed analysis was required. A Monte-Carlo simulation (Mohsen et al., 2022) was used to assess the probability that the project would be completed on time, due to the uncertainties regarding the underground soil, which affected the tunneling excavation rate and introduced possible risks during the shaft excavation (due to groundwater ingression or shaft collapse).

First, the Monte-Carlo simulation examined the tunneling works, as these would need to be completed in either case. The duration of the tunneling tasks were represented by a beta probability distribution function, which required defining three scenarios: optimistic, most likely, and pessimistic. The tunneling works were divided into several segments with different geological properties. For each segment, the duration was calculated according to the segment length and the production rate for the three scenarios. For the optimistic scenario the duration was calculated according to the assumptions regarding structural reinforcement made in the preliminary design and the GBR. For the most likely scenario the duration was calculated according to the actual decrease in the production rate in the tunneling work up to the date the simulation was run. For the pessimistic scenario, the duration was calculated according to the most conservative structural reinforcement.

Then, both RB and SS were simulated in a similar manner. Since SS includes the installation of supports throughout, it was more robust in the face of the uncertain ground conditions as opposed to RB. RB remained the faster option, taking six fewer months to complete, but as shown in Figure 3, because SS could be conducted in parallel to tunneling, it had the advantage. It was found that RB would lead to a probability of less than 30% of completing the project on time, whereas SS would introduce a Total Slack of several months, which meant that the probability of completing the project on time was higher.

Soil Stability Risk

With the soil instabilities that were discovered, this factor examined the risk of collapse of the shaft excavation. The evaluation criteria employed a 5x5 Impact-Probability Matrix (Ni et al., 2010) to quantify the risk, by multiplying the impact ranking (which ranged from 1 [negligible] to 5 [catastrophic]) by the probability ranking (from 1 [Rare] to 5 [Almost Certain]). The resulting product was graded as very low (1-2), low (3-4), medium (5-9), high (10-12), very high (15-19), and extreme (20-25).

For RB, in light of the unpredictable ground conditions, it was decided that instability events were likely (ranked 4). Based on experience from previous projects in which incidence of instability occurred, it was decided that the damage that could be caused by such an event would be major (ranked 5). Thus, the rank for the risk was extreme (a total of 20).

For SS, support work is performed on the walls of the shaft as the excavation progresses. As a result, the risk of instability events was unlikely (ranked 2), and if an event occurs, the coping ability would be good leading to a relatively minor impact (ranked 2). Thus, the rank for the risk was low (a total of 4).

Safety Risk

Underground instabilities in the ground condition meant that worker safety had to be considered. Similar to the soil stability risk, this criterion was evaluated with a 5x5 Impact-Probability Matrix, as part of the periodic risk management meetings.

For RB, the excavated material falls down to the bottom of the shaft, which is a significant safety risk for the workers tasked with removing it through the tunnel. Based on experience from previous projects, it was assumed that the probability for safety events caused by the removal of material through the hole made by the reamer head was possible (ranked 3). If a safety event had occurred it could lead to costs of human life, and therefore was severe (ranked 5). Thus, the total rank was very high (15).

For SS, the safety risks derive from possible collapses and falling pieces of rock and soil from the shaft walls down to the working area. Because temporary supports are erected along the shaft as a matter of course, the risk of collapse and falling debris was deemed unlikely (ranked 2). If a safety event were to occur it could lead to costs of human life, ranked as severe (ranked 5). Thus, the total rank for the risk was high (10).

Applying CBA Weighting to the Factors

The additional factors that were identified are summed up in Table 2

Table 2: Additional Risk Factors

Factor	RB	SS
Schedule Risk: Probability of completing project on time	Low: <30%	High: >90%
Soil Stability Risk	Extreme: 20	Low: 4
Safety Risk	Very high: 15	High: 10

In the CBA method, once the factors have been enumerated and evaluated for the options, the next step is to compare the factors to decide their relative weighting. The factor that is considered the most significant is pegged at a weighting of 100, and then the others are scaled accordingly. The option with the greatest advantage for that factor receives the full value of the weighting for that factor, and (in the case of two options like in this project) the other option receives zero. This process is carried out collaboratively by the team, and necessarily carries a degree of subjectivity, while based on the objective observations gathered previously. Then the values are summed to determine the relative advantage of each.

Schedule risk was given the highest weighting, since the project team felt that delivering the project late to the owner would have negative side effects in terms both financial and reputational, and even possibly litigious. Of note, cost is not on this list, as under CBA, cost is not an advantage. Only once the advantages have been assessed is the cost considered, and a determination is made about whether the cost is justified to obtain the advantages of the respective option.

The CBA summation appears in Table 3, which combines the factors from Table 1 and Table 2 and adds the assignment of the advantage points to each factor/option.

The cost of SS was determined to be roughly double the cost of RB. Thus, at the final stage of the process, considering the costs of the alternatives, it was clear that the decision came down to a tradeoff between cost and risk: a high risk alternative at a relatively lower cost, and a low risk alternative at a relatively higher cost. Ultimately, it was decided that the higher cost of this one component of the overall project was indeed worth the advantages that SS offered, primarily in terms of reduced risk to the entire project, and the decision was made to switch from RB to SS.

Table 3: Summarized Advantages/Conclusions for the Alternatives

Factor	RB		SS	
Schedule Risk (Probability of completing project on time)	Att: Low: <30%		Att: High: >90%	
			Adv: 60% Increase in probability to complete the project on time	Imp: 100
Soil Stability Risk	Att: Extreme: 20		Att: Low: 4	
			Adv: Risk reduction from very high to medium	Imp: 60
Safety Risk	Att: Very high: 15		Att: High: 10	
			Adv: Risk reduction from very high to medium	Imp: 80
Resources	Att: Advanced equipment & low labor input		Att: Traditional equipment & extensive labor input required	
		Imp: 40		
Impact on other works	Att: Low		Att: High	
	Adv: Less impact on other works	Imp: 40		
Logistics	Att: Low complexity		Att: High complexity	
	Adv: Lower complexity	Imp: 35		
Duration	Att: 14 months		Att: 24 months	
	Adv: Shorter duration	Imp: 30		
Total Sum of Advantages		**145**		**240**

DISCUSSION

The case study above demonstrates the phenomenon of optimism bias in construction and suggests a coping mechanism based on sound and transparent decision-making processes, achieved through CBA implementation. It is likely that if we ask the "5 Whys" (Ōno, 2008) regarding many of the faults in construction, optimism bias may be among the root causes. From the contractor's side, optimism bias may lead to unrealistically low tender-winning prices (leading to the "winner's curse"), perhaps with the hope that additional profit sources will be found along the way (e.g. change orders, acceleration incentives, etc.). From the owner's side, optimism bias may push immature projects to the construction phase before all preconditions are met, assuming things will work out along the road. Optimism is also reflected in the way a project status is reported to stakeholders and financing bodies, so funding won't be jeopardized by hints of doubt. But a dose of reality is often exactly what the project needs to steer it back to on track to a successful outcome.

The case of the PHES facility demonstrates how taking the right action, especially at the last responsible moment (Howell and Lichtig 2008), requires a sound process that relies on objective facts and supporting data (like statistical analyses) that are communicated to decision makers and stakeholders. Despite the hindsight observation that changing construction methods was required once the soil conditions were discovered, in practice it was not simple at all. SS was more expensive and considered “less advanced”, two strikes against it for the instincts of many professionals in the organization. It took a lot of deliberation, and the CBA process was the key to making the right decision for the project. Thus, this implementation reinforces and demonstrates the findings of previous research (Arroyo et al., 2015; Schöttle et al., 2023), emphasizing it being a simple, clear, transparent, and well documented MCDM process, which assists in avoiding falling into optimism bias. Ultimately, using CBA, the team was able to determine that paying more for SS was worth it as it reduced the project risks.

In addition, this paper adds to the body of knowledge on CBA, by providing framework to emphasize risk factors as part of the decision-making process. The Monte Carlo simulation was found immensely useful to quantify the likelihood and impact of the risks to the schedule, which in turn led to it being recognized as the anchored advantage for the CBA analysis. Additionally, it demonstrated how the different (and sometimes fragmented) disciplines of traditional project management practice (budget, schedule, quality, risks, etc.) can be drawn together by the CBA process, making them relevant and influential to the path of the project.

CONCLUSIONS

Decision making in a complex, multi-input and multi-variable setting like a construction project is hard, made only more-so by the innate psychological biases that humans possess. But as shown in this paper, systematic approaches to decision making can help.

The reality is that most people involved in construction projects want the project to succeed, and want to believe that it will succeed. But choosing only the most optimistic interpretations of the situation and future outcomes does not ultimately serve the long-term interests of the project outcomes. Therefore, picking what seems to be the cheapest or quickest path based on those assumptions could lead to getting stuck in a less-globally-optimal path, if it is dependent upon everything going smoothly. CBA can create the space to have the tough conversations in a proactive manner and not only once everything has gone awry, and it puts consideration of cost as the last step, instead of following the industry convention of always going with the low-cost alternative. As such, this paper contributes to the body of knowledge around CBA by suggesting a key use-case for the approach in addressing the planning fallacy.

In terms of limitations, like any case study, our data set is severely limited. The authors think that, on the balance, the case study indicates that CBA can be an effective antidote to the optimism bias, and one that would benefit from further study. The “gold standard” for future work would be a randomized trial, examining outcomes of some projects that employ CBA versus a non-CBA intervention (to combat the Hawthorne Effect (Landsberger, 1961), particularly as a double-blind trial is not feasible in this case), and applying metrics for measuring optimism bias and/or the planning fallacy. This would admittedly be quite a challenge to implement, so at a minimum more case studies could be trialed.

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AN EXPLORATION OF PSYCHOLOGICAL SAFETY AND TEAM BEHAVIORS IN A CONSTRUCTION GLOBAL TEAM

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ABSTRACT

Psychological safety is a construct that has garnered attention in academia and industries over the last two decades. Research has shown the connection between psychological safety and several team behaviors, from learning to active caring. Most research however has focused on exploring psychological safety within traditional teams. This paper extends the research on psychological safety by capturing the psychological safety and behavioral dynamics of a global virtual corporate team in the construction industry. We found that psychological safety positively relates to some behaviors such as making reliable promises and active listening, and these in turn positively relate to better team performance. This paper also describes actions the team in the study committed to follow to improve, based on the assessment conducted in this study. Future research should concentrate on using longitudinal assessments to explore variations within the team over time and understand what interventions can improve team dynamics.

KEYWORDS

Psychological safety, behaviors, team dynamics, global teams, learning, reliable promising.

INTRODUCTION

Edmondson and Bransby (2023) highlighted the boom of research focused on psychological safety due to the recognition of the “challenge of navigating uncertainty and change.” Psychological safety has been studied in-depth in many industries such as healthcare, manufacturing, and technology. However, its exploration in the construction industry is still nascent (Shen et al. 2015; Gomez et al., 2019; Gomez et al., 2020; Gomez, 2023). Moreover, the literature exploring psychological safety in construction is limited to studying project teams working geographically together to deliver a construction project.

A team is a “collection of individuals who are interdependent in their tasks, who share responsibilities for outcomes, who see themselves and who are seen by others as an intact social entity embedded in one or more larger social systems (for example, business unit or the corporation), and who manage their relationship across organizational boundaries.” (Cohen & Bailey, 1997). Psychological safety within a team depends on a number of variables such as

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interpersonal relationships, organizational norms (Kahn, 1990), leader behavior, group dynamics, trust and respect, organizational context (Edmondson, 1999; Zhang et al., 2010). Psychological safety is established through interactions in which team members make assessments of how they treat one another (Duhigg, 2016; Gomez et al., 2019). For instance, leaders using hostile verbal and non-verbal behaviors can negatively affect their team psychological safety (Tepper, 2000; Burris et al., 2008; Agarwal & Anantatmula, 2021). However, leaders using inclusive behaviors can positively affect psychological safety (Feitosa & Salas, 2021). Psychological safety is a key differentiating factor in understanding teams that thrive and learn together versus those who build defensiveness routines (Argyris, 1985; Schein, 1985; Schein, 1992; Edmondson, 1999). Such routines, typically triggered for personal protection, can hinder the team learning process (Sterman, 1994). Many studies explored the role of psychological safety on team behaviors (what we refer to as team dynamics), from learning with the seminal work of Edmondson (1999) to speaking up, (Detert & Burris, 2007) to being respectful and actively caring for others (Gomez et al., 2019; Gomez et al., 2023), etc.

The purpose of this study is threefold. First, we review the literature on psychological safety, team dynamics, and global teams. Second, we explore these within a specific team: a corporate services global team that oversees the quality department for general contractor company with presence in America, Europe, and Asia. To the authors knowledge, this is the first study focused on understanding psychological safety in a global team in the construction industry. Third, we describe some actions the team decided on taking that can lead to further improvements. The following questions were explored in this study:

- *RQ1: what is the relationship between psychological safety and team behaviors in a global team?*
- *RQ2: what actions can global teams take to foster psychological safety?*

LITERATURE REVIEW

TEAMS IN THE CONSTRUCTION INDUSTRY

Most teams in the construction industry are assembled at the project level with people from diverse backgrounds (e.g., builders, architects, electrical engineers) who come together temporarily with one objective, delivering a project within certain constraints (Jefferies et al., 1999). Although team members share this common goal, each might have their own priorities ranging from job stability to optimizing the profitability of their companies. These teams need to learn quickly how to work together as a team and build the project to achieve the expectations safely using the resources they have (Cornick & Mather, 1999). Other teams, typically at the corporate service level, are assembled for longer durations to plan corporate strategies concerned with "operations of the entire organization" (Cheah & Garvin, 2004).

Project and corporate teams' complexity may vary depending on several factors, from team size to geographical distribution (e.g., teams being co-located versus geographically dispersed) to diversity of skills and backgrounds. Corporate teams of large multinational corporations, the core of this research, typically function as global virtual teams. Our understanding of global virtual teams is those who are constituted by "geographically and culturally dispersed individuals assembled through communication technologies" (Massey et al., 2003).

CHALLENGES IN GLOBAL TEAMS

Development Dimensions International (DDI) et al. (2018) analyzed leadership readiness in this digital era and reported that *leading virtual and remote teams* is still a weakness in leaders' readiness and suggested paying attention to developing this competency. Some of the challenges when working in these teams include:

- Communication problems and misunderstandings due to different languages (Chen at al., 2006). Positives of global teams (e.g., diversity of perspectives) can be hindered if members are not able to communicate effectively (Berg & Holtbrügge, 2010).
- The lack of social cues in virtual meetings, such as eye contact or voice inflections (Straus & McGrath, 1994), make it difficult to assess participants' reactions or engagement.
- Higher instances of members feeling isolated or getting distracted (Edmondson & Daley, 2020).
- Cultural differences and its impact on how people interact with each other, including individualism-collectivism, power distance, masculinity-femininity, uncertainty avoidance (Hofstede, 2001; Hofstede et al., 2010).

Dusenberry and Robinson (2020) highlighted a common but probably wrong assumption. They said, "we (when working in teams) assume that how to collaborate is already known or emerges from practice." However, global virtual teams may struggle with less cohesion, engagement, and satisfaction (de Pillis & Furumo, 2006), resulting in lower productivity than face-to-face teams (Straus & McGrath, 1994). One mitigating strategy to the challenges faced in these teams is fostering psychological safety (Gibson & Gibbs, 2006; Feitosa & Salas, 2021).

TEAM DYNAMICS: PSYCHOLOGICAL SAFETY AND TEAM BEHAVIORS

Literature that explores speaking up and the organizational conditions that favor voice or silence behavior have looked at several things, from the individual's personality and characteristics (e.g., LePine & Van Dyne, 1998) to their attitudes (e.g., Rusbult et al., 1988) to their assessment of whether it is safe for them to speak up (e.g., Edmondson, 1999, Milliken et al., 2003). For the latter, people assess the perceived costs of speaking up to themselves (e.g., humiliation, termination) in order to decide whether to do so (Edmondson, 1999; Gomez et al., 2019).

Cheah and Garvin (2004) suggested that organizations should treat human resources (the people in a team) as one of the building blocks of corporate strategy. They pointed out that a "new technological process in construction by itself may not create a sustainable advantage unless the process also draws support from proper human resource strategy (e.g., a proper training program in place)." Given that the attention to the construct of psychological safety in construction is growing, understanding how it applies to global teams in this context is critical for the development of corporate strategies. To illustrate, psychological safety can help corporate teams deciding what efforts to pursue by improving the concept screening process used to assess go/no-go decisions for moving forward with an idea (Cole et al., 2022)

Psychological safety is one of the most important factors distinguishing high-performing teams from average ones (Rozovsky, 2015). Researchers have found positive correlations among psychological safety and learning, performance (Edmondson, 1999), knowledge creation (Cauwelier et al., 2019), knowledge sharing (Mura et al., 2016), creativity (Agarwal & Farndale, 2017; Liu et al., 2021), innovation (Gu et al., 2013). Gomez (2023) conducted a number of case studies and analyzed how psychological safety impacted team members' behaviors such as active caring, active listening, and making reliable promises. A team's psychological safety and the behaviors displayed in this context represent what we understand as the team dynamics (i.e., how a team functions together). Gomez' work was focused on teams managing quality, therefore we used her framework to explore the team dynamics for this research.

LEADING GLOBAL TEAMS

Knowing that psychological safety creates favorable conditions for speaking up (Edmondson, 1999, Edmondson & Bransby, 2023), a number of leadership constructs have been studied as precursors to psychological safety, e.g., leader-member exchange (Cong et al., 2023), inclusive leadership (Carmeli et al., 2009), shared leadership (Gu et al., 2016). Detert and Burris (2007) highlighted the importance of leaders in fostering psychological safety to promote voice behavior. He said, “a subordinate’s current overall performance likely includes his/her manager’s reaction to prior speaking up.” Due to the key role of leaders in driving or not a psychologically safe work environment, we highlight some of the strategies to lead these teams:

- Take advantage of virtual platforms to get to know each member at a deeper level (Feitosa & Salas, 2021). For instance, recording sessions when deemed necessary to allow access to those who cannot join the meeting live, facilitating connections through virtual happy hours, encouraging e-introductions when new members join, setting time aside in team meetings to allow and promote members participation in the conversation.
- Design strategies to allow team members socialize and get to know each other in a personal way (Lagerström & Andersson, 2003; Ford et al. 2017).
- Model behaviors that enhance psychological safety such as listening, competence, and transparency (Edmondson & Bransby, 2023).

Edmondson and Daley (2020) said that “(virtual) teams can be lonely places… building psychological safety in virtual teams takes effort and strategy that pays off in engagement, collegiality, productive dissent, and idea generation.” Team dynamics may improve when people are well acquainted as members feel more psychologically safe, improving therefore the team’s effectiveness and efficiency (Chevrier, 2003)

METHODOLOGY

We used an exploratory case study (Yin, 2013) to conduct a detailed analysis of a particular team, explore its dynamics, and describe the opportunities for improvement proposed. Our case is a team within a company that placed among the top 10 of the Engineering News Record’s 2023 Top 400 Contractors ranking. This team, known internally as the “Quality Leadership Network (QLN)”, had 16 active members at the time the study took place.

We used a questionnaire to assess the constructs of our study (i.e., psychological safety and team behaviors) from a single global team. The questionnaire included some questions measured on a 7-point Likert scale that were adapted from prior research, and some open-ended questions (see full list of questions used in Gomez (2023)). Participation was voluntary and individual responses were kept confidential and reported at a team level for research purposes.

The numbered questions were used to measure the team dynamics on a scale. The open-ended questions were used to gather participants input on what actions their team could take to help them feel safer. This input served the team to discuss how to nurture the desired behaviors to continuously grow and commit to specific actions for improvement.

RESULTS AND DISCUSSION

A total of 12 team members answered the questionnaire, representing a 75% participation rate. We included the following control variables: (1) team tenure (time spent working with this team), (2) company tenure, and (3) role. Members of this team played one of the following roles: quality engineer, quality manager, project manager, or superintendent. Other control variables (e.g., ethnicity, race, age, gender) were not included due to the team size limitation.

PSYCHOLOGICAL SAFETY, TEAM BEHAVIORS, AND PERFORMANCE

Although some authors measure psychological safety at the team level using one score only, combining team members’ perspective regarding their coworkers and supervisors, we used Gomez’ (2023) scale that assesses psychological safety, both in relation to coworkers and to supervisors separately. Past research shows that supervisor behavior is “one of the most important sources of cues about whether it is worthwhile and safe to voice” because they are typically the target of voice and because of the power they hold over employees’ outcomes such as promotions and pay (Morrison 2011). However, the influence of coworkers on employee behaviors has also a role to play on whether they are more willing to speak up, e.g., by modeling speaking up (Subhakaran & Dyaram, 2018; Ng et al., 2021). Construction, particularly, can be a very hierarchical industry so we treat psychological safety with respect to both targets as separate but related facets. A high score indicated high levels of psychological safety. Sample items include, “I am able to bring up problems and tough issues to my team leader”, and “If I make a mistake while doing my work on this team, I feel safe speaking up to my team leader.”

Table 1 shows the results for the team members’ perception of psychological safety broken down with respect to the team leader and their coworkers. Table 2 breaks down the results by tenure. Previous studies measuring psychological safety by tenure identified some curvilinear relationship between psychological safety and team tenure (Koopmann et al., 2016) while others suggest a positive relationship between tenure and voice behavior (Detert & Burris, 2007; Burris et al., 2008), which can be partially attributable to psychological safety. Due to the team’ sample size, we cannot make an assessment with statistical validity, but results show more variation when comparing tenure in team versus tenure in company, which is consistent with the construct of psychological safety measured at the team level.

Table 1: Team Psychological Safety Results (1=low, 7=high psychological safety)

Psychological Safety in Relation to	Team Perception
Team leader	5.604 (sd=0.98)
Coworkers/other members of your team	5.833 (sd=1.18)

Table 2: Team Psychological Safety Results by Tenure (1=low, 7=high psychological safety)

By Team Tenure	By Company Tenure	Team Psychological Safety
< 1 month		4.188
1 – 6 months		5.938
6 – 12 months		6.281
> 1 year		5.742
	1 – 5 years	5.800
	5 – 10 years	5.828
	> 10 years	5.438

The open-ended responses provided more insight into what the team was doing well to foster psychological safety. These responses can be used to foster awareness and reinforce the actions that were helping the team move toward a more psychologically safe environment. Examples below illustrate the team’s input:

“I feel my team provides a lot of comfort when it comes to discussing day-to-day issues or upcoming deadlines. I don’t feel like I have a fear of speaking up or mentioning something that I feel would improve our processes.”

"I feel extremely blessed to be a part of [this team]. I hope that we can be the leading example for other work groups within [our company]."

Some opportunities for improvement were also raised, which were used along with the team dynamics assessment in the team's brainstorming session to determine actions moving forward:

"I would say an opportunity for improvement could be to assure that the team is doing well outside of work as well… Opening the floor to the team to talk about external problems that may be affecting their work could be a way the team feels more supported."

"I'll avoid bringing up simple issues, as I do not match the academic or professional status as others have."

"Create more vulnerable moments within the team. Give the team members more opportunities to participate."

Our study of team dynamics included measuring the behaviors described in Gomez (2023) due to its relevance for a corporate team managing quality. We used the questions developed in that study to assess each of the behaviors shown in Figure 1. To illustrate, a sample item to assess the behavior of *being respectful* was, "Members of my team are valued and their contribution to the team matters." Similarly, an item to assess the behavior of *making reliable promises* was, "Members of my team make sure there is clarity around acceptance criteria before proceeding."

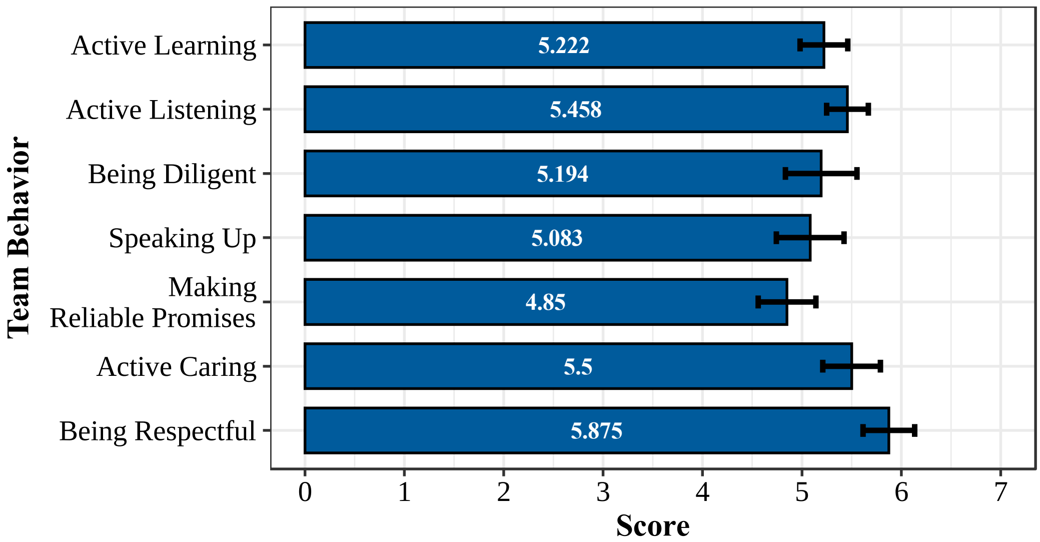

Figure 1: Team Behaviors Assessed

Measuring the team dynamics by breaking the analysis down to specific behaviors helped the team to analyze their strengths and opportunities for improvement on specific areas. These behaviors, connected through social interactions, are intertwined. In some ways, psychological safety promotes respect and respect promotes psychological safety. For instance, when individuals feel psychologically safe and express their ideas, others will react in ways that show respect and appreciation. Similarly, when team members are trusted to act independently, they perceive a sense of well-being and respect that in turn fosters psychological safety (Fenner et al., 2023). Actions the team decided to implement based on analyzing these results are described in the next section.

We also measured performance using the questions developed in Gomez (2023). Table 3 shows the correlations we found between our study variables, grouping the behaviors we deemed to study as one variable called "desired team behaviors." As shown, psychological safety is highly correlated to the behaviors we studied (r = 0.729), and this, in turn, is highly correlated to team performance (r = 0.909).

Table 3: Correlations of Study Variables

n = 12	Psychological Safety	Desired Team Behaviors	Team Performance
Psychological Safety	1.000	0.729	0.691
Desired Team Behaviors		1.000	0.909
Team Performance			1.000

All correlations shown in this table are significant at $p < 0.01$

Since the sample size in our study is limited, we cannot properly make statistical conclusions. However, our results are consistent with past studies that identified positive relationships, for example, between psychological safety, team behaviors such as learning, and resulting performance (Edmondson, 1999; Wilhelm et al. 2019; Gomez, 2023), psychological safety, learning, and knowledge creation (Cauwelier et al., 2019), and listening, psychological safety and creativity (Castro et al., 2018).

TEAM'S ACTIONS FOR IMPROVEMENT

Reviewing the team dynamics assessment results allowed the team to start acting on it. The team hosted a start-stop-continue working session to analyze the study results and brainstormed ideas for a path forward. Some of the actions the team decided to take included:

- Launch a book club to dive deep into specific concepts. Salas et al. (2008) found that training may improve a team's outcomes. Dusenberry and Robinson (2020) proposed that psychological safety can be improved through training interventions that can foster personal awareness of how team members depend on each other for their teams to be successful. For instance, the team behavior that needed further improvement per the survey was making reliable promises. The team committed to go over the seminal book Conversations for Actions and Collected Essays from Flores (2012).
- Be intentional in celebrating big and small wins as a team and keep shoutouts as an agenda item consistently in weekly team meetings. Team leaders inviting and showing appreciation for other member's input fosters psychological safety (Nembhard & Edmondson, 2006) and therefore members participation and engagement (Carmeli et al., 2009; Zhang et al., 2010).
- Continue hosting an annual in-person meeting. Dixon (2017) described an in-depth study of a virtual team that used face-to-face interactions as part of their strategy to facilitate learning and foster psychological safety. Some strategies he highlighted for these in-person meetings included, for example, having the team codesigning an agenda, and the use of facilitators and whiteboards to encourage experimentation. This leader in this team stated how he envisioned these meetings to help the team, "In order to advance our team, it was critical that we met face-to-face at least once over the year. The focus of our in-person meeting was largely on fostering trust, openness, and to create alignment around our goals and priorities. All too often remote teams use the face-to-face meeting formats to get as much done as possible and miss the critical (and often only) time to truly align the team culturally."

- Use video in virtual meetings, to the extent possible. Ford et al., (2017) suggested that leaders in virtual environments should use gestures (e.g., facial expressions to convey emotions and show attentiveness, smiling to create a welcoming atmosphere, nodding to indicate agreement or understanding) and be trained on virtual skills such as detecting early signs of conflict or withdrawal (e.g., lack of eye contact, participants joining late or leaving early consistently, frowning eyebrows but not voicing their thoughts).
- Align on weekly meeting rules regarding content and format (e.g., making sure an agenda is sent out before meeting, so members know what the meeting purpose and topics are ahead of time, avoiding running over time as participants may have other commitments to attend, rotating meeting facilitators).
- Spend time on project sites to oversee the implementation of corporate strategies and provide feedback to the team (e.g., what processes project teams are struggling with, what resources they need).
- Assess team dynamics once a year, review commitments from prior year , and rethink actions for improvement (interventions) for the upcoming year. The team leader pointed out that this assessment was a critical step in the endeavor of creating an environment where deeper conversations can occur, one of psychological safety.

Additional opportunities to explore from the literature include:

- Considering the challenges of global teams due to a number of cultures coming together, conduct interventions that focus on cultural intelligence, which is a "person's capability to adapt effectively to new cultural context" (Earley & Ang 2003, p. 59).
- Deliberately plan interventions to foster open communication and make interventions team-specific. Cong et al. (2023) suggested that "high-quality exchanges with leaders help improve the psychological safety of construction workers." Also, Dusenberry and Robinson (2020) described that when training is specifically designed for a target, it increases "personal awareness of interdependence among team members."
- Modeling the behaviors expected from the team so others can imitate them. The social learning theory suggests that behaviors can be acquired through role modeling, involving the observation of others' behaviors and their associated consequences (Bandura, 1977).Other team members' behavior plays a key role in creating psychologically safe spaces (Subhakaran & Dyaram, 2018; Gomez et al., 2019; Ng et al., 2021). For instance, if team members observe that speaking up to share mistakes is not only encouraged but welcomed and rewarded in the team, resulting in the person getting help to solve the mistake rather than punishment, then they would be more willing and open to sharing when they make a mistake rather than trying to hide it.
- Design actions to strengthen coworker-to-coworker and supervisor-worker communication. Both coworkers and supervisors have great influence on shaping employees' beliefs about what behaviors are acceptable and valued in the team (Zohar & Polachek, 2014; Gao et al., 2016).

CONCLUSIONS

Research on psychological safety, although prominent in many industries, has "largely studied old-fashioned intact teams" (Edmondson & Bransby, 2023). Our study represents the first attempt to document psychological safety and the behavioral dynamics of a global virtual team in the construction industry. Our findings have important implications in practice. We confirmed a relationship identified in past studies between psychological safety, learning, and team performance for a "non-traditional" team. In addition, we extended this analysis to explore whether this relationship remains for other behaviors such as making reliable promises. Teams looking to nurture the behaviors assessed here can start paying attention to also fostering psychological safety, so these behaviors occur more naturally. Further, we described actions that this team committed to do for improvement based on the team dynamics assessment used. While the impacts of these actions had not been analyzed yet, they serve as inspiration for other teams trying to foster similar team dynamics or struggling with the challenges of global work.

This research explored psychological safety and its implications in one global team, which poses some limitations. First, generalizability of our findings is limited. Our sample, even though representative for the team considering its participation rate, is small and only represents the results of a single team. Although not a large enough sample to undertake reliability analysis of the constructs used in this study, we used previously designed instruments that showed reliability in Gomez (2023). Second, because our study describes the team dynamics at a single point in time, we cannot predict the impact of the actions for improvement the team designed as a result of the initial diagnosis. Little research exists about what creates psychological safety and the longitudinal nature of team dynamics (Dusenberry & Robinson, 2020; Edmondson & Bransby, 2023), highlighting the need to first understand how these dynamics shift over time and second to identify specific interventions that can facilitate building psychologically safe environments. A longitudinal study with this team over several time periods, currently planned, could provide a better understanding of the results of implementing the efforts for improvement proposed. Third, this case study is limited to one global team in the construction industry. Future research could include cross-team and company comparisons, within construction and other industries, using longitudinal data to assess whether the relationships found in this study represent other contexts and are maintained over periods of time, or the nuances that can be observed.

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AN INVESTIGATION OF PSYCHOLOGICAL SAFETY IN CONSTRUCTION PROJECTS AND ITS INFLUENCE ON TEAM LEARNING BEHAVIOUR: A SURVEY-BASED STUDY

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ABSTRACT

Due to a construction project's dynamic, interdependent, and complex environment, it is crucial that team members are able to talk openly about risks, mistakes, ideas and best practices without fearing interpersonal risks such as punishment or dismissal. Sharing knowledge is especially critical as team structures change over a project. Therefore, psychological safety is an essential key enabler in such project environments. This paper is built upon a cross-sectional survey-based study (N=163) used to assess the current level of psychological safety within teams of the Owner, Architect, Engineering, and Construction (OAEC) industry based on the views of individuals in different teams. Furthermore, the study aimed to identify factors that can enhance psychological safety in construction project teams. These include, for example, a good failure culture, communication, and a mindset toward collaboration. The results show a strong positive relationship between psychological safety and team learning behavior, with psychological safety as a predictor explaining 50% of the variance in team learning behavior.

KEYWORDS

Construction project teams, psychological safety, team learning behaviour.

INTRODUCTION

One of the biggest challenges within construction projects is fostering open communication to create synergies, address mistakes, and thus learn together (Baiden et al., 2006). However, based on mainly traditional structures, competitive relationships and a lack of collaboration are particularly prevalent in the industry, highlighting issues such as a low level of trust, inadequate communication, and unfair risk sharing. The resulting time and cost overruns due to disputes, for example, are commonplace within the industry, so poor performance is often attributed to the lack of effective working relationships between project participants (e. g., Faris et al., 2019; Sumner & Slattery, 2010; Schöttle & Gehbauer, 2013; Fulford & Standing, 2014; Rooke, 2014; Rosenfeld, 2014; Schöttle, 2022). This can have a significant impact not only on the success of the project but also on its execution, especially on the physical safety of those involved (Gomez et al., 2020; Faris et al., 2019). By addressing issues and mistakes early on and collaborating to benefit from shared information and experience, risks and mistakes can be reduced or eliminated during the design and construction phases (Howell et al., 2017).

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Due to the dynamic and uncertain nature of a construction project's environment, errors and hazards are frequently unavoidable. Therefore, it is essential that they are addressed openly and that the team is given the opportunity to learn from them so that they do not recur and that long-term solutions can be found through shared learning and innovative approaches (Gomez et al., 2020). However, the fact that those who have pointed out errors or a lack of knowledge have been punished with negative consequences, has led to significant inadequacies (Gomez et al., 2020). In many cases, an environment where employees are ignored, ridiculed, or even disciplined for speaking out can be dangerous, especially when employees feel that their word counts for nothing and conclude that it is not worth speaking out due to self-protection (Edmondson, 2019). This is particularly difficult in a traditional sector such as construction, where the credo "we've always done it this way" often applies (Santorella, 2011).

As conceptualized by Edmondson (1999), psychological safety refers to a person's perception of the team environment as safe for taking interpersonal risks. When team members perceive a high level of psychological safety, they are more willing to engage in open discussions, share knowledge, and experiment with new approaches, leading to improved team learning (Edmondson, 1999; 2002). This includes, among other things, team members feeling encouraged to contribute their expertise, share their ideas, and provide constructive feedback to improve team performance and, thus, project performance. The interpersonal risk of raising a concern or question with a more senior person is also described by Santorella (2011) as “showing vulnerability,” which is distinct from psychological safety as a construct. In general, vulnerability requires courage to be open and authentic and often involves a degree of risk as you cannot be sure how others will react (Brown, 2018). Nonetheless, the two constructs are generally closely related and can have a positive reciprocal effect, as showing vulnerability by individuals can help to build trust and psychological safety within a group or team (Edmondson, 1999). Consequently, the construct of psychological safety within the construction industry is vital in reducing the anxiety of interpersonal risk, thereby creating essential conditions for improving productivity, safety, quality, and innovation (Gomez, 2023).

Zhang and Fai Ng (2012) describe the construction industry as a knowledge-intensive industry in which it is crucial for professionals to share their knowledge, build mutual understanding, and work together to find effective solutions to improve the efficiency of project delivery. According to Howell et al. (2017), learning organizations are essential in construction projects to minimize the difference between as-found and as-planned work. They argue that the need for organizational learning is demonstrated by workers speaking up when there is a potential obstacle to the execution of a job or by the team on a construction project working together to find the safest way to execute a job (Howell et al., 2017). Furthermore, studies have shown that psychological safety is a driver of team learning behaviors (Gomez, 2023; Gomez et al., 2019; Newman et al., 2017; Van den Bossche et al., 2006; Edmondon, 1999).

The main aim of the study is to address a significant research gap by examining the concept of psychological safety within a portion of the OAEC industry and its impact on team learning behavior. Additionally, the study seeks to raise awareness within the construction industry regarding the importance of psychological safety and offer valuable insights and practical recommendations. The research questions were:

- How psychologically safe do people feel in the OAEC industry?
- How can psychological safety be enhanced in construction project teams?
- How does psychological safety affect team learning behavior?

Also, the following research hypothesis was proposed:

H_1 Psychological safety is positively correlated with team learning behavior in construction project teams.

H_0 There is no significant correlation between psychological safety and team learning behavior in construction project teams.

THEORETICAL BACKGORUND

PSYCHOLOGICAL SAFETY AND LEAN

The concept of psychological safety, as defined by Edmondson (1999), has started to gain traction in the construction industry, particularly in terms of its connection to Lean and the impact it's having on project teams (Gomez et al., 2019; Gomez et al., 2020; Howell et al., 2017; Demirkesen et al., 2021; Gomez, 2023). For example, Demirkesen et al. (2021) discovered in a multi-method study conducted in the U.S. that projects using lean construction had more psychological safety. Gomez (2023) also investigated the relationship between psychological safety, Lean, and team behavioral dynamics, highlighting how some Lean principles, such as "respect for people," relate to psychological safety and the interdependent role that one plays in promoting the other.

Psychological safety is achieved when team members trust and respect each other and are able to open up (Edmondson, 2002). Edmondson's (1996, 1999, 2019) definition differs from Kahn's (1990) definition by expanding the construct of psychological safety for the first time as "a team-level climate" rather than an individual's perception of a feeling (Newman et al., 2017, p. 523). It was found that people working closely together tended to have similar perceptions of psychological safety, whereas scores varied between groups within the same organization (Newman et al., 2017). This difference in an employee's feeling of psychological safety within an organization, from department to department and from team to team, can be attributed primarily to differences in the behavior of local managers and supervisors, regardless of how strong the corporate culture is (Edmondson 1999, 2003).

TEAM LEARNING BEHAVIOUR

Team learning is particularly important for working together effectively in a constantly changing environment, which is the case for construction project teams (Decuyper et al., 2010; Zhang & Fai Ng, 2012). There are several definitions of team learning. Each of them describes it as a complex concept that can be viewed from different perspectives, and its meaning can vary depending on the context and discipline (Decuyper et al., 2010; Edmondson et al., 2007). Edmondson et al. (2007) referred to team learning as an umbrella term that encompasses and connects multiple theories and studies. Generally, the well-known definitions can be divided into learning as a process (Edmondson, 1999; 2002), learning as an outcome (Ellis et al., 2003), and learning as a mixture of both (Storm et al., 2010).

Edmondson's (1999) definition of team learning is adopted for this study as it describes several concrete and different learning behaviors and is dominant in research (Savelsbergh et al., 2009; Edmondson, 2002; Storm et al., 2010). Edmondson (1999) defines team learning as "an ongoing process of collective reflection and action characterized by (a) exploration, (b) reflection, (c) discussion of mistakes and unexpected outcomes of action, (d) seeking feedback, and (e) experimentation within and as a team" (Savelsbergh et al., 2009, p. 582). She distinguished the learning process from the learning outcomes using the phrase "team learning behavior," which was also adopted for the present study (Edmondson, 1999).

METHODOLOGY

RESEARCH DESIGN AND SAMPLING APPROACH

The research design of the present study is based on a quantitative cross-sectional survey in which data was collected in the form of an online-based questionnaire for self-completion. In addition, to give participants a chance to contribute their perspectives and possibly uncover novel insights in the field, as in a qualitative research approach, the questionnaire included an open-ended question providing qualitative data about psychological safety and how it can be improved within construction project teams.

The selection of the sample was guided by predetermined criteria to fulfill the research questions and hypotheses precise demands and guarantee the data's comparability. The desired sample consists of people who work within the construction industry (filter question 1) and are members of an interdisciplinary construction project team when answering the questionnaire (filter question 2). In order to keep the complexity of the questionnaire low with regard to the different disciplines of a construction project team, only the superordinate areas of design, execution, project management and control, consultancy, and the owner or owner's representatives are considered (filter question 3). Chan et al. (2004) also identified these as key areas.

INSTRUMENT OF DATA COLLECTION

The questionnaire comprises a total of 36 items and offers the option to be completed in German or English. Furthermore, the questionnaire is structured into five main sections: sample filtering, control variables, psychological safety, team learning behavior, and personal information (such as gender and age). The following control variables were asked to ensure generalizability: project volume, team size, team meetings (regularity, online vs. face-to-face vs. hybrid), existence of informal team events (e.g., joint lunches, after-work events), country of work, and whether the respondent is in a management position. Furthermore, the respondents of the desired sample were asked to answer from the perspective of the project on which they are presently spending the majority of their working hours.

To measure psychological safety, the seven items (questions) developed by Edmondson (1999) were used to maintain high content validity (Newman et al., 2017). She used a 7-point Likert scale to assess participants' responses, ranging from "very inaccurate" to "very accurate," including a neutral middle category. This study employed a 6-point scale without a neutral middle category, ranging from "strongly disagree," coded as 1, to "strongly agree," coded as 6. In the context of interpreting the values, it is considered that values equal to or beyond 4, which align with the category of "slightly agree" or higher, are indicative of psychological safety. By removing the neutral middle category, participants are required to adopt a distinct stance on either low or high psychological safety. This is also important due to a statement by Edmondson and Bransby (2022), in which they say that it does make more sense that psychological safety is reported at the individual level for individuals working with different people at different times rather than aggregated in a group context, as in most studies, due to a lack of stability.

Given that each study participant may be responding from the perspective of a different team, the scores for psychological safety are thus left at the individual level. Therefore, the calculated mean score of individuals can be better interpreted without a neutral middle category. The seven questions used to assess psychological safety, including the response options, can be seen in Figure 1.

Psychological safety

Please select the answer option that applies.
The answer depends on how much you think the statement applies to the team on the project on which you currently spend most of your working time.

If you make a mistake on this team, it is often held against you.	☐ Strongly disagree	☐ Disagree	☐ Slightly disagree	☐ Slightly agree	☐ Agree	☐ Strongly Agree
Members of this team are able to bring up problems and tough issues.	☐ Strongly disagree	☐ Disagree	☐ Slightly disagree	☐ Slightly agree	☐ Agree	☐ Strongly Agree
It is safe to take a risk on this team.	☐ Strongly disagree	☐ Disagree	☐ Slightly disagree	☐ Slightly agree	☐ Agree	☐ Strongly Agree
It is difficult to ask other members of this team for help.	☐ Strongly disagree	☐ Disagree	☐ Slightly disagree	☐ Slightly agree	☐ Agree	☐ Strongly Agree
No one on this team would deliberately act in a way that undermines my efforts.	☐ Strongly disagree	☐ Disagree	☐ Slightly disagree	☐ Slightly agree	☐ Agree	☐ Strongly Agree
Working with members of this team, my unique skills and talents are valued and utilized.	☐ Strongly disagree	☐ Disagree	☐ Slightly disagree	☐ Slightly agree	☐ Agree	☐ Strongly Agree
People on this team sometimes reject others for being different.	☐ Strongly disagree	☐ Disagree	☐ Slightly disagree	☐ Slightly agree	☐ Agree	☐ Strongly Agree

Figure 1: 7-item scale to measure psychological safety and answer options.

Similarly, as for psychological safety, for the measurement of team learning behavior, the 7-item scale by Edmondson (1999) was used due to its strong content validity. The items for team learning behavior are also assessed using a 6-point scale without a neutral middle category. This was modified due to the measurement of psychological safety to facilitate a more accurate comparison of the mean scores of the two variables in subsequent analyses. Consequently, in the context of interpreting the values, it is considered that values equal to or beyond 4, which align with the category of "slightly agree" or higher, indicate team learning behavior. The seven questions used to assess team learning behavior, including the response options (see Figure 2).

Team learning behavior

Please select the answer option that applies. The answer depends on how much you think the statement applies to the team on the project on which you currently spend most of your working time.						
We regularly take time to figure out ways to improve our team's work processes.	☐ Strongly disagree	☐ Disagree	☐ Slightly disagree	☐ Slightly agree	☐ Agree	☐ Strongly Agree
This team tends to handle differences of opinion privately or off-line, rather than addressing them directly as a group.	☐ Strongly disagree	☐ Disagree	☐ Slightly disagree	☐ Slightly agree	☐ Agree	☐ Strongly Agree
Team members go out and get all the information they possibly can from others, such as specialists or other companies.	☐ Strongly disagree	☐ Disagree	☐ Slightly disagree	☐ Slightly agree	☐ Agree	☐ Strongly Agree
This team frequently seeks new information that leads us to make important changes.	☐ Strongly disagree	☐ Disagree	☐ Slightly disagree	☐ Slightly agree	☐ Agree	☐ Strongly Agree
In this team, someone always makes sure that we stop to reflect on the team's work process.	☐ Strongly disagree	☐ Disagree	☐ Slightly disagree	☐ Slightly agree	☐ Agree	☐ Strongly Agree
People in this team often speak up to test assumptions about issues under discussion.	☐ Strongly disagree	☐ Disagree	☐ Slightly disagree	☐ Slightly agree	☐ Agree	☐ Strongly Agree
We invite people from outside the team to present information or have discussions with us.	☐ Strongly disagree	☐ Disagree	☐ Slightly disagree	☐ Slightly agree	☐ Agree	☐ Strongly Agree

Figure 2: 7-item scale to measure team learning behavior and answer options.

DATA COLLECTION AND SAMPLE

To ensure the questionnaire's validity and reliability and minimize any misconceptions in the wording of the questions and instructions, a pilot test (N = 10) was undertaken prior to the distribution of the survey. The data collection itself took place between June 23 and August 12, 2023, using Unipark's EFS 22.2 Survey software. The survey was distributed via hyperlink and QR code through online social media platforms, as well as directly via email to the researcher's network of construction industry professionals.

As shown in Table 1 on the next page, the participants in the sample are distributed across various sectors within the construction industry, with the majority originating from Germany. Additionally, the gender distribution is nearly equal, with a slight female predominance. Furthermore, a significant proportion of participants aged between 20 and 40, with 1 to 10 years of professional experience, contributed to the study. This demographic profile should be taken into account when interpreting the findings.

RESEARCH FINDINGS

Considering the population of individuals working in the construction industry in the surveyed countries, the sample size of N = 163 is sufficient to provide general conclusions, with the research findings demonstrating a 90% confidence interval with a margin of error of 10%.

MEASURING PSYCHOLOGICAL SAFETY

First of all, a reliability analysis was conducted to assess the internal consistency of the construct of psychological safety prior to the final calculation. Cronbach's alpha is (α) =.78, which is, according to Field (2018), "acceptable." Therefore, the seven items could be summarized as psychological safety. Utilizing a descriptive frequency analysis afterwards, it was possible to determine the current state of psychological safety within construction project.

Table 1: The sample's sociodemographic characteristics

Attributes		Frequency	%	Min.	Max.	Mean	SD
Gender	Female	88	54%				
	Male	75	46%				
Work country	Germany	140	85,90%				
	Austria	16	9,80%				
	Switzerland	7	4,30%				
Working area	Design	30	18,40%				
	Construction	59	36,20%				
	Project Management/Control	34	20,90%				
	Owner	20	12,30%				
	Consultancy	20	12,30%				
Age in years	20-30	67	41,10%	20	62	35	8,72
	31-40	65	39,88%				
	41-50	19	11,66%				
	51-60	9	5,53%				
	61-70	3	1,83%				
Work experience in years	1-5	53	32,52%	1	40	11	8,86
	6-10	48	29,45%				
	11-15	25	15,34%				
	16-20	14	8,59%				
	21-25	9	5,52%				
	26-30	5	3,07%				
	31-35	6	3,68%				
	36-40	3	1,84%				
	41-45	1	0,06%				

The results indicate that the participants in the study (N = 163) perceive a high level of psychological safety within their interdisciplinary project teams, where they currently spend the most working time. The mean score for psychological safety was calculated to be 4.5, with a standard deviation (SD) of 0.76. The result corresponds to a high value for psychological safety, as the value of 4.5 is to be classified within the higher end of the scale, ranging from 1 (indicating little to no psychological safety) to 6 (indicating a high degree of psychological safety). In addition, the participant who reported the lowest level of psychological safety has an individual mean score of 2.29, while the participant who reported the highest level of psychological safety has an individual mean score of 6.00. The graph in Figure 3 illustrates the distribution of the mean values within the sample.

Using an independent-sample t-test, a one-sided statistically significant difference was found between individuals who reported having *regular team meetings* to exchange information and their psychological safety score and those who did not, $t(161) = 1.7$, $p<.044$. The mean score of psychological safety for those with regular meetings was around 0.45 points higher on average (90%-CI [0.016, 0.87]) (see Table 2). Another statistically significant difference in psychological safety was found between individuals who have *informal team events* in their team, such as joint lunches and after-work gatherings (53.4%), and those who do not (42.9%), using a t-test for independent samples, t (120.53) = 3.26, p<.001. The mean score of psychological safety was around 0.40 points higher on average for those who reported informal team meetings (90%-CI [0. 20, 0.60]).

Figure 3: The level of psychological safety

Table 2: Group statistics for the independent-samples t-tests

Team meetings	**N**	**Psychological safety Mean**	**SD**	**Std. Error Mean**
Yes	154	4,53	0,75	0,06
No	9	4,08	0,83	0,28
Team events	**N**	**Psychological safety Mean**	**SD**	**Std. Error Mean**
Yes	87	4,69	0,61	0,07
No	70	4,29	0,86	0,10

However, *no significant mean differences or correlations* could be found between the psychological safety scores and variables such as gender, age, work experience, managerial position, country of work (Germany, Austria, Switzerland), area of work (design, execution, project management/control, consulting, owner), team size, or project volume.

WHAT WOULD HELP TO INCREASE PSYCHOLOGICAL SAFETY?

The open-ended question in the questionnaire was: "What would help you to feel safe in this team to raise concerns, make suggestions, ask questions, and talk about risks and mistakes?" In total, 64 of the 163 participants responded to this question. A content analysis was conducted to identify ways to improve psychological safety on a construction project team. The content analysis resulted in nine themes, along with their respective subcategories. The nine categories are: Feeling safe (12,5% (8 mentions) of the participants mentioned that they already feel very secure in their team and have no suggestions for improvement); failure culture (39,1% (25 mentions)); communication (34,4% (22 mentions)); relationship with other team members (20,3% (13 mentions)); mindset (12,5% (8 mentions)); support (7,8% (5 mentions)); environment (6,3% (4 mentions)); clarity/Structure: (3,1% (2 mentions)); extra time slots for psychological safety (3,1% (2 mentions)).

THE INFLUENCE OF PSYCHOLOGICAL SAFETY ON TEAM LEARNING BEHAVIOR

Before running the analysis, the internal consistency of team learning behavior was checked using a reliability analysis. Cronbach's alpha is (α) =.79, which is "good" according to Field (2018). Consequently, the construct of team learning behavior could be formed as a dependent variable via the mean of the seven items. Subsequently, a correlation analysis and a simple regression analysis were conducted between the two variables to examine the presence of a positive correlation and gain a deeper understanding of the extent to which the variance can be accounted for in the model team learning behavior.

Using Pearson's correlation, a strong positive correlation between psychological safety and team learning behavior could be demonstrated according to Cohen (1988), $r = .709$, $p<.001$. This means that the more psychologically safe team members in construction project teams felt within this study, the more likely team learning behavior could be perceived within the team. Due to the significance level of $p<.001$, the H0 can be rejected, and the H1 can be accepted. This means that psychological safety positively correlates with team learning behavior in construction project teams.

The result of the simple regression analysis with team learning behavior as the dependent variable and psychological safety as the explanatory variable is significant, $F(1,161) = 162.47$, $p < .001$. In addition, the regression analysis yielded an R-squared of .50, which means that psychological safety can explain 50% of the model team learning behavior. Since there are no similar studies within the industry yet and the pilot study data is no longer accessible, according to Cohen (1988), the smallest effect size can be used that is still perceived as practically relevant. For the present study, R-Square= .50, according to Cohen (1988), is considered a very large effect. Due to the significance level of $p<.001$, the H0 can be rejected, and the H1 can be accepted, which means that psychological safety has a statistically significant influence on team learning behavior.

DISCUSSION OF THE RESEARCH FINDINGS

HOW PSYCHOLOGICALLY SAFE DO PEOPLE FEEL IN THEIR CONSTRUCTION PROJECT TEAMS?

Although a first impression guided by the mean score of 4.5 on a scale from 1 (low) to 6 (high) regarding psychological safety can be that the level of psychological safety in the population studied is quite high, Figure 1 shows a good number of respondents' scores being closer to a value of 1-3. This high deviation in the results shows that while some people in this industry feel safe, we still have plenty of work to do to improve the work environment. Other studies in construction industry teams reported means of 5.68 and 6.66 (on a 7-point scale), differentiating the perception of psychological safety from the perspective of craftworkers and staff members, respectively (Gomez et al., 2023). While we cannot directly compare these results because this study collected responses from the view of individuals in different teams, other studies in construction have focused on analyzing psychological safety within one team (Gomez et al., 2019; Gomez, 2023), the results of this study expand upon prior work that focused on ways to enhance psychological safety within this population done by Gomez et al. (2020).

HOW CAN PSYCHOLOGICAL SAFETY BE ENHANCED IN CONSTRUCTION PROJECT TEAMS?

According to Demirkesen et al. (2021), lean construction projects typically have a greater level of psychological safety because meetings are more collaborative and transparent, resulting in improved communication. The study's findings suggest that regular team meetings and informal gatherings can improve psychological safety. This phenomenon can be attributed to two key factors that improve psychological safety: familiarity and the level of prior interaction among team members (Roberto, 2002; Newman et al., 2017). Furthermore, promoting equal interactions between leaders and team members through informal events fosters an environment that encourages open expression regardless of hierarchical structures, as the supervisory relationship is critical for psychological safety in construction projects (Gomez et al., 2020). This, in turn, can decrease the phenomenon of "status anxiety," as discussed by Santorella (2011).

Furthermore, a good failure culture enhances psychological safety, as previously discussed. The participants in this study interpreted a good failure culture as an inclusive setting where team members feel comfortable discussing and acknowledging mistakes as well as engaging in subsequent reflection (Edmondson, 2019). It is important to note that it is primarily up to the manager to establish such a robust failure culture (Edmondson, 2019). However, other coworkers' behaviors can also influence individuals' perceptions of how safe the work environment is (Subhakaran & Dyaram, 2018; Ng et al., 2021). Based on the participants' responses in this study, mindset is primarily about openness to new ideas and innovations that do not correspond to the traditional way of thinking: "We have always done it this way." Additionally, this also includes a collaborative attitude towards working together and driving continuous improvement. Therefore, it is primarily the manager's responsibility to adopt a curious, productive mindset instead of an avoidant one, as well as to reframe problems and mistakes as opportunities to learn and develop.

HOW DOES PSYCHOLOGICAL SAFETY AFFECT TEAM LEARNING BEHAVIOR?

The present study found a significantly strong positive correlation between psychological safety and team learning behavior. Therefore, evidence suggests that the more psychological safety is present in a construction project team, the more team learning behavior is indicated. Thus, in terms of practical implications, enhancing psychological safety in a construction project team is worthwhile, as it is one of the essential prerequisites for team learning behavior. The study aligns with previous research conducted by Edmondson (1999) in terms of examining the strength of the link. Nevertheless, it is important to be aware that a direct comparison of these values is not feasible due to different response scales. However, as previously emphasized by Edmondson and Lei (2014), psychological safety is not the sole determinant of team learning and performance. Instead, it is dependent on the existence of certain conditions that necessitate learning and communication. This is confirmed by the regression analysis conducted as part of this research, as psychological safety is only able to explain 50% of team learning behavior.

LIMITATIONS OF THE RESEARCH

First of all, it is important to acknowledge that there are certain limitations related to the definitions of the variables. Although scientifically accepted definitions were used, there are many definitions of a construction project team, as well as the concepts of psychological safety and team learning behavior, which can make comparisons with studies difficult. Furthermore, by choosing a quantitative research design, the study is limited in terms of the depth and complexity of the examined constructs, as psychological safety and team learning behaviors are multi-layered constructs that are difficult to represent in one single study. Therefore, it is important to note that the study's cross-sectional methodology limits the ability to demonstrate causal links as the data were obtained at a singular time. In addition, self-completion questionnaires are vulnerable to the influence of social desirability and response bias. Also, removing the neutral middle category in the response scales of the constructs of psychological safety and team learning behavior may introduce certain constraints in the results because participants who lack a neutral option may feel obligated to select an opinion that does not accurately reflect their true sentiments just to provide a response. Moreover, the survey participants came from different organizations and teams, which has the disadvantage that other unknown variables may have had an impact on the constructs that were not captured. Finally, it is important to note that the findings of this study have limited generalizability because the sample comprises solely of construction project teams, and the number of participants is limited and biased according to their sociodemographic. As a result, the findings are only applicable to the construction industry and cannot be easily adapted to other industries or contexts.

CONCLUSION

In conclusion, the study was able to enhance the recognition and importance of psychological safety within construction project teams. The study revealed that the sample's current level of psychological safety was high. However, there was also a considerable percentage of participants with low levels of psychological safety. Consequently, it is important to enhance the industry's comprehension and awareness of psychological safety. In particular, fostering regular team interaction through collective meetings or informal team events improves psychological safety. Additionally, cultivating a good failure culture and an open mindset towards collaboration can also contribute to establishing a psychologically safe environment. However, it is important to acknowledge that psychological safety should not be regarded as a cure-all for addressing every challenge related to organizational collaboration and learning (Edmondson & Lei, 2014). It is more about psychological safety being seen as an 'engine' — an interpersonal climate of safety— which, combined with other essential components (e.g., strategy, goals, supportive leadership, etc.), can facilitate better learning and performance (Edmondson, 2019). To conclude, any unacknowledged voice or unspoken mistake, risk, or idea from a team member can contribute to a culture of silence, thereby decreasing psychological safety. Not only can this affect the project's success, but in a dangerous industry like construction, it could even be a matter of life and death (Sumner & Slattery, 2010) and inhibit improvement and change within the industry.

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THE RIGHT KIND OF WRONG IN CONSTRUCTION: ANALYSIS FROM A GENERAL CONTRACTOR PERSPECTIVE

Paz Arroyo[1] and Sulyn Gomez Villanueva[2]

ABSTRACT

The idea that not every mistake is preventable and that we can make mistakes and not be ashamed of them if we learn from them is not new in Lean Construction; however, new research from the field of psychology sheds light on human behavior and our willingness to explore and learn from failure. This paper explores how these new findings apply to construction. In this paper, we study different types of failure using Edmonson's classifications of basic, complex, and intelligent failure. We illustrate with cases of failure collected in the Building Quality Builders Class, which is an internal training provided by a general contractor in the USA. Finally, we present strategies for preventing basic and complex failures and encouraging intelligent failures in the context of construction projects. More research is needed to develop a culture to foster learning from all types of failure.

KEYWORDS

Failures, psychological safety, continuous improvement, quality, and learning.

INTRODUCTION

Understanding how mistakes happen, what the consequences are, and how to learn from them and prevent them has been at the center of lean and quality research for a long time. However, there is a lack of a comprehensive framework to make sense of how to deal with different types of mistakes or failures and how to understand human behavior in relationship with failure. Are all mistakes preventable? What messages are we sending to construction workers when we believe that?

Many construction companies use slogans such as "Do things right the first time," "zero defect zone," etc. According to Latzko & Saunders (1996), Dr. Edwards Deming was very clear that these slogans, even though well-intentioned, alone do not create change and can also work against a culture of reporting mistakes.

What type of culture allows the creation of high-performance teams? Amy Edmonson's research points out that teams that have a better reporting culture perform better; they are not afraid of sharing their mistakes and create an environment of psychological safety (Edmonson, 2023; Edmonson, 1999; Edmondson & Bransby, 2023). The concept of psychological safety has been studied in construction, as well as its relationship with lean construction and positive impacts on quality performance (Gomez et al., 2019, 2020, and 2023; Gomez, 2023).

Creating a culture where people feel safe and empowered to share and learn from each other's mistakes is not an easy task. This paper explores the different types of mistakes that

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happen in construction using Edmondson's (2023) classification of mistakes, tries to make sense of these problems, and discusses strategies to encourage learning in a General Contractor context.

LITERATURE REVIEW

This section presents a literature review of both the ideas presented in Edmonson's (2023) book and lean management practices.

RIGHT KIND OF WRONG

Edmonson (2023) published a book called *Right Kind of Wrong*; in this book, the Harvard professor summarizes years of research on the topic of understanding failure and our emotional and social response to it. Edmondson has studied the human capacity to learn from mistakes for a long time; she has stated that this is easier said than done (Edmonson, 1996). She is well known for leading the research on Psychological Safety (Edmonson, 1999), which she defines as feeling safe to take interpersonal risks, speak up, disagree openly, and surface concerns without fear of negative repercussions or pressure to sugarcoat bad news. This concept is key to avoiding the fear of learning from mistakes.

In addition, and what is more relevant to this paper, is her recent differentiation in the different types of failures and the strategies that can be applied in organizations to deal with them. Table 1 describes the classification she proposed according to the context in which they occur.

Table 1: Types of failure (Modified from Table 1.1 in Edmonson, 2023)

Context	Uncertainty	Stage of Knowledge
Basic Failure	Low	Well- developed
Complex Failure	Medium	Well-developed knowledge, vulnerable to unexpected events
Intelligent Failure	High	Limited

Cannon & Edmondson (2005) defined strategies to fail intelligently. Different types of failure will require different strategies, given that the context and the reasons they might happen are different.

LEAN AND MISTAKES

In Lean philosophy, mistakes are not viewed as failures but rather as opportunities for learning and improvement. The Lean approach encourages a culture of continuous improvement, where identifying and addressing mistakes is an integral part of the process. This perspective aligns with the broader Lean principles of minimizing waste, optimizing processes, and creating value for the customer. The Lean literature is wide in its approach to dealing with mistakes; we highlight some of the core concepts from our review:

Mistake proofing

Nakajo and Kume (1985) observed that humans are prone to making mistakes in the face of complex information or when subject to various interpretations. Mistakeproofing "makes it impossible for an error [mistake] to occur or makes the error [mistake] immediately obvious once it has occurred" (ASQ, n.d.). The process of mistake-proofing involves a thorough examination of mistakes, analyzing their consequences, and implementing measures to prevent their recurrence (Nakajo and Kume 1985, Shingo 1986, Godfrey et al. 2005, Tommelein and

Demirkesen 2018). In the event of an error, the aim is to detect the error as close as possible to its occurrence to minimize associated damages.

In construction projects, mistakes can stem from misinterpreting information or individual judgment. Within the framework of Built-in Quality (BiQ), mistakeproofing principles contribute to fostering a culture of prevention and enhancing people's awareness of improvement opportunities (Shingo 1986, Tommelein and Demirkesen 2018).

First Run Studies

FRS involves prototyping production processes to gain insights and identify areas for enhancement. This aids in developing efficient operations that align with established expectations (Ballard and Tommelein, 2016; 2021).

Continuous Improvement and Plan-Do-Check-Act (PDCA) Cycle

Mistakes are seen as valuable learning opportunities. When mistakes occur, they provide insights into what went wrong and why. Understanding the root causes of mistakes allows organizations to implement changes that prevent similar issues in the future.

Lean philosophy emphasizes continuous improvement, also known as Kaizen. Mistakes are considered important feedback for this improvement process. Teams are encouraged to analyse mistakes, make adjustments, and implement changes to enhance processes and outcomes.

PDCA involves a cycle of formulating hypotheses, conducting experiments, testing, and acting based on the outcomes. The emphasis is on learning and perpetual enhancement by implementing corrective measures and averting the recurrence of issues. This iterative process is set in motion either through proactive planning, execution, and the identification of improvement opportunities or as a response to the failure to deliver high-quality products (Shewhart, 1939; Deming, 1986).

The PDCA cycle is a fundamental concept in Lean. When mistakes happen, the PDCA cycle plans improvements, implements changes, checks the results, and acts on the findings. This iterative process ensures that organizations are continually refining their processes.

Root Cause Analysis

When mistakes occur, Lean principles encourage a thorough investigation into the root causes. This involves repeatedly asking " why " to uncover the underlying issues rather than addressing only the surface symptoms. By addressing root causes, organizations can implement more effective and sustainable solutions. It is a methodical approach to learning from breakdowns or failures, promoting continuous learning and improvement (Fischer et al., 2014

Blame-Free Culture:

Lean promotes a blame-free culture where individuals are not punished for making mistakes. Instead, the focus is on identifying systemic issues and finding solutions collaboratively, and allowing for innovations to happen (Angelis and Fernandes, 2012). This approach fosters a positive and open working environment, encouraging employees to share insights without fear of reprisal, which is connected with the concept of Psychological safety (Edmonson 1999).

Respect for People:

Lean philosophy places a strong emphasis on respecting people and their contributions. This includes recognizing that everyone is fallible and can make mistakes. Organizations can create an environment that encourages creativity and problem-solving by acknowledging mistakes without blame.

In summary, the Lean philosophy views mistakes as opportunities for improvement rather than failures. Embracing a mindset that values learning, continuous improvement, and a blame-free culture helps organizations foster innovation and resilience in the face of challenges.

METHODOLOGY

The research questions are:

- *RQ1: what are examples of the three types of failure in construction (basic failure, complex failure, and intelligent failure)?*
- *RQ2: what strategies can we use for each type of failure in a construction company?*

This paper uses exploratory case studies (Yin, 2013) to analyze documented mistakes and lessons learned documented by a General Contractor. The researchers also worked on the construction company at the time of the research and had access to several data points. The following data inputs were used to explore the kind of mistakes or failures reported by employees:

- Cases were documented through Building Quality Builders (BQB) classes (Arroyo and Gomez 2021, Arroyo et al. 2022), where project participants were asked to share a story on the misalignment of expectations resulting in rework. Please note that not all these examples happened at their current employment; some of these stories are from early in the person's career, and many happened in a different company. Both researchers are also facilitators of this class.
- Insurance claims and lessons learned from them. The first author participated in a one-day workshop prepared annually by the insurance team, where several instances of mistakes were studied and analyzed. The results of these findings are not shared publicly. However, it helped guide the selection of cases to understand typical problems or mistakes in the construction industry.

This study does not present a comprehensive study of all mistakes that happen in the company. Rather, we are more interested in understanding the nature of the mistakes and examples to categorize them according to Edmonson's (2023) classification: *basic failures*, which are preventable in nature; *complex failures* that happen when multiple people and factors interact in somewhat unpredictable ways; and *intelligent failures*, which are calculated risks to learn something new. After understanding the nature of each type of example we propose strategies to deal with them based on the literature review and the company best practices.

RESULTS AND DISCUSSION

The following section presents examples of each type of failure documented in the BQB class and discusses strategies to prevent them.

BASIC FAILURES

There is no shortage of basic failure examples in the data set; in every BQB session, people tell their stories of misalignments of expectations and re-work. Here are some that we are qualifying as basic failures because they are preventable and with low uncertainty:

Wrong layout.

"Had a surveyor measuring floor levels for a building tie-in and did not communicate long enough about his exact scope. I took measures, and I assumed he was going to pull measures off a benchmark on the print and correlate back. He never saw the benchmark on the drawing and used a "0" datum. Luckily we caught later that a BM on the drawing for first floor was off that tied into the whole civil package." – Senior Superintendent

This mistake is clearly a human error, easily preventable by setting a clear benchmark for surveying and making sure all surveyors know such a point was defined; the cause of this could have been a lack of communication or knowledge from the surveyor.

Bathroom Pod manufacturing error.

"*At (Bathroom Prefab Facility), consistency is key. We had a lack of communication recently which resulted in not installing a piece of door trim consistent with the customer approved mock-up bathroom pod. This resulted in rework for about 30 pods. This could have been easily avoided with a simple visual board showing expectations, or just a look at the mock-up pod." – Production Control at Prefab*

To prevent the mentioned mistake, ensure consistent communication and adherence to customer-approved requirements; the cause could have been a lack of internal communication in the prefabricated plant or a lack of education of plan workers. Readily available visuals in the field are also a great way of avoiding basic failure.

Ordering the wrong equipment.

"During my first internship, there was a discrepancy with the data communication and power supply equipment as 1-phase power supply was ordered on bulk while the equipment called for (in the specs was*) 3-phase power. The project was a demolition, add-on to existing Main Computer Room .... the facility was the main operation center for the airport.." – Project Engineer*

The need for constantly back-checking information is crucial in construction, especially for bulk and long lead items. Ordering the wrong equipment can have devastating consequences for the project; clear roles and responsibilities and diligent checking of documentation are needed.

Concrete finish unrealistic and misaligned expectations.

"On multiple projects recently, polished concrete has been a finish chosen by the project architect. As it is a trending finish these days, the designers love the look of the concrete in small doses and then tend to apply that look to large format areas and typically it doesn't work or doesn't meet with clients expectations. The design team has an acceptable level of defects in the concrete but it is rarely ever completely understood by the client and rejected because of the misunderstanding or miscommunication of what's expected. Everyone loves a 10' x 10' mock up in a controlled environment, but in the harsh realities of construction, the end product is very difficult to deliver to a client or designer who wants a level of perfection that cannot be provided." – Senior Superintendent

This mistake is preventable by setting a clear expectation of what level of finish can be achieved on a large scale for concrete; the cause of this could have been a lack of communication from the contractor to educate the architects and owner. We have seen other teams clearly defining metrics for success in Concrete. Making Mock-ups more realistic is key to success.

"On our project, we are having a misunderstanding between the owner & architect and the concrete contractor. The owner knows the look they want, and they know 1 way to achieve it, but it requires a lot of rework. They've specifically said they want to minimize the rework on this project while achieving the same look. The concrete contractor has been stood down multiple times to review that the owner wants them to control everything they can to minimize the rework. Part of the struggle is based on the assumptions at buy-out and going the extra mile in the field and making sure the terms are fair to all involved in putting the work in place. Getting the trade partner to slow down and focus on the quality has been a difficult process and they haven't had a real "win" yet." – Project manager

In this case, the owner knows what they want; however, the conditions for the trade partner to execute the job were not aligned early on during the buyout process.

Strategies to prevent basic failures.

Some human factors that create basic failure are inattention, neglect, overconfidence, and faulty assumptions (Edmonson, 2023). We can see those across the examples displayed in the previous section. Typically, basic failures do not have a huge impact if they are caught early on; however, if we keep making the same mistakes as in the case of the bathroom pods, this has severe negative consequences for the project and the company. What are strategies to avoid this type of mistake, and what can we do at a company level? Here are some strategies from the literature review:

- **Befriending error**, according to Edmonson (2023), human beings hate to be wrong, and naturally, this induces shame; we see admitting a mistake as a choice vs. protecting our self-image. To choose to learn is to choose to go past our instincts of finding excuses to protect ourselves from shame. Psychologists have studied *fundamental attribution error* bias; Edmonson (2023) provides a clear example: If I am late to a meeting, it is because the traffic is terrible. If my colleague is late to a meeting it is because he is lazy or disorganized. For people in the construction industry, this is hard; the way the information is requested to learn from a mistake, the way that supervisors respond, and whether there are personal consequences will affect the willingness of a person to speak up; these behaviours set the norms of the project. It requires a psychologically safe environment.
- **Befriending vulnerability**, in addition to befriending error, we must have the courage to admit mistakes and be willing to dig deeper to see one part of it, regardless of how large or small. Edmonson (2023) states that the practice of admitting errors is good for two reasons: one, it makes it easier for others to do the same, and second, other people will see you as more approachable and trustworthy. Brene Brown make the topic of vulnerability relevant, and it is deeply connected with shame (Brown, 2015). The practice of sharing failure stories in the BQB training during the first session helps with both befriending error and vulnerability. Anecdotally, when people do not have a failure story to share from their carries, it brings a warning sign for facilitators; maybe the person is not open to learning yet. However, as the weeks go by in the BQB training people relax and bring up personal failure stories more naturally.
- **Safety first policies** help create a “habit of excellence” when people commit to attention to detail and a culture where every employee is willing to push back against unsafe practices and point out others' small errors; it creates the basis of a psychologically safe workplace. This is consistent with what we have seen in practice when safety leadership encourages and promotes a culture of excellence that every employee is part of., we believe will bring long-term benefits for quality, work environment, and profitability too.
- **Culture of blameless reporting**. Expect and catch errors. A lean example of this is the Andon Cord that Toyota created, where any worker in the manufacturing plant can report a mistake, then the supervisor comes, and together they assess the error and find a solution; if they can't solve it quickly, the line stops. Blameless reporting is key; the promise is that reporting will not be penalized (Edmonson, 2023).
- **Codification (or checklist):** Learn as much as you can from failures, then codify it and create checklists. Gawande (2009) has studied extensively the benefits of checklists in the medical field. However, checklists are not infallible, and they need to be updated

and adapted to the context, especially in construction settings where buildings have unique expectations according to local regulations and owners' needs and wants.

- **Preventive maintenance** programs: processes like identifying distinguishing features to align on measurable acceptance criteria for the project (**add our DFs papers here**), pre-construction meetings, and built-in quality (checking own work before passing it on) can help identify misalignment of expectations of the final product, communicate the right sequence, and catch mistakes as early as possible respectively.
- **Required Training** is key to avoiding basic failure; industries such as aviation are at the forefront of preparing pilots for flying in the first place. Unfortunately, construction industry segregation and hyper-segmentation make the base knowledge very variable; many construction workers are trained by the union, but that is not universal everywhere in the USA. Also, the hourly pay system makes it harder for the project to make the budget and time to educate workers.
- **Error-proofing, or Poka-yoke,** originated in the Toyota production system. This is a very practical tool in the construction industry, too. Tommelein (2008) presents examples to illustrate how mistake proofing applies to the work done within one specialty trade, how manufacturers and fabricators can design their products so they cannot be constructed defectively, and how architects and engineers may conceive of system designs that are less likely to fail during construction or in a product's life cycle. In the case of the GC, one of the bathroom pods, the workers created a Poka-Yoke tool, a C-shaped wood assembly that will help to measure that the total dimension of the pod is within tolerances.

COMPLEX FAILURES

Complex failures are harder to document and understand the whole story. This happens in a more complex environment and is not easily preventable. According to Edmonson (2024), they often include at least one external seemingly unforeseeable factor; here, it is easy to think about supply chain issues during the COVID-19 pandemic that was not foreseeable for most construction projects going on at that time. Another typical unexpected factor is severe weather conditions. The following are some examples of recent complex failures reported by BQB participants where the main issue is a misalignment of expectations among several parties or mistakes where many stakeholders interact:

Managing Tolerances

"…On an exterior of a building to meet schedule and long lead time items we ordered Metal Panels, Concrete Panels and Curtain wall with "Hold to dimensions" Tolerances that threw this work off were the 1st two installations were the Concrete slab on grade and the Steel. These were both installed per their tolerances but it would ultimately throw off the framing, curtain wall, and everything following it. The architect's intention was for the joints of the concrete and metal panels and curtain wall to match, lights, and architectural shade devices to match as well. Some hold to dimension were unachievable because the steel and concrete didn't allow for all of the next finishes to be installed properly and keep the hold to opening sizes. Some of the framing and blue skin and roll on water proofing thicknesses didn't match the mock ups and the variances in the framing didn't allow for proper alignment of the supporting bracket for the Metal and Concrete panels. Several trades had to do quite a bit of shimming and added work to make this work out. Lots of rework in general and the start of all of this work from was tolerances." – Super Intendent

We classified this as a complex failure; there are several components coming together, the team preordered material ahead of time and when installing it the tolerances of all the assembly did not work. Even though tolerances are a known problem, the variance of materials is hard to predict, in addition the was added mistakes in the thickness of the materials received vs the ones the team used in the mock-ups, not sure is this was a procurement mistake or material variation. Finally, the last trades installing had the worst conditions to execute their work.

New Flooring Material Installation

"The client and designer had never before specified or worked with a specialty flooring material (concrete based). Additionally, the flooring material had never been attempted in the city where it was intended to be installed. After a lengthy qualification and bid process, we selected a installer (who met the requirements of the specifications). We performed several mockups, with multiple configurations (stair nosing's, reveals, strips). During the pre-construction portion of the project, the owner stressed the importance of maintaining the schedule and controlling of costs. Once a large section of flooring was installed, the owner was displeased. The designer reached out to factory representatives, and industry experts, who explained the limitations of the product (hazing, wavy finish, cracking at sharp corners). In the end, the owner was painted in a corner (leaves one with no good alternative or solution), no option to remedy the unpleasant installed product, no budget or schedule remaining to pursue other options (hard tile, terrazzo, lvt, etc). Everyone walked away empty." -Regional Quality Leader

This example was hard to classify because it started as an intelligent failure by recognizing uncertainty in the use of a new flooring product, apparently seeking to innovate with a new product, and making mock-ups to learn and select the right installation partner. However, it is not an intelligent failure because of the big risk taken when the review with the client was made, "*Once a large section of flooring was installed, the owner was displeased".* The team did not allocated enough resources (time and money) to explore alternatives to this new product if it did not meet owner's expectations. Basically, it was not planned to be an experiment. They understood the limitations of the product when applied at a large scale after there was no option to change it.

Strategies to learn and prevent complex failures.

In this section we discuss some strategies to prevent complex failures pointed out in Edmonson (2023) in the context of construction projects considering the previous examples:

- Learn from past complex failures. One of the tools this GC uses that can help in this process is Cause Mapping, where several courses can be understood to lead to the failure. The team can decide to implement changes in multiple aspects of the process, this can be applicable to any complex failure in constructions, from tolerances to unwanted finishes.
- Pay attention to early warnings. In this context, some of the early warnings are new materials, new assemblies, and new trade partners. In addition, having a culture that supports project team members raising issues that can lead to mistakes downstream is important. In the case of tolerances issues, a warning before buying metal and concrete panels and coordination early with trade partners can help.
- Leverage the recovery window: Mock-ups- give a recovery window; between what we can learn from the mock-up and the actual installation, there is a window of opportunity for learning and changing the plan; if mock-ups are planned with enough anticipation, construction teams can learn to change the sequence, materials, finishes, among other aspects of the work. Learning from issues in the same building also provides a recovery window. If you have a repetitive construction project and make a mistake on the floor 1, you can improve on floor 2, and so on.

- Welcome false alarms: Edmonson (2023) highlights the strategy of creating a Rapid Response Team (RRT) so employees can raise concerns to them, regardless of them being a false alarm; she provides the example of Andon cords in Toyota. Can we have experts ready to help when a problem starts in construction? This is an interesting approach; many construction companies have expertise in-house, but are experts available and ready to be summoned when needed?
- Embracing the possibility of failure to reduce the occurrence of failure, again practicing, rehearsing, testing, and learning from it is key. The use of first-run studies in construction presents an opportunity to learn in a more controlled environment, Tsao et al. (2000) present an example of how this is applied in metal framing.

According to Edmonson (2023), organizations that do well at avoiding complex failure are not because they somehow figure out how to eliminate human error; on the contrary, they have good records because they learn how to catch and correct errors. That takes practice and includes a culture that celebrates it. Moreover, Edmonson (2023) states "*It's not possible to build a contingency plan for every failure. But it is possible to build the emotional and behavioural muscles that allow us to respond to human error and unexpected events alike with speed and grace.*"

INTELLIGENT FAILURES

Intelligent failures, by definition, happen under uncertain conditions, and they are not preventable because you are testing something you want to learn in new territory. In general, innovation projects and pilots are classified in this category. According to Edmonson (2023), how to tell if a failure is intelligent includes:

- It takes place in a new territory.
- Opportunity driven.
- Informed by previous knowledge.
- As small as possible. Limiting risk exposure.
- Bonus: You learned from it.

The following is an example of an intelligent failure as reported by BQB participants:

Exterior Skin Mock-Up alignment

"We had a very complex exterior skin system with Terracotta tiles. The drawings and specs called out for a specific standard joint dimension, and the specs allowed for a certain tolerance in tile sizes. The mock-up was built, and although it held to the requirements in the contract documents, the design team still did not like the aesthetic. New MACs (Measurable Acceptance Criteria) *had to be negotiated, which was a long and painful process. Fortunately, we discovered this misalignment at a mock-up and not the final install."- Project Engineer*

This is an intelligent failure because the team was able to learn from the mock-up of the exterior system, which is a calculated risk, and understood how to achieve all requirements in addition to the owner's expectations that were not aligned with the trade- partners at that point, which avoided failure at the final installation. As the project engineer reports the process was long and painful, probably because they were learning and adjusting to the new understanding.

Promoting intelligent failures and learning from them.

How do we promote intelligent failures in construction teams? How can we ensure they are willing to take calculated risks to learn something new? According to Edmonson (2023), here are some high-level strategies to overcome barriers to failing well (Figure 1):

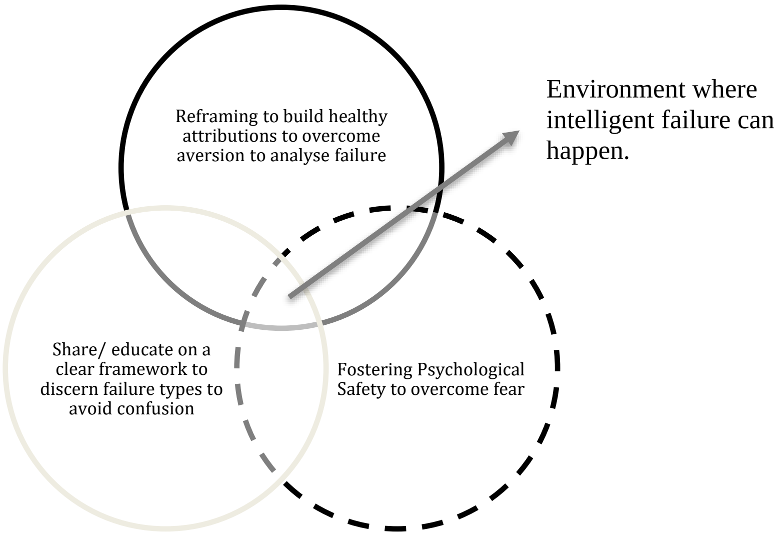

Figure 1: Strategies for creating a culture of intelligent failure.

How can we create a psychologically safe environment in construction? According to Gomez et al. (2019 and 2020), some key skills people must develop are active caring and active listening. None of these skills are common in construction. However, they can be improved if training and practice are provided. It is also important to assess how psychologically safe a project or team is. Doing this opens the possibility of sharing ideas for improvement.

How can we have a healthy attribution to the failure and be willing to understand what role one has played in it? First, we must understand our human pre-conditioning, such as acknowledging that learning from our failures is hard, accepting negative feedback and learning from it does not come naturally to most people, accept that we are blind and limited by our previous experiences. Therefore, our emotional preparation, and the culture we are working on takes a big part on the possibility for learning from intelligent failure or any other type of failure. Edmonson (2023) recommends practices that allow us to learn from failure:

- Thinking carefully about what went wrong and what factors might have caused it. This means avoiding the human tendency to skip the analysis and think we will try harder next time.
- Analysing what different causes of the failure suggest on what to try next. This is particularly useful for creating new best practices for new projects in similar circumstances.
- Digging in to understand your own contribution to the failure (small or large) means avoiding self-serving analysis.

Additionally, to allow for intelligent failures, project teams in construction must set aside the right resources to try new things. For example, many projects do mock-ups with the intention of succeeding in them and probably unconsciously avoiding the potential for learning. Ideally, a mock-up is representative of how the work will be performed at a large scale, and we are testing different ideas; this means that the result of the mock-up can lead to changes in materials or construction assemblies. We wonder how many projects are set up to allow for that learning to happen. In practice, many projects do not have other options to move on with whatever the result of the mock-up is because there is no time allocated for changes. Building a project to allow for true experimentation and learning requires a different setup; an Integrated Project Delivery (IPD) project can probably set the stage for intelligent failure if the right culture is in place.

Finally, education to recognize the different types of failure helps to know when you are dealing with an intelligent failure, which avoids confusion and creating the right incentives.

CONCLUSIONS

This paper studies different types of failure in the construction industry and the human aspects implicit in the possibility of learning from failure. We also illustrated cases of failures in the construction industry and offered a possible categorization within the failure types presented in Edmondson (2023). Understanding failure and its different categories helps us understand what reasonable strategies are to prevent basic failure, learn from complex failure, and encourage intelligent failure in the General Contractor company and in construction projects in general. More research is needed to test recommended strategies in the context of construction projects and see potential improvements. In addition, researchers are curious about how these failure classifications could help teams approach construction mistakes differently, how to train people to reframe their relationship with failures, and how to create a psychological safety culture at a large scale in construction to improve our learning from all types of failures.

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A FUZZY EXPERT SYSTEM FOR MEASURING THE DEGREE OF LEAN IMPLEMENTATION IN CONSTRUCTION PROJECTS

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ABSTRACT

Lean construction has emerged as a production management philosophy that can achieve significant performance improvements within the construction industry. However, the industry has not yet achieved full potential in terms of the implementation of Lean principles as compared to other industries. Such achievement necessitates continuous improvements throughout the project lifecycle. However, it is first necessary to understand the current level of Lean implementation to identify opportunities for improvement. Previous researchers have developed frameworks for measuring the degree of Lean implementation of an organization as a means to assess continuous improvements. However, being on the organizational level, these frameworks might not provide the means for assessing the incremental improvements toward transforming into a "Lean" construction company. There is a need to gauge the level of lean implementation at the project level, serving as a crucial stepping stone for overall organizational achievement. Accordingly, this study aims to develop a framework for measuring the degree of Lean implementation in a construction project using fuzzy expert systems (FES). This system provides decision-makers with an evaluation of the current implementation of Lean in construction which, in turn, provides a direction on further opportunities for improvement.

KEYWORDS

Lean construction, Lean implementation, fuzzy expert systems (FES).

INTRODUCTION

Lean is the application of a set of principles developed by Taiichi Ohno and Eiji Toyoda to reduce waste in processes and increase production efficiency (Koskela et al., 2007). This

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requires reducing the impact of factors that might not add value to the end user. If applied correctly, Lean principles can transform organizations to be more flexible and profitable in the long term (Womack & Jones, 1996).

In the construction industry, practitioners have been adopting several Lean tools in their projects including 5S, the Last Planner System, visual management, error proofing and many others. Such integration has shown to be beneficial in terms of reducing waste, reducing and mitigating mistakes, managing inventory, reducing rework, etc. (Koskela et al., 2007; Singh & Kumar, 2020). Despite these benefits, the construction industry has not yet achieved the level of improvement seen in other industries upon Lean implementation (Pantazis et al., 2022). As such, it is necessary to first understand the current status of Lean implementation in a construction project in order to identify potential opportunities and areas of improvement in the pursuit of continuous improvement. This can potentially be achieved by developing a Lean construction implementation index that helps quantify and assess the implementation of Lean tools and techniques (Cocca et al., 2019). Developing such an index can be supported with fuzzy logic approaches given their ability to mimic humans when making decisions especially when the context of the data is ambiguous (Tavana & Hajipour, 2020).

Numerous researchers have introduced metrics to assess the implementation of lean practices in the construction industry (Amaral et al., 2019; Cano et al., 2020; Comelli et al., 2019; Dragone et al., 2021; Elfving & Seppänen, 2022; Kallassy & Hamzeh, 2021; Salvatierra et al., 2020). However, existing studies have primarily concentrated on evaluating the extent of lean adoption at the company or organizational level. While this approach is advantageous, it may pose challenges for companies aiming to implement lean practices comprehensively from the outset. Therefore, it is crucial to establish a methodology for measuring the incremental progress toward transforming into a "Lean" construction company. Specifically, there is a need to gauge the level of lean implementation at the project level, serving as a crucial stepping stone for overall organizational achievement. Consequently, the objective of this paper is to formulate a fuzzy expert system (FES) designed for assessing the degree of lean implementation in construction projects either before or during execution. This involves the creation of a Lean Construction Implementation Index (LCII) that considers the unique characteristics of each project.

LITERATURE REVIEW

The literature review section is divided into 3 subsections. The first subsection tackles the successful implementation of Lean in the construction industry and the need for continuous improvement. The second subsection elaborates on the LCII along with the assessment approaches adopted in the manufacturing industry. As for the third subsection, it provides an overview of FESs.

LEAN CONSTRUCTION

It is well-know that the applications of Lean originated from the manufacturing industry. However, its principles were adopted to a wide spectrum of industries one of which is the construction industry. Several studies in the construction industry have investigated the application of Lean principles and tools in construction and identified the factors that could facilitate or impede their implementation (Singh & Kumar, 2020).

Some of the tools that were regarded as being efficient in the implementation of the Lean principles include the 5S, Last Planner System, Poka Yoke and visual management. The application of these tools was proven to be effective in terms of waste reduction, mistake proofing as well as inventory management (Li et al., 2019; Salvatierra-Garrido & Pasquire, 2011). Additionally, collaborative process making, Heijunka and Andon were proven to be beneficial in terms of reducing the amount of rework, standardizing scheduling and improving workplace cleanliness (Ansah & Sorooshian, 2017; Dombrowski & Mielke, 2013).

The successful implementation of Lean principles and techniques in construction requires a cultural shift towards collaboration, continuous improvement, and stakeholder involvement. Effective leadership, communication, and training are also essential for creating a Lean culture and sustaining Lean practices. Successful implementation of Lean in construction can lead to improved project outcomes, including reduced waste, increased productivity, and enhanced stakeholder satisfaction (Al-Aomar & Hussain, 2018).

Some researchers argue that the construction industry has not yet reached its full potential in terms of Lean implementation as compared to other industries (Pantazis et al., 2022). As such, it is deemed necessary to understand the level of Lean implementation in a construction project in an effort to identify opportunities for continuous improvement. One potential way to achieve this is through developing certain indices or metrics that help quantify the level of Lean implementation.

LEAN MEASUREMENT APPROACHES

With the increased adoption and improvement of Lean applications in the construction industry (Elfving & Seppänen, 2022), it becomes significant to measure and evaluate its implementation. The development of Lean implementation metrics has the potential to support decision makers to first monitor and evaluate the current status of the project or organization given Lean tools implementation, and to second propose the integration of new tools and techniques based on the evaluation outcome. This approach ensures that the organization continuously pursues and adopts improvements (Cocca et al., 2019). For this reason, researchers have developed various Lean implementation metrics to quantify the impact of the introduced Lean tools and initiatives in the construction industry.

Nesensohn et al. (2014) proposed a Lean Construction Maturity Model (LCMM) designed to measure the maturity within organisations embedding Lean Construction. This model consists of five maturity levels, 11 key attributes and 60 defined behaviours. Subsequently, Nesensohn et al. (2016) validated the LCMM they proposed using focus groups. In 2017, Nesensohn (2017) established a self-assessment template of the LCMM to obtain the current maturity level of any organization. Comelli et al. (2019) developed an audit protocol to evaluate the level of Lean implementation. This protocol was initially shaped by existing literature and refined through its implementation in four companies. The refined protocol was evaluated and validated through interviews with Lean construction experts. Barth et al. (2019) adapted the performance metrics of five construction companies to assess the performance of Lean production system. Amaral et al. (2019) collected data from six construction companies to evaluate the impact of each criterion in the Lean Construction Assessment Tool (LCAT) on the level of Lean implement. Kallassy and Hamzeh (2021) developed a Lean Culture Index (LCI) to assess the readiness of construction companies in Lebanon to apply Lean. Results demonstrated that while some companies had a flexible and consistent approach, there remained room for improvement in training, trust, and human focus. Mohamed (2021) proposed a Lean Construction Assessment Tool (LCAT) to evaluate the lean awareness in a company. He provided nine steps for lean construction assessment, formed 20 questions covered in 10 categories, and generated 5 levels of maturity as results.

However, despite the development of valuable metrics in these studies, their focus remains primarily on the organizational level (i.e., the company). There are only a few researchers who developed metrics for Lean implementation at the project level. Salem et al. (2006) developed a new Lean assessment tool including six Lean construction elements to quantify the results of Lean implemenations in construction projects. The tool was tested in two teams in one project through on-site survey. Cano et al. (2020) proposed a model to assess the maturity level of construction project management. They identified the elements related to maturity by consulting existing literature and experts in Lean Construction. Salvatierra et al. (2020) established 12 main dimensions to evaluate the Lean approach in construction projects. These dimensions were identified, and their relative importance was evaluated through online questionnaires and interviews.

Despite their valuable exploration, the subjectivity cannot be completely avoided due to the use of site visits and interviews in assigning scores for questions. Furthermore, the interactions between metrics is often not considered. Thus, it is necessary to further investigate Lean implementation assessment tools at the project level in the construction industry, while integrating approaches that help reduce subjectivity such as fuzzy-based approaches.

FUZZY EXPERT SYSTEMS (FES)

Expert systems mimic the ability of humans to make decisions in a certain area of specialty. As such, they can be beneficial for decision makers when solving certain problems (Tavana & Hajipour, 2020). Given that real-world problems are often described ambiguously and might hold elements of uncertainty, FES can be used for reliable data-driven decision making (Zadeh, 1983).

A FES uses a collection of fuzzy membership functions and rules to emulate the reasoning process of a human expert within a specific domain of knowledge; it synthesizes knowledge and experience from different experts and makes it available to non-experts (Klir & Yuan., 1995). In order to reduce the subjectivity, other FES approaches were developed such as that proposed by Shaheen et al. (2009). In this method, he develops a structured approach to defining the if-then rule base rather than determining them subjectively in consultation with domain experts. Accordingly, FESs are useful in decision support, learning, diagnosis and research, and planning.

Given the above conducted literature review, there seems to be a gap in the effective evaluation of Lean implementation in the construction industry on a project level. As such, this paper aims to develop a FES to evaluate the level of Lean implementation in construction projects through developing a LCII.

RESEARCH METHOD

This section describes the research method used to develop the FES for measuring the degree of Lean implementation in a construction project. **Error! Reference source not found.**Figure 1 illustrates the steps the authors followed to develop the FES. The first step, factor identification and analysis, establishes the knowledge base pertaining to the problem, i.e. the input factors that will affect the final output. The second step involves the development of the fuzzy expert system including the fuzzy membership functions and fuzzy rules. Both steps will be described in further detail below. The different components will be encapsulated in the expert system shell to be re-used in the future.

FACTORS' IDENTIFICATION AND ANALYSIS

As discussed above, several factors have been employed in the literature to measure the degree of Lean implementation. The authors reviewed previous research studies to identify the relevant factors for construction projects and proposed a number of new factors that capture the degree of implementation of Lean construction.

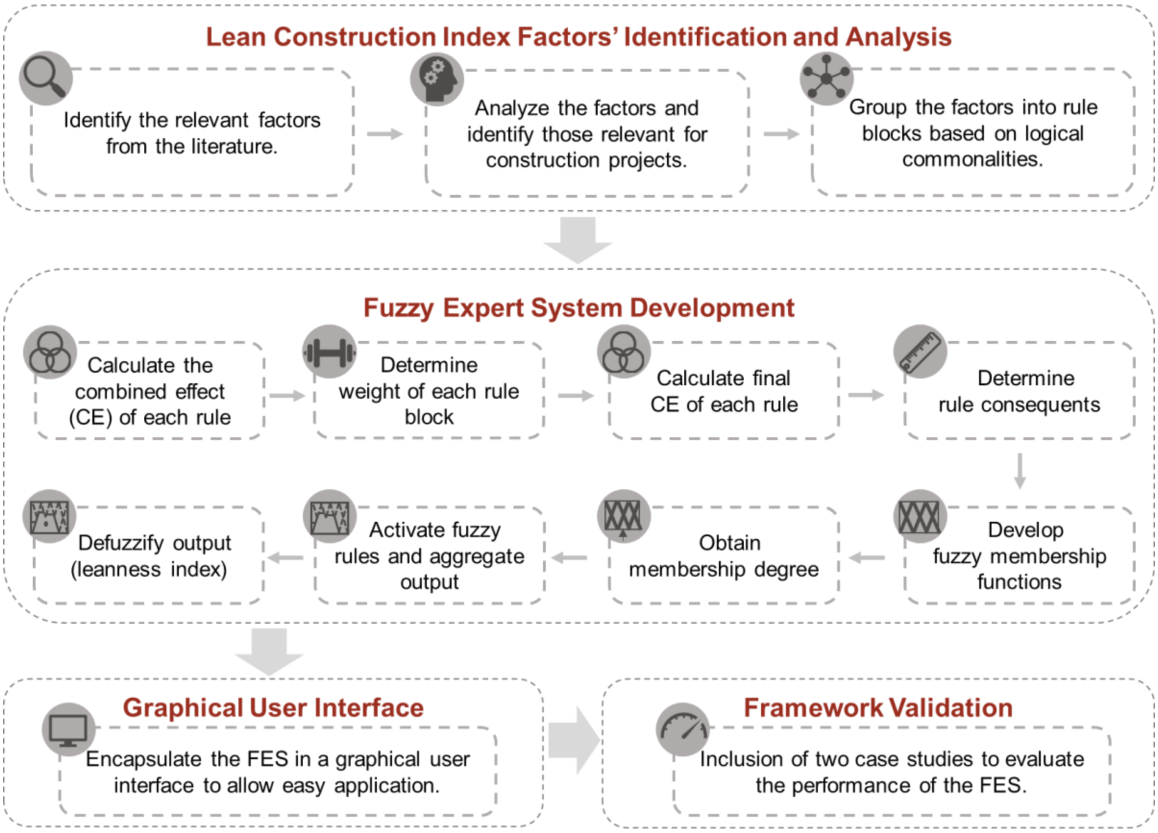

Figure 1 Research Method

FUZZY EXPERT RULES

The development of the rule consequents for the FES follows the method proposed by (Shaheen et al., 2009). This structured approach reduces the subjectivity associated with defining the if-then rules that capture the experts' ways of thinking (Shaheen et al., 2009). Additionally, it

controls the exponential growth of the rule base by grouping factors based on logical commonalities, as performed above. **Error! Reference source not found.** illustrates the steps to defining the rule consequents based on this technique. In this method, the impact of each state of a certain factor on the output (degree of Lean implementation) and the relative importance (RI) of that factor are solicited from experts. For each rule, the combined effect (CE) is calculated as shown in equation (1):

$$CE(R_n) = (F_1)_{RI} \times F_1(state_1)_{Impact} + (F_2)_{RI} \times F_2(state_1)_{Impact} + \cdots (F_m)_{RI} \times F_m(state_1)_{Impact}$$

Once the CE is calculated for each rule, the importance of each rule block relative to the final output is determined. Weights are assigned to each rule block and the normalized weight is calculated. Next, the final CE is calculated by multiplying the CE of each rule by the normalized weight of the rule block to which the rule belongs.

$$CE_{final}(R_n) = CE(R_n) \times Rule\ Block\ weight$$

The normalized combined effect is then calculated as:

$$CE_{Normalized}(R_n) = [CE_{final}(R_n) - CE_{min}]/[CE_{max} - CE_{min}]$$

The reader is referred to Shaheen (2009) for further details on the process. In this case, the factors correspond to those factors described in the previous section, and the states correspond to the 3 linguistic variables that describe the level of implementation of each factor (i.e., low, medium, and high). The relative importance of all factors is considered equal and the impact of being at a certain state is determined on a scale from 1-5, where 1 corresponds to very low and 5 corresponds to very high. Once the CE for each rule is calculated, the values are normalized using the equation above. The normalized combined effect is compared to a 5 -point scale where each interval corresponds to a linguistic term of the consequent (LCII) as shown in Figure 2.

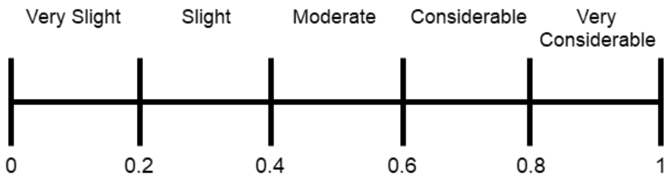

Figure 2 5-point scale for defining rule consequents

FUZZY MEMBERSHIP FUNCTIONS

The next step is to develop the fuzzy membership functions for the different factors. Although expert opinion or historical data are generally preferred for the development of membership functions, due to the limited time for this research, the authors assumed the values for the membership functions. Additionally, for ease of implementation, the same membership function was used for all the factors (inputs) as illustrated in Figure 3. The membership function for the output, the LCII, was also assumed (Figure 4).

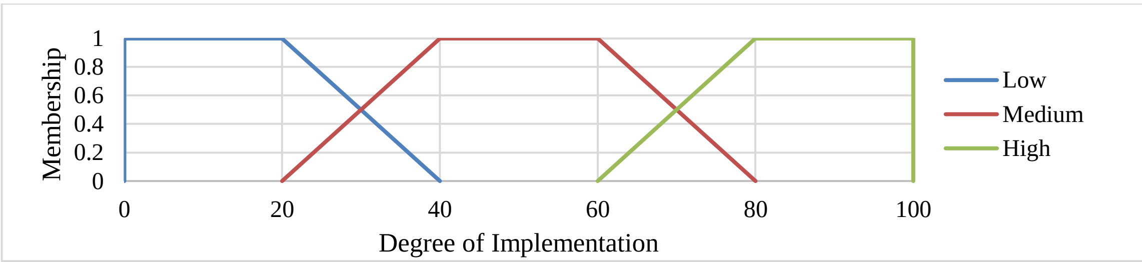

Figure 3 Membership function for factors

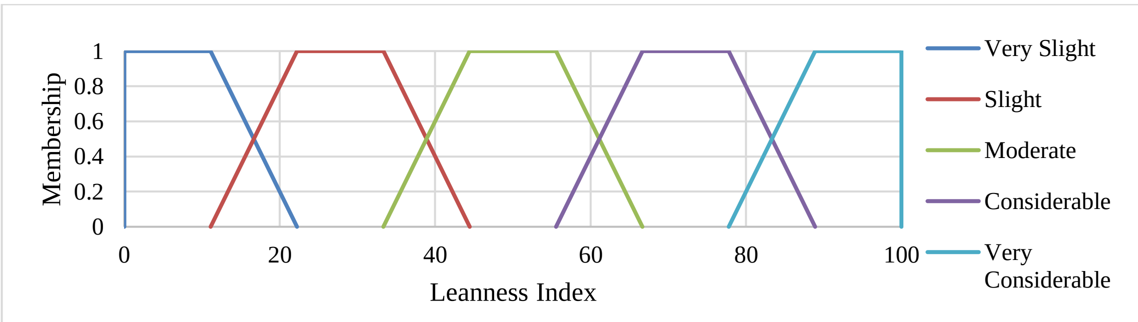

Figure 4 Membership function for LCII

FUZZY INFERENCE SYSTEM

Users of the FIS would input the level of implementation of each factor, whether expressed as crisp values or linguistic term, to calculate the degree of membership for each linguistic term defining those variables based on the fuzzy membership functions. The FIS model then uses the following operators: (1) input aggregation is minimum, (2) output aggregation is maximum, (3) implication method is minimum, (4) defuzzification method is the center of area method, and (5) all rules are given equal weighting. The LCII is then calculated as the defuzzied output of the model.

RESULTS

IDENTIFIED FACTORS

After an extensive literature review and analysis, several factors were identified from the literature. Table 1 shows the factors that were collected and the different categories that they were grouped into.

GRAPHICAL USER INTERFACE

A graphical user interface was developed on MATLAB to allow the user to enter scores for each of the defined factors to reach a LCII for the project being assessed. Figure 5 shows a sample of the interface window, where the user would drag the pointer assigned to each factor until the desired score is attained. The 30 factors are distributed over 5 pages, which the user can navigate between by selecting the required tab.

Once the scores are assigned to all the factors, and the user clicks on the "Evaluate" button on the last window, the model will calculate the LCII. The LCII will be displayed to the user in the same window, and a graphical representation of the equivalent degree of Lean implementation will also be generated to give the user a better sense of how Lean the project is.

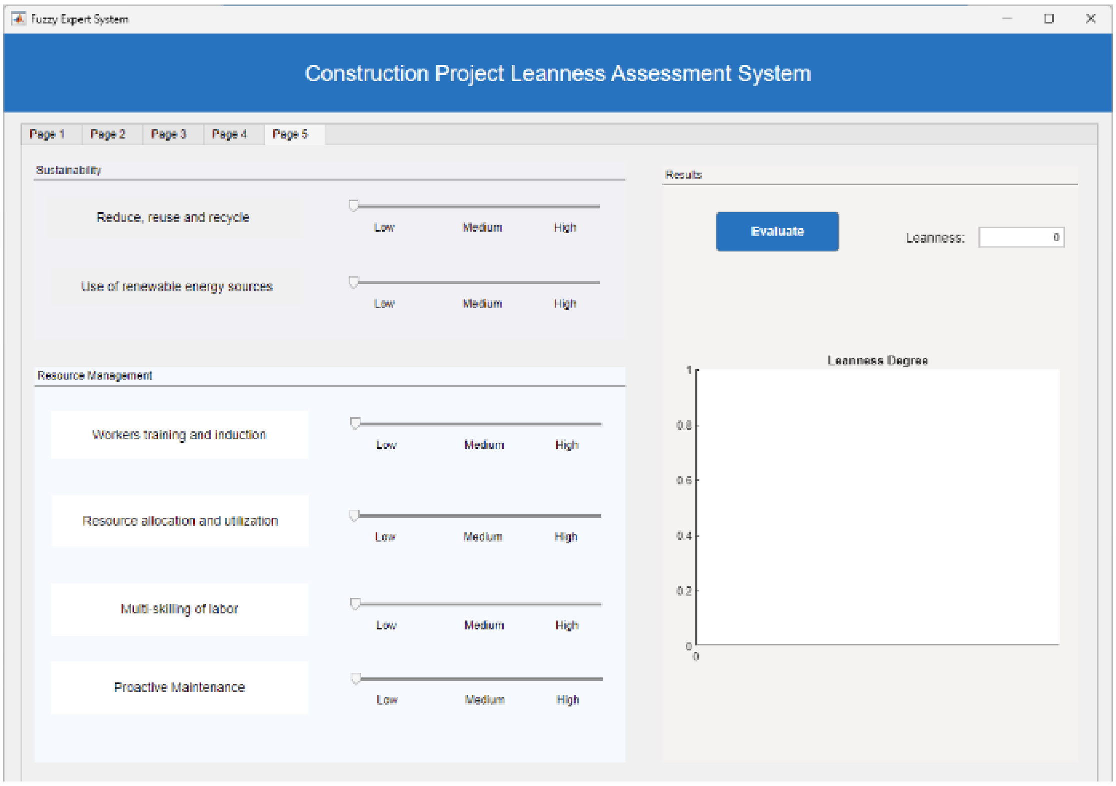

Figure 5 FES User Interface

Table 1 LCII Factors

Category	Factor	References
Collaboration	F1: Transparency in information sharing	(Cano et al., 2020; Comelli et al., 2019; Salem et al., 2006)
	F2: Efficient communication system	Proposed
Construction Methods	F3: Integration of prefabricated and modular construction	Proposed
	F4: Adoption of autonomation tools	Proposed
	F5: Incorporation of the Last Planner System or its alternatives	(Salem et al., 2006; Smith & Ngo, 2017)
Continuous Improvement	F6: Implementation of kaizen strategy	(Comelli et al., 2019; Dragone et al., 2021; Saleeshya & Binu, 2019; Salem et al., 2006; Salvatierra et al., 2020)
	F7: Implementation of the 5 Why's and Root Cause analysis	
Customer Value	F8: Incorporation of customer feedback	(Dahda et al., 2020)
	F9: Capturing customer requirements	
	F10: Sharing work status information	Proposed
Delivery and Supply	F11: Just in time procurement of materials and equipment	(Dahda et al., 2020; Smith & Ngo, 2017)
	F12: Involvement of suppliers	(Salvatierra et al., 2020)
	F13: Supplier evaluation/feedback	(Amaral et al., 2019; Saleeshya & Binu, 2019)
General Site Conditions	F14: Order and cleanliness of the site	(Smith & Ngo, 2017)
	F15: Effective planning of laydown areas	(Saleeshya & Binu, 2019)
Management	F16: Empowerment of workers (Andon systems)	(Comelli et al., 2019)
	F17: Providing employee incentives	(Susilawati et al., 2015)
	F18: Timely disbursement of due payments to suppliers and subcontractors	Proposed
Process	F19: Utilization of work cells	(Dahda et al., 2020)
	F20: Implementation of Kanban system	(Dragone et al., 2021)
	F21: Implementation of visual management	(Susilawati et al., 2015)
	F22: Use of tool kits	Proposed
Quality	F23: Minimizing the percentage of rework	Proposed
	F24: Use of tested and reliable technology (drones, computer vision, etc.)	(Salvatierra et al., 2020)
Resource Management	F25: Workers' training and induction	(Amaral et al., 2019)
	F26: Resource allocation and utilization	(Dahda et al., 2020)
	F27: Multi-skilling of labor	
	F28: Proactive maintenance	Proposed
Sustainability	F29: Reduce, reuse and recycle	(Comelli et al., 2019; Salem et al., 2006)
	F30: Use of renewable energy sources	Proposed

ILLUSTRATIVE EXAMPLE

In order to evaluate the proposed FES's capability to assess the degree of Lean implementation in construction projects, the model was tested on two construction case studies. The first project is an industrial project that follows a traditional project delivery method (non-IPD) while the second one is a wastewater treatment facility project that follows an IPD project delivery method. The authors selected an IPD project and a non-IPD project to showcase the model's potential in providing a reasonable LCII as it is anticipated that the non-IPD project is likely to have low Lean implementation as opposed to the IPD one. The authors interviewed an expert on each of the two projects and were able to get a general idea about the Lean implementation on each of the two projects. In the first one, although the expert was well informed about the different Lean tools and techniques that can be potentially applied in the project, it did not seem that these were implemented. As for the second project, the interviewed expert was comfortable discussing the different applications of Lean tools in the project. As such, the authors collected data from the experts on the 30 factors previously identified using the developed interface. Tables 2 below summarize the scores obtained for the case studies.

Table 2 Case studies' data

Case study 1						**Case study 2**					
Factor ID	Score	**Factor ID**	Score	**Factor ID**	Score	**Factor ID**	Score	**Factor ID**	Score	**Factor ID**	Score
F1	20	**F11**	5	**F21**	80	**F1**	100	**F11**	80	**F21**	50
F2	50	**F12**	5	**F22**	15	**F2**	100	**F12**	90	**F22**	50
F3	55	**F13**	60	**F23**	10	**F3**	33	**F13**	66	**F23**	66
F4	65	**F14**	80	**F24**	10	**F4**	33	**F14**	90	**F24**	85
F5	15	**F15**	65	**F25**	65	**F5**	90	**F15**	95	**F25**	85
F6	65	**F16**	15	**F26**	60	**F6**	75	**F16**	90	**F26**	85
F7	40	**F17**	55	**F27**	10	**F7**	40	**F17**	75	**F27**	66
F8	60	**F18**	85	**F28**	15	**F8**	95	**F18**	85	**F28**	80
F9	15	**F19**	50	**F29**	10	**F9**	95	**F19**	66	**F29**	66
F10	65	**F20**	45	**F30**	10	**F10**	85	**F20**	50	**F30**	66
LCII: 30.64						**LCII: 55.92**					

Given the above scores, the LCII for each project was obtained. The first case study has a slight implementation of Lean tools and techniques whereas the second one has a moderate to considerable implementation. As expected, the LCII obtained for the second case study is higher than that for the first case study. As such, the developed FES model to measure the degree of Lean implementation in a construction project portrayed modeling robustness.

MODEL VERIFICATION

Sargent (2007) defines model verification as "ensuring that the computer program of the computerized model and its implementation are correct" Since the FES described in this study was developed in MATLAB, it was important to verify it. The authors performed a sensitivity analysis where the values of the inputs were changed to observe the effect on the output. Accordingly, the authors performed two tests, where the values of all the factors were set to '0' in the first test and to '100' in the second test. The results of the sensitivity analysis are shown in Table 3.

Table 3 Sensitivity Analysis

Test	Input Value for Each Factor	LCII
1	0	8.38
2	100	91.61

The results of the sensitivity analysis align with the predicted expectations. Notably, when all factors receive a rating of 0, the LCII is determined to be "very slight," whereas a rating of 100 for all factors results in a "very considerable" LCII. However, contrary to initial assumptions, the LCII is not necessarily 0 and 100 when all inputs are 0 and 100, respectively. This observation can be attributed to the influence of the FES design on the output, including the selection of operators and the consequences of the fuzzy expert rules.

CONCLUSION AND RECOMMENDATIONS

In summary, this study has made a valuable contribution to the development of frameworks for measuring the degree of Lean implementation in the construction industry. By proposing a fuzzy expert system, decision makers now have a reliable and easily applicable tool for evaluating the current level of Lean implementation on construction projects. Additionally, the use of fuzzy logic allows decision makers to capture and evaluate uncertain information, leading to more accurate and reliable evaluations. The proposed framework can help decision makers to identify opportunities for improvement and guide future Lean initiatives in the construction industry. Additionally, decision makers can use the proposed tool on projects that are already in the execution phase and on projects that are to be executed given that the identified factors used in the evaluation process apply to both.

One limitation of this study is that the fuzzy membership functions were assumed. Future research could involve experts in the development of these functions to improve the accuracy of the system. Additionally, future research could investigate the use of different quantifiable indicators that can objectively capture the level of implementation of each factor to reduce bias. Improvements to the GUI also have the potential to enhance the application and make it more user-friendly. These include labelling the inputs and outputs to provide a clearer explanation of the different categories and adding different features such as the ability to save and export results.

The proposed framework has the potential to facilitate the adoption and implementation of Lean principles in construction projects. This can lead to better project outcomes, such as improved productivity, reduced waste, and increased profitability. Moreover, the adoption of Lean principles can contribute to overall industry performance and competitiveness.

In conclusion, the development of a FES for evaluating the degree of Lean implementation on construction projects is an important step towards achieving continuous improvement throughout the project lifecycle. Furthermore, while the proposed framework is designed for project-level application, its adaptability allows implementation in organizations and broader contexts. Future research can build upon the findings of this study to further refine the FES and explore additional factors.

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TOWARDS SUSTAINABLE LEAN CONSTRUCTION IN INDONESIAN CONTRACTOR: EFFORT & LEARNING FROM PTPP (A GOVERNMENT-CONTROLLED CONSTRUCTION & INVESTMENT COMPANY)

Rina Asri Aisyah[1] and Prama Putra[2]

ABSTRACT

The construction industry must adapt to contemporary challenges; there is a need to change the paradigm of the industry, including in Indonesia. Lean thinking is an example of the evolving paradigm in the construction industry, called lean construction. It emphasises maximising efficiency, minimising waste, and delivering value to the customer through collaborations, optimised workflows, and project performance enhancement. For a construction company such as PT PP (Persero) Tbk (a government-controlled construction & investment company), which have adopted the lean concept in the last five years, there is a need to create an environment that supports lean as quickly as possible. For a company that is relatively new to lean involvement and methodology, education is crucial for raising awareness and understanding of lean construction among the company members. This paper presents an exposition of effort and learning for lean transformation by using Community of Practice as a method to disseminate lean knowledge and experience and share details of the activities about programs as an action learning. The authors will share their experience and learning of making the sustainable change in the company through the lessons learned.

KEYWORDS

Lean Construction, Sustainable, Collaboration, Lean Education, Action Learning, Community of Practice

INTRODUCTION

The construction industry is one of the biggest industries in the world. Like others, the construction industry has been evolving because of many issues such as inefficiencies, productivity, overrun cost, technological advancement, labour, regulation, expectation, environmental impact, etc. For the construction industry to adapt to these challenges, there is a need to change the paradigm of the industry. Lean thinking is an example of the evolving paradigm in the construction industry where the principle was adopted from manufacturing. The Lean Management (LM) system was first brought to bear by the Toyota Motor Corporation in the late 1950s and was named Toyota Production System (Shingo, 1981), while the lean

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construction (LC) terminology emerged in the 1990s initiated by the work of Koskela (Koskela, 1992). It emphasises maximising efficiency, minimising waste, and delivering value to the customer through collaborations, optimised workflows, and project performance enhancement. Different studies have suggested that the implementation of lean construction improves performance, raises the value of money and resources, and reduces waste (Amaro et al., 2019; Shaqour 2022; Bajjou & Chafi, 2018, Tezel et al., 2020, Singh et al., 2018, Erol et al., 2017). Despite the benefits, the slow adaptation of lean concepts in the construction industry created a wide gap and broad interpretation of lean construction (Common et al., 2000). This condition produced some barriers for implementation such as skill-and-knowledge-related, behaviour-related, management-related, financial-related, technical-related, and government-related issues (Sarhan & Fox, 2013; Kanafani, 2015; Nwaki et al., 2021; Albalkhy et al., 2021; Shang & Pheng, 2014; Albalkhy & Sweis, 2021, Ayarkwa et al., 2011; Bashir et al., 2015).

LC has been disseminated and taught across the world, including Indonesia. The specific introduction of the LC concept in Indonesia has yet to be officially documented (Abduh et al., 2005). However, we may be able to say that the first major brick of lean construction was the *Kompetisi Konstruksi Ramping (K2R)* event in 2016 (Faculty of Civil and Environmental Engineering, Bandung Institute of Technology 2024). The concept was introduced through a simulation of construction projects. Since LC in Indonesia is relatively young and still in the dawn phase, there is a need to increase contractors' understanding and awareness of lean principles in the construction industry. Studies from other countries implementing LC suggested that barriers vary between countries. For example, the lack of backing from upper management, limited awareness of LC, inadequate training, and a lack of transparency were vital obstacles that significantly impede the acceptance of LC in Jordan (Albalkhy et al., 2021), incomplete or intricate designs, the cyclical nature of the construction industry, limited engagement of contractors and specialists in the design process, insufficient understanding of lean principles, and inadequate communication among all stakeholders represented the top five significant barriers in the UAE (Kanafani, 2015), the major obstacles in China included the absence of a long-term philosophy, a lack of a lean culture within the organisation, and the use of multi-layer subcontracting (Gao & Pheng, 2014), insufficient awareness and comprehension of lean principles, a lack of commitment from top management, and cultural and attitudinal challenges among the workforce were prominent issues in the UK (Sarhan & Fox, 2013), challenges in grasping lean concepts, variability in government policies, unclear project definitions, incomplete designs, absence of standardisation, and a lack of enduring relationships with suppliers were obstacles that impeded the implementation of lean practices in Ghana (Ayarkwa et al., 2011). However, we underline from these studies that people and systems are key factors in determining the success of lean implementation.

This paper aims to present an exposition of effort and learning at an Indonesian contractor, PT PP (Persero) Tbk (called PTPP), that has initiated and adopted LC since 2019. The major effort to achieve the code of conduct of LC at the company was the education of lean principles. The first purpose was to raise awareness of LC amongst company members and to increase their understanding of LC. Another effort was providing in-house training about the Last Planner System (Ballard & Howell, 1994; Lehman & Raiser, 2000) as a tool of lean construction that describes a comprehensive system to address project variability (Maradzano et al., 2019), to optimise the planning, and execution of a construction project (Sarhan & Fox, 2013). The trainers of this training were from the same company. Further effort in implementing LC at PTPP was waste-register method implementation at construction works (Aisyah et al., 2023). This accomplishment was an example of the successful execution of the lean principles at the company. The last effort was to standardise the LC system at the company, although it still needs to be finished. All the above-mentioned efforts were conceptualised under the Community of Practice (CoP) Lean Construction PTPP. CoP is usually used for an event in a country or larger region. To our knowledge, the notion of CoP at the level of a company is the smallest unit of CoP compared to the usual form of CoP, and it is now well-recognised at the company.

In the next section, we will review the concept of CoP and lean construction education. Sections 3 and 4 will describe the initiation and journey of CoP at PTPP, while Section 5 will explain further challenges towards sustainable lean construction. Ultimately, Section 6 gives the overall conclusion of our work.

LITERATURE REVIEW

LEAN CONSTRUCTION EDUCATION

People and systems are two striking keywords of the identified barriers from different studies on lean construction implementation. Although other factors, such as technical and behavioural issues, are also important, creating awareness and understanding is crucial in preparing for LC. Different studies have suggested that the lack of knowledge hinders people from adopting a new concept (Albalkhy & Sweis, 2021; Gao & Pheng, 2014; Bajjou & Chafi, 2018; Nwaki et al., 2021; Sarhan & Fox, 2013; Moradi & Sormunen, 2023). The problems could be a lack of skill, low level of education, insufficient training, or lack of understanding related to lean (Albalkhy & Weis, 2021). Ultimately, the problems could unconsciously affect the implementation of LC as a system. Due to unawareness, top management could ignore the adoption process, leading to an unsupportive environment. To overcome such barriers, providing training and development investment as part of education was considered a good strategy (Gao & Shang, 2014). The solution could lead to a change in perspective at the top management level and cultural change.

Transferring lean knowledge and skills involves training individuals in the principles of lean thinking. The goal is to provide professionals with sufficient knowledge and skills to improve project delivery, efficiency, and value and reduce waste. Lean education was widely offered at universities worldwide (Tsao et al., 2013). The university-based lean education consisted of theoretical coursework and practical simulations (Rybkowski et al., 2018). The teaching usually contained reading assignments, paper-based reflections, class and online discussions, and simulation exercises to develop students' strong understanding of lean concepts (Tsao et al., 2013; Hamzeh et al., 2016).

The university-based lean education, without question, becomes an ideal notion for learning lean concepts where students can learn and deepen their understanding through theory and practice. However, for a construction company such as PTPP, which have adopted the lean concept in the last five years, there is a need to create an environment that supports lean as quickly as possible. For a company that is relatively new to lean involvement and methodology, the education at the company is typically conducted as training for project teams (Forbes et al., 2018). Forbes et al. took examples and learnt from different companies in the US. For example, JE Dunn introduced the lean concept through the LegoTM Airplane Game, the Parade of Trades, and Silent Squares. In addition to the simulations, it provided training that focuses on introducing lean principles and tools that a project will use. DPR Construction took another path to teach lean thinking, involving Stanford and UC Berkeley to run workshops. Another example from a regional manager of an owner organisation provided hands-on training at the project level and found that the internal construction administration plays a key role in creating a lean culture. The last example was aligned with the finding that transferring and sharing lessons learned within the organisation encourages a successful lean education and culture (González et al., 2014).

Based on the above, there were many forms of lean education at the level of construction companies. The goal was to disseminate and raise awareness of lean thinking within the company as rapidly as possible. Companies could engage universities or lean consultants to provide education.

COMMUNITY OF PRACTICE IN LEAN CONSTRUCTION

One of many ways to teach and accelerate lean manifestation was through a community of practice (CoP). It is known as a group of people who have the same interests and discuss and explore things for their future goals. They used any methods, especially brainstorming and sharing sessions, through their knowledge and experience (Wenger & Snyder, 2000). CoP was initially developed as a learning theory that promotes self-empowerment and professional development, but as the theory evolved, it became a management tool for improving an organisation's competitiveness (Li et al., 2009). Despite many views, the CoP concept emphasises learning and sharing knowledge and supports formal and informal group interactions.

In the context of lean construction itself, CoP Lean is a group of people interested in LC. The event was usually regional based around the US. An official Community of Practice of Lean Construction was held by the Lean Construction Institute (LCI) (Lean Construction Institute, n.d). Their goal was achieving industry-wide collaboration through communities of practice; whether a skilled practitioner in Lean Design and Construction or just getting started, there was support and a chance to keep learning. LCI nationally supported CoPs after opportunities to connect locally, participate in education courses and workshops, hear from local lean project teams, attend Gemba walks, and more. Since LCI was also present in some European and Asian countries such as the UK, France, Japan, Singapore, and India, the CoP was held chiefly regionally. As the construction industry in Indonesia is growing, such activity is strongly needed to disseminate and teach the lean principle and manifest it in construction in Indonesia.

COMMUNITY OF PRACTICE INITIATION

CoP Lean Construction (CoP LC) is one of the CoPs that exist in the PTPP. The other CoPs are the CoP Green Building, CoP Mechanical & Electrical, CoP Strategic Business Management, CoP Seaport, CoP Power Renewable Energy, CoP Building Information Modelling (BIM), CoP Innovation, and CoP Lean Construction. The CoP LC has three fundamental elements: domain, community, and practice. The domain element is divided based on their operational expertise: building, bridge and road DAM, and Engineering, Procurement and Construction. The community element consists of people who are curious or as simply as they want to know about LC. The last element consists of the method and module used for knowledge sharing of LC. The coordination of all elements is through three divisions of the company: Division of Strategy, Planning and Technology (Stratec), Division of Operation, and Division of Project. These parties determine the operation of CoP LC and improve it. The Division of Stratec is responsible for planning and monitoring corporate LC and innovation implementation, choosing value creation, workshops, socialisation and refreshment as a corporation. The Division of Operation is accountable for monitoring LC of all the projects based on their expertise. The Division of Project is responsible for gaining value creation for the corporation.

CoP LC in PTPP was established in October 2019 after management declared committing to implementing lean construction in March 20219. This idea came when the company followed the LC Villego competition, called K2R 4.0 (Kompetisi Konstruksi Ramping), held by Institut Teknologi Bandung in 2019. There were many projects representing different sectors, such as building, toll-road, and infrastructure. The CoP LC took a role in uniting the PTPP representatives and won the contest. Based on that, the CoP LC creates big goals for having big impacts on the company as much as possible. CoP Lean PTPP was supported by the Human

Capital Management System in order to build awareness. The group organised gathering events in the first year to share CoP LC's agenda. The group collected advice and remarks to highlight the needs of the projects. CoP Lean PTPP is basically under the Department of Knowledge Management System in the Division of Strategy, Planning and Technology and held by the Division of Creative, Engineering and Technology, which is now known as the Division of Innovation, Lean, BIM and Technology.

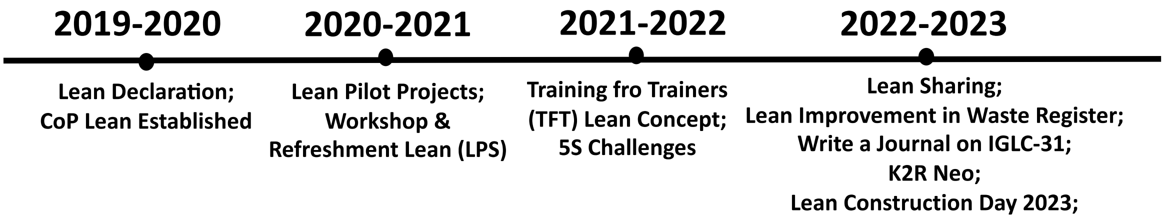

Figure 1 Timeline of CoP Lean Construction PTPP Journey

COP LEAN PTPP JOURNEY

2019 – 2020

As mentioned in Figure 1, CoP LC PTPP was established in October 2019; that year, we focused on all the LC competitions held in Indonesia: Construction Funday GAPENSKI 2019 and Villego Competition (K2R 4.0) 2019. Firstly, we started by doing a site visit project in PLTD Senayan Jakarta to benchmark LC that was implemented first there. This project ran the Last Planner System (LPS) because the project owner was Wartsila, a foreign country. For some project owners, it was usual to do a daily collaboration. This condition was an opportunity for us to know directly how their experience was in it and get some insight through that project.

Because of that experience, we exercised regularly until we won that competition. This initiative project was a milestone in gaining another success story in the next section. In that history, CoP LC did a Sharing Session with the winning team, discussing how strategy, collaboration, and planning affected their win to get some lessons learned that reflect on being implemented in their project. Some lessons learned were how to produce a building that meets the values desired by its users (owners), effective and efficient implementation (time), fit the design (quality), and there was little waste production (cost).

After the competition, we focused on making the modules of The Last Planner System to be implemented in the project. There were so many adjustments from the Villego Competition to the actual project condition, so we learnt to arrange how the methodology was implemented using that basic understanding of LPS through Villego games. On the other side, we initiated the digitalisation of the concept of LPS itself using The PP Planner. It made us collaborate with the Information & Technology (IT) system to apply the project to using LPS as a digital-based project management system.

From the journey of this year, we remark on three key lessons learned that made the CoP LC succeed. First, Last Planner System is crucial in understanding lean construction and its implementation. The members of CoP LC covered the gap of LC understanding in the beginning and LPS was an important first step. Second, collaboration with academic universities becomes vital. The collaboration was done through the competition held by a university, and this event became a milestone in checking the understanding of LC within the company, at least among CoP LC members. Third, the information gathered must be formulated quickly and it was based on experience. By doing such activities, the CoP LC helped the company design lean education and implementation within the company.

2020 – 2021

The work program of CoP LC PTPP continued the year after it was established. We did some correspondence between the CoP LC PTPP committee and the project. The first was to do a workshop on the topic and go back to basics, which was about scheduling and planning. The first workshop was held in April 2020, Workshop Ms Project Integrated with LPS and Workshop Optiwaste (The method for knowing cutting-off reinforcement in the field).

After that, because we should have a recommendation and suggestion to do next, we often did regular *focus group discussions* over time, both directly and indirectly. Directly, we did *Lean Sharing* each month with multitopic, which was an option for following the issue and problem in the project. This lean sharing was an easy and effective method of sharing knowledge over poor construction. We got some suggestions through the discussion and Question & Answer after the materials were disseminated by the speaker. Besides lean sharing, we continued workshops with different experts to minimise the gap in knowledge and experience of poor construction. Indirectly, we made the group to get instant messages and discussions through WhatsApp. Another thing was the newsletter knowledge (PP WIN), a weekly magazine PTPP, and we ended up with the online meeting/ workshop.

This methodology was used to develop CoP LC PTPP, which was customised with the COVID-19 limitations that we got to reach more closely. Still, we also found out how to make an effective and efficient method that could be accepted by all the projects throughout the Indonesian region from Sabang to Merauke.

From this journey, we highlight that creating a medium for sharing and learning boosts awareness and understanding of lean construction. Sharing and learning must not be limited, and it is better to start with the company members' experience related to lean theory and application.

2021 – 2022

In 2021, CoP LC was trying to explore knowledge widely by benchmarking abroad nationwide. We held Training-for-Trainers (TFT) by Chyntia Tsao (NAVILEAN). This TFT ran for eight months (sixteen meet-ups) from May until September 2021 during the COVID-19 pandemic.

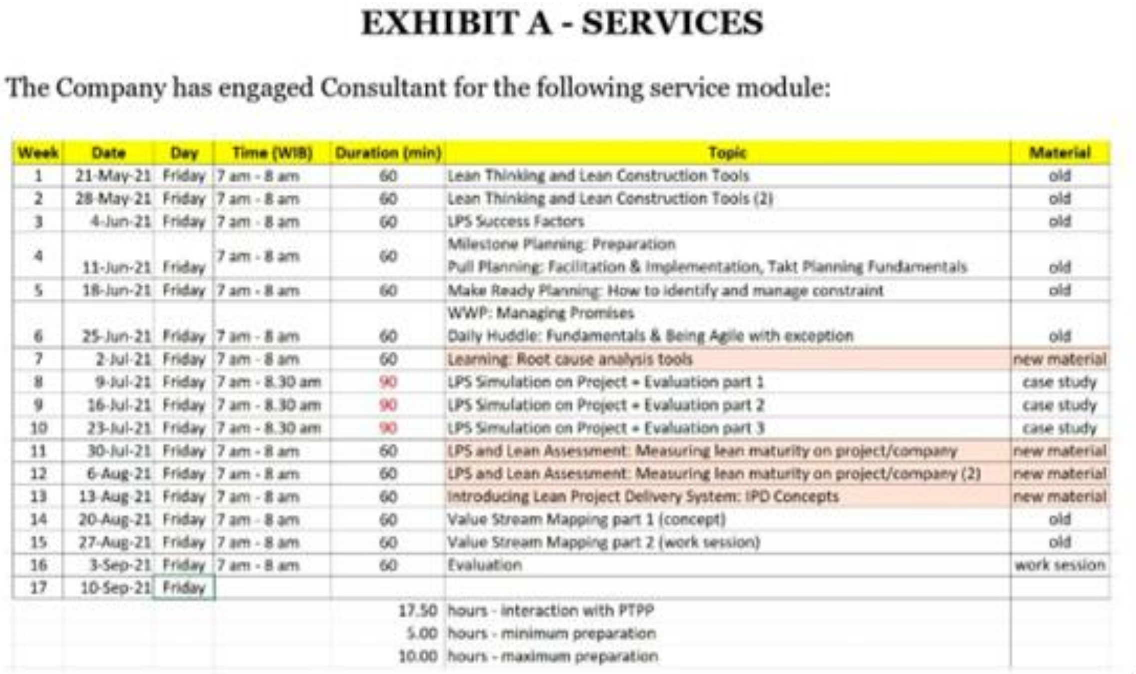

EXHIBIT A - SERVICES

The Company has engaged Consultant for the following service module:

Week	Date	Day	Time (WIB)	Duration (min)	Topic	Material
1	21-May-21	Friday	7 am - 8 am	60	Lean Thinking and Lean Construction Tools	old
2	28-May-21	Friday	7 am - 8 am	60	Lean Thinking and Lean Construction Tools (2)	old
3	4-Jun-21	Friday	7 am - 8 am	60	LPS Success Factors	old
4	11-Jun-21	Friday	7 am - 8 am	60	Milestone Planning: Preparation Pull Planning: Facilitation & Implementation, Takt Planning Fundamentals	old
5	18-Jun-21	Friday	7 am - 8 am	60	Make Ready Planning: How to identify and manage constraint	old
6	25-Jun-21	Friday	7 am - 8 am	60	WWP: Managing Promises Daily Huddle: Fundamentals & Being Agile with exception	old
7	2-Jul-21	Friday	7 am - 8 am	60	Learning: Root cause analysis tools	new material
8	9-Jul-21	Friday	7 am - 8.30 am	90	LPS Simulation on Project + Evaluation part 1	case study
9	16-Jul-21	Friday	7 am - 8.30 am	90	LPS Simulation on Project + Evaluation part 2	case study
10	23-Jul-21	Friday	7 am - 8.30 am	90	LPS Simulation on Project + Evaluation part 3	case study
11	30-Jul-21	Friday	7 am - 8 am	60	LPS and Lean Assessment: Measuring lean maturity on project/company	new material
12	6-Aug-21	Friday	7 am - 8 am	60	LPS and Lean Assessment: Measuring lean maturity on project/company (2)	new material
13	13-Aug-21	Friday	7 am - 8 am	60	Introducing Lean Project Delivery System: IPD Concepts	new material
14	20-Aug-21	Friday	7 am - 8 am	60	Value Stream Mapping part 1 (concept)	old
15	27-Aug-21	Friday	7 am - 8 am	60	Value Stream Mapping part 2 (work session)	old
16	3-Sep-21	Friday	7 am - 8 am	60	Evaluation	work session
17	10-Sep-21	Friday				
				17.50	hours - interaction with PTPP	
				5.00	hours - minimum preparation	
				10.00	hours - maximum preparation	

Figure 2 Module Planning Example

This was followed by the top ten CoP LC participants. During the training, we learnt step-by-step how lean could be implemented; the success story project implemented lean and then discussed many things related to lean construction implementation in PTPP. To know how we understand the result of TFT, in parallel, we gathered by did an online workshop to transfer the knowledge to the project and continue Lean Sharing, which has several topics:

1. Lean Sharing-1: LPS Project Story PLTD Senayan
2. Lean Sharing-2: PP Planner (Implementation LPS by the digital tools)
3. Lean Sharing-3: Book Sharing – “Lean Thinking”
4. Lean Sharing-4: Between BIM & Lean
5. Lean Sharing-5: Value Stream Mapping
6. Lean Sharing-6: Introducing Lean Construction and Its Development
7. Lean Sharing-7: Waste Identification - DOWNTIME
8. Lean Sharing-8: Lean Culture – The Key to Lean Implementation
9. Lean Sharing-9: LPS – Lean Project Execution
10. Lean Sharing-10: Improve Productivity with Lean Project Execution
11. Lean Sharing-11: Lean 5S Implementation
12. Lean Sharing-12: Digital Lean Construction

Lean Sharing invited both an internal and external PTPP speaker to gain knowledge through its lean construction expertise. We rewarded the participants who actively reached out during the Q&A and often follow skinny sharing. Also, the community members got rewards from Knowledge Center (KC) point platforms when they became speakers in lean sharing, contributed to the CoP product output, did sharing through the CoP LC agenda and participated in the Training-For-Training (TFT) workshop. The other event was the 5S Challenge. CoP LC held this competition, and the participants were from different projects. This was a review of what and how the project implements 5S in the project. There was a winner of that competition: Stadion Banten Project, Engineering, Procurement & Construction (EPC) Divisions, and the Depo Makassar Project—three top projects chosen by assessment by internal and external PTPP expertise.

In the third year of CoP LC PTPP, we note that continuous improvement is a key factor that makes lean education successful and sustain at PTPP. This is aligned with approaches taken by the CoP lean, for example, providing a Training-for-Trainers and creating a structured and systematic sharing and learning means within a year. The provided training becomes a tool to yield new agents of lean within the company. The lean education is boosted not only by systematic sharing sessions, but also by providing reward to the company members who contribute to lean construction improvement at the company. Continuous improvement becomes a core value of CoP lean PTPP and it motivates CoP lean to provide novel topics for lean construction sharing sessions and yield an important milestone explained in the next section.

2022 – 2023

In 2022, CoP LC were continuing lean sharing with a new topic to be discussed:

13. Lean Sharing-13: Book Sharing – “The Second Lean”
14. Lean Sharing-14: Construction Waste Register
15. Lean Sharing-15: Integration LPS & CPM
16. Lean Sharing-16: Lean Implementation for Cost Performance

17. Lean Sharing-17: Takt Time Planning for Schedule Project Improvement
18. Lean Sharing-18: Dealing with Construction Waste by Lean Project Execution
19. Lean Sharing-19: Lean Canvas: The Simple Business Model
20. Lean Sharing-20: Lesson Learned K2R Neo 1.0 & Pull Planning Concept

Another learning that we have been through was by following The Lean Construction Conference online. There were so many topics that were related to current conditions, so we were equipped with knowledge and experience from aboard. In 2023, CoP got some highlights of the agenda; one of them was to present our journal of production, planning and control with focusing waste registered. The title of PTPP's journal was Lean Construction Through Waste Register Method: A Case Studies Project in Indonesia. The journal focuses on implementing lean construction for physical construction waste. Furthermore, this article presented Indonesian case studies to illustrate the impact of lean construction on building projects. The study analysed waste management impacts across three periods of time. Lean waste management provided an early warning evaluation in the short term that was used as an indicator so the project could evaluate and follow up as an effort to reduce waste, which in this study showed a reduction of waste from 2.1% to 1.7%. Addressing common waste in the medium-term increased project productivity by 50% and improved cost and duration efficiency. It reduced many possible wastages due to defects, overproduction, non-utilised talent, inventory, transportation, motion, waiting, and extra processing (DOWNTIME). Sustainable waste reduction practices could become a productivity standard in the long term by continuously improving the cycle of writing, categorising, analysing, and writing for each job.

We presented our journal in Lille, France, for the first time and only for Indonesia as a presenter. The goals were reaching out insights through the lean construction international conference, establishing strategic partnerships with practitioners and academics in the international scope, improving PTPP's branding in the implementation of lean construction and getting insight into lessons learned on project site visits on an international scale to increase lean construction awareness for the futures. After IGLC's 2023 in June-July 2023, we moved into the Indonesian competition of lean construction (K2R Neo) event on 1 October, 2023. As mentioned before, this agenda was held by academic institutions and followed by Indonesian construction practitioners and academicians. CoP prepared seriously until we won two champions at once. The goal following this event as an innovative collaboration platform was to gain a deep understanding and competency in the lean construction concepts of the LPS.

The other agenda by CoP LC presents Lean Construction Day 2023 (LCD 2023). PTPP's Lean Construction Day 2023 was one of the agendas for increasing the competency of project participants in the form of sharing sessions, talk shows, workshops, and other similar activities regarding the implementation of lean construction, which were carried out by PTPP through its CoP LC. A similar agenda was previously carried out in 2022 and was then carried out again on 3 November, 2023. The purpose of LCD 2023 was to: 1. Accelerate the increase in corporate knowledge in implementing lean construction; 2. Refreshment of knowledge and experience of implementing lean construction from the perspective of regulators (Ministry of Public Works & Housing - PUPR), academics (Dr. Gao Shang) and practitioners (PTPP) and 3. Creating value-added in the form of positive branding to stakeholders that PTPP was concerned with implementing lean construction and PUPR Ministerial Regulation No. 9 of 2021: Guidelines for Implementing Sustainable Construction.

FURTHER CHALLENGES TOWARDS SUSTAINABLE LEAN CONSTRUCTION

Lean implementations (in construction and beyond) because of barriers hindering successful implementation, including respect for people who are not specific to construction. These challenges involved an excessive focus on continuous improvement and a lack of complete understanding or underestimation of the importance of respect for people to the sustained success of lean principles (Korb, 2016). Beyond those initial barriers, a further challenge towards sustainable lean construction was creating the same perception of future constructions. People, which is one of the critical aspects, can be developed through CoP at the company and have the same vision to disseminate lean principles as a community. In the CoP Lean PTPP, the majority of CoP members were young people who tended to have the courage to make a better change through continuous improvement actions. After people, the big challenge towards LC implementation was the systems, which we identified to three points. The first point was that the company needed agents of lean. These people had roles to continue, evaluate, and improvise LC implementation. The second point was that LC implementation standards and legal were mandatory for every project in PTPP. The last point was the involvement of the top management, which could influence the adoption and implementation of LC at the company.

CONCLUDING REMARKS

This work describes the effort and learning of lean construction education at the PTPP, which started adopting lean thinking in 2019. In particular, lean education at the company was conducted through a community of practice, which became a place to learn and share theories, experiences, practices, and tools related to lean construction. CoP lean at PTPP, in the last four years, has disseminated learning throughout the company members, including top management level and company experts. Lean sharing has become the most frequent activity for raising awareness and understanding of the concept. It was then made into a more significant event, Lean Construction Day, which disseminated lean construction to broader participants and involved universities. At the project level, team members also received hands-on training about the Last Planner System using Villego. CoP was an excellent strategy to raise people's awareness and understanding. The company must have agents of lean to ensure that the learning process continues throughout the time and did not depend on the company member's position. However, some challenges remained regarding the system for developing sustainable lean construction at the PTPP. Top management support was the most important because of their influence and authority in establishing standards and legal lean construction implementation at the company.

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COLLABORATION STRATEGIES FOR INFRASTRUCTURE PROJECTS OF GERMANY'S FEDERAL WATERWAYS AND SHIPPING ADMINISTRATION

Elisa Schwarzweller[1] and Shervin Haghsheno[2]

ABSTRACT

The improvement of collaboration in construction projects can lead to a more stable and efficient project delivery. Nevertheless, Germany's Federal Waterways and Shipping Administration (WSV) has limited experience with strategically implementing elements to promote collaboration in construction projects. Therefore, initial steps have been taken in the WSV by identifying major infrastructure projects along Germany's waterways to initiate the implementation of collaborative elements, such as Lean Construction methods. The aim thereby is to make experiences to improve future projects. This article describes a research project which was set up to systematically record and document experiences with collaboration elements in selected pilot projects. Also, the outcomes of an initial survey which gives insights into the pilot projects are presented. Furthermore, the results of a survey regarding experiences during the procurement phase of one chosen pilot project are presented. The results show that there is no clear definition of collaboration within construction projects in the WSV and that there is a need for further research to develop solutions and recommendations for the improvement in future projects by utilizing collaboration elements.

KEYWORDS

Collaboration strategies, infrastructure projects, waterway construction, system change.

INTRODUCTION

Collaboration between the participants of construction projects promotes the achievement of objectives and increases efficiency in planning and building services. Therefore, the implementation of elements to improve collaboration in projects is recommended in the Reform Commission for Major Construction Projects, the Planning Acceleration Strategy, as well as in the Major Projects Guideline by the German Federal Ministry for Digital and Transport (BMDV 2015, 2017, 2018).

Especially, large and complex construction projects are not usually accomplished within the intended time frame and budget. This also applies to projects of the Federal

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Waterways and Shipping Administration (WSV). For example, in some projects of the WSV the prescribed budget was exceeded by more than 30 %, and the construction time was doubled. In various water lock projects along Germany's waterways, it even has been observed that both the construction time and costs have quadrupled. (Schwarzweller et. al 2023) For example, these problems can be addressed by the utilization of methods that promote collaboration in construction projects, such as Lean Construction methods or Building Information Modeling.

Up to this point, there are only limited experiences within the WSV of implementing collaboration elements that potentially lead to more stable and efficient project deliveries. With this background, initial steps have been taken by the Federal Waterways and Shipping Agency (GDWS) to gather experiences with a strategic promoting of collaboration elements in the delivery of construction projects along Germany's waterways. Therefore, several infrastructure projects were identified throughout the WSV. Additionally, in 2022, a 'Charter for Collaboration on Construction Sites along Federal Waterways' was created and signed between the Association of the German Construction Industry (HDB) and the WSV. (WSV 2022)

The Institute of Technology and Management in Construction (TMB) of the Karlsruhe Institute of Technology (KIT) supports the GDWS, as organization unit of the WSV, with a systemized recording and documentation of the experiences in the selected projects. The aim hereby is to develop solution approaches and recommendations for the strategic implementation of collaboration elements to improve project deliveries of future projects along Germany's waterways. This paper presents the first results of the systemized recording and documentation of experiences up to this point.

COLLABORATION ELEMENTS IN CONSTRUCTION PROJECTS

In construction projects, the terms collaboration and cooperation are commonly used interchangeably in literature as well as intentionally distinguished from each other (Camarinha-Matos et al., 2009, p. 47). Therefore, it is not consistently possible to precisely delineate what is meant by these terms. Below are exemplary definitions for collaboration and cooperation.

Cooperation can be defined as "the authentic pursuit of the goals of the respective contracting partner or a goal alignment of the partners, in order to achieve a 'win/win' situation" (Schlabach, 2013, p. 50). Furthermore, according to Camarinha-Matos et al. (2009, p. 48), cooperation can also be understood as communication, information exchange, mutual activity adjustments, and shared resource utilization aimed at achieving common goals.

In contrast to cooperation, collaboration can be understood as a more enduring and comprehensive form of cooperation, where previously separate organizations work intensively on a common mission within a new structure (Mattessich & Monsey, 1992, p. 42). Additionally, collaboration is also perceived as a more communicative, intensive, and holistic form of cooperation, where the shared commitment to achieving project success and the establishment of a communal project culture are essential (Ibrom, 2022, p. 46).

Based on a literature review of various definitions of cooperation and collaboration, Schöttle et al. (2014, p. 1274) have developed an overview that allows differentiation based on various factors. The resulting definition of collaboration is meant when using the term within this study:

> *Collaboration is 'an interorganizational relationship with a shared vision to create a joint project organization with a collectively defined structure and a new and*

> *collaboratively developed project culture based on trust and transparency, aiming to maximize customer value collaboratively by solving problems through interactive processes that are jointly planned, and by sharing responsibilities, risks, and rewards among the key stakeholders'*
>
> (Schöttle et al., 2014, p. 1275).

There are various elements to promote collaboration in construction projects. These can be categorized into project culture and conflict management, organizational and procurement models, incentive systems within the compensation model, as well as methods to promote collaboration.

In many countries the necessity to improve collaboration in construction projects has been identified. Therefore, the implementation and utilization of work methods as well as project delivery models that promote collaboration are intensively discussed, e. g. in France (Attouri et al. 2023), Norway, Denmark (Paulsen et al. 2023), Peru (Prado Lujan & Murguia 2022), India (Pal & Nassarudin 2020), Lebanon (Abou Dargham et al. 2019), China (Li & Ma 2017), Saudi Arabia (Alsaggaf & Parrish 2016) or Colombia (Forero et. al 2015).

ANALYSIS AND EVALUATION OF COLLABORATION ELEMENTS IN WATERWAY INFRASTRUCTURE PROJECTS

OBJECTIVES AND STEPS OF THE RESEARCH PROJECT

Based on the assumption that successful implementation of construction projects is facilitated, among other factors, by the utilization of collaboration elements, the GDWS has developed a procurement strategy for major projects. Within this strategy, pilot projects were identified to initiate the implementation of collaborative elements and to gather experiences. Table 1 contains the 8 selected infrastructure projects in the field of waterway construction for this purpose.

Table 1: Overview of selected pilot projects

No.	Type of structure	Location	Brief description of undertaking
1	Weir	Wieblingen at River Neckar	Replacement construction
2	6 Weirs	Erlabrunn, Harrbach, Steinbach, Rothenfels, Faulbach and Freudenberg at River Main	Complete maintenance
3	Water lock	Oberesslingen at River Neckar	Maintenance during operation
4	Water lock	Hessigheim at River Neckar	Landside soil improvement
5	Water lock	Kriegenbrunn at Main-Danube Canal	Replacement construction
6	Water lock	Herbrum at Dortmund-Ems Canal	Demolition of old lock & new construction
7	2 Water locks (small)	Kiel at Kiel Canal	Replacement construction
8	Dry dock & gate berths	Brunsbüttel at Kiel Canal	New construction

The Institute of Technology and Management in Construction (TMB) of the Karlsruhe Institute of Technology (KIT) supports the GDWS with a systemized recording and documentation of the experiences in the selected projects. In the course of the scientific support, the following overarching goals are pursued in particular:

- Development of common terms and systematic approach of the diverse elements to promote collaboration in waterway construction projects.
- Elaboration of a systematic approach ('Roadmap') and an overview ('Project Map') for testing relevant elements, considering already initiated experiences.
- Project-accompanying systematic recording and documentation of experiences within the projects.
- Development of recommendations for implementation of elements within the structure and processes of the WSV based on the evaluation of projects.

All the selected projects share a high level of complexity. Furthermore, all projects are of great relevance for ensuring the operational functionality of waterways in Germany. However, table 1 indicates that the projects not only differ in terms of the type of structure but also in terms of the respective undertaking (e. g. new construction, complete maintenance). In addition, the chosen project delivery models differ, as well as the current stages of completed phases in each project. Due to this variety and complexity, a suitable systematization of data becomes necessary to enable a proper capture of experiences.

A high number of project participants must be involved when it comes to the collection and evaluation of experiences within the projects. To improve the exchange of experiences among project participants a platform called Soundingboard was established in the WSV. It takes place semi-annually in person and facilitates feedback with those responsible for the procurement strategy of GDWS, as well as with the scientific support of TMB. Additionally, a so-called 'Online-Board' takes place digitally in shorter cycles to keep the project participants up to date about relevant topics, e. g. Lean Construction methods.

To systematically collect experiences, methods of empirical social research are being utilized. At first, structural and general correlations as well as the measurement of social incidents need to be examined within the pilot projects. Therefore, a quantitative research method has to be used. As a second step, a qualitative research method has to be used to explain the reasons for the outcome of quantitative research methods. (Raithel 2008)

The first quantitative approach to collect experiences within the pilot projects is described in the following chapter 'data collection with project questionnaires'. The second quantitative approach to collect experiences in the procurement phase of a chosen pilot project is described in chapter 'experiences during the procurement phase'. In both cases the qualitative approaches are in progress and will be part of further research. For example, expert interviews can lead to a deeper understanding of the participants‘ statements in the foregoing surveys (Marotzki 2006).

DATA COLLECTION WITH PROJECT QUESTIONNAIRES

For the data collection in the pilot projects, a questionnaire was designed to be filled out semi-annually by the respective project managers. This questionnaire will be continuously adjusted to fit the projects' development. In the following, the segments of the questionnaire for the first data collection are presented:

- brief project description
- alternative organization and procurement model
- incentivized compensation structure
- further approaches to improve collaboration
- involvement of external support
- insights and suggestions for further development

The segment *'brief project description'* contains the project's title, a summary of content and tasks, volume, duration, and necessity of the project. These details enable a quick overview of the selected projects and are intended to be incorporated into a project map which can be used as a control tool in the future by the GDWS.

Originally, the procurement strategy for major projects mainly focused on testing procurement models which were utilized rarely in the WSV up to this point. However, within the scientific support a holistic approach is being pursued, amongst others including organizational and compensation-related approaches.

Therefore, in the segment *'alternative organization and procurement model'* the questionnaire contains the procurement model for planning services, the procurement model for construction services, the utilization of a 2-phase-model, and the type of performance specifications. Additionally, the current label of the project's alternative strategy, costs for the procurement phase and the reasons for choosing an alternative strategy are requested. The segment *'incentivized compensation structure'* currently focuses on the compensation system for building services and requests the existence of a bonus malus system.

The alternative organization and procurement model as well as the incentivized compensation structure themselves are considered as elements that can improve collaboration within a project. Hence, the questionnaire contains *'further approaches to improve collaboration'*, such as a project kick-off, team reflections, conflict-solving mechanisms and other collaborative project management and work methods.

With a view to future projects, it is also of high relevance to the GDWS to estimate the costs and necessity of external services. That is why the segment *'involvement of external support'* was included. It contains the information about the support of legal advisors, support of technical advisors, services of coaches (e. g. Lean Coaches), costs for external support and special experiences made with the external support.

Furthermore, an additional segment *'insights and suggestions for further development'* was added. This segment enables an open collection of additional findings and can be used to share suggestions for further development.

INSIGHT IN ANALYSIS OF QUESTIONNAIRES

In the following, a selection of the data given in the first questionnaires is presented and discussed. The data show that the project volumes range from 16.7 million (project No. 4) to 650 million (project No. 7) euros. However, these numbers should be questioned critically because the included costs are interpreted differently for each project. A similar issue appears for project durations. For example, in some projects the start is interpreted as the project's approval whereas in others as the beginning of the planning phase.

A clearer picture is drawn by the utilized type of procurement model in each project. As shown in table 2, in 7 projects a negotiated procedure with prior competition was chosen. Only in 1 project no information is provided due to the project's early status. In 5 projects a functional specification is utilized and in 2 projects a detailed specification is utilized. Moreover, in two projects a 2-phase model is established. In 5 of the projects a general contractor is contracted for the building services. Moreover, there is 1 project with a total contractor and 1 project using a multi-party-agreement within an Integrated Project Delivery. The compensation models are distributed to 3 projects using a fixed price, 1 using direct costs, 1 using a mixed model, 1 using unit prices and 2 have no information provided yet. In 3 projects an incentive system is established and in 2 projects the utilization of an incentive system is currently discussed. In 2 projects no information is provided yet and 1 project replied that no incentive system is utilized.

Table 2: Elements: procurement model, 2-phase model, organization, and incentivized compensation

Project Element	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8
Procurement model	neg. wpc.*	neg. wpc.	neg. wpc.	neg. wpc.	neg. wpc.	neg. wpc.	neg. wpc.	neg. wpc.
Service specification	func.**	func.	func.	detailed	detailed	-	func.	func.
2-phase model	yes	no	yes	no	no	-	no	no
Organization model (build)	general contr.***	general contr.	total contr.	general contr.	general contr.	-	general contr.	multi-party
Compensatio n model	-	fixed price	fixed price	mixed forms	unit prices	-	fixed price	direct costs
Incentive system	-	perhaps	perhaps	yes	no	-	yes	yes

*negotiation with prior competition; **functional; ***contractor

The combination of the organization and procurement model, and the type of performance specifications, together with the incentivized compensation structure will lead to specific terms to describe each project's delivery model. This is necessary to address the lack of commonly used terms in the WSV.

Besides the elements mentioned above the projects implement further approaches to improve collaboration, as shown in table 3. In 6 projects a project kick-off is or will be utilized, 5 projects include team-reflections. Conflict-solving mechanisms are included in

5 projects. Additionally, Lean methods and/or Building Information Modeling are named as further approaches to improve collaboration in 5 projects.

Table 3: Elements of further improvement of collaboration

Project Element	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8
Project kick-off	-	yes	yes	yes	yes	-	yes	yes
Team reflections	-	yes	yes	yes	yes	-	no	yes
Conflict-solving	-	yes	yes	no	yes	-	yes	yes
Collaborative methods	-	no	yes (Lean)	yes (BIM)	yes (BIM, Lean)	-	yes (BIM)	yes (Lean)

A lack of information in the filled-out questionnaires can generally be explained by a project's early status. Additionally, it can be mentioned that after the first data is collected the questionnaires must be partly specified to avoid room for interpretation for any following data collections to ensure a better comparability between projects.

COMPREHENSIVE INSIGHTS INTO A R&D WATERWAY INFRASTRUCTURE PROJECT

PROJECT DESCRIPTION

In a second quantitative approach the experiences in the procurement phase of one particular pilot project are examined. The project 'Component Tests Oberesslingen' (Project No. 3, table 1) is an R&D project and aims to gain practical experiences in several methods for maintaining water locks under continuous operation. This means that the maintenance is alternating with the locking of ships. The definition of the duration for the maintenance per day is project specific. (Westendarp 2017) The maintenance of the 'Component Tests Oberesslingen' on River Neckar must be performed within 12 h per day.

Generally, to maintain a complete water lock can take up to 3 or more years. During this time, the water lock is out of operation, which is unacceptable considering the consequence of shifting freight transportation to alternative traffic carriers, like streets and railways. The significance of this circumstance becomes even clearer when looking at a high demand for maintenance and a lack of redundancy, with a total amount of circa 260 water locks in Germany that only have one chamber. To bypass this problem, the only alternative to conventional maintenance currently is to construct a replacement lock, which generally comes with high costs and needs significant space. Therefore, maintenance under continuous operation can be a meaningful alternative for the WSV in future. (Westendarp 2017)

The component tests include amongst others: a mobile inspection closure, the installation of dam boards in guide rails, the demolition of chamber walls by milling and high-pressure water jetting, reprofiling chamber walls with pre-cast segments, in-situ concrete, bulkheads, and shotcrete. The different methods will be tested on different blocks of the chamber while the filling and draining within the 12 h closure will be simulated. Adding to this, the reprofiling of chamber walls with pre-cast segments and in-situ concrete containing micro-hollow spheres will be tested during a full closure.

Due to the high complexity in planning and construction, a project specific so called ‘Partnering Package Model’ was chosen for the delivery of the project. In this context, the term ‘Package’ means that planning and construction services are awarded to a total contractor through a negotiated procedure with prior competition. This allows the expertise of construction companies to be already incorporated during the preparation of bids before the award of the contract. (HKLW 2020) Regarding the term ‘Partnering ’, the preamble of the contract between the client and the contractor notes that the parties intend to shape a project collaboration based on the ‘Charter for Collaboration on Construction Sites along Federal Waterways’ (WSV 2022).

Furthermore, the contract includes a section related to the implementation of a collaborative decision-making process. Additionally, other project documents, such as the functional performance specification, contain expressions like ‘collaborative coordination’, ‘collaborative processing’, or ‘collaboratively decided’. However, the specific implementation of this collaboration is not conclusively defined, allowing a level of creativity for the project participants.

EXPERIENCES DURING THE PROCUREMENT PHASE

For this particular project a survey was used to save the experiences made in the procurement phase, including a foregoing market study, the prior competition, and the negotiated procedure including two negotiation rounds, as shown in Figure 1.

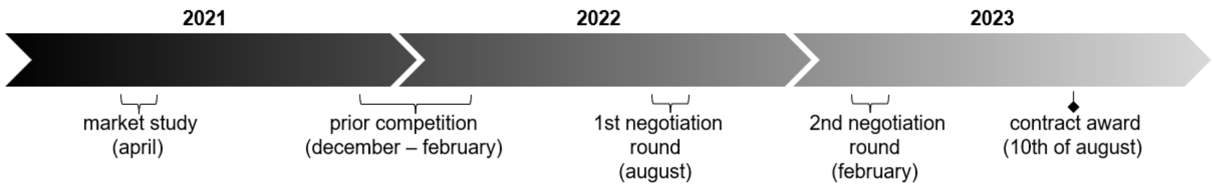

Figure 1: Procurement phase of the project 'Component Test Oberesslingen'

Both perspectives, of the client and the bidders, were taken into account. The condition to be contacted as a participant of the survey was the participation in least one of the procurement phase’s steps (market study, prior competition and negotiated procedure). This includes in total 64 persons on the bidders’ side and 17 persons on the client’s side who received a survey link via email. 19 of 64 persons on the bidders’ side and 10 of 17 persons on the client’s side filled out the survey. A higher number of participants might have been achieved by sending the survey earlier. However, the survey was sent 2 months after the contract had been awarded. The effect may have been enhanced for bidders that had not been awarded due to a loss of interest in the procurement phase.

Due to the number of participants and the fact that this survey concentrates on a project-specific procurement phase the data cannot be generalized. Nevertheless, it shows tendencies and gives ideas for further research. In the following, a selection of data focusing on the negotiated procedure is presented and discussed. The examples in Figures 2 through 7 give an insight of the different perspectives on client’s and bidders’ point of view in the procurement phase of the ‘Component Test Oberesslingen’.

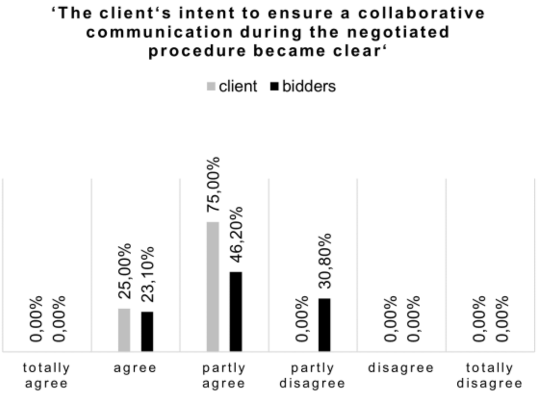

Figure 2: communication with bidders

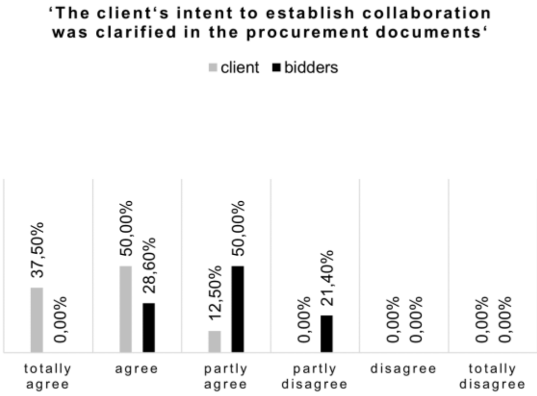

Figure 3: procurement documents

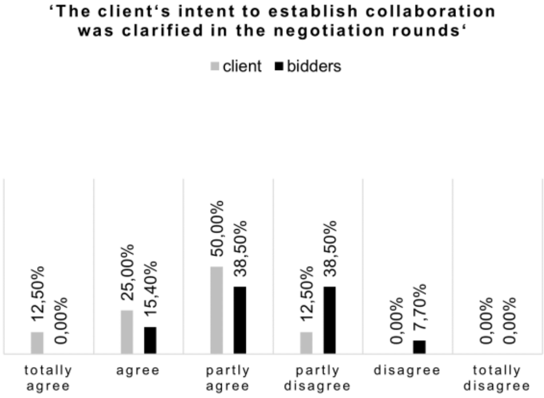

Figure 4: negotiation rounds

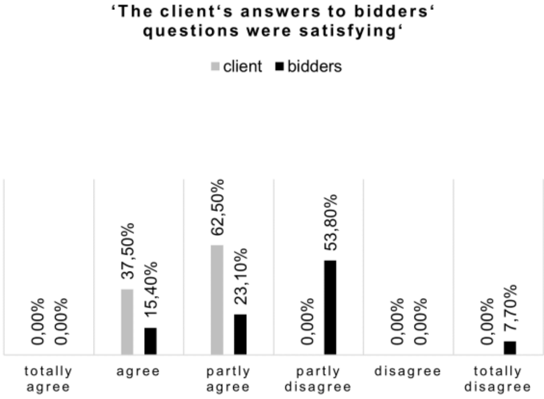

Figure 5: bidders' questions

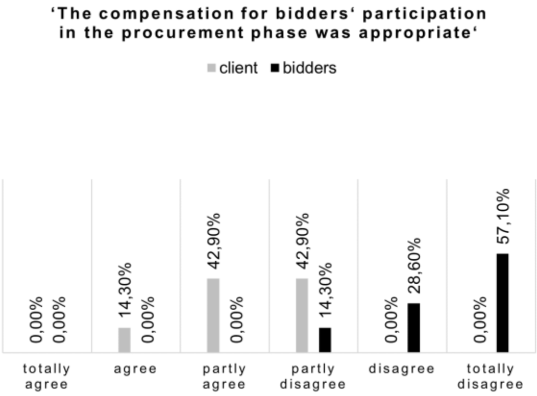

Figure 6: procurement phase compensation

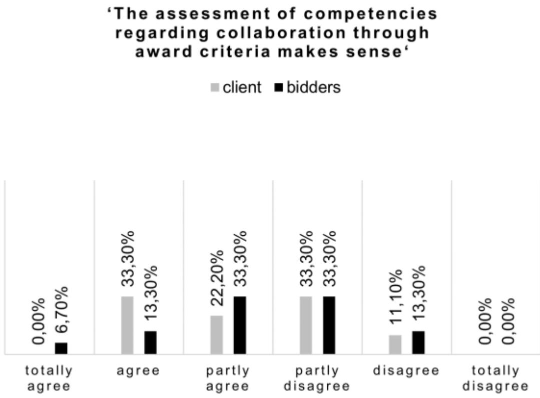

Figure 7: collaboration in award criteria

On the client's side as well as on the bidders' side 0,0 % of the participants disagreed or totally disagreed on the statements 'the client's intent to ensure a collaborative communication during the negotiated procedure became clear' (Figure 2) and 'the client's intent to establish collaboration was clarified in the procurement documents' (Figure 3). Nevertheless, it is noticeable that the tendency to agree to both of the statements is higher on the client's side. This tendency is also visible in the answers regarding the statement 'the client's intent to establish collaboration was clarified in the negotiation rounds' (Figure

4). A possible reason for the discrepancies between both perspectives could be a different understanding of the term collaboration. Even though the client had developed an understanding about collaboration on his side, the term might not have been defined and communicated clearly enough and by this also left room for interpretation in the procurement documents.

During the negotiated procedure bidders' questions were answered by the client via a digital platform. The tendency to agree with the statement 'the client's answers to bidders' questions were satisfying' (Figure 5) again is higher on the client's side. A possible reason for the discrepancies could be that the client answered bidders' questions as detailed as possible but could not address each question as needed to remain equal treatment of each bidder. On bidders' side this could have led to confusion or to unsolved problems during the work on their offers.

In the end of the procurement phase all bidders providing a final offer received a compensation of 75,000 euros. A majority of 57,1 % on bidders' side totally disagreed with the statement that 'the compensation for bidders' participation in the procurement phase was appropriate' (Figure 6). Participants on client's side tend to respond more favorably to this statement. Possible reasons for this distribution of answers could be that the client might have underestimated the required work on bidders' side to fulfill the requirements for the final offers. Also, the procurement phase lasted longer than expected. On the other hand, the required work described in the procurement documents might have been underestimated by the bidders as well.

The award criteria in the procurement phase of the 'Component Test Oberesslingen' did not include any criteria regarding collaborative competencies of the bidders. Nevertheless, in a general question the participants were asked about their opinion on the assessment of these criteria. Besides others, this question was included in the survey to receive an insight into the motivation to participate in future procurement procedures including award criteria regarding collaborative competencies. As shown in Figure 7 there is no clear tendency shown in the distribution of answers on the bidders' and on the client's side.

Currently, experts on bidders' and client's side are interviewed to find out more about the possible reasons for the discrepancies in the survey's outcome. It is intended to take the same steps (survey and following expert interviews) within the other 7 pilot projects to ensure a better comparability between projects.

CONCLUSION

In the WSV, first steps have been taken to establish and promote collaboration in construction projects. This includes, for example, the 'Charter for Collaboration on Construction Sites along Federal Waterways' with the HDB. Additionally, another charter is currently being developed between the WSV and design offices. Nevertheless, there are limited experiences with the strategic promoting of collaboration in projects along Germany's waterways, such as the implementation of Lean Construction methods. Therefore, major infrastructure projects were identified throughout the WSV to initiate the implementation of collaborative elements and to gather experiences.

The strategic implementation of collaboration elements in the WSV as a public client in Germany is a new use case for academia. Furthermore, the upcoming changes require the adaptation of the construction industry to new forms of project deliveries in projects along Germany's waterways.

This contribution hereby focuses on 8 selected infrastructure projects and discusses first outcomes of a data collection. This data is intended to be systematized and analyzed to develop solution approaches and recommendations for future projects. The first results show that there is no clear definition of collaboration within construction projects in the WSV and that there is a need for further research because it is not possible to make sound recommendations for future projects yet. The need for further research can also be emphasized by the current lack of qualitative research results. Adding to this, more quantitative research results are needed to deduce general conclusions from the first gathered tendencies.

Major projects within the WSV tend to significantly exceed cost and time frames. The solution approaches and recommendations made in further research potentially have a meaningful influence on the stability and efficiency of future project deliveries of projects along Germany's waterways.

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DRIVING THE MOMENTUM TOWARDS ADOPTING WEARABLE COGNITIVE ASSISTANCE IN LEAN CONSTRUCTION 4.0

Amira Eltahan[1], Lynn Shehab[2] and Farook Hamzeh[3]

ABSTRACT

Despite the transformative potential of Wearable Cognitive Assistance Devices (WCADs), their integration into the construction industry remains limited, marked by challenges such as practicality and regulatory barriers. Additionally, the increasing interest in implementing Lean principles in construction for enhanced project performance creates a potential intersection. This study aims to bridge both concepts by developing a conceptual framework for the implementation of WCADs in construction tasks within the Lean Construction 4.0 paradigm. It first explores the current state of WCAD in various industries and proposes a WCAD implementation framework for construction. The framework employs a stepwise approach, and its theoretical implementation in masonry works illustrates its adaptability to specific construction contexts. This framework's contribution lies in its potential to offer dynamic, adaptive, and personalized support, optimizing cognitive functions, and promoting safer and more productive task execution. This framework utilizes wearable sensors as one it's data collection methods; thereafter, the integration of the data collected will then provide users with near real-time feedback to mitigate risks and enhance workers performance. As a theoretical foundation, this research paves the way for practical validation and future enhancements, aiming to enhance the construction industry's approach to worker well-being and performance.

KEYWORDS

Lean Construction, Design Science, Continuous Improvement, Wearable Cognitive Assistance.

INTRODUCTION

In the dynamic nature of construction, where innovation meets the rigors of the job site, Wearable Cognitive Assistance Devices (WCADs) emerge as transformative tools to redefine how tasks are executed and managed. These devices, equipped with advanced sensing technologies and real-time cognitive support capabilities, hold the potential to improve the construction industry's approach to worker well-being, safety, and overall productivity.

WCADs can be envisioned as intelligent companions for construction professionals and practitioners, seamlessly integrating into their work environment to provide not only physical assistance but also cognitive support. These devices comprise of a combination of wearable sensor devices (WSDs), including but not limited to Electrocardiogram (ECG) sensors, Skin conductance sensors, Temperature sensors, Electrodermal Activity Sensors (EDA), Electroencephalogram (EEG) Sensors, and more (Shehab & Hamzeh, 2023). By collecting physiological data from WSDs, such as heart rate, skin conductivity, and brainwave patterns,

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WCADs gain holistic insights into the wearer's cognitive state and physical well-being. These devices transcend traditional wearables by not only tracking physical activities but also offering real-time feedback and assistance based on the wearer's cognitive state and the specific tasks at hand (Belletier et al., 2021). Imagine a construction professional receiving instant alerts about potential safety hazards, personalized guidance on optimal work postures, or timely reminders to mitigate fatigue—all delivered through a compact, unobtrusive wearable device.

Despite their transformative potential, the integration of WCADs into the construction industry has not been fulfilled yet. Therefore, this study seeks to explore the merging of WCADs with Lean Construction 4.0 (LC 4.0) —a paradigm that converges traditional Lean principles with the transformative capabilities of Industry 4.0 technologies (Sanders et al., 2016). Through the lens of this merging, the aim of this study is to develop a conceptual framework for the effective implementation of WCADs in construction tasks. LC 4.0, a strategic merging of methodologies, emphasizes efficiency, waste reduction, and continuous improvement while leveraging advanced digital tools.

The principles of LC 4.0 prioritize the well-being of the construction team and are complemented by cutting-edge technologies (Hamzeh et al., 2021), including sensor network devices that are suggested in this study. These technologies not only monitor the site but provide real-time insights that enhance safety and allow immediate responses to challenges, aligning with the objective of improving workers' well-being, safety, and productivity through WCADs.

The synergy between LC 4.0 principles and WCADs offers a dynamic and adaptive system, connecting the transformative potential of both methodologies to drive sustainable improvements in construction project management. The proposed framework offers near-real-time feedback based on the collected cognitive data from construction workers. To achieve this, a stepwise approach is developed where it includes three major stages with a total of five steps.

Whereas the major objective is to gain a refined understanding of the worker's cognitive and physical state during task execution and thereby provide near-real time feedback. This paper begins with a literature review on LC 4.0 and WSDs. Afterwards, WCADs are introduced, and the conceptual framework is proposed. A theoretical implementation of the framework is presented, followed by final conclusions.

LITERATURE REVIEW

LEAN CONSTRUCTION 4.0 PRINCIPLES AND TOOLS

Lean Construction 4.0 (LC 4.0) represents a convergence of traditional Lean Construction principles with the transformative capabilities offered by Industry 4.0 technologies. Industry 4.0, characterized by the integration of digital technologies, automation, and data-driven processes, has ushered in a new era of efficiency and innovation across various industries (Lasi et al., 2014). In construction, the integration of Industry 4.0 into Lean Construction practices has the potential to enhance productivity, improve workers' safety and wellbeing, and optimize resource utilization (Noueihed & Hamzeh, 2022).

Several researchers have explored the relationship between Industry 4.0 and Lean Construction, recognizing the similar nature of both approaches. Studies such as that conducted by Sanders et al., (2016) have explored the impact of Industry 4.0 technologies on traditional Lean principles, shedding light on how advancements like Internet of Things (IoT), big data analytics, and automation can reshape lean methodologies.

Other studies (Hines et al., 2023; Karmaoui et al., 2023) have also provided perspectives on the interplay between Industry 4.0 and Lean Construction through the analysis of existing practices, applications, and technologies. They collectively emphasize the transformative potential of integrating digital technologies and lean principles in construction.LC 4.0, therefore, is not merely an integration of terms, but a strategic merging of methodologies aimed at creating a holistic and technologically advanced approach to construction project management. The utilization of Industry 4.0 technologies within Lean Construction practices presents opportunities for real-time monitoring, predictive analytics, and improved decision-making throughout the project lifecycle (González et al., 2022). As the construction industry continues to evolve, LC 4.0 emerges as a pivotal paradigm that not only embraces the advancements of the Fourth Industrial Revolution but also harnesses them to drive sustainable improvements in the construction industry's overall efficiency and effectiveness.

At its core, LC 4.0 emphasizes the relentless pursuit of efficiency, waste reduction, and continuous improvement, all while leveraging advanced digital tools to enhance these objectives (González et al., 2022). However, the principles and tools are not just about cutting-edge technologies; they are centered around enhancing the human experience within construction projects. The principles prioritize the well-being of the construction team, focusing on minimizing risks and overburden and ensuring that every effort contributes meaningfully to the project.

Some of the main technologies for Construction 4.0 were discussed by (McHugh et al., 2022), such as Building Information Modeling (BIM), which acts like a shared visual language that brings everyone together, fostering collaboration and understanding. Moreover, Artificial Intelligence (AI) enables analyzing data to predict potential obstacles or threats and offers valuable insights for informed decision-making. Reality capture is another technology that captures construction sites as point cloud models for depicting real site conditions, providing significant aid in building spatial awareness within the production team, producing realistic ad systematic construction logistics and site planning, and more (McHugh et al., 2022).

From a human-centric perspective, these technologies can be used to train construction teams for safety and hazard prevention and recovery drills, all while avoiding real injuries or risks. Finally, Internet of Things (IoT) and sensor network devices act as essential enablers, not just monitoring the site, but providing real-time insights that enhance safety and allow immediate responses to challenges. Safety and hazard indicators are described as sensors that detect potential safety hazards and notify the production team by providing safety alerts are warnings (McHugh et al., 2022). They also aim at capturing worker health and safety conditions with the ultimate goal of maintaining productive and healthy workspaces.

WEARABLE SENSOR DEVICES (WSDS)

The advancement of wearable sensing technology in recent years has expanded the potential for monitoring workers’ behaviour on construction sites. Researchers have explored the potential of using wearable sensors for worker behaviour monitoring. Such sensors collect data including physiological responses (W. Lee et al., 2017; Shehab & Hamzeh, 2023), gaze movement (Cheng et al., 2022), musculoskeletal engagement (tendons, bones, etc.) (Alwasel et al. 2011), gait (Inertial measurement unit IMU sensors) (Ren et al., 2022), and posture (Nath et al., 2018; Ren et al., 2022). These studies have demonstrated the effectiveness of using sensing-based approaches to study the factors affecting workers’ safety behaviour, such as emotion and stress levels. Physiological response data can be collected through various WSDs, such as Electrocardiogram (ECG or EKG) sensors, Skin conductance sensors (Galvanic Skin Response), Temperature sensors, Electrodermal Activity Sensors (EDA), blood pressure sensors, Electroencephalogram (EEG) Sensors, Electromyography (EMG) Sensors, Camera sensors, microphones and audio sensors, moisture and sweat sensors, chemical sensors, etc.

Regarding musculoskeletal involvement, gait, and posture, numerous studies have explored the movement patterns of physical activity, with a specific focus on the lower body movements of workers. These studies propose that the sensory data derived from lower body movements can offer valuable insights into workers' safety behaviours, particularly their responses to slip, trip, and fall hazards (Ren et al., 2022). This is attributed to the cyclical nature of lower body movements, where monitoring these movements can unveil individuals' responses to various environments or objects through alterations in leg movement patterns. For instance, research in construction safety has utilized gait data obtained from inertial measurement unit (IMU) sensors to examine how workers modify their walking patterns in high-risk conditions (Ren et al., 2022) or in proximity to slip/trip/fall hazards at construction sites (Yang et al., 2016). These studies indicate that employees alter their walking style upon identifying a nearby hazard or sensing a potential risk. Different sensory signals, including visual, auditory, and somatosensory inputs, influence the intentional regulation of human walking, impacting factors such as locomotion direction, speed, and the adjustment of stride to environmental limitations.

THE CURRENT STATE OF WSDS IN CONSTRUCTION

WSDs are becoming increasingly prevalent in the construction industry due to their potential to enhance safety, productivity, and overall efficiency on job sites. These sensors can provide real-time data and insights to both workers and management, helping to prevent accidents, optimize workflows, and improve decision-making. WSDs in the construction industry are gaining traction, but their adoption is not yet universal. They have witnessed a tremendous advancement over the course of the past 10 years. Yet the challenges that come with implementing it on construction sites have hindered the industrial use of these devices.

The emergence of wearables started in early 2010s with the first generation of smartwatches and fitness trackers (Mukhopadhyay, 2015). Thereafter, in mid 2010s the introduction of safety helmets and safety wearables were explored (Park et al., 2015). These helmets were designed to monitor workers’ movements to improve safety on construction sites. In late 2010s the augmented reality (AR) technology led to more advancement in the field of wearable technology including the development of eye tracking and AR glasses (Cheng et al., 2022).

The common objective in implementing WSDs in construction has been occupational safety and hazard assessment (G. Lee et al., 2021). Ahn et al. (2019) have divided the applications for implementing WSDs in construction health and safety as reported in literature into: preventing musculoskeletal disorders, preventing falls, assessing physical workload and fatigue, evaluating hazard recognition abilities, and monitoring workers’ mental status. Shehab & Hamzeh (2023) have summarized the use of physiological sensors in construction. They have identified 20 studies that measured physiological markers using wearable sensors and correlated it with performance (safety behaviours and productivity). Anwer et al. (2021) used textile wearable sensors measuring heart rate, breathing rate, and skin temperature to monitor physical fatigue. This study was conducted on bar bending and fixing construction tasks and a moderate to excellent correlations was concluded between physical fatigue and the measured physiological markers.

Ke et al., 2021 have attempted to detect distraction in workers using wearable electrocochleography (EEG). This study has established a link between attention (cognitive ability) and the measured signals of EEG. Exoskeletons (Nnaji et al., 2023) are used to reduce strain on workers body when strenuous activities are executed where WSDs are used to collect data related to fatigue and musculoskeletal engagement to reduce the risk of musculoskeletal injuries. Also, Kinematic sensors, including accelerometers and gyroscopes, were employed to record instances of workers narrowly avoiding falls and uncomfortable postures during their work (Nath et al., 2018).

Research on WSDs aimed to establish a link between using wearable sensors and individualized performance (safety behaviours, and self-reported productivity). However, no study has no study has systematically investigated the integration of Wearable Cognitive Assistance Devices (WCADs) within the context of LC 4.0 to enhance both the physical and cognitive aspects of worker performance. Existing studies often focus on the physiological aspects, neglecting the potential of cognitive support through real-time feedback. Therefore, this study aims to explore the application of these technologies as a tool to enhance workers' cognitive abilities and decision-making process through real-time feedback to proactively introduce remedial measures. By addressing this gap, our research aims to contribute valuable insights to the effective implementation of WCADs in construction, aligning with LC 4.0 principles and advancing the holistic well-being, safety, and productivity of workers.

METHODOLOGY

This paper aims to develop a conceptual framework for the implementation of WCADs in construction from an LC 4.0 perspective. To achieve this goal, this paper follows a Design Science Research (DSR) methodology. DSR is a scientific method for developing a new artifact that addresses an identified problem, followed by the evaluation of this artifact (Rocha et al., 2012).

In this study, the problem is identified as the unsafe conditions that prevail on construction sites and the lack of a real-time feedback system that provides workers with cognitive support to enhance their safety and well-being. Therefore, and in order to contextualize the study within LC 4.0, the paper begins with a comprehensive review of Lean Construction (LC) 4.0 principles and tools, followed by a review of WSDs in general and their current state in construction. Afterwards, the study proceeds to identify the gap: the absence of a real-time feedback system supporting workers' cognitive functions. This identification sets the stage for the introduction of WCADs and their applications, followed by the development of a conceptual framework for adopting WCADs in LC 4.0.

This framework aligns with LC 4.0 principles, which include continuous improvement, real-time monitoring, data-driven decision-making, worker-centric focus, and utilizing advanced digital tools. The framework is divided into three major phases which include model design, model development and cognitive assistance feedback as explained in section 5. To validate the theoretical implementation of the framework, it is tested theoretically on a masonry construction example.

WEARABLE COGNITIVE ASSISTANCE DEVICES

Wearable Cognitive Assistance Devices (WCAD) are wearable devices that offer real-time cognitive assistance. These devices can provide support and guidance through sending warnings or alerts based on the wearer's cognitive state and the tasks at hand (Belletier et al., 2021). They integrate the data collected using WSDs to offer a real time feedback using the collected data. There are various applications of WCADs, including healthcare, manufacturing industry, education and training, sports and fitness, and military and defence. In healthcare, they are used to monitor the patients' cognitive states to provide real time updates to healthcare professionals to ease timely interventions. In the manufacturing industry, they can be used to enhance safety by providing safety alerts to workers once it detects unsafe conditions. In sports and fitness, these devices are used extensively by various competing companies to provide users with personalized feedback and fitness programs based on the collected psychological data using wearable sensors. Regarding military and defence, WCADs can be used to track the vital signs of soldiers as well as enhancing their situational awareness. Table 1 lists some of the examples where WCAD are used in different industries and the objective of each of those applications.

Table 1. Examples of WCAD Applications in different Industries

Industry	Study	Objectives
Healthcare	Zhao et al., 2020	An automatic external defibrillator
	Wu et al., 2018	Wearable watch for monitoring patients with chronic compulsory pulmonary disease
Manufacturing	Oyekan et al., 2021	Tracking assembly tasks and ergonomic indicators
Sport and fitness	Hajj-Boutros et al., 2023	Tracking stress levels by monitoring heart rate, EDA, ECG, and skin temperature using wearable watch
	H. Jung et al., 2022	Provide a holistic view of wellbeing through sleep tracking, heart rate monitoring, and stress levels using a wearable watch
Military and Defence	Admile & Barguje, 2023	Situational awareness and monitoring vital signs

DEVELOPMENT OF CONCEPTUAL FRAMEWORK FOR USING WCADS IN LEAN CONSTRUCTION 4.0

The developed conceptual framework offers a way to implement WCADs in construction within the context of LC 4.0 by using the established work by various researchers, confirming the correlation between various physiological markers and various indicators on the performance of construction workers. Thereafter, such indicators could be used to offer near real-time feedback to workers to enhance their performance.

To achieve this, the conceptual framework presented in Figure 1 was developed. This framework is generic and could be tailored to any construction task of interest. Construction tasks requires physical strength for various activities such as lifting heavy materials, digging, carrying, welding, operating machinery, and performing tasks that require physical endurance. Therefore, enhancing individual performance is a key contributor to the overall project success. In this study, the definition of individual performance as introduced by Hurrell & McLaney, 1988 was adopted. It includes self-reported productivity and safety behaviours.

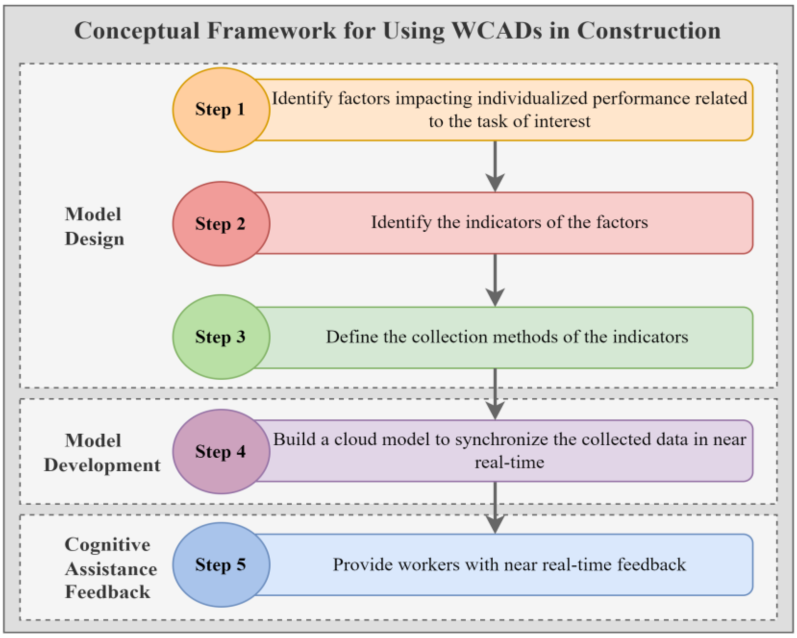

Figure 1. Framework for implementing WCADs in Construction

The first step in the framework is identifying the factors that could impact the individualized performance in the task of interest (Step 1). The purpose of this step is shortlisting the contributors to poor safety behaviours and loss of productivity. The nature of the task of interest is an important factor to consider, as construction tasks vary in terms of the required physical and mental workloads. For example, the demands and risks associated with masonry works are different than those of concrete works. Drawing from LC 4.0 principles, which prioritize efficiency and continuous improvement, the critical role of individual performance in overall project success is recognized.

After identifying the factors influencing performance, Step 2 involves determining the means to detect the existence of these factors. These detection methods, referred to as indicators, encompass various measures such as physiological markers, site conditions (e.g., environmental factors), and worker-based data (e.g., sleep patterns, stress levels, fitness levels). This step focuses on recognizing and quantifying the elements impacting individualized performance in construction tasks. It aligns with the LC 4.0 emphasis on real-time monitoring and data-driven decision-making.

Afterwards, the collection methods of these indicators need to be defined (Step 3). This step describes how these indicators are to be converted into quantifiable data to be able to perform further analysis. Such data could either be quantitative (physiological data from WSDs) or qualitative (questionnaires). Inspired by LC 4.0, where principles emphasize the relentless pursuit of efficiency and waste reduction, this framework ensures a harmonious integration of quantitative measures, such as physiological qualitative inputs. This holistic approach aligns with LC 4.0's emphasis on utilizing advanced digital tools for enhancing project objectives.

This framework aims to enhance the cognitive abilities through merging various forms of data collection methods to provide users with a proactive near real-time support during tasks execution. Since humans are not commodities, and since individual performance varies from one individual to another, it is important to capture these individual differences to be able to tailor the expected performance from one user to another. Therefore, step 4 involves the integration of diverse data collection methods, such as the aforementioned WSDs capturing physiological responses and qualitative inputs from questionnaires. These data then undergo a comprehensive sorting process. This sorting is executed in a secure cloud-based infrastructure that serves as the central repository for data integration and analysis. Within this cloud environment, data analytics are performed. These analytics examine the attributes of the collected data, recognizing patterns, correlations, and individual characteristics. The objective is to gain a refined understanding of the worker's cognitive and physical state during task execution. Individual differences are thoroughly calibrated during this analytical phase. External factors, including environmental conditions, and internal factors, including physiological responses, are factored into the calibration process. This ensures that the feedback provided is not only constructive but also highly personalized, acknowledging the unique characteristics of each worker. The aim of this step is to harness the power of data analytics within a cloud-based framework, offering a dynamic and adaptive system that goes beyond generic support. By tailoring feedback based on individual characteristics, the model optimizes its effectiveness in enhancing cognitive functions and promoting safer and more productive task execution. In alignment with LC 4.0 principles, this step emphasizes the individualized calibration of feedback considering external and internal factors.

Finally, in Step 5, users receive proactive near real-time support during task execution, aligning with the LC 4.0 principles of continuous improvement and worker-centric focus. Recognizing the inherent variability in individual performance among workers, this step underlines the significance of capturing these differences to customize expected performance tailored to each user. By integrating the LC 4.0 principles of optimizing human experience within construction projects, this model not only seeks to boost cognitive functions but also to contribute to LC's overarching goal of creating a safer, more productive, and efficient construction environment. Ultimately, this integration ensures that advancements in technology are employed not just for technological sake but with a profound commitment to improving the well-being and performance of the construction workforce, echoing the human-centric principles inherent in LC 4.0.

THEORETICAL IMPLEMENTATION OF THE FRAMEWORK IN MASONRY WORKS

In this section, a theoretical implementation of the developed framework in masonry construction is presented. Various factors impact the performance of construction workers and can lead to loss in reported productivity and poor safety behaviours, as listed in Table 2. Regarding the first factor, physical fatigue and posture are significant considerations in the occupational health and safety of masonry workers. The nature of masonry work, which often involves repetitive tasks, heavy lifting, and prolonged periods of standing or kneeling, can contribute to musculoskeletal issues and fatigue. Various researchers correlated between physical exertion/ fatigue and labour productivity using WSDs (Umer et al., 2020). In this study we adopted the technique used by Umer et al., 2020 by using the EQ02 LifeMonitor (Akintola et al., 2016) with embedded ECG electrodes, skin temperature sensor and respiration sensor interwoven invest to monitor masonry workers' physical exertion on construction sites. The selection of this method takes into consideration the comfort of the workers and the nature of movement during task execution. The state of personal well-being is another factor, which varies among individuals and can also fluctuate within the same individual from day to day. Therefore, it is suggested to demonstrate some questions to workers at the beginning of every day as a daily check in for their mental status, including their number of sleeping hours, perceived health status on a scale of 1-5, and a ranking of personal stressors (if any) on a scale of 1-5 (Alhola & Polo-Kantola, 2007). It has been reported that the average sleep length to maintain adequate cognition is between 7 and 8.5 hours per day (Carskadon & Dement, 2005).

Biomechanical stress, along with considerations of posture and body mechanics, plays a significant role in influencing musculoskeletal health and the potential for injuries among construction masonry workers. Therefore, it is one of the crucial factors to include for masonry works. Various researchers have linked gait and ergonomics with safety behaviours and enhancing occupational health and safety of workers (Ren et al., 2022) to prevent musculoskeletal injuries and fall hazards. The suggested collection methods are wearable electromyography (EMG), Inertial measurement units (IMUS) which includes accelerometers and gyroscopes.

Situational awareness for construction masonry workers is crucial for ensuring safety, productivity, and the successful completion of projects. Situational awareness involves being aware of one's surroundings, understanding the current situation, and anticipating potential hazards or challenges (Lappalainen et al., 2021). Therefore, time is of essence when it comes to notifying workers with surrounding hazards, which could include chemical exposure, temperature extremes, fall hazards, electricity hazards, moving equipment as well as oxygen levels in confined spaces.

External factors including time of day and noise have been reported to affect productivity and postural control (Weizenbaum et al., 2020). Therefore, including the time of day could reduce the potential errors of the system and help calibrate the system in a realistic way to mimic expected human behaviour. Also, excess noise level should be detected and mitigated to support performance.

The level of stress and emotional responses can have a substantial impact on the performance of individuals working in construction. Research in construction has established a link between performance and emotional states through using WSDs including electrocochleography (EEG) and wearable tracking glasses that monitor gaze and eye movement to detect the individual's emotional state (Arpaia et al., 2020).

Table 2. Factors, Indicators, and Collection Methods for WCADs in Masonry Works

Factors Affecting Individualized Performance in Masonry works	Indicators	Collection method
Fatigue/Physical Strain (Umer et al., 2020)	Electrical Activity in the heart	ECG
	Skin Temperature	Infrared Skin Temperature Sensor
	Respiration Rate	Respiration Sensor
Personal well-being (Alhola & Polo-Kantola 2007)	Sleeping hours, perceived health status, personal stressors	Questionnaire
Biomechanical Stress/ Posture and Body Mechanics (musculoskeletal injuries) (Ren et al., 2022)	Gait Analysis, Posture and Ergonomics	Wearable EMG
		Wearable Strain Sensors
		IMUs
	Fall detection	Wearable fall detection devices
	Material handling Excess weight	Wearable EMG
	Medical History of musculoskeletal injuries history	Questionnaire
Surrounding Hazards - Situational awareness (Lappalainen et al., 2021)	Chemical Exposure	Gas Sensors on site
	Temperature Extremes (heat stress or cold stress)	Thermal Sensors, EDA sensor
	Electricity Hazards	Voltage Detectors
	Moving Equipment	Proximity sensors
	Confined Spaces	Oxygen Sensors
External Factors (Weizenbaum et al., 2020)	Time of day	Sensor Networks
	Noise	Sound level metrics
Stress level and emotional responses (Arpaia et al., 2020)	Gaze, Eye movement, Facial expressions	Wearable Eye Trackers
	Electrical activity in the brain	EEG
Attention levels (Ke et al., 2021)	Electrical activity in the brain	EEG
Perceived Risk (G. Lee et al., 2021)	Heart volumetric change	PPG
	skin electric properties	EDA
	skin temperature	Thermopile
Demographics of worker (Murman, 2015)	Years of Experience, age, fitness level	Questionnaire

Additionally, attention level could also be detected using wearable EEG (Ke et al., 2021), which contributes to safety behaviour and individual productivity. Moreover, perceived risk is one of the influences of safety behaviours demonstrated by workers on construction sites and it was quantified by G. Lee et al., 2021 by measuring the heart volumetric change, skin electric properties, and skin temperature.

Finally, demographics of the workers will aid the calibrations and personalization of the model according to the individual's years of experience, age, and fitness level.

This section establishes how the factors - that are expected to impact the performance of masonry construction workers - can be collected on site. Future steps could include uploading collected data to the cloud-based model that can be developed to mimic the expected cognitive performance tailored to the individual's input data. Once the analysis is complete, proactive near real-time support is offered to masonry construction workers during task execution.

CONCLUSION

This paper presents a comprehensive conceptual framework for the implementation of WCADs in construction, with a LC 4.0 perspective. The primary aim is to enhance workers' well-being, safety, and productivity by leveraging WCADs to provide near real-time feedback. The developed framework, presented in five sequential steps, offers a generic yet adaptable approach applicable to various construction tasks.

The framework begins with the identification of factors impacting individualized performance, acknowledging the diverse demands and risks associated with distinct construction activities. Following steps involve determining detection methods (indicators), defining collection methods, and integrating diverse data collection methods, including WSDs and qualitative inputs. The cloud-based analytical phase plays a pivotal role in calibrating individual differences, considering external and internal factors.

The theoretical implementation of the framework in masonry works exemplifies its practical application. Factors influencing masonry workers' performance, such as physical fatigue, personal well-being, biomechanical stress, situational awareness, external factors, and emotional responses, are considered. The proposed collection methods offer a holistic approach to understanding and enhancing workers' cognitive and physical states. Moreover, the inclusion of worker demographics facilitates the calibration and personalization of the model, reflecting individual variations in experience, age, and fitness level. The result of the model, housed within a cloud-based system, provides users with proactive near real-time support during task execution, accommodating the inherent variability in individual performance.

This research contributes to the evolving environment of LC 4.0 by bridging the gap between theoretical advancements and practical implementation in the construction industry. The proposed framework, centred on WCADs, not only addresses safety and productivity concerns but also prioritizes the well-being of construction workers. As the construction industry continues to embrace technological innovations, this framework stands as a progressive step towards fostering a safer, more efficient, and worker-centric construction environment.

While this conceptual framework provides a foundation for integrating WCADs into construction tasks, certain limitations are acknowledged. First, the effectiveness of the framework heavily relies on the current state of WCADs and their technological capabilities. Rapid advancements in wearable technology are expected, and the framework may need adjustments to accommodate future innovations. The integration of cloud-based systems for data analytics could also raise concerns about data privacy and security. Adequate measures must be in place to ensure the protection of sensitive information collected from workers.

Recommendations for future work include evaluating the proposed framework practically through a longer-term study that should include surveys questionnaires with an expert panel focused on the use of WSDs and WCADs in construction.

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THE IMPACT OF LEAN KNOWLEDGE AND LEAN OPERATION ON CONSTRUCTION WORKERS' JOB SATISFACTION

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ABSTRACT

This study is part of an ongoing research project that aims to understand workers' job satisfaction in the construction industry. For that, a survey was applied among construction workers in Denmark. This paper aims to identify the impact of Lean Construction on job satisfaction. Data from 2176 responses were analysed using framework analysis, shorting the answers into three categories: Lean knowledge; Lean application; and Lean operation, even though they declared not knowing Lean. The study investigated the impact of the different levels of Lean familiarity on job satisfaction within five aspects: Project progress; Management-employee relationship; Employee work monitoring; Workload; and Workflow. Findings indicate that only 15% of respondents have some knowledge of Lean concepts, with only 8% confirming its application. The strongest correlation (R^2=0.557) was found between the Lean practice of "organization attempt to keep workers informed" and the job satisfaction factor of "manager-worker relationship". Allowing the workers to evolve and improve presented, also, a strong correlation with job satisfaction. The study highlights that Lean practices that lead or require Respect for People are the aspects that impact the most on job satisfaction. The results emphasize that implementing Lean principles effectively matters more than merely being familiar with them.

KEYWORDS

Job satisfaction, Survey, Respect for people, Communication.

INTRODUCTION

Successful organizations are often characterized by an environment in which mutual respect prevails (Coetzee et al., 2019). With that in mind, Lean successful management philosophy, and its two principles Respect For People (RFP) and Continuous improvement can be a good choice when organizations want or need to improve. The concept of RFP is not of the emotional kind, but rather *ought-respect*; in other words, respect is due consideration (Coetzee et al., 2019). RFP corresponds to the Japanese term of "ningensei" - personhood/humanity - that according to Toyota is about bringing out the capacity of thinking and producing in every human being.

In the study conducted by a Ljungblom and Lennerfors (2021), the authors identified that "hitozukuri" – the development of people – is deeply connected to "monozukuri" – the art of

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making things or craftsmanship – and that the RFP principle is related to hitozukuri. This message of definition can be seen as: Toyota does not just build cars. They build people. This is in line with the motto that "monozukuri is hitozukuri". At the same time, RFP means enhancing workers' involvement and their voluntary efforts and drawing out their full capacity. This message of definition could be: Toyota build cars, using people (Ljungblom and Lennerfors, 2021).

Thus, implementing RFP in the organizational culture can positively impact team effectiveness. The principle is also strongly correlated with job satisfaction (McKinnon et al., 2003). In a construction context, job satisfaction has also been identified as one of the most influential motivators for improved labor productivity (Kazaz & Ulubeyli, 2007). Hence, knowledge about workers' job satisfaction is highly valuable. Job satisfaction includes all aspects of working life, including health and safety, leadership and management, communication, worker engagement, work environment, rewards, and compensation (Memon et al., 2023). In light of these considerations, the research seeks to address the following Research Question:

- How does the level of familiarity with Lean Construction (LC) impact on job satisfaction among construction workers?

LITERATURE REVIEW

Questionnaires, Interviews, and Checklist have been widely applied in research to investigate various topics that affect job satisfaction and the mental and physical well-being of employees. Table 1 offers a summary of the primary themes explored in the existing literature about job satisfaction surveys, particularly within the construction industry.

Table 1: Themes evaluated in job satisfaction surveys and their adopted approaches (Q=Questionnaire, I=Interview, C=Checklist)

Themes	Rani et al.	Nidadhavolu	Hassan et al.	Ni et al.	Kharo et al.	Raziq and Maulabaksh	Emmanuel et al.
Health and Safety	√		√	√	√	√	√
Leadership and Management	√	√	√	√	√	√	√
Communication	√	√	√	√	√	√	
Worker Engagement				√	√		√
Work environment	√		√			√	√
Rewards and Compensation		√	√		√	√	√
Method	Q+I	Q+I	Q+C	Q	Q	Q	Q

Rani et al. (2022) have identified critical factors influencing workplace well-being in construction projects, those being: Health and safety; leadership and management; communication; and work environment. However, the authors emphasize that the factors affecting workspace well-being were mainly highlighted by project managers, quantity surveyors, architects, and engineers, not hands-on construction workers worker. Thus, suggesting that future scholars can conduct similar research using construction workers as the target population. There might be new and different factors that affect construction workers.

Another study discussed the crucial connectedness of types of leadership and job satisfaction on construction sites (Nidadhavolu, 2018). Enyan; Michael et al. (2023) have explored communication and how it plays a pivotal role in shaping employees' job satisfaction, as it functions as a keyway to share information and foster collaboration. Health and safety can be a wide term with different aspects and questions. Risk behavior is one topic of health and safety, which by Hassan; Che C.R. et al. (2007) was measured and analysed in construction. Furthermore, Ni et al. (2020) studied the mediating roles of work engagement and safety knowledge sharing. In contrast, Khahro et al. (2023), explored job satisfaction models and even proposed an integrated job satisfaction model for construction industry workers. Among many themes, work environment is an important factor in job satisfaction.

The work environment can be, according to Raziq and Maulabakhsh (2015), represented through topics such as salary packages, working hours, workflow, or relationships between management and employees. Additionally, Emmanuel et al. (2015) dived into the organizational factors influencing worker satisfaction. This included recognition, work environment, wage and so on. Finally, a study by Ullah (2018) dived into how the organization's contribution through rewards and recognition is a must to enhance the contribution of the workers.

A common thread across the studies is the recognition of the complex interplay between organizational dynamics, leadership and management styles, communication between managers to workers, and employee engagement in shaping job satisfaction. Health and safety is also an ongoing theme across the studies. While the studies collectively emphasize the importance of different factors, there may be variations in their interpretations and research methodologies. In general, those studied did not associate those factors with the LC philosophy and how Lean practices could impact workers' well-being. For that reason, the present study aims to identify the impact of the adoption of LC on construction workers' job satisfaction.

RESEARCH METHODOLOGY

The study adopted the survey method as the main research approach. This paper represents an ongoing research project that aims to understand the job satisfaction of construction workers. The detailed activities conducted during the survey development were described in detail in Salling et al. (2023) and briefly described as follows:

1. **Link to the theoretical level:** The authors identified nine themes mainly applied for understanding job satisfaction through the literature review of survey studies in different industries. The authors categorized those job satisfaction themes into Project Management (PM), Work Environment (WE), and Health and Safety (HS).
2. **Survey design:** A 48-question questionnaire was designed. The study population was limited to all construction workers affiliated with a union and working in Denmark. The survey used non-probabilistic sampling to obtain as much data as possible.
3. **Pilot test:** Conducted two rounds of assessment, including an online meeting with experts and individual evaluations, resulting in a final 39-question questionnaire. The questions are grouped into: (1) 12 demographic questions; (2) 12 questions related to PM; (3) 8 questions of WE; and (4) 7 questions of HS. The questionnaire was available in the four predominant languages spoken on Danish job sites: Danish, Polish, Romanian, and Italian.
4. **Data collection:** The survey was administered through SurveyXact via email, open for responses from January to March of 2023. A sum of 3393 survey participants responded. In the previous study Salling et al. (2023), the authors presented a descriptive analysis of the answers related to the 12 PM questions. In the present paper, the goal of the study was to

understand the impact of the adoption of LC on workers' job satisfaction. Hence, the authors performed a data cleaning to handle missing values and inconsistencies in the data set.

5. **Data Cleaning:** To ensure result consistency, unanswered or mostly incomplete surveys were discarded. The percentage of responses per survey was calculated, and only those with 50% or more responses were considered, resulting in the exclusion of 1217 surveys. Despite the 62% reduction from the initial quantity, the set of 2176 surveys remain relevant for subsequent analysis and correlations. Subsequently, category mapping was performed, associating integer values with each response to facilitate the analysis of relationships between variables. These operations were carried out using routines programmed by the authors, allowing for a massive analysis and treatment of the information.
6. **Data analysis:** The analysis was designed with the aim of revealing the influence of LC on job satisfaction. Although, the survey had been constructed with the purpose of gathering comprehensive data in the fields of PM; WE, and HS; few sections in the questionnaire can be highlighted, as which the Lean knowledge and practices had been emphasized.
7. **Identify correlations:** For identifying questions with higher correlation, a correlation matrix was utilized. That is, by comparing all questions with each other, the Pearson coefficient is determined for each pair. Once this was done, the analysis focused on questions related to Lean Knowledge and Lean Operation. In particular, a list of the top twenty pairs showing the highest correlation coefficient was compiled, thus allowing the identification of the most relevant response pairs for analysis. To validate the obtained results, a cross-validation was performed, consisting of randomly dividing the data into subsets, on which Pearson coefficients were recalculated for each pair. The results obtained did not differ in the most unfavourable groups by almost 5%, which is acceptable and indicates consistent results.

DATA ANALYSIS CONDUCTED

The analysis has been performed using Python and MS Excel. Python was used majorly in correlation analysis while Excel was used in data visualization. The authors selected 10 questions from the questionnaire that can be related to the knowledge and/or application of Lean as expressed in Table 2. Data were analysed using a framework analysis, which consisted of classifying the answer into three categories: (1) Lean Knowledge; (2) Declaration of Application of LC, named for short Lean "Application"; and (3) Lean application even though they declared not knowing LC, named for short "Lean Operation". The study conducted four kinds of analysis: (1) descriptive analysis of the Lean knowledge and Application, (2) impact of Lean Knowledge on job satisfaction; (3) impact of Lean Operation on job satisfaction; and (4) comparison between knowing Lean and applying Lean.

Table 2: Analysis framework

No.	Questions	Answers classification			ref. Fig 8
		Lean Know.	Lean Appli.	Lean Operation	
2.3	I participate in planning meetings on site.	-	-	Always, very often	A
2.4	I finish my work on time according to the plan.	-	-	Always, very often	B
2.5.1	Regarding the project schedule, I know… ...the tasks that I should do according to the plan	-	-	Strongly agree, Agree	C
2.5.3	Regarding the project schedule, I know… ... my tasks one week from now.	-	-	Strongly agree, Agree	D
2. 7	I am encouraged to come up with better ways of doing things.	-	-	Strongly agree, Agree	E
2.11	State whether you know the following LC concept/tools/methods.	Yes	-		-
2.12	State whether the following LC concepts/tools/methods are applied on the project you work on.	-	Yes		-
3.1.	How satisfied are you with the following factors in your current job:	-	-	Very satisfied, Satisfied	-
3.3.1	This organisation does an excellent job of keeping employees informed about matters affecting us	-	-	Strongly agree, Agree	F
3.3.4	My work gives me the opportunity to evolve and improve my skills (also through formal training)	-	-	Strongly agree, Agree	G

1. Descriptive analysis of the knowledge of Lean

The first analysis consists of a general overview of the answers regarding the LC knowledge and application (knowingly) of six tools/methods/concepts in questions 2.11 and 2.12, those being: (1) Last Planner System (LPS); (2) Percent Planned Completed (PPC); (3) Location-Based Scheduling (LBS); (4) Just-in-time (JIT); (5) Value Stream Mapping (VSM); and (6) Work Sampling (WS). The answers have also been examined by trade, nationality, position in the company, and size of the current project.

2. Impact of Lean Knowledge on job satisfaction

The second analysis aimed to understand how Lean knowledge impacts on **some** job satisfaction factors. It was considered that a worker knows Lean if at least he knows three of the six tools/methods/concepts asked in question 2.11, however the question does not provide in detail whether the worker (a) has heard about Lean or (b) has a thorough grasp of the concept. But, assumed it can be both (a), (b) or in between. Under section 3.1 of the questionnaire, workers had been asked to answer about their job satisfaction under 14 aspects. For this study, only five aspects are being discussed, namely (1) Workflow of the work; (2) Project progress; (3) Relationship between management and employees; (4) Employee work monitoring; and (5) Workload.

3. Impact of Lean Operation on job satisfaction

The third analysis aimed to evaluate the impact of applying Lean on job satisfaction. Workers who have declared that they know the LC, necessarily do not have to practice them. Apart from direct declaration, indirect implications of Lean practices also had been identified. In the questionnaire, there are seven questions, which it can be assumed about the application of Lean practices in the job site. Despite not knowing about LC, workers have been practicing it unknowingly on the site. The seven indicators of Lean application at the job site are summarized in Table 2 (see letters from A to G). To make sure that workers are practicing Lean, only certain answers were selected. As an example, for the question 2.3 where it obtains the statement "I participate in planning meetings on site"; people who had given answers "Always" and "very often", were categorized as workers practicing Lean (can be seen as example of the LPS) in their site. Another example is "2.7. I am encouraged to come up with better ways of doing things", it can be considered as a RFP practice. Compliment to that, answers given as "sometimes", "rarely" and "I don't know" would suggest that they might not follow Lean strictly. Hence, those workers were categorized as the workers who do not practice Lean.

4. Comparison between Lean knowledge and Lean operation

Lastly, a correlation analysis was carried out to explore the degree of influence of Lean knowledge and Lean operation per the analysis framework, impact on job satisfaction factors (selected) by the seven Lean operation factors will be investigated. As per the criteria in Table 2, a correlation analysis had been conducted to identify significant influences. After the identification, major aspects of the nature of the influence have been discussed.

SAMPLE CHARACTERIZATION

Figure 1 displays an overview of the 12 survey answers regarding the participants' demographics and work-related information. These results offer insights into the gender distribution, ethnic composition, age demographics, trades represented, years of experience, positions within companies, and various aspects of companies' operations.

The initial graph highlights a male majority among respondents (92%), followed by a visualization indicating a dominance of Danish individuals (95%). Over 62% of respondents are aged 40 and above, signalling a lack of younger individuals in the industry. Carpenters lead the trades (26%), with varying experience levels: 21% having over 35 years in the field and 20% with 1-5 years of experience. Notably, 42% have spent 1-5 years in their current company, indicating a significant number of changes despite their considerable experience. Journeyman positions dominate. Companies mainly fall within the 10-49 employee range (34%), predominantly Danish-owned (96%). Regarding contracts and projects, most respondents' companies serve as contractors (39%) or subcontractors (37%). Project size remains uncertain for 31% of respondents, while 50% are engaged in building renovations.

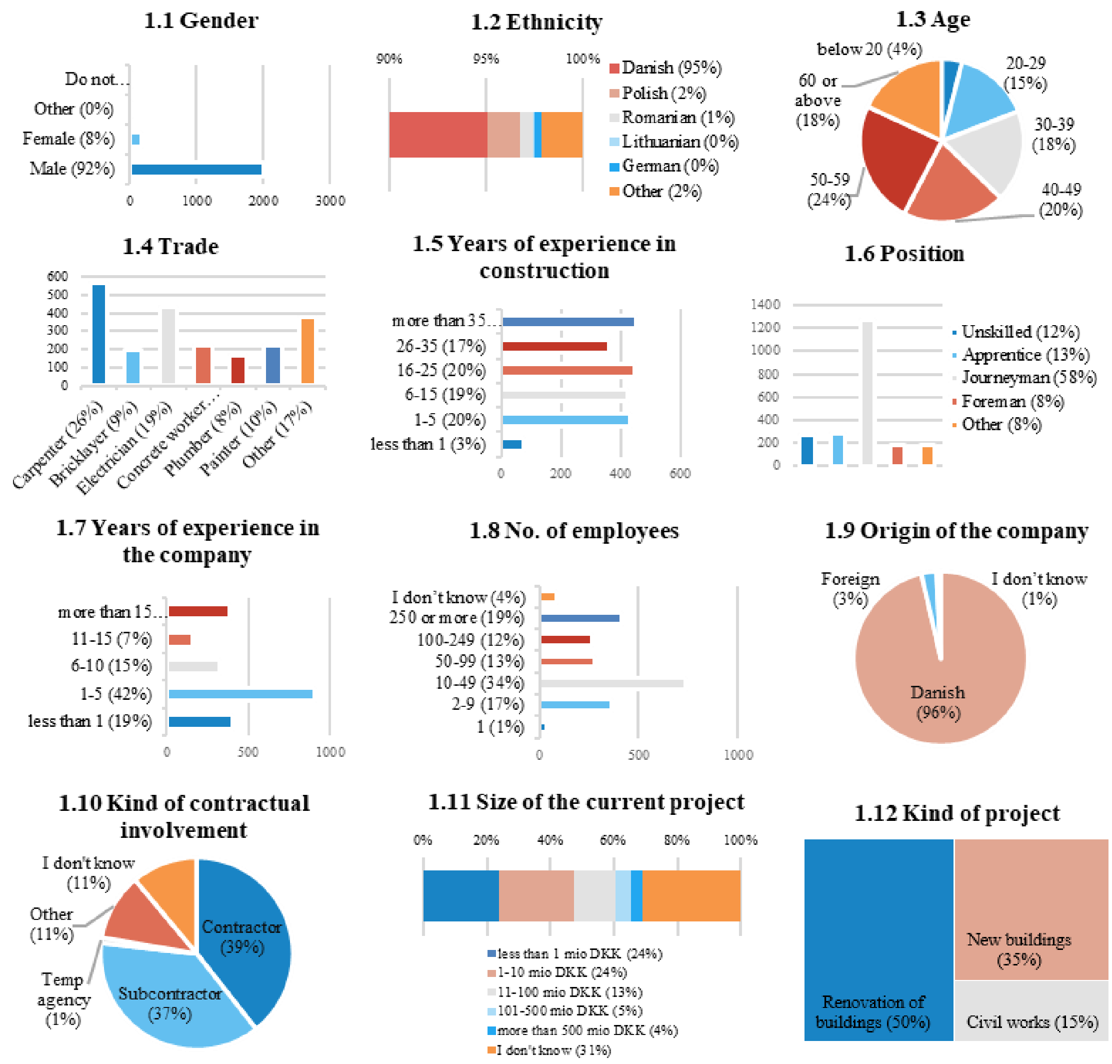

Figure 1: Demographic Profile of Respondents

RESULTS AND DISCUSSION

DESCRIPTIVE ANALYSIS OF THE KNOWLEDGE OF LC

The survey results revealed a substantial lack of familiarity among respondents regarding various LC tools, methods and concepts (Figure 2a). In addition to respondents' familiarity rates, the practical application of these Lean tools remained limited (Figure 2b). Uncertainty about their application ranged from 71% to 77% among respondents. VSM stands out as the least known methodology with 92% unfamiliarity. Among those evaluated concepts, LBS and JIT were the most two known concepts among the respondents, knowing by 18% and 14% of respondents respectively. However, the known adoption of those two concepts rates are 10% to 8% respectively.

Figure 3 provides a view of LC awareness and its distribution across trades, position, and project size. Across all trades (Figure 3a), the LC knowledge is uniformly low at 16%. There is a little difference with bricklayers displaying the highest awareness at 21%, while carpenters and bricklayers lag at 13%. The analysis also included positional variations (Figure 3b), which highlighted the influential role of leadership. The foreman exhibits the highest awareness at 36%, emphasizing the importance of leadership in LC implementation. On the other hand, the apprentices and unskilled show a low awareness, suggesting the need for targeted training programs to foster the same comprehensive understanding. Considering the project size (Figure 3c), a positive relationship is noted between project cost and LC knowledge. Smaller projects demonstrate lower awareness (11%), while larger projects exhibit higher awareness (25%). This can be possible explained because the significance of resource allocation for training on smaller projects to ensure comprehensive LC implementation.

Figure 4 illustrates attendance for planning meetings in relation to different trades (Figure 4a) and positions (Figure 4b). For instance, plumbers and electricians exhibit a significant presence, with 22% and 20% reporting "always" and "very often" attendance. Similarly, in the position-based attendance chart, foreman position stands out predominantly, with 49% "always" and "very often" reporting attendance.

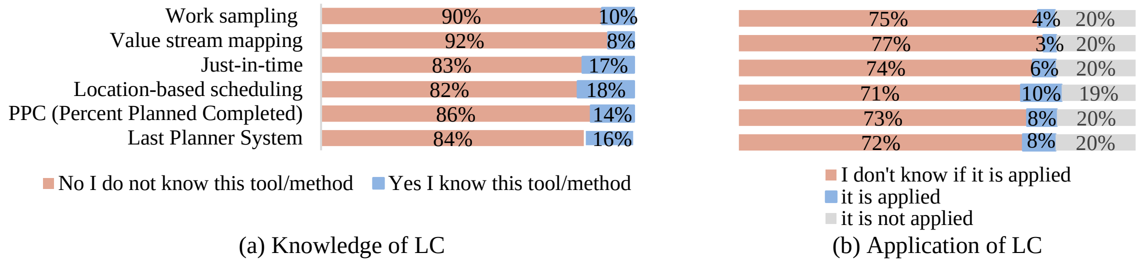

Figure 2: LC responses: (a) knowledge; and (b) application

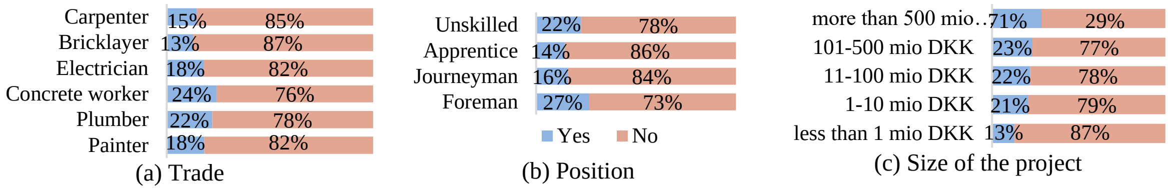

Figure 3: Knowledge of LC regarding: (a) trade; (b) position; and (c) project size

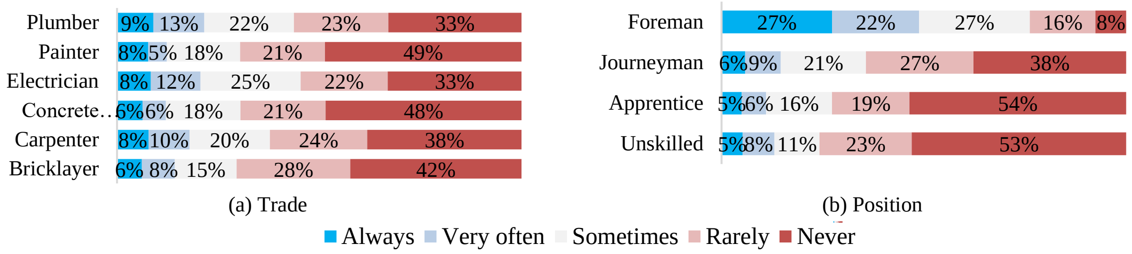

Figure 4: Meeting participation on site regarding: (a) trade; and (b) position

IMPACT OF LEAN KNOWLEDGE ON JOB SATISFACTION

Two of the five factors asked in question 3.1 were selected to understand the impact of declaring knowing Lean on job satisfaction. Figure 5 represents the effect of knowing the Lean concept of JIT and the Lean Technique of WS within the level of satisfaction regarding "work monitoring" and "management-worker relationship". As per the Figure 5a, job satisfaction of workers who declared knew JIT ('Yes' bar in Figure 5a) in employee work monitoring was marginally higher than workers who did not know ('No' bar in Figure 5a). It was 41% and 38% respectively. However, as per Figure 5b; workers who did not know JIT had barely more job satisfaction (52%) than rest (51%) in "manager -worker relationship". As per Figure 5c and Figure 5d, knowing WS has a slight edge out, than whoever else in job satisfaction on both selected aspects. Statistically, workers knew WS has shown 10% and 3% improvement in job satisfaction under "work monitoring" and "manager-worker relationship" respectively. Hence, these representations implies that the impact of declaring knowing some Lean tools/concepts/method is not significant for affecting job satisfaction. Hence, to examine the impact of LC application on job satisfaction, the next approach was adapted.

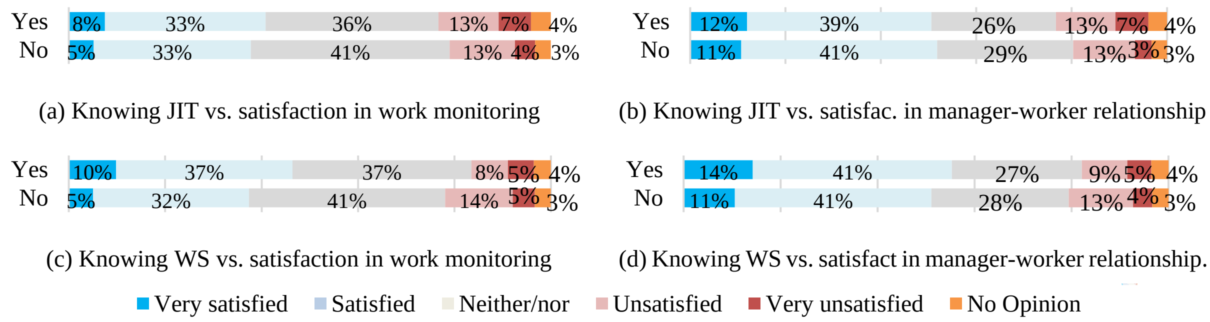

Figure 5: Impact of Lean knowledge of JIT and WS in satisfaction: (a & c) work monitoring, (b & d) manager-worker relationship.

IMPACT OF LEAN OPERATION ON JOB SATISFACTION

For understanding the impact of applying Lean on workers satisfaction, the authors selected how the "attendance in meetings" impact the satisfaction regarding "the workflow of the project" and the satisfaction regarding the "manager-worker relationship".

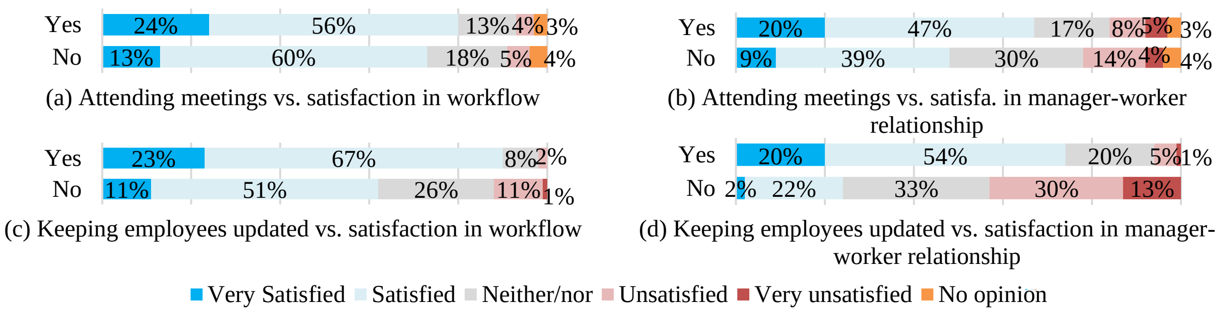

Figure 6: Impact of "attending planning meetings" (a & b), and "keeping workers informed" (c & d) on job satisfaction in "workflow" and "manager-worker relationship"

From Figure 6a and 6b, it can be seen that "participating in planning meetings" have a slight, but a noticeable impact on the job satisfaction criteria selected. When the workers did not attend the planning meetings job satisfaction in both the workflow and the "manager-worker relationship" was respectively 73% and 48%. However, workers who participate in the planning meetings show 80% and 67% satisfaction in the same criteria (Figure 6a and b). Although the relationship was weaker compared to other variables, it shows a 7% and a 19% (respectively) increase in job satisfaction. "Keeping workers updated" shows a relatively remarkable influence (Figure 6c and d). The impact on job satisfaction under "manager-worker relationship" has improved from 24% to 74% which is nearly three times of the percentage of the "workers who was not kept informed about the things mattered". Noteworthy, the influence of Lean operations is more apparent when compared to Lean knowledge.

Another noticeable observation was, how participation in planning meetings affected PM aspects. As illustrated in Figure 7, workers who participate always and very often in planning meetings ("Yes" in Figure 7) have better chance of finishing their work on time (Figure 7a), know better about their tasks according to the plan (Figure 7b), know better of their tasks ahead of one week (Figure 7c) and one month (Figure 7d). In essence, this indicates how regular engagement in planning meetings contributes to improved project management outcomes.

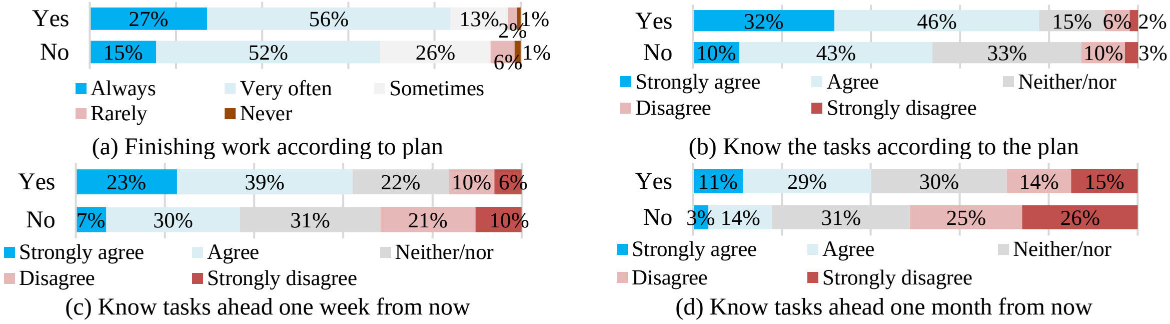

Figure 7: Effects of attending planning meetings on PM

COMPARISON OF LEAN KNOWLEDGE AND LEAN OPERATIONS

The last analysis aimed to understand the impact of having Lean knowledge on the job satisfaction (selected five fields) using the correlation analysis. As per Figure 8a, knowing Lean showed a varied influence on the selected factors. The correlations observed were barely noticeable, indicating a weak association between the variables considered, which infer that there is no correlation between the variables at all. However, for the sake of further investigation, it was noted that the largest correlation factor was found to be between WS and the satisfaction in "workload of the workers" (R^2 value of R^2=0.067) and the least being between PPC and the job satisfaction in "relationship between managers and workers" (0.001). Another observation is that JIT shows a negative correlation to all the job satisfaction factors besides job satisfaction in "work monitoring". However, it can be assumed that these correlations do not imply causation due to their insignificant magnitude.

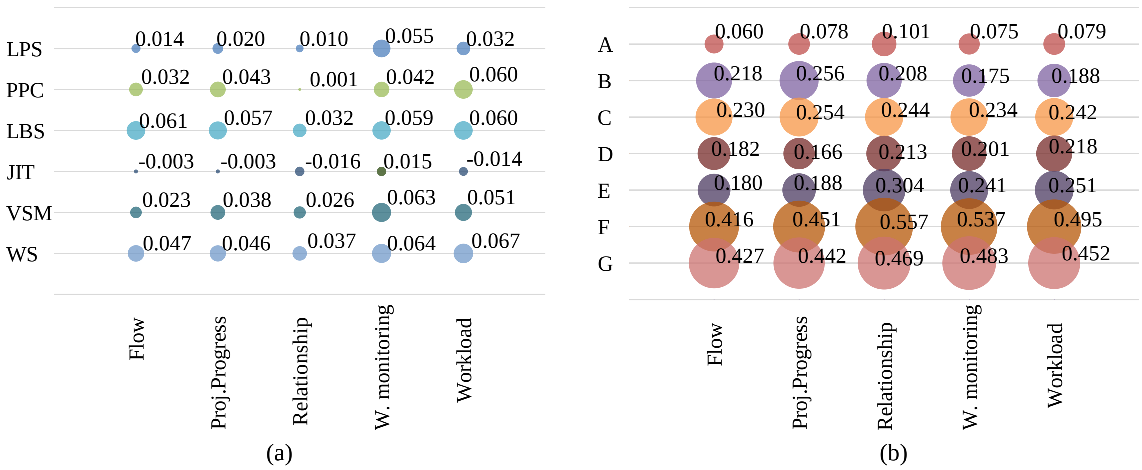

Figure 8: Correlations (R^2) of Job satisfaction: (a) Lean knowledge and (b) Lean operation

Within the designed analysis framework, correlations were explored for Lean operations (Figure 8b). The first observation was that the correlations were significantly higher than in Figure 8a, which suggests that Lean operations have a stronger influence on job satisfaction than Lean knowledge. Possessing Lean knowledge doesn't necessarily reflect whether that knowledge is actively implemented and practiced in a job site. However, it is the active practice of Lean that generates tangible results and could directly impact job satisfaction within the selected criteria. Further, when the attention is directed towards Lean operations, "3.3.1. organizations' attempt to keep workers informed about matters affecting them (Letter F in Figure 8b)" and "3.3.4. allowing the workers to evolve and improve (Letter G in Figure 8b)" have the greater influence on job satisfaction. R^2 value of R^2=0.557 is the strongest correlation factor of them, which is between "organization keeping workers informed" and satisfaction in "manager-worker relationship". This observation seems obvious, and it can be inferred that effective and efficient communication between the organization and the workers is crucial. The least significant correlation (0.060) in the lot was with “3.1. Participation in planning meetings (Letter A in Figure 8b)”. Even though “meeting participation” is expected to impact more on job satisfaction, the intended objective of planning meetings might not have been achieved. Frequently, meetings might be perceived as time-consuming, and workers may feel that extensive meeting participation takes away from their productive time. Nevertheless, operations related to RFP (F and G), has shown significant effect on task execution and planning awareness.

CONCLUSION

This study is part of an ongoing research project that aims to understand workers' job satisfaction in the construction industry. Data from 2176 responses were analysed using framework analysis, shorting the answers into three categories (Lean knowledge, application, and operation) to understand how the level of familiarity with LC impacts on job satisfaction.

The answers analysis has revealed a significant lack of awareness in various Lean approaches and their applications; meaning that most of the construction workers did not know LC and, they didn’t even know whether they are practiced. Apart from that, “participation in planning meetings”, which was classified as a Lean operation in this paper, was given closer attention as well. This unveiled that meeting attendance had a positive impact on PM where workers attending meetings had more tendency to finish work on time and knowing the project plan and their tasks 1- 4 weeks ahead.

The main contribution of this paper is understanding the influence of Lean knowledge and Lean operation on job satisfaction. The correlations between Lean knowledge and job satisfaction demonstrated a generally weak association, suggesting that the variables considered do not exhibit significant correlations. Shifting the focus to Lean operations, the strongest correlation was found between organizational communication practices and satisfaction in manager-worker relationships. Thus, Lean practices that lead or require RFP are the aspects that impact more on job satisfaction.

The study has some limitations that should be addressed in future research. Firstly, the results are limited to the Danish construction scenario. Thus, caution is necessary when extrapolating findings to other countries. For that, a broader data collection across various countries and regions could facilitate comparisons and offer insights into the impact in Lean in job satisfaction. To overcome that, the authors have been working with other researchers from other countries and the questionnaire is going to be applied in France, Lebanon, UK, Peru and Chile. Secondly, the assumption considered during the categorization into knowing Lean or not could have impacted in the results. The respondents were considered familiar with Lean when affirming knew at least three concepts. However, other assumptions could be considered for that categorization. For example, a Lean knowledge degree and/or a Lean implementation degree could be used. Thirdly, the impact of having Lean knowledge and Lean operation on job satisfaction was conducted only considering five selected factors; however, other factors asked in question 3.1 could be considered.

Despite the need for caution in applying the study's findings to different countries, they still offer valuable insights into the factors influencing job satisfaction in construction projects. Future research could focus on developing roadmaps based on these findings, tailored to meet specific local needs and contexts to promote RFP.

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RESPECT FOR PEOPLE AND LEAN CONSTRUCTION: GOOD PRACTICES, BENEFITS AND BARRIERS

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ABSTRACT

Respect for People (RFP) is a crucial element in Lean Construction philosophy, along with continuous improvement. However, despite its importance, research on RFP is still limited. Therefore, the following article aims to identify good practices, benefits, and barriers generated by its implementation on the construction site. The research begins with a literature review, following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) criteria. Subsequently, with the list of good practices, benefits, and barriers, nine lean experts were interviewed, validating the information obtained from the literature review. This process identified eleven good practices, eleven benefits of implementing RFP in construction projects, and nine barriers. The upcoming research will serve as a valuable contribution for professionals seeking to implement good practices of RFP on the construction site and researchers aiming to delve deeper into this concept.

KEYWORDS

Respect for People, Lean Construction, benefits, barriers, good practices

INTRODUCTION

The construction sector stands out as one of the most relevant economic sectors globally (Sarmiento-Rojas et al., 2020), employing many individuals in its diverse activities. Despite its importance, construction faces several challenges, such as lack of productivity (Barbosa et al., 2017 and Del Savio et al., 2022), inadequate planning in work (Gomez & Morales, 2016), limited collaboration, fragmentation of the supply chain (Schöttle et al., 2014), environmental impact (UNEP, 2022). These problems are primarily related to people in construction projects. Since people play a crucial role in the construction industry's success (e.g., workers and managers), strategies to improve the construction industry should consider people and try to understand the role of people involved in construction projects (Golzad et al., 2023).

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Within the Toyota Production System (TPS), there are two fundamental pillars: continuous improvement and Respect for People (RFP), as highlighted by Miller (2017). Therefore, in the context of Lean philosophy, people play a crucial role, as it acknowledges that the success of any system or process depends significantly on the commitment, motivation, and respect for the individuals who comprise it. Thus, it promotes a work environment that values and respects individual contributions, fostering collaboration, innovation, and personal and organizational growth.

Despite its importance in Lean Construction, literature regarding RFP is scarce. Korb (2016) conducted a literature review and defined the concept of RFP based on various perspectives, examining barriers to developing this principle and analyzing ways to cultivate RFP in lean construction implementation. His research revealed a significant disparity in the number of papers dedicated to RFP compared to those focused on continuous improvement. Specifically, only 33 papers related to RFP were found, while 451 papers were identified on continuous improvement in the International Group for Lean Construction (IGLC). Current results obtained from a quick review in Scopus conducted by the authors confirm the trend observed previously by Korb. Only 166 papers on RFP and a culture of respect were identified, compared to 19,905 papers on continuous improvement. This significant difference in the number of publications again underscores the lack of attention and study dedicated to RFP compared to continuous improvement in Lean Construction. These findings highlight the need for further research and recognition of the importance of RFP in successfully implementing Lean Construction.

Therefore, the following research aims to delve into the concept of RFP in the context of Lean Construction. A comprehensive literature review identified a list of good practices, barriers, and associated benefits concerning people in construction projects. Subsequently, this information was validated and supplemented through interviews conducted with nine experts in the field. This paper aims to generate guidelines or good practices that can be effectively applied in various construction projects. Additionally, it seeks to identify the barriers and benefits associated with implementing RFP in terms of the professionals' perceptions and the obstacles that could hinder its full implementation on the construction site. This research aims to enrich the understanding of the concept of RFP in Lean Construction and provide practical tools for its successful application in the construction industry.

BACKGROUND

RESPECT FOR PEOPLE AND LEAN PRODUCTION

In the 1950s, the TPS laid the foundation for Lean Manufacturing, focusing on waste elimination and continuous improvement. The first pillar of TPS, continuous improvement, enables the expected results to be achieved; however, the second pillar, RFP, makes the former possible in the first place, considering Toyota's statement: "We make people before we make cars" (Korb, 2016).

Liker (2004) highlights RFP as critical for achieving operational excellence and sustainable efficiency. On the other hand, Womack and Jones (1997) emphasize how RFP is integrated into the Lean organizational culture, recognizing the importance of each individual in the production process. Finally, Rother (2009) mentions that lean tools are structured frameworks with the fundamental objective of developing and improving people's problem-solving capabilities. Together, these authors offer an in-depth view of the early history of Lean, revealing how the harmonious interaction between efficiency and RFP shaped a philosophy that transcends manufacturing to impact various sectors positively.

According to Ljungblom and Lennerfors (2021), RFP is understood as consideration and respect for individuals, emphasizing developing their capabilities in a positive, not necessarily emotional, atmosphere. On the other hand, key topics related to RFP include teamwork, personal development, motivation, problem-solving capacity development, waste elimination, and safety (Coetzee et al., 2019). Additionally, teamwork helps improve construction safety (Yin et al., 2023). Teamwork is about collaborating in an organized way to achieve a common goal. This involves understanding the interdependencies among team members and making the most of them (Cardona et al., 2006).

RESPECT FOR PEOPLE AND LEAN CONSTRUCTION

Korb (2016) emphasizes that RFP in Lean Construction goes beyond treating people fairly and safely, focusing on actively engaging employees in identifying waste and improvement opportunities. Furthermore, it is highlighted that RFP is crucial for the success of Lean Construction, as it enables continuous improvement and sustained employee engagement at all levels of the organization. This approach involves empowering people to identify improvement opportunities and value their contributions. Additionally, Filho et al. (2018) conducted a study on RFP from the meditation perspective, confirming the feasibility of its implementation because workers agreed that meditation valued it and recommended its implementation in other projects. Furthermore, they concluded that the company was building people before houses with these actions, thus demonstrating RFP.

Furthermore, other authors have explored the concept of RFP, relating it to psychological safety. In this regard, Gomez et al. (2019) analyze psychological safety in a construction project to create a safer environment that promotes RFP; Gomez et al. (2020) explore psychological safety and how it fosters a better working environment and RFP, allowing individuals to feel free to voice their opinions and participate more actively in the project; Demirkesen et al. (2021) demonstrate that construction workers feel more psychologically safe and respected in projects implementing Lean Construction.

In this context, the authors conceive respect for people as crucial. They recognize the importance of each individual in the development of the Lean construction project and value their skills, knowledge, and contributions. This focus on respect promotes a more positive work environment and stimulates collaboration and innovation in the workplace.

RESEARCH METHOD

Figure 1 illustrates the two phases of the research development. In the first phase, a literature review on RFP in construction was conducted to extract a list of good practices, benefits, and barriers. In the second phase, nine semi-structured interviews were conducted with expert professionals to validate the lists found in the literature and gather their professional experience regarding RFP.

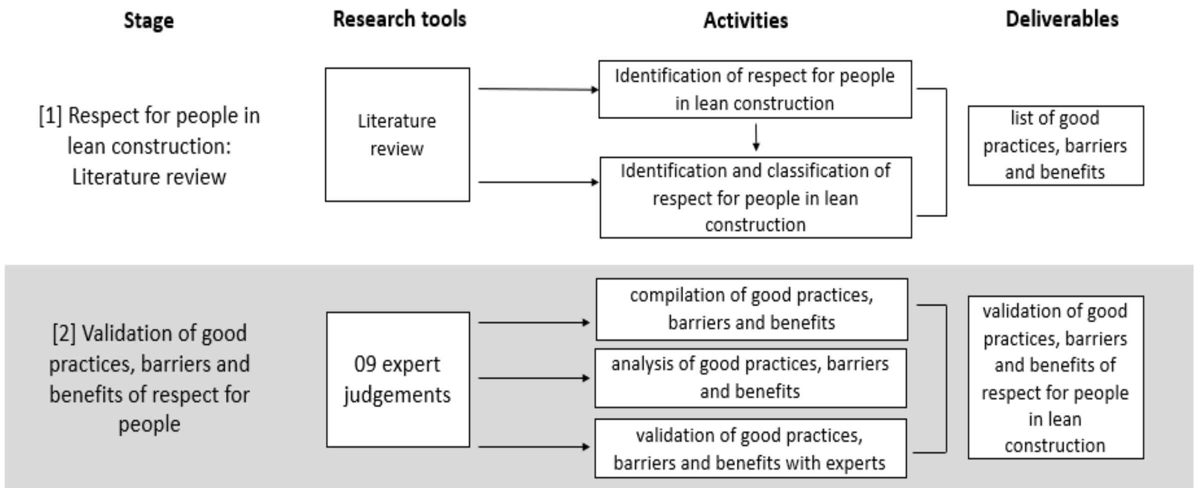

Figure 1: Research Stages

First stage: Prisma review

A literature review was conducted to identify and select the articles evaluated in this study, following each step of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology. For the literature review, a search was conducted in the IGLC database and Scopus for "Lean Construction" and "RFP" publications. Scopus is one of the databases with a broader domain in construction research compared to others (Galaz-Delgado et al., 2021), and the IGLC database hosts most publications on the application of Lean Construction worldwide (Daniel et al., 2015). For the Scopus database, the keywords used for the search were "Respect for People" AND "lean construction," and for the IGLC database, it was "Respect for People." No publication year filter was applied, resulting in 22 articles.

Nine duplicate publications were removed for the eligibility phase, leaving 13 papers. Subsequently, it was reviewed whether articles that did not refer to RFP in Lean Construction should be excluded. In this phase, all articles referenced the evaluated item, so there were no exclusions. In total, 13 articles were considered for the research.

Second stage: Qualitative Study

The qualitative research approach examines variables such as experience, attitudes, behavioral aspects, and participants' opinions in the data collection process (McCusker & Gunaydin, 2015). This method is suited for gathering human opinions and knowledge on a subject from different perspectives (Malterud, 2016).

It has been previously used with topics related to Lean Construction, for example, to identify the positive impacts and challenges of LPS in Brazilian companies (Viana et al., 2010) and to identify tools and facilitators for lean adoption (Marhani et al., 2018). Moreover, qualitative studies have been used for issues related to people, in the construction sector. For example, Demirkensen et al. (2021) conducted a study to evaluate the influence of psychological safety in the USA using qualitative studies to identify the relationship between the principles of Lean Construction in the context of safety. Similarly, in Chile, Paez et al. (2024) employed the qualitative study with the objective of analyzing the perceptions of experts related to emotional intelligence in the construction sector, using interviews with 11 Chilean professionals.

Given the scarcity of research on the topic of respect for people within Lean Construction, this study aims to serve as a foundational piece for future investigations. By identifying good practices, barriers, and benefits associated with respect in Lean Construction, it endeavors to pave the way for further exploration into this important aspect.

Therefore, expert judgments were used due to the need to obtain insights and specialized perspectives in the field of Lean Construction and respect for people in this discipline. For this stage, 15 experts were initially contacted, following the snowball criteria; however, only 9 of them agreed to the interview, Table 1 describes the profile of the interviewees.

For the selection of the experts, a careful process was carried out in which professionals and academics with extensive experience and knowledge in Lean Construction were identified. Experts with a minimum experience of 10 years in the Lean philosophy were considered, as well as in issues related to respect for people in work environments. Geographic and professional experience diversity was prioritized to ensure a diverse representation of opinions and approaches. Although the sample is not large (nine experts), it can be considered appropriate for qualitative studies. Several studies mention that additional responses do not significantly increase the information, like Demirkensen et al. (2021), where they achieved saturation after the 12th interview in their study that was also related to people in the construction industry. In the case of the present research, saturation was observed after the 8th interview.

The interviews were conducted via Zoom or Meet video calls and lasted 30 to 60 minutes with each participant. The interview was divided into two stages: a first stage where information about the interviewee was collected, including years of experience applying Lean Construction, types of projects they worked on, company size, and their position. In the second stage, the identified good practices, barriers, and benefits from the literature review were validated. The experts were asked if they had observed any additional good practices, barriers, or benefits throughout their careers that were not included in the lists presented.

Table 1: Expert profiles

ID	Academic level	Country	Experience	LC Experience	Current role
EX1	Ph. D.	Ecuador	32 years	32 years	Director of Civil Engineering
EX2	Ph. D.	Chile	14 years	11 years	Professor and researcher
EX3	Ph. D.	Brazil	15 years	15 years	Professor and researcher
EX4	Ph. D. (c)	Ecuador	15 years	10 years	Manager
EX5	Ph. D.	España	13 years	12 years	Professor
EX6	Ph. D.	Chile	18 years	18 years	General Manager
EX7	Ph. D.	Chile	40 years	32 years	Director of a Research Center
EX8	Magister	Perú	42 years	28 years	General Manager
EX9	Magister	Perú	12 years	10 years	General Manager

RESULTS AND DISCUSSION

GOOD PRACTICES

During the literature review, nine good practices were identified. These were subsequently validated and supplemented with two good practices from expert interviews. The details of these practices are presented in Table 2.

BP1 suggests the pressing need to establish an organizational environment conducive to continuous process optimization and reducing inefficiencies (Richert & McGuffey, 2019). All experts are in favor of this good practice. EX1 emphasizes the positivity of this practice but stresses, *["It is necessary to link it with a performance measurement culture."]*. EX2 highlights that *["It is important to establish a suggestion system in conjunction with this practice*."].

Regarding BP2, the importance of valuing individual successes and collective achievements is highlighted (Korb, 2016). This approach acts as a motivational catalyst for employees and strengthens the culture of continuous improvement, contributing to creating a positive work environment. EX1 shares their experience, stating that *["This practice is beneficial without incurring significant additional costs."*]. On the other hand, EX4 cautions about the careful design of incentives *["This could promote negative practices related to tight deadlines, compromising safety and work quality."]*. EX7 emphasizes, based on their experience, that *["This practice satisfies motivational needs at work."]*. Experts unanimously support this practice, considering that it would significantly contribute to fostering respect for individuals in the workplace.

Table 2: Good practices associated with RFP.

N°	Good practice	References
BP1	Establishing a culture that promotes continuous improvement	(Korb, 2016); (Richert & McGuffey, 2019)
BP2	Recognizing and celebrating achievements	(Korb, 2016)
BP3	Providing regular constructive feedback to support personal and professional development	(Korb, 2016)
BP4	Establish Clear and Shared Objectives	(Gomez et al., 2020); (Howell et al., 2017)
BP5	Encourage active participation of employees in decision-making related to their work and processes.	(Gomez et al., 2020); (Demirkesen et al., 2021); (Gomez et al., 2019); (Howell et al., 2017); (Filho et al., 2018)
BP6	Ensure safety in the construction environment by implementing measures that safeguard workers' physical integrity.	(Howell et al., 2017); (Gomez et al., 2020)
BP7	Establish a warm and friendly working environment.	(Richert & McGuffey, 2019); (Filho et al., 2018)
BP8	Ensure the recruitment and retention of high-quality employees.	(Filho et al., 2018)
BP9	Create a psychologically safe environment that fosters collaboration and learning.	(Howell et al., 2017); (Demirkesen et al., 2021); (Gomez et al., 2019); (Arroyo et al., 2018)
BP10	Value jobs with fair wages	Suggested by the expert panel
BP11	Instill a culture of respect among each team member.	Suggested by the expert panel

Concerning BP3, the importance of continuously providing positive and constructive feedback to support personal and professional growth is highlighted (Korb, 2016). EX1 maintains that *["This good practice should be applied to both technical staff and field personnel of the company."]*. Experts express that the lack of training is due to high employee turnover in the industry.

For BP4, EX1 mentions that *["It is a good practice that should be addressed in planning meetings with the team."]*. EX3 agrees, noting that it will depend on the formality level of the company. EX4 highlights the importance *of ["Objectives being cross-cutting and benefiting everyone."]*. EX5 emphasizes that *["Involving others in the common goal is a sign of respect."]*. EX6 expresses disagreement due to a lack of interest. The other four experts agree with this good practice.

The BP5 refers to involving employees in decision-making that directly affects their responsibilities (Howell et al., 2017). EX3 comments*: ["When studying resilience in workplace safety, safety should be addressed collaboratively."]*. Other six experts also express their agreement.

About BP6, which refers to implementing measures and protocols aimed at ensuring a safe working environment for employees, EX6 highlights that: *["This demonstrates concern for workers and is a good practice."]*. The other experts validated this practice.

BP7 suggests cultivating a positive and welcoming work environment (Filho et al., 2018). EX2 notes that *["The terms are very general and should mention how to achieve a warm and friendly environment."]*. EX4 prefers a friendly environment over a warm one to promote a collaborative atmosphere. EX5 emphasizes that *["Working in a happy place increases productivity."]*. EX6 mentions that, although the good practice should be applied, making friends is unnecessary to create a warm work environment. The other experts validated this good practice.

Regarding BP8, which refers to the importance of selecting and retaining highly competent and skilled professionals in the organization, EX6 and EX7 expressed their disapproval, mentioning that *["The construction industry is characterized by its temporary nature and fluctuation, so implementing this practice would not be suitable in this context"]*. The other seven experts approved this good practice.

BP9 ensures that workers are not punished for reporting errors or asking questions. Expert 1 mentions that ["It is difficult to implement due to the diversity of individual issues."] The other eight experts validate this good practice.

BP10 involves recognizing and adequately compensating employees' work and ensuring that salaries are fair and reflect each individual's contribution and value to the organization. The majority of experts supported this recommendation, with five mentions.

BP11 refers to knowing that each team member is essential for the project's completion and cultivating norms within the company that promote respect, incentivizing values and ethics. Three of the experts suggested this good practice.

BENEFITS

Six benefits were found during the literature review. These were then confirmed and reinforced by five further benefits that surfaced from expert interviews. Table 3 presents the benefits identified in this study.

B1 involves cultivating a sense of belonging and recognition among collaborators. Eight experts have validated this benefit. EX3 highlighted that: *["While this benefit could be a consequence of implementing good practices, it is crucial to conduct further research, such as a pilot test, to validate its effectiveness"]*.

Regarding B2, which entails recognizing the importance of maintaining a comprehensive approach within the Lean framework, over 88.8% of experts endorsed this benefit according to their opinions.

Concerning B3, which involves creating an organizational environment conducive to employees' professional and personal growth, this benefit was corroborated by the experience of three experts.

Table 3: Benefits identified.

N°	Benefits	Reference
B1	It creates an environment where employees feel valued and an integral part of continuous improvement.	Suggested by the expert panel
B2	Prevents Lean tools from deviating from their primary focus on continuous improvement.	(Korb, 2016)
B3	Facilitates development and innovation	Suggested by the expert panel
B4	Leads to increased productivity.	(Demirkesen et al., 2021); (Filho et al., 2018)
B5	Encourages an open and transparent communication environment	(Filho et al., 2018); (Demirkesen et al., 2021); (Arroyo et al., 2018)
B6	Employee loyalty to the company	Suggested by the expert panel
B7	Eliminates inefficiencies and waste	(Demirkesen et al., 2021)
B8	Facilitates the creation of a culture of adaptability and flexibility	Suggested by the expert panel
B9	Contributes to the development of more potent and more respectful working relationships	(Richert & McGuffey, 2019)
B10	Contributes to the emotional well-being of employees	(Filho et al., 2018)
B11	Increases occupational safety and security	Suggested by the expert panel

Regarding B4, which involves various improvements and approaches that contribute to increased efficiency and performance in the workplace, experts 2, 4, 5, 6, 7, 8, and 9 validated this benefit. EX1 emphasized that *["productivity is enhanced by at least 10% by improving worker performance"].* However, EX3 noted the need for further research to validate this claim due to the various variables that may influence it.

Concerning B5, which involves fostering an environment of open and transparent communication, EX3 mentioned that *["By having open communication with the team, not only does it strengthen trust and collaboration among members, but it also facilitates the efficient identification and resolution of challenges"].* All experts validated this benefit.

As for B6, according to EX5, applying good practices of respect for individuals can generate loyalty in high-quality workers, thereby increasing the company's personnel quality.

Regarding B7, which allows for eliminating inefficiencies and waste, all the showed their approval. EX1 mentioned that *["By using 5S, material waste and accidents are eliminated"],* while other experts highlighted eliminating unused talent waste and reducing waiting times due to coordination.

Regarding B8, which implies that applying good practices of respect for individuals establishes an environment conducive to continuous adaptation and flexibility, experts 3 and 4 mentioned that, based on their experience, this benefit has been observed. They emphasize that ["People, when feeling heard and in a positive environment of respect, show a higher likelihood of flexibility towards ideas and working methods"].

Regarding B9, EX5 expressed skepticism and suggested the need to verify it, as relationships between people depend on multiple factors that are difficult to measure. Despite this, other experts approved based on their experience with projects.

As for B10, EX3 disagreed, arguing that *["There are other factors that can affect emotional well-being"]*. However, other experts have validated this good practice.

Seven experts validated the last benefit (B11), which increases occupational safety by creating a safer work environment. EX1 mentioned having achieved zero accidents on a construction site by applying these concepts of good practices, thus supporting the effectiveness of such measures.

BARRIERS AND CHALLENGES

During the literature review, a total of 6 barriers were identified. These were subsequently validated and supplemented with three additional barriers, which emerged from expert interviews. The details of these barriers are presented in Table 4.

Table 4: Barriers and Challenges Associated with RFP.

N°	Barriers and Challenges	Reference
Ch1	Lack of active employee participation	(Gomez et al., 2020); (Richert & McGuffey, 2019)
Ch2	Lack of transparent communication	(Gomez et al., 2020); (Richert & McGuffey, 2019)
Ch3	Culture of blame for mistakes	Suggested by the expert panel
Ch4	Technocracy exists in the construction industry	Suggested by the expert panel
Ch5	Authoritarian decisions	(Filho et al., 2018)
Ch6	Inequality and discrimination	(Richert & McGuffey, 2019)
Ch7	Resistance to Change and lack of flexibility in working methods	(Richert & McGuffey, 2019)
Ch8	Lack of career development opportunities and recognition	(Korb, 2016)
Ch9	Destructive skills	Suggested by the expert panel

The Ch1 implies that employee reluctance or lack of commitment to continuous improvement initiatives could pose a significant obstacle. While most experts (8 in total) endorsed this barrier, EX1 presented a different perspective by arguing that *["This barrier reflects more an organizational culture where responsibility is assigned based on specific training for a task"]*. Additionally, EX5 pointed out that, *["Employee active participation may be underestimated, as some apply lean practices without full knowledge of it"]*.

Regarding Ch2, EX1 highlighted its impact, especially in supplier communication. Other eight experts supported the existence of this barrier. Furthermore, EX5 noted that *["Sometimes workers are communicated to without fully explaining the reason behind tasks, which can lead to lack of participation"]*.

Although EX5 did not fully validate Ch3, seven other experts endorsed a culture of blame and stigmatization for errors, emphasizing the need to address this aspect in the workplace.

Regarding Ch4, according to EX7, *["Many companies prioritize indicators and performance without considering people"]*. EX3 and EX5 supported the existence of this barrier in the construction industry, pointing out the lack of consideration for human aspects in process optimization.

Ch5 refers to "Authoritarian Decisions." Although EX1 does not fully support this barrier and highlights that *["There is a contradiction with the Lean philosophy of integrating knowledge from the bottom up"]*, other five experts corroborated the presence of this barrier. In this regard, EX7 presents the perspective that *["Rather than being a barrier, it could be considered a bad practice"]*, suggesting that although this dynamic may represent a challenge, it can also be interpreted as inefficient behavior within the operational framework.

Regarding Ch6, according to EX1, *["This barrier involves wage disparities and discrimination against female crews"]*, while EX4 and EX8 highlighted wage inequality, although most experts supported the existence of this barrier, EX7 mentioned that *["This barrier was seen more as a bad practice than as a structural barrier"].*

Regarding Ch7, experts 1, 3, and 6 supported the existence of this barrier, pointing out cultural resistance and rigidity in traditional practices. The remaining experts also expressed their agreement with its presence.

Concerning Ch8, EX1 considered that *["This affects employee contribution"],* while another three experts are not entirely in agreement with classifying this as a barrier. However, other experts have expressed their agreement with this barrier.

As for Ch9, EX1 and EX2 emphasized that *["This occurs because there is a lack of a collaborative culture"].* Although some experts (3 and 5) do not strictly consider it a barrier, all the other experts in the interview validated its existence, highlighting the importance of fostering a collaborative environment to prevent destructive competition.

CONCLUSIONS

This study identified eleven good practices, eleven benefits, and nine barriers related to respect for individuals in construction projects. Nine experts validated these findings. Based on these results, guidelines have been established that can be applied in various construction projects to implement these practices, identify barriers present in companies or projects that hinder their full implementation on the construction site, and ultimately reap the benefits after implementing respect for individuals.

It is important to note that this study may have some limitations. For example, the identified good practices could be influenced by the cultural characteristics of the places where Lean Construction is implemented. Additionally, it is crucial to validate these good practices, benefits, and barriers in various construction projects to ensure their widespread applicability, and further research is suggested to expand the list of good practices.

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EXPLORATION OF LEAN CONSTRUCTION IN JAPAN AND ITS PARADOXICAL STANCE

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ABSTRACT

Japanese construction, appraised for its high quality and production efficiency, holds virtues that Lean advocates have long admired in the Toyota Production System. However, Japanese building construction academia and industry organizations have remained disconnected from the mainstream IGLC community until recently. Therefore, its current state is insufficiently understood overseas. This study has employed a literature review, including resources in English and Japanese languages, and gathered first-hand testimonials to shed light on such a gap. This paper identified practices and routines from Japanese construction sites that could be incorporated into the Lean Construction repertoire, and identified points from which Japan could learn, such as the role of dynamic ecosystems in the birth and expansion of the Lean Construction movement and the presence of heavy-weight champions who nurtured conduit leaders. Japanese constructors have aspired to pull their engineering strength to the next level and combine it with innovative management practices, including incorporating good ones learned from overseas. That is where the role of Lean resides. Lean may help fill the gap of converting tacit knowledge into structured knowledge, increasing transparency, smoothing the transmission of know-how, creating more efficient project deliveries, and turning itself into a more attractive business.

KEYWORDS

Lean Construction, Japan, Theory, Toyota Production System, Ecosystem.

INTRODUCTION

The 1990s provided a fertile ground for rethinking construction engineering and management from the perspectives of technology, processes, and people (Tzortzopoulos et al., 2020). It was when (Western) construction started to apprehend quality management as in manufacturing. Improvements observed in the automotive sector have not been a product of a radical technology change but the result of the application of a new production philosophy, which was the generalization of partial approaches such as JIT and TQM (Alarcón, 1996). The seminal report *Application of the New Production Philosophy to Construction* (Koskela, 1992) led to the reconceptualization of production theory and practice in construction, which has matured over 30 years to a large extent around the International Group for Lean Construction (IGLC).

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Lean Construction is the counterpart to Lean Production evolved in the context of construction. Lean Production is a generalization of the Toyota Production System (TPS), which is successfully applied in diverse business scenes. However, in Japan, the birthplace of the TPS, the conceptualization of Lean, in general, has been less evident. Iwao (2021) identifies a "conceptualization weakness" related to its high-context culture. Consequently, outstanding management techniques have been conceptualized in other countries and brought back to Japan later. Nonaka and Takeuchi (2019) praise the role of practical wisdom (phronesis) in continuous innovation but emphasize the necessity of both informal and formal interactions to convey the essential meaning of strategies in action. Japanese construction has arguably succeeded without formalized Lean, but there is room for improvement by adopting the "old-new" approach.

When it comes to the construction sector in Japan, it is intriguing that signs of applications of Just-in-Time (JIT), Total Quality Control (TQC), Concurrent Engineering (CE), and Value Engineering (VE) existed since the 1970 and 1980s. They have been little explored, perhaps due to the language barrier. For example, Tamura (2009) cited Taylor's influence in the incorporation of good practices from manufacturing, while Furusaka (2009) and Matsumura (2010) mentioned TQM and VE as innovations that transformed the construction gemba with tools and mindset. Still, there was no clear demonstration of how Lean Construction works at Japanese construction gemba and in white-collar offices, whether it exists in the first place.

Despite the "feel" that something tacit exists, there was no evidence in the "open" literature.

> *Many people are interested in the Japanese state of Lean Construction because Lean Construction has been born out from the Toyota Production System. Although I have been studying and introducing Lean Construction for some years, even now people who know the term "Lean Construction" seem to be less than 50 in number inside Japan (Dr. Inokuma to the Lean Construction Blog, 2017).*

Motived by the unprecedented exchange between Japan and the IGLC community in recent years and the approaching IGLC 2025 scheduled to take place in Osaka and Kyoto, this study aims to revisit the origins of the Lean Construction movement and discuss the paradoxical stance of the Japanese building industry, providing a historical background and reflections aspiring to trigger future exchange opportunities for mutual evolution.

RESEARCH METHOD

This study has employed an interpretivist research philosophy, holding a relativist ontological position, lying closer to a subjective epistemology and a constructivist axiology, according to the classification suggested by Saunders et al. (2009). It is exploratory and aims to shed light on the paradox that has kept the Lean Construction community apart from the Japanese construction academia and industrial societies (and vice-versa), even though a critical source of inspiration came from their manufacturing counterparts.

Quantitative tertiary data were collected from the IGLC proceedings. Qualitative secondary data were attained through a bibliographic review, including untranslated materials. Primary data were obtained through semi-structured interviews. The targets were three experienced engineers from a major Japanese General Contractor, hereinafter (J_n), and Western academics (co-authors to this paper) with a long track record in Lean Construction, hereinafter (W). Participants included: (J_1) Senior Chief Researcher from the R&D (32 years of experience), (J_2) BIM Lead from the Construction Division (21 years of experience), and (J_3) General Manager of Planning & Administration from the Construction Division (33 years of experience).

The approach was inspired by the "catch-ball" game, whose concept has been employed in organizational contexts, conveying the idea of an iterative dialogue, in this case, by correspondence. The specific questions can be followed along with the testimonials, which provide first-hand impressions based on empirical background. The expression "*nama no koe*" (literally *raw voice*) refers to the collection of heartfelt experiences. The discussed topics have long been the object of curiosity in this field and disclose hitherto little-known faces of history.

HISTORICAL BACKGROUND AND CURRENT SITUATION

The origins of the Japanese-style management are not uncontroversial. It is believed that Scientific Management principles met the post-war technocratic rationality of the *Sangyō Gōrika* movement to set the foundations for Japanese manufacturing (*Monozukuri*) as a "revised Taylorite" model (Tsutsui, 1998). Monozukuri practices emerged from unrelated improvements whose underlying principles that led to success were hazy in their inception.

In the realm of building production (*Kenchiku Seisan*), innovations were not understood as "Lean" efforts. Instead, they were likely the product of consecutive kaizens until becoming "ordinary" routine practices. Despite the skepticism toward accepting methods employed in manufacturing, there was a sense of admiration regarding the outstanding performance of TPS. TQC (later renamed to TQM) policies were how those ideas penetrated construction sites, suggesting activities and tools associated with Lean Production without calling them Lean.

To provide a concrete example, Takenaka Corporation has promoted Total Quality Control (TQC) efforts since 1976 and won the Deming Prize in 1979. The following passage conveys the context and spirit of that period (free translation from the original text in Japanese):

> *My father [Ren'ichi Takenaka] began exploring more fundamental business improvements and turned his attention to the automotive industry, where TQC was already advancing. With the guidance of Hino Motors, he came to know the name of Prof. Tetsuichi Asaka (Professor Emeritus at The University of Tokyo and a pioneering leader of TQC). We immediately requested Prof. Asaka's guidance, but he initially declined to accept. However, driven by our determination to ensure the continuation of the Takenaka's family business, we persisted and finally obtained his approval on the third attempt. This happened in 1976. Prof. Asaka had a policy of guiding one company per industry, and our company was chosen for guidance in the construction industry. By the way, in the automotive industry, Toyota Motor Corporation received his guidance. In the electric power industry, it was Kansai Electric Power Company (Toichi Takenaka in Kigyō sonzai kachi no sōzō: Hinshitsu keiei, Takenaka Corporation, TQM Promotion Department, 2022, p.26).*

Endeavors based on a similar philosophy antecede the creation of the IGLC. Nevertheless, the Japanese academia did not devise a formal theory of Lean Production for construction. As a result, Lean-like applications were and, arguably, continue to be essentially tacit.

Recently, prominent former UTokyo Prof. Fujimoto (Economics) collaborated with Prof. Yashiro (Architecture) to "theorize" building production through the lenses of Monozukuri. The joint research resulted in the untranslated book *Kenchiku Monozukuri-ron* (Fujimoto et al., 2015). Intriguingly, it did not mention Lean Construction's TFV theory. Also, there is no report of firms intentionally reformulating their production systems into formal Lean inspired by it.

Fig. 1 illustrates the transmission routes across the movements, including the obstructed but existing path from TPS to Japanese construction and the gap with the formal Lean Construction.

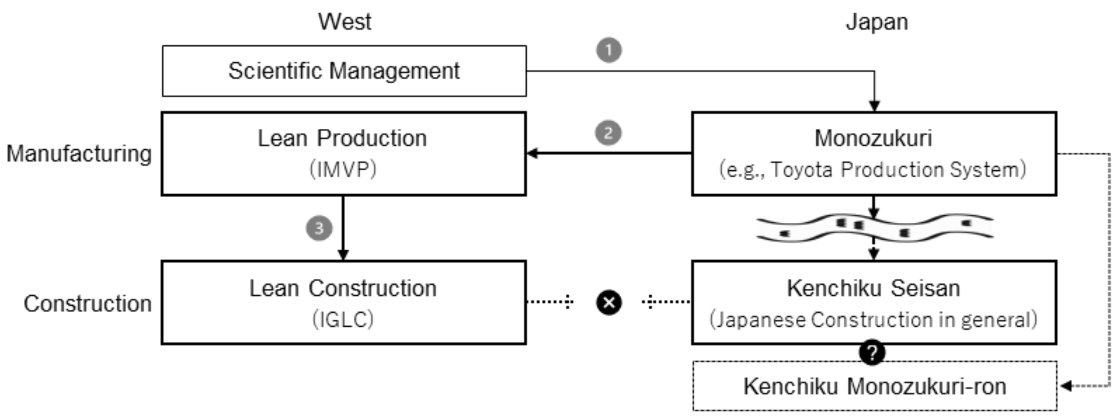

Figure 1: The path to Lean Construction and the disconnection with the Japanese construction

On the whole, Japanese construction has elements of Lean philosophy, introduced via TQC/TQM, but has not systematically deployed Lean Construction methods as in the West. In Japan, the initial focus was more on quality over production efficiency.

HOW DIFFERENT IS THE ORTHODOX JAPANESE APPROACH TO LEAN?

One of the few but most consistent studies on Lean Construction has been conducted by the Research Institute of Construction and Economy (RICE). Yamane et al. (2000) provided a concise yet comprehensive overview of the early days of Lean Construction, mentioning the Egan Report (1988) and research on TPS by European and American scholars as a strategy to overcome issues left unsolved by what the so-called Project Management (PM) methods were not able to do, particularly in terms of dealing with uncertainty and variability.

There was a sense that construction sites operated based on know-how accumulated over many years, and that would be the cornerstone for improving efficiency. They recognized that construction lagged behind manufacturing in many aspects of production systems and production management methods based on “theory”. In a footnote, they cited the Ministry of Construction’s “Construction Industry Technology Strategy (2000)”, which stated that the country had not necessarily accumulated management skills compatible with the international community, so it was necessary to improve the sophistication of management approaches.

One of the interesting points discussed by Yamane et al. (2000) was the comparison between the Last Planner System (LPS) and the Japanese-style construction management. Since the main differences pointed out by that article could be outdated, the four points were checked against the field by authors who updated their descriptions with contemporary reflections.

1. **Lookahead Planning and its associated processes.**
The Lookahead Planning resembles the Japanese *Gekkan Keikaku* (monthly planning). However, the Lean Construction way not only derives “should” from the master plan but considers the “can”, making explicit the necessary conditions in an iterative system reviewed weekly. In comparison, Japanese planning derives monthly and weekly work plans from the master plan and makes sub-processes adhere to them. However, there is no systematic procedure for constraint identification and elimination, which are carried organically.

2. **Last Planner and its associated processes.**
The Last Planner shares characteristics with the Japanese *Shūkan Keikaku* (weekly planning). The Lean way “shields” production by verifying work start conditions based on objective criteria. In comparison, the Japanese way also checks the readiness before moving a task from the monthly to the weekly work plan. The judgment, though, is heavily empirical and relies on tactic knowledge. The adherence to schedule is effective (partially due to its strict discipline) but not necessarily efficient since there is no systematic variability measurement.

3. **PPC metrics and progress lines.**
The PPC is a quantitative indicator of the process plan’s “quality” or “reliability”. It grounds the determination of investigations of the causes of planning failures and poor adherence. By comparison, Japanese sites draw *Shinchoku-sen* (progress line) on process charts that resemble the Line of Balance, updating them weekly and monthly. However, such a practice evaluates the results quantitatively but does not provide a notion of the production system’s “goodness” in terms of “healthy work allocation” and overall process reliability.

4. **Planning responsibility, collaborative kaizen studies, and daily huddles.**
By definition, the LPS promotes the empowerment of frontline workers by engaging them in co-creating the Lookahead and Commitment plans. In Japanese sites, active discussions are held with the foremen regularly in meetings equivalent to “daily huddles” to consider improvements to the production system. In the *Chōrei* (morning assemblies), the communication is mostly direct from the main contractor to the workers. But, in the so-called

"11:30 meetings" for progress and safety management alignment, foremen positively engage with operational decisions and fine-tune countermeasures to arising issues. Still, in most cases, the staff of the main contractor elaborates the process plans in the site office.

THE PARADOXICAL GAP WITH THE LEAN CONSTRUCTION COMMUNITY

Japanese building production took advantage of specific management ideas successfully implemented in manufacturing but never called itself Lean Construction. Despite sharing operational characteristics, its development occurred independently. On the other hand, Lean Construction embodied pre-digested conceptualizations from Lean Production and not directly from Japanese construction sites. Therefore, casual similarities arise from latent ties in their shared sources of inspiration rather than being the product of active exchange and collaboration.

Lean Construction has employed Japanese vocabulary to convey specific ideas, positioning them as holding a different meaning from the customary (i.e., embedding the new philosophy). As elucidated by the text mining conducted by Shigaki et al. (2021), many words that became popular because of the TPS have been utilized without translation at construction sites. The continuity over the years suggests that such a lexicon has become part of the daily vocabulary. They are now an intrinsic part of management systems. Nonetheless, there was no mention of terminology exclusive to construction. The most cited authors are Ohno (1988) and Shingo (1985), with no significant quotes from Japanese architecture or civil engineering academics.

Fig. 2 shows that the tokens "Japan" and "Toyota" appeared the most to contextualize the source of inspiration, followed by specific principles, methods, and tools in IGLC papers.

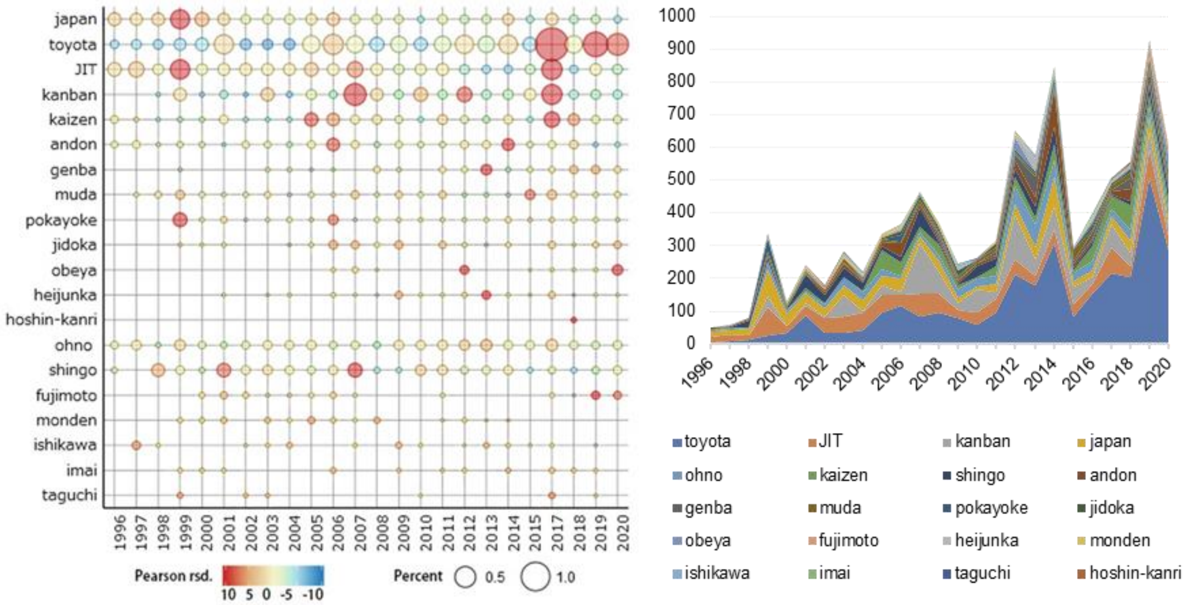

Figure 2: Japan-related keywords in IGLC conference papers (1996-2020) (Source: Shigaki et al. 2021)

The increasing number of participants in the IGLC conferences suggests that the topic is not exhausted. Adaptive in nature, Lean has merged with trending topics to respond to pressing issues such as contracting systems, digital transformation, sustainability, and well-being. It has also broadened its coverage to include more regions across the globe. However, the Japanese participation has been modest, disproportional to its expected position as the source of the TPS.

As for publications in the IGLC, considering the first authors, Japan stands at the 26th position among 50 countries, with only nine papers accounting for 0,42% of all articles (2004, 2005, 2006, 2014, 2017, 2018, 3x in 2023). Three of those papers were presented at the IGLC Conference in Lille, along with two industry day presentations, a record high engagement.

Historically, the countries that hosted more IGLC conferences have the most publications, even though it is difficult to conjecture about the industry-wide level of awareness and organization of their Lean Construction ecosystems. For instance, the US hosted the IGLC six times and is accountable for 21.7% of IGLC papers (affiliations of the first author), followed by Brazil (3x and 14.2%) and the UK (3x and 11.0%). As Osaka and Kyoto will host the IGLC 2025, one can expect growth in the exchange between Japan and the IGLC community.

The first appearance was of a graduate student during his study abroad at Penn State (counted as US), whose research had no direct relation to Japanese construction (see Sakamoto et al., 2002). The first official record is from Prof. Yoshitaka Nakagawa, who said, at that time, that "only a few contractors and house building companies are introducing this Lean Construction system" (see Nakagawa & Shimizu, 2004; Nakagawa, 2005; Nakagawa, 2006).

Then, Dr. Akira Inokuma from the Japan Federation of Construction Management Engineers Association (JCM) published the intriguing "Absence in the Provenance." He stated that "ironically, dialogue on Lean Construction has been limited in Japan, and almost gives a perception that LC is not applied in Japanese construction projects" (Inokuma et al., 2014).

After that, Prof. Koichi Murata, with an industrial engineering background, collaborated with long-standing IGLC members based in the UK, establishing the first formal bridge with the IGLC community (see Murata et al., 2017; Murata et al., 2018; Murata, 2023). In the last conference, Prof. Kaori Nagai, with substantial experience in construction R&D, debuted at an IGLC conference (see Nagai et al., 2023). She coincidently belongs to the same University as the previous professor. Nevertheless, their encounter at the conference was serendipity.

The last publication was of an expat (counted as Japan) who had previously learned Lean Construction abroad but was affiliated with Japanese institutions. The transmission pattern was the opposite of the first one. With an "outside-inside" view, the authors identified tacit manifestations of the Lean philosophy in Japanese construction (see Shigaki & Yashiro, 2023).

Table 1 indicates the co-authorship patterns of the nine papers previously mentioned in terms of "Japanese x International" and "Industry x Academia" allocations.

Table 1: Collaboration patterns of IGLC papers from authors related to Japan (1996-2023)

Pub. Year	First Author	Japan. co-authors		Intl. co-authors		Co-author's affiliation
		Academia	Industry	Academia	Industry	
2004	YN	1	1	-	-	Mid-sized GC
2005	YN	1	-	-	-	-
2006	YN	1	-	-	-	-
2014	AI	-	5	-	-	Consultants
2017	KM	1	-	3	-	U. Huddersfield (UK)
2018	KM	1	-	3	-	U. Huddersfield (UK)
2023	KM	1	-	-	-	-
2023	KN	2	2	-	-	Nihon U, Mid-sized GC, Dev.
2023	JS	2	-	-	-	U. Tokyo

A search for "Lean Construction" in the J-Stage platform (https://www.jstage.jst.go.jp) will lead to only two papers (Nakagawa, 2005; Inokuma, 2014). Both are repeat authors from the IGLC articles shortlist. To explain Lean Construction to the local audience, they both referred to the TPS. The former mentions the Last Planner System as an approach that originated in construction. The latter does not mention specific methods but has the IGLC homepage in the bibliography. The oldest record, however, could only be found in a printed source: the

Proceedings of the 15th Kenchiku Seisan Symposium organized by the Architectural Institute of Japan (AIJ) by Prof. Jun Shiino who did not publish at the IGLC (see Shiino et al., 1999). That is the only paper with "Lean" in the title since 1985.

BRIDGING THE GAP: A CATCH-BALL DIALOGUE

HOW DID JAPANESE CONSTRUCTION INFLUENCE LEAN CONSTRUCTION?

The origin of Lean Construction dates to Lauri Koskela's visit to Stanford University in the early 1990s. Despite the well-known history involving Lauri Koskela, Glenn Ballard, and Gregory Howell, there is little discussion on the role weight of Japanese construction as a source of inspiration for the development of Lean Construction.

When asked about the triggers for interest in the TPS and the American pre-digested Lean Production, Koskela said:

> *For me, there was a specific, concrete trigger: A colleague asked whether we in construction have considered simplifying operations before automating them. I found that his question was inspired by Japanese experiences and started to look for the "new production philosophy" as embodied in the TPS.*

In the preface of his doctoral thesis, Koskela (2000) acknowledged a Japanese person affiliated with a leading house manufacturing company who contributed with a case study. However, such interaction does not seem to have significantly influenced the theorization of Lean Construction. When asked about the exchange with the Japanese person, he said:

> *Such interactions played only a minor role. I had been in Japan earlier for an extended period and had made readings in Japanese culture, but I do not think these experiences were much discussed in the 1992 report.*

WHEN AND HOW DID THE JAPANESE LEARN ABOUT LEAN CONSTRUCTION?

Even among the few people acquainted with Lean Construction, the learning routes and the degree of awareness can be diverse. The testimonials below confirm such a scenario.

> ***[J1]*** *In Japanese construction, scientific management methods, such as TQC, were introduced in the 1970s. By the time I joined the company in 1992, they had become well-established and are still in use. Around 1993, the collapse of the bubble economy made corporate competition fierce. In 1995, I began researching production systems that could significantly reduce costs and improve productivity. Then, I started paying attention to TPS and learning about it from books, including materials by Fujimoto-san. I remember hearing the term "Lean" around that time. However, I did not pay much attention to Lean Construction research when considering ways of applying Toyota's methods. It was around 2009 when I learned about the Last Planner. I got very interested in it and started paying attention to Lean Construction.*

> ***[J2]*** *Coming from the construction site, I started working in software development three years ago (2021) and became interested in Agile. I wondered if this methodology could be applied in construction and began researching examples. It was when I came across the term "Lean Construction". About a year and a half ago (2022), when visiting a hospital project in Norway that utilized a workflow with certain BIM tools, the director of that software vendor taught me that Lean Construction concepts had been employed there.*

> ***[J3]*** *I'm not very familiar with it in the first place. I have a vague understanding that Lean Production has derived from TPS, which focuses on improving bottleneck processes.*

WHY HAS THERE BEEN LESS INTEREST IN LEAN CONSTRUCTION IN JAPAN?

The less interest reflects the low level of awareness, partially due to the language barrier and the difference between high-context and low-context cultures compared to the West.

> ***[J1]*** *Lean Construction is hardly known in Japan. However, just because there is less interest in Lean Construction, it does not mean that the Japanese construction industry is lagging behind in production methods (don't get me wrong). There are several possible reasons why Lean Construction has not received attention. (1) There is a tendency to value "tacit knowledge from the gemba", which has led to a gap in awareness between practitioners and researchers; (2) It is assumed that production methods that have been studied are somewhat difficult to understand and may not be suitable for practice use (if you can't*

engage practitioners in the field, no matter how good the method is, it will die without evolving); (3) There were attempts to learn directly from the TPS, but the translation from manufacturing to construction has not been successful; (4) English has been a barrier, so translation tools in recent years have been a great help.

***[J₂]** Many people just do not know the word. Additionally, there is a bias that since architecture involves creating one-of-a-kind products, it would not be possible to apply manufacturing processes directly. Consequently, only a few individuals are inclined to study the TPS. Also, Japanese people don't frequently search for information in English, so they do not come across information related to Lean Construction.*

***[J₃]** In Japan, production improvement efforts started with the Zero Defects movement, followed by QC activities, TQC, and then TQM. This approach was adopted not only in construction but in all industries. In post-war years, "Made in Japan" was synonymous with poor quality. As a national policy response, quality management began to gain importance. Organizations such as JUSE (Union of Japanese Scientists and Engineers) held QC conferences for all industries, and these activities continue to this day. However, the concept of Lean did not resonate in this country.*

WHY HAS IT BEEN HARD TO COLLABORATE WITH JAPAN SO FAR?

As part of the catch-ball process, the authors of this paper identified several difficulties in establishing deeper connections with Japan and pointed out some directions, summarized below.

***[W]** Understanding the research, business, and cultural context of construction in Japan has proven to be challenging. We need more "conduits" like the professors who already attend the IGLC conferences. There is also this language barrier, as only a few works have been published in English. We also need more research projects with set targets and budgets for collaborations with Japan. It is difficult to obtain funds, at least in the UK, focusing on Lean Construction from traditional research funders. Japanese business organizations could be more active in that regard. Due to the lack of engagement of Japan with the global Lean Construction community until now, Japan is seen as a "no Lean Construction zone" by many.*

WHAT COULD JAPANESE CONSTRUCTION LEARN FROM LEAN CONSTRUCTION?

Towards the wrap-up, the Japanese players reflected on the opportunities to take the good parts of the Lean Construction to further improve their so far tacit approach.

***[J₁]** By learning sophisticated "philosophy" and "methods" that are easy to understand for practitioners and putting them into practice. Lean Construction could be used to make explicit what is done implicitly.*

***[J₂]** Key aspects: (1) Respect for people: It is critical to have conduct guidelines for practicing it. In Japan, there is a tendency to appraise value delivery through self-sacrifice, which has hindered the ability to respect individuals. The concept of "humility", which is admired by foreigners, may intersect with this issue. (2) Logification and verbalization: Japan has struggled with formalizing and articulating systems. The ability to turn tacit knowledge into explicit knowledge is an urgent social matter. (3) Simplifying building structures and working with margins: In Japan, there is also a tendency to favor processes with "no gaps" or minimal downtime. Adopting a mindset that allows buffers could enable smoother processes and more flexibility. (4) Roles: Setting new roles with unique skills, such as coaching and facilitation, have become necessary to implement Lean. Practical examples from overseas could provide valuable insights.*

***[J₃]** I want to learn the concepts and examples of Lean Construction held overseas first. As of now, I cannot provide any definitive insights as I am not well-versed in this area.*

Finally, the authors of this paper provide their perspective on this matter.

***[W]** Japanese construction is well-known for completing projects to a high standard and adhering strictly to the schedule, which may require employing additional resources, working extended hours, or investing in more technologies. To avoid overburden (muri), the Western construction industry has been focusing on health, safety, and well-being. These aspects could be transferred into the Japanese approach. Besides, Lean Construction techniques, such as the Last Planner System, Takt Planning, and Location-Based Planning could be of interest to Japan. Lean design and engineering (beyond construction) could also be new for the Japanese context. Above all, we need to go to the gemba and see what we can offer.*

WHAT COULD THE LEAN CONSTRUCTION MOVEMENT LEARN FROM THE CURRENT JAPANESE CONSTRUCTION MANAGEMENT METHODOLOGIES?

The answer is more about put light on what exists but has not been revealed thus far.

> ***[J₁]*** *Lean Construction could add new methods, such as sound planning and execution resulting from the excellent cooperation between main and subcontractors, by (re-)interpreting Japanese Kenchiku Seisan.*

> ***[J₂]*** *Key aspects: (1) Management techniques such as "shisa-koshō (literally pointing and calling)" and the daily meetings. (2) The highly organized site operation routine for quality, safety, and hygiene management in close cooperation with the subcontractor' foremen. (3) While it may not necessarily be considered a positive aspect, Japanese companies can complete construction work quickly. On the other hand, it might require a significant number of workers and extended working hours before its completion.*

> ***[J₃]*** *Overseas companies tend to be more litigious and have documentation excesses as a defensive management approach. Consequently, the cost of construction guarantees from insurance companies is significantly. By offering "full turnkey" solutions, Japanese General Contractors take comprehensive control and spend less with those kinds of issues. Additionally, General Contractors have advanced in construction technology development, providing solutions such as "composite construction methods (fukugōka kōhō)" and "reverse construction methods (sakauchi kōhō)" that I have not heard about out there. However, due to fundamental cultural differences, it is challenging to make direct comparisons.*

Like in the prior question, the authors provide their perspective on this matter too.

> ***[W]*** *Japan seems to have implemented innovative management practices, drawing inspiration directly from the source, that is, the Toyota Production System. Rather than simply adopting techniques from a toolbox, Japanese-style management returns to the fundamental concepts that underpin these practices. Many overseas organizations, however, implement different tools without considering fundamental concepts, which can affect results. By prioritizing a deep understanding of the underlying theory and principles, overseas organizations may be able to develop a more holistic approach. Also, new management techniques from Japan can be added to the Lean Construction arsenal. Recently, for instance, a large design consultancy company in the UK introduced ji-kōtei kanketsu, which became very successful.*

DISCUSSION: LESSONS FROM ABROAD

There are two main lessons from which Japan could take advantage when organizing itself regarding Lean Construction's future directions. (1) The role of dynamic ecosystems in the birth and expansion of the Lean Construction movement; and (2) The presence of heavy-weight champions who actively developed "conduits" leaders. The importance of the Californian ecosystem can be recognized in the intertwined biographies of exponents of this subject.

The "*Festschrift honouring Dr. Glenn Ballard*" (see Koskela et al., 2022) reports the story of a "maker at heart" who gained first-hand experience as a field worker on-site and then broke through to managerial positions and gradually transitioned from industry to academia. His collaboration with Gregory Howell, Lauri Koskela, and Iris Tommelein gave him access to widen his connections and enable enriching exchanges with construction companies, industry organizations, and Universities, where he met field workers, executives, notable professors, and students, each contributing to the development and maturation of innovative ideas.

This part of the history is also found in the inspiring first-person narrative of Iris Tommelein in her "*Journey Toward Lean Construction*" storytelling (see Tommelein, 2015). Colleagues from multidisciplinary backgrounds, encouragements to "go to the gemba" as an academic, the transit between lively Universities, the field experience in a Sabbatical, and the establishment and direction of a dynamic research laboratory (PS2L) with strong ties with the industry were contributing factors to enriching the path of a champion that transmitted the knowledge to talented students who have helped conduct the paradigm shift in the AEC industry.

Moving the focus to Scandinavia, Lohne et al. (2022) narrated the "*Emergence of Lean Construction in Norway*", which, as they said, was a phenomenon occurring within a setting that is generally advantageous but also following an effort carried out on several levels. The specificities of the Norwegian context included, for instance, the early experimentation by its largest contractor (Veidekke), the formal introduction of Lean Construction in the academic curriculum, and publication by authors from industry, universities, and research institutions. The appointment of Glenn Ballard as an adjunct professor at NTNU was also emphasized.

Going to a specific case, Elving (2022) narrated "*A Decade of Lessons Learned*" at Skanska Finland, pointing out what worked and what did not work in taking academic concepts to industry. The advice from Glenn Ballard was again highlighted. In the case of experimenting with the Last Planner System implementation, he emphasized the significance of industry-level approaches and technology platforms to logistics and supply development.

Clients and asset owners have also played an important role in the Lean Construction ecosystem. In the UK, for instance, National Highways' Lean Construction agenda has driven application in their supply chain (NH, 2020). In the US, Sutter Health has been a large client organization demanding Lean Construction application, recognized by the LCI for "moving the industry forward in embracing and implementing Lean tools on capital projects (LCI, n.d.)".

Regarding the heavy-weight champions, beyond his own contributions to the Lean Construction discipline through the TFV theory, Lauri Koskela also nurtured pupils who have made remarkable contributions. To name a few, Sergio Kemmer has been a successful consultant to a range of company sizes and regions. Bhargav Dave has led a startup whose core product emerged from PhD research. Daniel Forgues and Algan Tezel have contributed from an academic position while building ties with the industry. Indeed, some champions have industry backgrounds. Sven Bertelsen (Denmark) and Dean Reed (US) are notable examples who observed and participated in the evolution of the Lean Construction movement.

It is also worth noting the successful stories from South America, personified by Prof. Carlos Formoso (Brazil) and Prof. Luis Alarcón (Chile), who not only actively promoted the Lean Construction agenda, but also taught key figures who are now spread all over the world in both academia and industry. The Southern Hemisphere could be an inspiration to the East. As a limitation, this paper does not cover many other exponents deserving acknowledgment spread in various locations. Many more could also provide insights for advancing Lean in Japan.

During Japan's rapid economic growth period, in the second half of the last century, quality issues demanded innovative solutions. Such a context relates to the project ordering system in which General Contractors control the whole process and take massive responsibility. By then, instead of applying Lean as we know it today, the idea was to merely "build things that do not turn out into problems". Because of such strong customer orientation, it turned out that the physicality of buildings and the processes required to erect them became complicated.

In that context, the solutions created to tackle those challenges had an earnest technological emphasis, developing "hard technologies" to enable the so-much-aspired rationalized construction processes and other "soft" management goals. The *fukugōka kōhō* (Shigaki & Yashiro, 2023) and *sakauchi kōhō*, strategies not widespread overseas, are expressions of their unique engineering strength, which are partially the result of well-structured R&D Institutes and excellent in-house designers. That was chronologically before the emergence of the Lean Construction movement in the West and has since developed independently. The takeaway from those experiences was the attempt to create solutions that help organize the entire business in a way that benefits the owner. Such an attitude reflects the Japanese "culture of matching".

Intriguingly, Japan has developed Lean-ish ideas as part of quality management efforts but has not formalized Lean Construction as a platform for improvement in the delivery of projects. Studying from foreign examples, a proper curriculum in architectural and civil engineering education would possibly help accelerate the process of converting tacit knowledge into know-how that could be more easily transmitted to next-generation practitioners. Currently, the AIJ has no active committee to discuss Lean Construction. Neither has the influential *Nikkenren* (Japan Federation of Construction Contractors) a working group on this topic. The next IGLC could be a trigger to move forward.

CONCLUSION

The testimonials confirmed that Japanese construction has elements of Lean ingrained in routine practices. However, they have not been deployed as formal Lean Construction methods as known in the IGLC community. Through the preliminary but engaging dialogue between Lean theorizers and Japanese construction practitioners, the paradoxical gap between them has started to be filled. The continuity of such exchange could trigger innovations that bridge and eventually unite excellent partial solutions.

As a next step, Japanese constructors have aspired to pull their engineering strength to the next level and combine it with innovative management practices, including incorporating good ones learned from overseas. That is where the role of Lean resides. Lean may help fill the gap of converting tacit knowledge into structured knowledge, increasing transparency, smoothing the transmission of know-how to business partners (externally) and young employees (internally), creating more efficient project deliveries, and turning itself into a more attractive business. They aspire to nurture talented people who "generate maximum value by creating works that amaze", powered by individual ingenuity and collective rationality.

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ASSESSING SOCIAL, TECHNICAL, AND OPERATIONAL MATURITY DIMENSIONS FOR DIGITAL TRANSFORMATION IN THE CONSTRUCTION PHASE

Luara L. A. Fernandes[1], Makarand Hastak[2] and Dayana B. Costa[3]

ABSTRACT

The importance of digital transformation (DT) has risen significantly in the past few years in several industry sectors, including construction. Some potential benefits of DT in construction include improvements in productivity, efficiency, safety, quality, and collaboration. However, fully embracing DT opportunities involves committed efforts in Key Project Areas (KPAs), and identifying these areas is still challenging. Therefore, this work aims to assess social, technical, and operational maturity dimensions for digital transformation in the construction phase. These dimensions are the KPAs construction managers should focus on throughout the construction environment DT process. A questionnaire was administered to 54 construction professionals from industry and academia. Data collected was analyzed using ranking analysis from the Relative Importance Index (RII) calculation. Results revealed that the participants did not rank technical aspects as the most significant; rather, these aspects were regarded with slightly less importance than other dimensions. The balance among social, technical, and operational factors in the ranking indicates that construction professionals recognize the insufficiency of technology implementation alone for driving significant changes; instead, human resources must lead the process improvement with the support of digital technologies. These findings align with Industry 5.0 and Lean Construction concepts, reflecting some synergies between them.

KEYWORDS

Digital transformation, Construction phase, Industry 5.0, Lean construction.

INTRODUCTION

Digital transformation has become a high-priority agenda theme for organizations and governments due to its competitive advantage in many sectors, including construction (Zomer et al., 2019). According to Tilson, Lyytinen, and Sorensen (2010), digitalization is "a sociotechnical process of applying digitizing techniques to broader social and institutional contexts that render digital technologies infrastructural." It is a deep transformation of business

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activities, processes, competencies, and models to embrace the changes and opportunities offered by digital technologies and their influence across society (Demirkan et al., 2016).

The emergence of Industry 4.0 in the construction industry (Construction 4.0) seeks to transform it towards digitally developed businesses (Alaoul et al., 2018). The industry definition of Industry 4.0 for construction encompasses several interdisciplinary technologies and concepts that enable the digitization, digitalization, automation, and integration of the construction process at different phases (Oesterreich & Teuteberg, 2016). González et al. (2022) presented the novel concept of Lean Construction 4.0, a Process-People-Technology Functional Model based on the idea that Lean Thinking can be the steppingstone for an effective adoption of IR 4.0 in construction. According to this approach, IR 4.0 technologies can potentially eliminate or reduce any of the seven Lean wastes identified originally by Shingo et al. (2005) and Taiichi (1988), while Lean Thinking supports eliminating waste and adding value, supporting a solid and efficient Industry 4.0 development and implementation.

In 2020, the concept of Industry 5.0 was launched to address challenges faced by environments under Industry 4.0 transformations, such as lack of resilience, insufficient attention to sustainable production approaches, and overemphasis on technology (Olah et al., 2020; Sindwani et al., 2022; Zizic et al., 2022). Industry 5.0 advocates balanced human-machine cooperation focusing on the diverse stakeholders' well-being (i.e., society, companies, human resources, and clients) (Noble et al., 2022). The application of Industry 5.0 in construction is still in its early stages.

According to Sony and Naik (2020), human-machine collaborations should be guided by the sociotechnical transformation. The sociotechnical systems approach concentrates on incorporating technology into the work system rather than focusing mainly on technology (Sackey et al., 2015). It is based on the observation that a successful technology implementation involves fully understanding the organizational context (structure, work, and workforce) (Sackey et al., 2015). While the original approach (Trist, 1981) describes a sociotechnical system as a combination of the social and technical subsystems, Vlachos et al. (2021) add the operational system, which, according to Fernandes and Costa (2024), is more suitable for construction environments.

Furthermore, incorporating digital technologies into construction environments can enhance productivity, safety, quality, and project management (Maskuriy et al., 2019). However, Joppen et al. (2019) highlight the challenges of measuring these transformations. Even though many analyses describe changes due to digital transformation, the instruments for recording them with the support of indicators are still poorly discussed (Joppen et al., 2019). Unlocking the advantages of technological advancement involves understanding how these transformed processes should be assessed and managed using assessment tools such as maturity models (Kloviene & Uosyte, 2019). In addition, to fully embrace IR 4.0 opportunities, managers should devise a strategy focused on Key Project Areas (KPAs) (Maskuriy et al., 2019). Nevertheless, identifying these KPAs remains challenging, and the existing literature still needs to explore this gap further. Considering a new sphere of knowledge, it is not possible to identify them only from the literature, and exploratory research methods, such as case study interviews (De Bruin et al., 2005), surveys, and on-site immersions, should be considered in this process.

Therefore, this work assesses social, technical, and operational maturity dimensions for digital transformation in the construction phase. These dimensions are the KPAs that need to be measured and managed throughout DT in the construction phase. This paper presents one stage of broader research in the context of a Ph.D. thesis, which aims to propose a Maturity Measurement System for an Intelligent Construction Environment, positioning the construction industry in the digital transformation path from a sociotechnical perspective. The first product of the Ph.D. work was a conceptual model for measuring the maturity of digital transformation in the construction phase (Fernandes & Costa, 2024). This model introduced 24 maturity dimensions (categorized into sociotechnical subsystems), which are the critical aspects construction managers should focus on and manage throughout the digital transformation process of the construction environment. The assessment of these dimensions is presented in this paper. The model is further presented in the Literature Review section.

This work's primary practical contribution is a preliminary proposition of measurable domain areas essential for continuous improvement, assessed in terms of importance, which directs construction projects toward an Intelligent Construction Environment. Theoretical contributions include insights into the challenges the Industry 4.0 technology-centric approach poses, potentially hindering the proper integration of these advancements into the construction sector. Additionally, the study explores the role of Industry 5.0 principles in this context and their potential synergies with Lean Construction concepts.

THE SOCIOTECHNICAL APPROACH IN THE DIGITAL TRANSFORMATION CONTEXT

A system is a social construct encompassing several relationships between elements expressed differently (Patriarca et al., 2021). Emery and Trist (1960) originally used the term "sociotechnical system" (STS) to describe systems that involve a complex interaction among humans, machines, and the environment in the work system. This approach considers that a change in one part of the system will lead to changes in other parts (Sony & Naik, 2020).

In the digital transformation context, Sony and Naik (2020) point out that, in addition to the integration of the cyber and physical domains through technology, Industry 4.0 is also a social (human-related) and technical (non-human-related) system. The sociotechnical approach unveils new opportunities for prompt development based on recognizing the importance of human work in the innovation process (Kagermann et al., 2013). According to Hirsch-Kreinsen et al. (2018), Industry 4.0, from a sociotechnical perspective, comprises the subsystems of technology, organization, and people and the interface among them. Patriarca et al. (2021) present the evolution of a sociotechnical system toward a Cyber-Socio-Technical System (CSTS). The CSTS extends to the social relations between humans and cyber artifacts and the collaboration of multiple cybernetic artifacts (Patriarca et al., 2021).

Furthermore, Vlachos et al. (2021) present a sociotechnical system as a combination of social, technical, and operational subsystems, more apparent in lean automation implementations. Fernandes and Costa (2024) designed the construction environment under digital transformation based on this three-subsystems concept, which is composed of the following elements: human resources, culture, digital technologies, work infrastructure, production processes, and performance.

DIGITAL TRANSFORMATION IN CONSTRUCTION

Digitalization is revolutionizing several construction processes, including planning, designing, constructing, operating, and maintaining structures (Ozturk, 2021). Forcael et al. (2020) point out that the pillars of Construction 4.0 are the digitalization of the construction industry and the industrialization of construction processes. According to Sawhney (2020), Construction 4.0 is a framework that is a confluence and convergence of the following areas:

- Industrial production – Prefabrication, 3D printing and assembly, and offsite manufacturing.
- Cyber-physical systems – Robots and cobots (collaborative robots) for repetitive and dangerous processes, drones for surveying and lifting, movement and positioning, and actuators.

- Digital technologies – BIM, video and laser scanning, IoT, sensors, AI and cloud computing, big data and data analytics, reality capture, blockchain, simulation, augmented reality, data standards, interoperability, and vertical and horizontal integration.

While the term Construction 4.0 straightforwardly applies the Industry 4.0 concept in the Construction Industry, Fernandes and Costa (2024) argue that digital transformation in construction environments should be driven by Industry 4.0 and Industry 5.0 principles. These authors presented the concept of an Intelligent Construction Environment as "an efficient, resilient, human-centered, and sustainable environment composed of a complex sociotechnical system that uses digital technologies as tools for continuous improvement (Fernandes & Costa, 2024). According to this study, its elements dynamically interact to achieve the following principles: Human centricity, Flexibility, Resilience, Transparency, Collaboration, Decentralization, Virtualization, Horizontal and vertical integration, Real-time capability, Sustainable management, Predictive capacity, and Interoperability.

Fernandes and Costa (2024) also presented 24 social, technical, and operational dimensions to measure the maturity of digital transformation in construction environments in the construction phase (Figure 1). These dimensions are the critical aspects construction managers should focus on and manage throughout the digital transformation process of the construction environment. The dimensions proposed are as follows:

- Social subsystem: Coordination, Sustainability, Innovation, Training, Participative decision-making, Communication, Occupational health and safety, and Promotion of formal education.
- Technical subsystem: Digital technology implementation and management, Development and maintenance of digital solutions, Collection, storage, processing, analysis, and management of massive and complex data, Data Security, Robots and cobots, Construction site layout, and Workspace.
- Operational subsystem: Complexity management, Production planning and control, Storage and logistics management, Timely prediction, Supply chain management, Quality management, Performance management, Cost reduction, and Timely action.

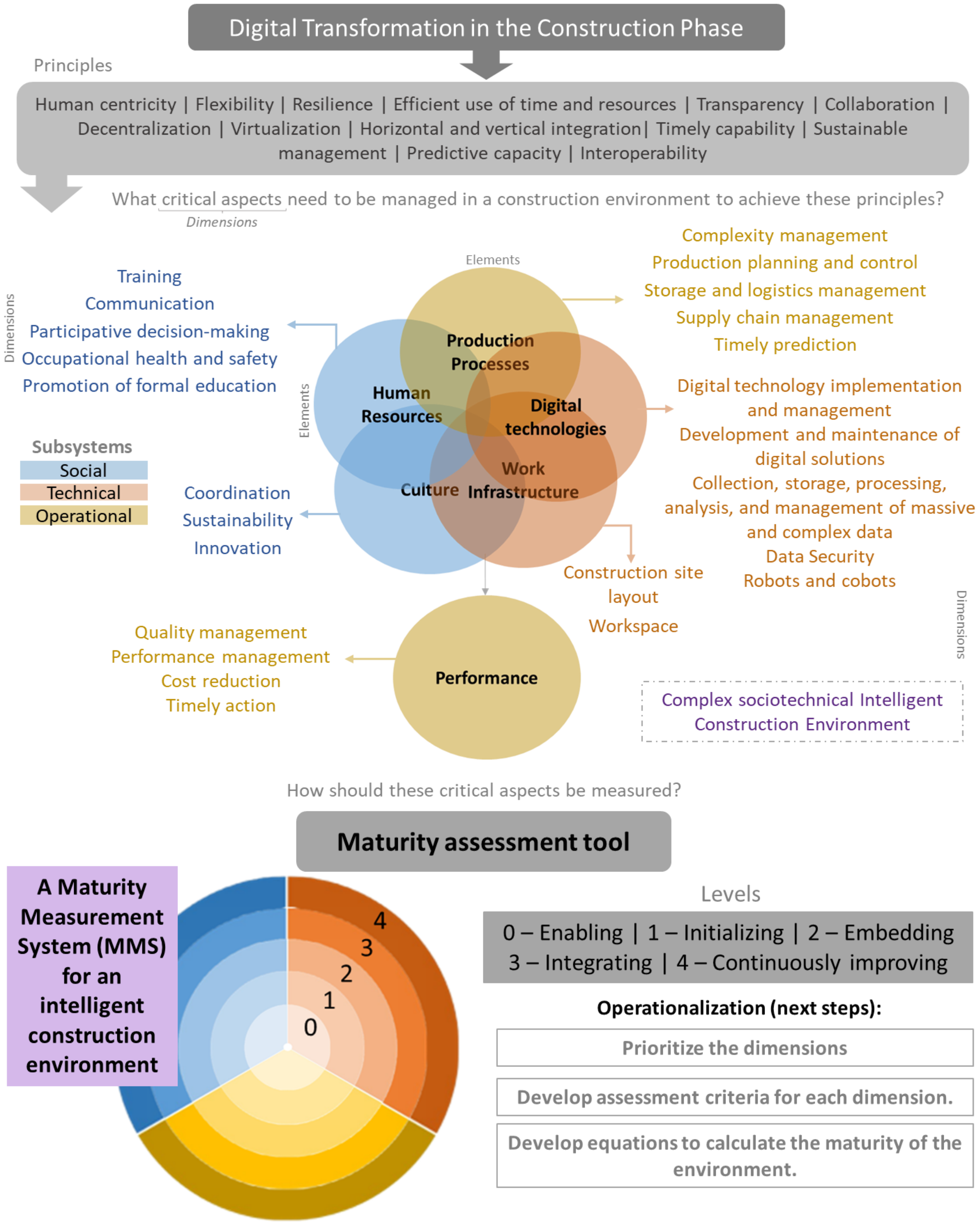

Figure 1 – The conceptual model for measuring the maturity of an Intelligent Construction Environment (Source: Fernandes and Costa, 2024).

The definition of each of these dimensions is presented in Fernandes and Costa (2024).

RESEARCH METHOD

The methodological approach adopted in the development of this study was a survey, which consists of a data collection procedure from a sample of individuals through responses to questions (Check & Schutt, 2012). The data collection instrument used was a questionnaire, and the sample was composed of construction management professionals from industry and academia. The survey aimed to assess the maturity dimensions proposed by Fernandes and Costa (2024) in terms of importance. Thus, the research team required the participants to answer the following question: "On a scale from 1-10, what weight should these dimensions have in their respective subsystems for assessing the maturity of an Intelligent Construction Environment?".

DATA COLLECTION

The study's development initially involved designing a structured questionnaire in the Google Forms platform. It consisted of 5 sections, which are the following: (a) Cover letter, including the research purposes and the definition of an Intelligent Construction Environment, and agreement terms; (b) Respondent profile, including major, occupation area, position, affiliated organization/university, and highest degree attained, (c) Social Dimensions, (d) Technical Dimensions, and (e) Operational dimensions. In the three last sections, the respondents were required to assign a weight from 1 to 10 to each dimension, according to the following degree of importance: 1-4 - Low Importance, 5-7 - High Importance, 8-10 – Essential. In addition, participants could also propose adding or removing dimensions and share notes or comments through open-ended questions. The instrument was tested with the GETEC (Research Group in Construction Technology and Management) research group on January 26, 2023. The pilot application involved 15 people, including 3 Ph.Ds., 3 MSCs, 1 Civil Engineer, and 8 Undergraduate Students (Civil and Electrical Eng.), and it was aimed at evaluating the understanding of the questions and the response time.

Then, the questionnaire was sent in English and Portuguese by e-mail to a list of 50 potential respondents from Industry and Academia. Then, after two weeks, the questionnaire was disseminated through LinkedIn, with the aim of engaging additional relevant members not initially included in the email list and to serve as a reminder for those who had received the email but did not respond. The intended participants were professionals in civil engineering and architecture from industry and academia. It was initially shared on August 4th, 2023, and remained collecting responses until September 1st, 2023.

A total of 55 responses were obtained - 43 from the Portuguese (Brazilian respondents) and 12 from the English form (Respondents from Denmark, India, Chile, Colombia, Portugal, South Africa, and the United States), of which 54 were considered valid because one was identified as a duplicate. Eight of the 54 respondents were not initially included in the email list.

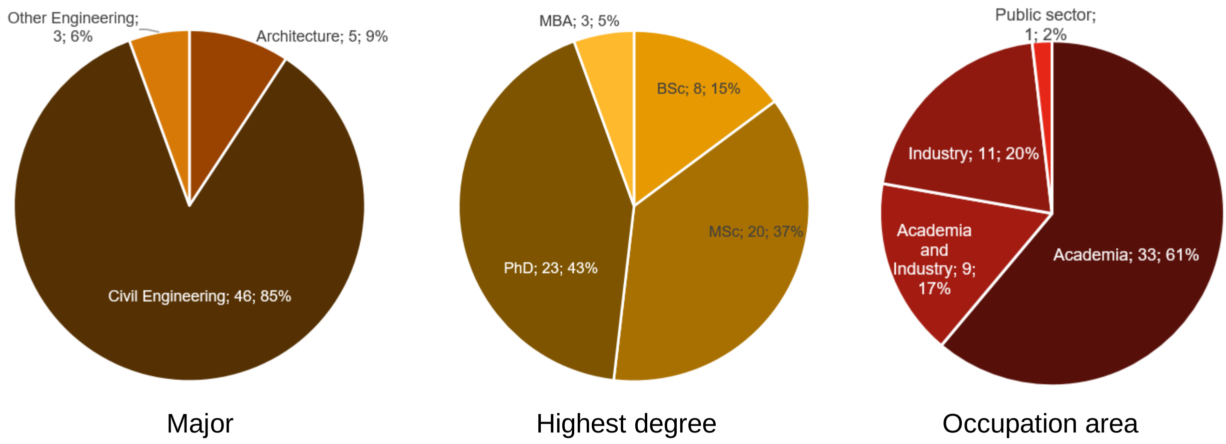

Figure 2 – Characterization of the respondents

DATA ANALYSIS

Data analysis first involved the calculation of Cronbach's alpha, denoted as Cα, a reliability coefficient. It was developed by Lee Cronbach in 1951 to measure the internal consistency of a test or scale (Tavakol & Denik, 2011). Internal consistency refers to the degree to which all items in a test measure the same concept, indicating the interconnectedness of test items, while reliability quantifies the extent of measurement error in the test (Tavakol & Denik, 2011). Cronbach's alpha is mathematically defined as the adjusted proportion of total variance of item scores explained by the sum of covariances between item scores, ranging from 0 to 1 when all covariance elements are non-negative (Heo et al., 2015). A higher Cronbach's alpha (Cα), approaching 1, indicates greater reliability. The following reliability scale (George & Mallery, 2003) was adopted in this work:

$\alpha \geq 0.9$ Excellent

$0.9 > \alpha \geq 0.8$ Good

$0.8 > \alpha \geq 0.7$ Acceptable

$0.7 > \alpha \geq 0.6$ Questionable

$0.6 > \alpha \geq 0.5$ Poor

$0.5 > \alpha$ Unacceptable

The Cronbach's alpha (Cα) was calculated in the SPSS software, resulting in a value of 0.901, which indicates excellent reliability.

Subsequently, data were analyzed using ranking analysis from the Relative Importance Index (RII) calculation. It is a non-parametric technique for analyzing structured questionnaire responses (Chung et al., 2021). The RII ranges from 0 to 1, enabling the identification of the most influential factors within a given set (Watfa et al., 2022). It has been widely employed in assessments of construction-related research and technology adoption drivers (Watfa et al., 2022). The dimensions' RIIs were calculated using the following equation:

$$\text{Relative Importance Index (RII)} = \frac{\sum W}{A \times N}$$

Where:

W = the weight assigned by the respondents to each dimension.

A = the highest weight that could be assigned.

N = the total number of respondents.

The data were converted to a Likert scale (1-5) to simplify the calculation process. The importance scale adopted to analyze the RIIs was the following (Chung et al., 2021):

High ($0.8 \leq RII \leq 1.0$),

High-Medium ($0.6 \leq RII < 0.8$),

Medium ($0.4 \leq RII < 0.8$),

Medium ($0.2 \leq RII < 0.4$),

Low ($0 \leq RII < 0.2$).

The findings obtained are presented in the next section.

FINDINGS

Table 1 summarizes the list of dimensions, with the respective subsystem, percentage of answers in each level of importance, the correspondent RII, and rank. The dimensions' RII values ranged from 0.652 to 0.956, classifying all dimensions with a high (87,5%) or high-medium (12,5%) importance level. The dimension "Communication" was ranked as the most important, followed by "Training" and "Production Planning and Control." These three dimensions were the only ones with an RII exceeding 0.9. Notably, none of these dimensions are technical, suggesting that the respondents do not prioritize technical aspects as the most crucial factors, indicating an alignment with Industry 5.0 principles.

Table 1 – Ranked dimensions.

Dimension	Subsystem	% of answers in each level of importance			RII	Rank
		(1-4)	(5-7)	(8-10)		
Communication	Social	0.00%	1.85%	98.15%	0.956	1
Training	Social	0.00%	9.26%	90.74%	0.933	2
Production planning and control	Operational	0.00%	14.81%	85.19%	0.933	2
Digital technology implementation and management	Technical	0.00%	16.67%	83.33%	0.896	4
Data Security	Technical	1.85%	20.37%	77.78%	0.896	4
Quality management	Operational	0.00%	16.67%	83.33%	0.896	4
Workspace	Technical	3.70%	22.22%	74.07%	0.881	7
Performance management	Operational	1.85%	16.67%	81.48%	0.881	7
Innovation	Social	0.00%	24.07%	75.93%	0.874	9
Timely action	Operational	1.85%	18.52%	79.63%	0.867	10
Supply chain management	Operational	5.56%	14.81%	79.63%	0.863	11
Development and maintenance of digital solutions	Technical	0.00%	37.04%	62.96%	0.859	12
Storage and logistics management	Operational	3.70%	22.22%	74.07%	0.859	12
Timely prediction	Operational	3.70%	27.78%	68.52%	0.856	14
Occupational health and safety	Social	3.70%	27.78%	68.52%	0.852	15
Collection, storage, processing, analysis, and management of massive and complex data	Technical	1.85%	29.63%	68.52%	0.852	15
Cost reduction	Operational	3.70%	27.78%	68.52%	0.844	17
Coordination	Social	3.70%	33.33%	62.96%	0.837	18
Construction site layout	Technical	3.70%	38.89%	57.41%	0.83	19
Participative decision-making	Social	5.56%	33.33%	61.11%	0.826	20
Sustainability	Social	5.56%	29.63%	64.81%	0.822	21
Complexity management	Operational	7.41%	40.74%	51.85%	0.785	22
Promotion of formal education	Social	11.11%	42.59%	46.30%	0.774	23
Robots and cobots	Technical	20.37%	57.41%	22.22%	0.652	24

Following them, the dimensions “Digital technology implementation and management,” “Data Security,” and “Quality management” share the fourth position. This alignment suggests that managers recognize the significance of protecting data, which encompasses preventing unauthorized access, using and disclosing stored information, and ensuring data privacy. Managing this aspect is crucial, especially considering that it is one of the foremost concerns associated with the progression of digital technologies in workspaces.

It is worth highlighting that among the top 9 dimensions, there are three of each subsystem (social, technical, and operational). Even if a "hypothetical" RII is calculated for the subsystems, based on the respondents' average weights assigned to dimensions within each subsystem, similar values are found among them: 0.830, 0.822, and 0.837 for the social, technical, and operational subsystems, respectively. This symmetry suggests that equal importance is given to social, technical, and operational aspects of the digital transformation process. It implies a recognition that effective management and successful outcomes in this context require a holistic consideration of not only technological factors but also social and operational features.

Nevertheless, the dimension "Robots and cobots" was ranked as the least important, followed by "Promotion of formal education" and "Complexity management." These were the only dimensions with an RII lower than 0.8. The lower RII was attributed to "Robots and cobots," which may be related to the construction sector's resistance to the replacement of human labor by technologies in production, as presented in Fernandes and Costa (2024), coupled with concerns about the potential financial impacts associated with such changes. Regarding the "Promotion of formal education," one respondent emphasized that the education dimension should prioritize pursuing learning opportunities over attaining a degree, considering the latter is not necessarily essential. Several respondents argued about the meaning of "Complexity management," which potentially influenced its assigned weight and contributed to the low RII of this dimension.

In response to open-ended questions, participants provided various additional comments. In the **social subsystem section**, the main suggestions involved the inclusion of dimensions related to mental health, strategy, transparency, and governance. It was also proposed addressing elements such as cultivating a culture of exchanging experiences among employees, establishing a non-judgmental environment, and relocating sustainability and participative decision-making from the operational (construction site) to the organizational level, suggesting that the latter two aspects should be strategically addressed at a broader organizational scale.

In the **technical subsystem section**, some respondents suggested that layout and workspace should be addressed as a single dimension, while others suggested a construction site dimension including all these aspects. Others recommended repositioning social dimensions, including occupational health and safety and communication, within the technical subsystem to align these aspects more closely with the technology and workspace dynamics. One participant suggested ensuring the accessibility of digital tools for workers across all hierarchical levels.

In the **operational section**, most comments were related to the dimensions "Cost reduction" and "Complexity management." Respondents argued that the emphasis should not be on cost reduction but on effective cost management, acknowledging that digital transformation may demand initial short-term increases. Regarding "Complexity management," several participants argued the meaning and purpose of this dimension, which implies that complexity studies in construction are still not properly disseminated, and the term is still not familiar among both industry and academic professionals. However, other respondents suggested that all the other dimensions already cover its aspects. One respondent emphasized that the most significant opportunities for improvement within the operational subsystem lie in this dimension, as traditional approaches already address time, cost, schedule, and quality concerns. Moreover, some participants suggested consolidating "Timely prediction" and "Timely action" into a single dimension, arguing the interdependence of these aspects.

DISCUSSION

In the past few years, the upsurge and fast dissemination of Industry 4.0 concepts and technologies have triggered several debates regarding applying these novelties in construction. It is already a consensus that this industry is behind in adopting these features, which can be attributed partly to its inherent characteristics, artisanal nature, heavy reliance on human labor, and the intrinsic complexity of its production environments. However, the IR 4.0 excessive focus on technology is also an obstacle to integrating these advancements into the construction sector. Fernandes and Costa (2024) argued in their study that digital transformation in construction must be driven by IR 4.0 and IR 5.0 principles, and the findings of this survey align with this perspective.

The results of this study revealed that the participants did not prioritize technical aspects. Instead, these aspects were regarded with slightly less importance than other dimensions. More specifically, none of the top three ranked dimensions (the only ones with an RII higher than 0.9) were technology-related; the first two were social dimensions related to human resources, while the third was an operational dimension concerning the production process element. Moreover, the balance among social, technical, and operational aspects in the rank suggests that construction professionals recognize that technology implementation by itself is not enough to promote significant changes; instead, human resources must lead the process improvement with the support of digital technologies.

Part of this awareness can be attributed to the construction industry's extensive journey in studying and implementing the principles of the lean production philosophy, which emphasizes people engagement, learning, and leadership, from shop-floor workers to managers, in process improvement. In fact, Lean Construction and Industry 5.0 share core values. For Mladineo et al. (2021), Lean management can be seen as an Industry 5.0 enabler. According to Faisal et al. (2024), combining these concepts may enable a cost-effective, sustainable, and efficient production system that enhances worker capabilities by optimizing productivity and minimizing waste.

The synergies between Lean management and Industry 5.0 principles (human centricity, resilience, and sustainability) have been individually explored in some studies. Solaimani and Sedighi (2020) identified that lean construction positively impacts all three pillars of sustainability in construction projects. Hamerski et al. (2023) pointed out that the Last Planner System, despite some limitations, can contribute to a resilience performance in construction. Mladineo et al. (2021) showed that most key success factors of Lean management and Lean tools implementations in SMEs are people-oriented, reflecting the human-centric approach to organizational and process improvement, as required by Industry 5.0. Nevertheless, these synergies have not been studied directly and holistically yet, which suggests an interesting gap to be explored in future works.

CONCLUSION

This work aimed to assess social, technical, and operational maturity dimensions for digital transformation in the construction phase. For that, it presented the results of a survey questionnaire administered to 54 construction professionals from both industry and academia. Data analysis involved ranking the dimensions by calculating their Relative Importance Index (RII) from the weights assigned by the respondents. Results show that technical dimensions were not ranked as the central ones, and the outcomes indicate an equilibrium among the importance of social, technical, and operational factors for digital transformation in the construction phase. Findings align with Industry 5.0 and Lean Construction concepts, indicating synergies among them. Although these synergies have been individually explored in some studies, they have not been studied directly and holistically yet, which suggests an interesting gap to be explored in future works.

This work is one of the stages in the development of a Ph.D. thesis, which aims to propose a Maturity Measurement System for an Intelligent Construction Environment. The findings presented in this paper support the assignment of weights and refinement of maturity measurement dimensions, which is the initial step in transforming the proposed conceptual model (Figure 1) into a practical tool—the Maturity Measurement System (MMS). Future steps involve (a) the proposition and validation of assessment criteria and equations to measure the maturity in each dimension, subsystem, and overall environment and (b) the application, test, and validation of the MMS, with subsequent guidelines for implementation.

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A CRITICAL ANALYSIS OF CHOOSING BY ADVANTAGES IMPLEMENTATION IN THE TENDERING PROCEDURE BASED ON EU DIRECTIVE AND GERMAN LEGISLATION

Annett Schöttle[1] and Fabian Behme[2]

ABSTRACT

The Choosing by Advantages (CBA) Tabular method is a decision-making method that differentiates between alternatives based on the importance of advantages. By doing so, cost-related factors are excluded from the table to better understand the value of each alternative. After evaluating the value, the cost/price of each alternative is analyzed in relation to the value. This is a crucial rule to avoid overestimating cost/price and underestimating the value of an alternative. In the public tendering procedure, price is usually the only factor or the main factor used to decide between proposals. As other authors have already pointed out, this leads to speculative bidder behavior that might be rewarded. Using CBA requires a change in thinking, but it will be beneficial in truly understanding the differences between proposals. Therefore, this paper examines the use of CBA in the tendering procedure based on EU Directives and German legislation. It was found that it is possible to implement CBA in the current tendering procedure without violating the principles of CBA. However, the adjustment needed to apply CBA within the current regulations clearly goes against what CBA intends. Therefore, we suggest changing the current reactive tendering procedure to an active decision-making process. This paper does not provide a final answer but aims to open the discussion.

KEYWORDS

Choosing by Advantages (CBA), legislation, public, tendering.

INTRODUCTION

Can a tendering procedure for large projects be fair based on price alone? In many projects, there is a tendency to prioritize the lowest price, or if other factors are considered, the price is given significantly more weight. This makes it difficult to understand the differences between proposals and creates room for speculation to win bids. Rosenfeld (2014) refers to these unrealistically low tender-winning prices as "suicide tendering." So, what happens when someone is contracted under these conditions? Over the years, numerous authors have already pointed out that competition based solely on price often leads to disputes and claims during project execution, creating an unhealthy project organization where the project ultimately suffers (e.g., BMVI, 2015; Elfving, 2005; Eriksson & Laan, 2007; Rosenfeld, 2014; Rooke, 2014; Schöttle & Gehbauer, 2013). However, public tendering has not undergone significant changes yet; the transactional approach still dominates the public system and is based on a

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misguided focus. Instead of focusing on project requirements and needs, the emphasis shifts to monetary transactions. Each tender partially sets the tone for the project because it represents the initial interaction between the owner and the contracted parties (Schöttle, 2022). The parties' behavior during the tendering procedure will ultimately impact the project execution. So, how can we improve the tendering procedure?

We believe that a tendering procedure based on a fair evaluation of proposals is essential, meaning an established method such as Choosing by Advantages (CBA) needs to be applied. The benefits of CBA in the tendering procedure were first mentioned by Schöttle et al. (2017). They explained that traditional methods, such as weighted sum, have two major issues. First, by mixing value with price/cost, they open the door for speculation. Second, it becomes difficult to differentiate between proposals when factors are the primary focus. Suhr (1999) refers to this as unanchored judgment and highlights the danger that arises from overestimating insignificant facts and underestimating significant ones. Both issues were further discussed by Schöttle and Arroyo (2017). They illustrated the magnitude of the price impact compared to other information and how irrelevant information influences decision-making.

We acknowledge that this is only one aspect of the overall procedure. However, this paper aims to enhance the evaluation of proposals, improve the differentiation between them, and select the best opportunity for the project. Therefore, the research question is: How can CBA be applied in the public tendering procedure in Germany?

With this in mind, we are not focusing on a specific delivery system. The proposed approach can be implemented in both traditional delivery settings and more collaborative approaches. Of course, a more collaborative approach already includes a different mindset as it involves selecting partners rather than just contractors. Implementing CBA in a traditional tendering procedure, however, offers owners a chance to better understand their expectations and the value at stake. We argue that this will change the owner's attitude toward task and risk transfer. Therefore, based on the EU Directive, this paper will demonstrate if and how CBA can be applied in the German public tendering procedure without violating the method. This will not only provide German public owners with a guideline but also offer guidance to other EU members and countries worldwide facing similar challenges.

Consequently, we will first introduce CBA and the prior anchoring procedure proposed by Suhr (1999). Second, we will explain the EU Directive and German legislation as the foundation for the tendering procedure. Then, we will outline the research method, discuss the findings from the focus groups, and conclude.

CHOOSING BY ADVANTAGES TABULAR METHOD WITH THE PRIOR ANCHORING PROCESS (PAP)

CBA is a decision-making system that compares alternatives by analyzing the importance of the advantages (Suhr 1999). The system is based on the following four principles: (1) decision-makers must learn and skillfully use sound decision-making methods; (2) decisions must be based on the importance of the advantage; (3) decisions must be anchored to the relevant facts, and (4) different types of decisions call for different sound methods of decision-making.

The comparison of advantages and the magnitude of the difference between them helps the decision-maker to see and understand the real differences between the alternatives. Differentiation is based solely on value, meaning price is not considered in the initial assessment. The price of each alternative will be analyzed in the final step by showing the relationship in a diagram. In CBA, it is a fundamental rule not to mix price with value, as cost-related data is seen as a message and medium of exchange (Suhr 1999). Once the money is spent, it cannot be spent again. Therefore, it is crucial to have a clear understanding of how money is being spent, especially if it is taxpayer money. In CBA, the ultimate question is whether decision-makers want to spend the proposed money on a specific value (importance of advantages [IoA]). This allows the decision-maker to understand and reflect on the trade-off. However, separating price from value and viewing price as a constraint is often one of the most challenging aspects of learning CBA (Arroyo et al. 2019), as commonly used scoring methods mix cost-related data with value to generate an apparently objective number.

For a public tendering procedure, Suhr (1999) introduced the prior anchoring process (PAP) because public authorities must transparently publish how proposals will be evaluated before the request for proposals. The prior anchoring process is an add-on to the CBA Tabular method and must be included in the tendering documents to evaluate the proposals using the Tabular method (see Figure 1). The PAP consists of the five steps (Suhr, 1999):

1. Define the factors.
2. Define the must and want-to-have criteria for each factor.
3. Estimate the expected range of attributes for each factor.
4. Define the expected range of advantages for each factor by defining the worst acceptable (WA) attribute, the worst expected (WE) attribute, and the best expected (BE) attribute as anchors for identifying future advantages. Select the least-preferred attribute, either WA or WE, or both if they are the same, and calculate the anchor-statement advantage (ASA), which is the difference between the least-preferred attribute and the BE.
5. Decide the importance of the expected advantages by choosing the paramount advantage (PA) from the ASA. Then, assign the importance weight of each ASA compared to the PA, and for each factor, create either a preference curve for qualitative data or a preference chart for qualitative data.

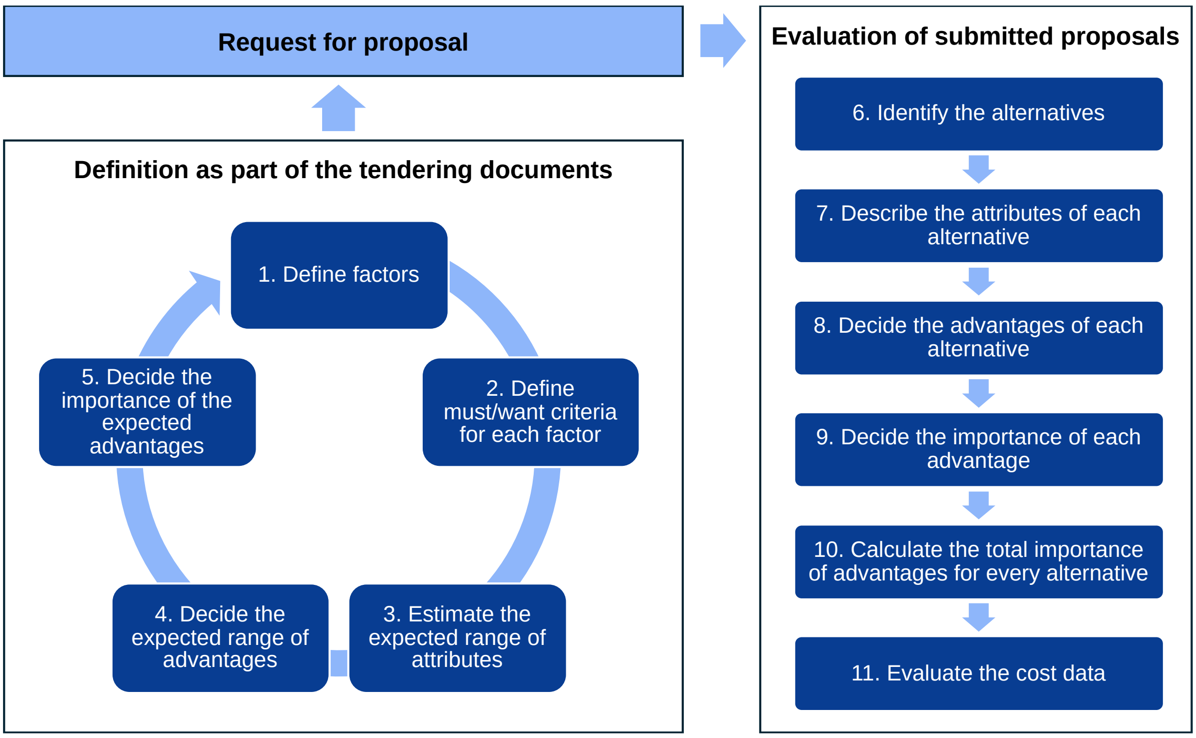

Figure 1: Process steps of CBA in the tendering procedure

Compared to Suhr (1999), Schöttle et al. (2017) introduced the minimum requirement (MR) as the attribute that must be achieved and defined ASA as the difference between BE and MR. However, we will not discuss whether WA, WE, or MR should be defined, as ultimately, they serve the same purpose. They help determine the ASA and identify the preference curve/chart.

While the PAP requires significant effort to develop, Suhr (1999) proposed that, if the law suffices, the RFP should simply state that CBA will be used to evaluate the proposals and to avoid favoritism, the proposal should be analyzed anonymously so that the bidder cannot be identified. This is feasible when there is no contact between the bidder and the judge during the tendering procedure. However, if a competition phase is included in the tendering procedure, it becomes difficult to avoid identifying bidders with their proposals, as both sides interact. This is where the PAP becomes necessary. Another option proposed by Suhr (1999) is to change the legal process, as the current assessment of the proposal is based on unanchored judgment. In this regard, Suhr (1999) points out that "factor weight and attribute ratings are unanchored judgment, and [...] that selecting a contractor based on unanchored judgment is legally unacceptable" (p. 225). Consequently, he argues that using a factor weight method in a legal procedure should be prohibited. However, using a PAP in the tendering procedure means that the price proposal and the proposal containing the technical and social aspects, referred to as the value proposal, must be submitted separately but simultaneously. The price proposal will be opened after evaluating the value proposals to overcome price bias.

Nevertheless, Suhr (1999) states in his book that it would be preferable to use CBA as simply as possible, and thus, not everything needs to be defined in advance. However, different countries have different rules and regulations, and what works in one country may not work in another. However, his book lacks evidence of whether CBA works within a public tendering procedure in a specific country or if the law needs to be adjusted to apply CBA effectively.

EU DIRECTIVE AND GERMAN LEGISLATION

In the European Union, the requirements for award criteria in public procurement law are primarily based on Directive 2014/24/EU, issued on 26 February 2014. Directives are not directly applicable but need to be transposed into national law by member states. Individual member states have the autonomy to determine how they implement these directives in practice. Since EU Directives are framework legislation, member states are obligated to implement them in a timely and proper manner. It can be assumed that the legal situation within the EU is generally harmonized. Therefore, the following statements apply to all EU member states.

"MOST ECONOMICALLY ADVANTAGEOUS TENDER" AND MINIMUM WEIGHTING OF PRICE

Article 67 of Directive 2014/24/EU provides the framework for national procurement regulations to design award criteria in a public procurement procedure. This European Directive allows contracting authorities considerable freedom by expressly permitting the inclusion of various factors such as quality, technical merit, aesthetics, expediency, organization, environmental characteristics, innovation, qualifications of the personnel entrusted with execution, and delivery or execution time as award criteria. However, a public contract must always be awarded based on the criterion of the "most economically advantageous tender" (Article 67, Paragraph 1, Directive 2014/24/EU). This limits the freedom of contracting authorities to include non-monetary, qualitative evaluation aspects in that these can only be factored into the procurement decision as part of a price-performance ratio. The price—or the costs, as Article 67 of the 2014/24/EU Directive also explicitly allows costs to be used instead of price—must be considered when evaluating tenders. However, there is no stipulation for a minimum weighting of the price, at least according to German jurisprudence. In fact, the Federal Court of Justice has clarified that qualitative award criteria should generally receive more weight the less the requested asset represents a standardized service customary in the market. An excessively one-sided focus on price carries the risk of award decisions that ultimately prove to be uneconomical because they fail to account for qualitative differences in the service (BGH X ZB 3/17, p. 16, para. 35).

The contracting authority is, therefore, mainly free to determine the relative weighting of the individual award criteria relative to each other, as the weighting of the selected award and sub-criteria interact with each other and significantly influence the award objective pursued. For an award—for example, for a bridge—the contracting authority will receive significantly different tenders with a weighting of 30 % price and 70 % quality than, for example, for an award with a weighting of 50 % price and 50 % quality.

Relative weighting only finds its limits in the prohibition of arbitrariness and discrimination. For example, in cases where an excessively marginal weighting of an individual award factor leads to a distortion of competition or unequal treatment of individual bidders. According to German jurisprudence, this is only the case "if qualitative evaluation criteria individually or as a whole are given a weighting that cannot be objectively justified and therefore suggests that the criteria have been designed in such a way that only one or individual companies have realistic prospects of being awarded the contract, while other bidders would have no chance from the outset despite (...) objectively given suitability." (BGH, X ZB 3/17, para. 38).

With the relative weighting of the award criteria, the contracting authority believes it ultimately makes its priorities clear to the bidders. It is an assumption that weighting factors are a powerful tool for achieving the award objective. However, this contains two major mistakes. First, assigning a numerical weight does not determine the method's objective, and second, the importance of a factor cannot be accurately represented by a single numerical value; rather, it is an evaluation based on an assumption (Suhr, 1999).

FURTHER REQUIREMENTS FOR THE INCLUSION OF NON-MONETARY CRITERIA

Link to the subject matter of the public contract (Article 67 (2) and (3) Directive 2014/24/EU)

A prerequisite for the admissibility of an award criterion is that it must be linked to the subject matter of the public contract, as stated in Articles 67 (2) and (3) of Directive 2014/24/EU. According to Article 67 (3) of the Directive, this link is established if the criterion relates in any respect and at any stage of the life cycle to the works, supplies, or services to be provided under the contract. This may concern, for example, the specific process of production or provision of works—or a specific process related to another stage of their life cycle. The specific criterion does not have to be part of the material substance of the subject matter of the contract. Thus, European Directive law provides extensive possibilities for including qualitative, non-monetary aspects in the evaluation.

No unrestricted freedom of choice (Article 67 (4) Directive 2014/24/EU)

According to European Directive law, an award criterion must not grant the contracting authority unrestricted freedom of choice. Therefore, the chosen award criterion must support the possibility of effective competition and be accompanied by specifications that enable an adequate review of the tenderers' information to assess how well the tenders meet the award criteria. Consequently, award criteria must ensure an objectifiable and verifiable decision-making process to prevent arbitrary decisions. However, this does not preclude subjective aspects—such as the aesthetics of a building—from consideration, provided certain conditions are met. For instance, multi-member evaluation committees should be established for such criteria to deter arbitrariness, and these may be contracted externally. For transparency reasons, the complete evaluation matrix, including the planned evaluation process, should be publicized beforehand. During the evaluation process itself, the criteria used to award points should be meticulously documented. Therefore, it is not advisable to base the evaluation of individual award criteria solely on oral statements made by bidders during a presentation meeting (Braun, 2021).

Weighting and specification in the procurement documents (Article 67 (5) Directive 2014/24/EU)

Article 67 (5) of Directive 2014/24/EU mandates that the contracting authority must weigh the individual criteria and present the intended weighting in the procurement documents. This obligation applies not only to the overall weighting but also to the respective sub-criteria. Only under very strict conditions may the contracting authority deviate from the principle that weighting rules for sub-criteria must be published in advance and cannot be introduced subsequently (ECJ, C-677/15P, para. 41 et seq.). The requirements for sub-criteria, particularly their substantive specification, are closely linked to the tender specifications. Therefore, an abstract description of the required depth of content cannot be expressed in abstract terms; it depends on the individual case.

Compliance with the general principles of Community law

In addition to the requirements of European Directive law, award criteria must also comply with the general principles of Community law. The transparency requirement is especially pertinent here. The requirement of transparency under public procurement law means that the award criteria provided by the contracting authority must be sufficiently specific and comprehensible in terms of content. As "quality" is not a self-explanatory criterion, the contracting authority is required to describe the qualitative requirements of the procurement object as precisely as possible and establish corresponding sub-criteria. Vague terms, such as "best possible fulfillment of requirements," may constitute a breach of the transparency requirement, as they hinder the genuine comparability of tenders.

A Real-life Example of Current Practices

Real-life example for a relative evaluation method (simplified): The tendering process was for external project supervision services for the megaproject second core line of the city train (2.SBSS) in Munich. The heart of the route is a 7-km-long tunnel connecting Munich Main Station, Marienhof Station, and Munich East Station. The route intersects several lines of Munich's subway network, with platforms to be constructed between 40 m and 16 m below ground.

Framework for the tender:

1. The tender with the lowest price receives 80 points. Bids exceeding 1.5 times the value of the lowest bid price receive 0 points. Points for other bids are linearly interpolated between the lowest bid price and 1.5 times that value.
2. Up to 20 points are available for the written and oral elaboration of the concept regarding the quality of the personnel and the software tools to be used.

Table 1 shows that bidder 1 reached 85 out of the maximum of 100 points and was awarded the contract.

Table 1: Result of the real-life tendering procedure

Bidder	Total Price (fictional)	Price Points	Quality Points	Total Points
1	40 €	80	5	85
2	50 €	40	10	50
3	60 €	0	20	20

This simplified example illustrates that within the specified legal framework, it is feasible to establish the legally required price-performance ratio by simply converting price and quality into evaluation points and determining “the most economically advantageous tender.” In this scenario, a relative evaluation method focused on the criterion “total price” was employed. Nevertheless, the setup of this tender clearly indicates that the decision was predominantly price-driven and that other factors had minimal influence. Moreover, this example starkly demonstrates that our judgments are based on scoring factors that do not provide a clear understanding of the differences between the proposals or their significance. This is precisely what Suhr (1999) criticizes as unsound. Thus, the authors will explore how CBA might be applied and its potential benefits for future tender processes.

RESEARCH METHOD

This paper aims to understand how CBA can be applied based on the EU Directive in the German public tendering procedure without violating the second and third CBA principles specifically. The research question is: How can CBA be applied in the public tendering procedure in Germany? This qualitative research utilized two focus groups to collect data from experts through discussion (Gray, 2009; Morgan & Krueger, 1993). The first group included contractual experts focusing on the EU Directive and German legislation, while the second group comprised three CBA experts (including the first author) to discuss whether the outcomes of the first group violated the second and third CBA principles.

In addition to the two authors (a CBA expert and a contract manager), the first focus group included an architect, a lawyer from the DB legal department, and a second contract manager from DB InfraGo. Additionally, a project manager shared his thoughts with the authors before the focus group, as he could not participate. During the first focus group, two significant questions were addressed:

- Can we apply the CBA Tabular method with the PAP proposed by Suhr (1999) in Germany?
- Is the diagram showing the price versus the IoA sufficient, or do we need to present the relation in a numerical ratio or weighted sum based on the EU Directive and German legislation?

Before discussing the questions, the participants were introduced to CBA. During the discussion, a simplified example was used to illustrate the table and diagram to facilitate a shared understanding. In the second focus group, the results from the first group were reviewed to determine if any aspect of the procedure violated the CBA principles or the intended approach.

DISCUSSION

In general, there are two options for implementing a method into the public tendering process: either the regulations concerning the tendering procedure need to be changed, thus altering the law, or the method needs to be adapted to comply with the second and third CBA principles. We will now discuss the questions from the two focus groups to determine how to apply CBA in the German public tendering procedure.

CAN WE APPLY THE CBA TABULAR METHOD WITH THE PAP PROPOSED BY SUHR (1999) IN GERMANY?

As the tendering procedure requires that the assessment method for proposals be published, the tabular method needs a more precise definition upfront. Suhr (1999) proposed that the CBA tabular method should be adjusted by integrating the PAP to help bidders understand how their proposals will be evaluated. During the discussion, the question of whether defining WA, WE, and BE is sufficient arose. The group concluded that defining WA, WE, and BE and the resulting ASA alone is challenging and agreed with Suhr (1999) that the preference curve/chart also needs to be defined. They argued that there is too much uncertainty about how the evaluation tends to be if we assume non-linearity. Since preferences are usually not linear (Suhr, 1999), the preference curve/chart for each factor must be clearly defined in the tendering procedure. This should not result in significant efforts to discuss mathematical functions. A set of curves/charts should be defined in advance so the owner team can select the one that best represents the relationship between attributes, advantages, and the IoA.

The exact number of curves/charts the set should contain is not specified and requires further research. However, it must be considered that Suhr (1999) states that preference curves are only for quantitative data and qualitative data must be represented using a preference chart, but it is unclear how detailed the chart for qualitative data must be. Further testing might also be necessary to determine whether qualitative data can be represented by a preference curve and if the scale of attributes can be defined in detail using the x-axis. Nevertheless, defining the preference chart will require more effort than defining the preference curve for quantitative data.

Another point of discussion was the definition of the criteria. According to Article 67 (4) of Directive 2014/24/EU, the criteria must be precisely defined to comply with the requirement to prevent unrestricted freedom of choice. For example, criteria such as "the less uncertain the construction schedule, the better" or "the higher the technical experience, the better" would be too vague and allow too much room for interpretation. Without further specification, these criteria would violate the prohibition of arbitrary freedom of choice and the principle of transparency. Therefore, it can be stated that the degree of detail and, therefore, the effort to set up a PAP is high.

Is the Diagram Showing the Price vs. the IoA sufficient, or Do We Need to Present the Relation in a Numerical Ratio or Weighted Sum Based on the EU Directive and German Legislation?

As noted, the public tendering procedure must represent a relationship between price and value. However, the specifics of how this relationship should be presented are not detailed in the EU Directive or German legislation. Under German case law, it is not necessary to assess price and quality criteria using the same method. In practice, the degree of fulfillment of a factor is commonly used for assessment. The contracting authority has considerable leeway in relating price and value. A standard of comparison must be established—for example, by converting the tender price into price points. Both absolute and relative evaluation methods are allowed. According to German case law, the price conversion formula can only be challenged under public procurement law if it is incompatible with the principle of fair award competition (BGH X ZB 3/17). The contracting authority has a broad margin of discretion. Therefore, the authors conclude that using CBA in a public procurement process is feasible under current legislation. Indeed, the owner is free to determine the weight of the price. In practice, public owners interpret the relationship as a ratio or weighted sum, but creating a ratio or weighted sum based on the IoA vs. price contradicts the third CBA principle that decisions must be anchored in relevant facts. In CBA, cost-related data is not mixed with value to produce a number as other scoring methods do.

Nevertheless, neither the EU Directive nor German legislation restricts using the IoA vs. price diagram to represent the proposals. The conflict with interpreting the diagram arises when considering how a public owner can justify selecting a proposal that has a higher IoA but also a higher price (see Figure 2, point A vs. point B). This is a tricky part. Therefore, the public owner may need to establish predefined rules on how to handle a trade-off in terms of IoA and price, for example, defining that a higher IoA could justify a specific price or specific price range.

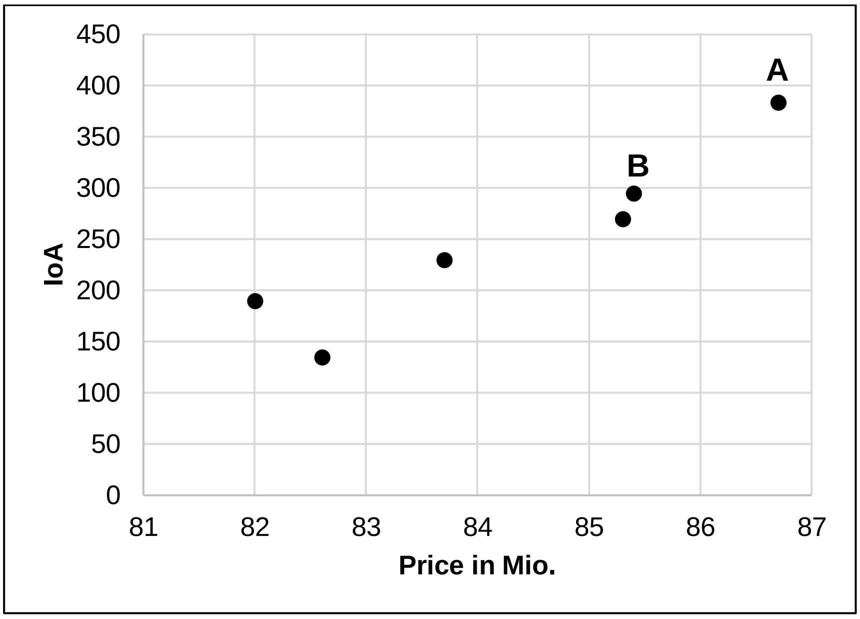

Figure 2: Example of the Importance of Advantages (IoA) vs. price diagram

DOES CBA GET VIOLATED BY THE CURRENT REGULATIONS?

As explained in the previous section, CBA is possible in a public procurement process under restrictions. However, does this violate the positive effects of CBA?

The current practice in the tendering procedure involves following the law and puts the decision-makers in a position where they are not truly making decisions. The decision-maker assists with the procedure rather than taking ownership. Making a decision is an investigation. But how can we investigate by defining everything upfront? Applying CBA in tendering procedures results in an endless number of rules that need to be set for every possible outcome. This makes CBA burdensome and almost impossible to implement in complex situations. CBA requires ownership and a mindset of investigating the differences and the importance of the differences represented in the IoA (second and third CBA principle). However, the high degree of upfront definition makes it difficult to see the benefit of the application. The current practice focuses on the procedure itself rather than the decision itself, and this needs to change for successful CBA implementation. This raises the question of whether the law can cover everything. Obviously, it cannot. So, what should be the focus? Should we prioritize fulfilling the procedure or invest in involving people who can address the needs and constraints together? Should we deflect or instead train people and establish processes to make effective decisions in the tendering procedure for the project’s success?

Another issue ignored by current practice is how to deal with new or unexpected information. Especially in megaprojects, where a tendering procedure can take months or even a year, new information is generated, and the tender documents quickly become outdated before the tender is awarded. This poses a dilemma for every project. Thus, we cannot freeze our information status, but we do freeze the tendering process, or we already know which claims to address. So, why can’t we act accordingly?

The tendering procedure is reactive. It does not provide the opportunity to correct mistakes as soon as the tendering document is published. For public owners, this means they must adhere to known practices. This is primarily due to political constraints and the fear of making a mistake. There is always the risk of project delays because bidders may have a claim against the tendering procedure. Nevertheless, there are good examples where public owners successfully changed the tendering procedure. For instance, the University of California San Francisco changed its scoring method during the evaluation process of a project, and even the non-winning bidder teams found the new procedure fair (Schöttle, 2022). Consequently, we need to change our mindset and understand tendering as a proactive decision-making process.

FINAL REMARK

There are only two options here: (1) Everything needs to be defined in such detail that decision-makers might avoid the use of CBA in a complex decision, although it is the right thing to do, or (2) the law needs to change to put the decision-maker in a position to really decide and not follow instructions no matter what. Understandably, favoritism and corruption must be stopped. However, in the current system, the tendering process can be manipulated to generate favoritism. Right now, people are not taking responsibility for their decisions as they frame them according to the law. Thus, the question is: What problem are we trying to solve here? No method alone can do so, as humans will find a creative way to circumvent it. The tendering procedure is a human-made artifact. What needs to happen is that a board of decision-makers with different perspectives should be empowered to make decisions. They should act as a court of law (see Koskela et al., 2018).

Therefore, the problem of favoritism and corruption cannot be solved by a rule; it can be minimized by making decisions as a group. The issue needs to be reframed, and with this paper, we invite you to start a discussion about how we select partners in the tendering procedure.

CONCLUSIONS

After providing a brief overview of the legal framework for awarding in the EU, the authors believe that CBA can be incorporated into public procurement procedures—even within the existing public procurement legislation framework. Therefore, the research question of whether and how CBA can be applied in the public tendering procedure in Germany can be answered by utilizing the PAP. This approach will not violate CBA principles. However, the adjustment required to apply CBA within the current regulations will discourage owners from using it, which goes against the intentions of the CBA. Public authorities must recognize that the current practice is reactive, subjective, unfair, and does not foster ownership. We need to shift our perspective and view the law as a means rather than an end goal that must be achieved. Therefore, we invite owners to engage in discussions regarding current practices and the implementation of CBA in the tendering procedure.

In addition to discussions, further research is necessary as this study has limitations in its theoretical approach. Data should be collected through experiments or applications to validate the theoretical findings. This should be the next step for future research.

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ISO 18404: A MODEL FOR LEAN TRANSFORMATION IN AN ALLIANCE

Paul J. Ebbs[1] and Steven A. Ward[2]

ABSTRACT

The literature and case studies reporting lean transformation in the construction/infrastructure sector are rare. This study's objective is to examine whether the Lean Standard, ISO 18404 provides a useful model for lean transformation. By Case Study and Participatory Action Research, the deployment of ISO 18404 and certification journey of a UK highway alliance (the Alliance) is reported, structured around four Themes for lean transformation. Findings are supported by the latest literature along with a quantitative and qualitative survey with those involved in 18404 deployment (n=35/58). The survey data was thematically analysed and is largely articulated through the four Themes for lean transformation. Whilst ISO 18404 is imperfect, it remains that ISO 18404 provides a useful model for lean transformation and can assist with embedding a culture of sustainable continuous improvement in an Alliance.

KEYWORDS

ISO 18404, Alliancing, Lean Transformation, Lean Leadership, Continuous Improvement

INTRODUCTION & BACKGROUND

This paper follows Ward and Caklais' (2019) case study that piloted the deployment of ISO 18404 to support organisational lean transformation in a UK housebuilder, Gilbert & Goode (G&G), and papers reporting the development of a Lean Project Delivery System for a UK Client Organisation (Pasquire and Ebbs, 2017; Ebbs and Pasquire, 2018; and Ebbs et al. 2018).

ISO 18404 is an international standard for lean and is proposed as a model for lean transformation (Ward & Caklais, 2019) and organisational improvement (Oudrhiri et al., 2022). When used together with the Royal Statistical Society's (RSS) sector scheme alongside ISO 9001, it provides a Lean Management System Standard that aligns the achievement of an organisations' strategic objectives with its lean architecture (Key Personnel and Tools) and requires demonstrable continuous improvement. ISO 18404 is sector agnostic and only abstractly prescribes how to deploy lean by focusing on aligning an organisations' strategy, architecture, and improvement activities through a series of Lean Competencies and ISO Clauses. For more on 18404 see Ward & Caklais (2019); Ward (2019) and BS ISO 18404:2015. Since Ward and Caklais' (2019) paper, Balfour Beatty Highways UK have been certified to ISO 18404 and have maintained their certification with annual British Standards Institute (BSI) Audits. In 2023, the BSI Auditor noted Balfour Beatty's Lean Management System was continuing to improve. However, in parallel, the ISO 18404 certification for pilot organisation G&G was not maintained. This was principally attributed to a change in Managing Director and many of the ISO 18404 Key Personnel (Lean Leaders and Practitioners) leaving the organisation, noting the previous Managing Director was a Royal Statistical Society certified ISO 18404 Lean Leader who personally delivered lean training to over 100 people (Ward, 2019).

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In 2019, the researchers were direct employees of a Global Engineering Firm who were tendering for a UK highway alliance framework (the Alliance). This was being procured through an NEC4 Alliance Contract to deliver c.£1.5bn-£3bn. of infrastructure upgrades to the UK's Strategic Road Network. The bid required those tendering to make appropriate tender commitments – ISO 18404 became one of these. The Alliance was commissioned in May 2020 and by March 2025 it will have substantially delivered several development projects and three programmes of work that are key to the Client's Roads Investment (2020-2025) Delivery Plan.

The research focus is on the deployment of ISO 18404 and rests on a single case study (a UK highway alliance) using the four Themes identified by Ward and Caklais (2019) to start framing and reporting the primary and tertiary data collected. The 4 Themes are:

1. Organisational Structure – supportive business model required
2. Roadmaps & Lean Concepts – need dual clarity before the critical mass will adopt lean
3. Leadership – senior leadership participation required and philosophy comes before tools
4. Change by Force – moving to clients specifying lean, training and use of the principles

The literature review below is followed by a summary of the primary case study data before exploring 18404 deployment methods through specific case study examples.

LITERATURE REVIEW

Ward and Caklais (2019) previously explored the question of whether the 18404 standard could assist lean construction transformations and carried out a literature review using the search terms "ISO 18404" and "transformation" on the IGLC website and on Google. 79 papers were identified and 15 found relevant. They found the four key Themes of interest noted above across the 15 papers. Five years have passed so this literature review was updated through Scopus using key words "Lean Transformation (+ Infrastructure +/or Construction)" and "ISO 18404".

New IGLC Papers

Peltokorpi et al. (2021) provided a view on construction sector transformation and identify five broken sub-systems: a) Products; b) Processes; c) Information and Digitalization; d) Value Creation; and e) Business Models. They observe that a systemic approach is essential for sustainable improvement and that all five sub-systems need to be simultaneously addressed. This partially aligns with the four Themes; however, these focus primarily on organisational transformation whereas Peltokorpi et al. (2021) examine the sector as a whole.

Other papers

Ward (2019) presented more information about the original certification pilot Gilbert & Goode in the final project report for the Construction Industry Training Board. It provides more detail about the initial pilot rather than any additional insights to report here. Antony et al. (2023) focused on a cross sector survey of Lean Six Sigma Blackbelts to explore the applicability of ISO 18404 to smaller enterprises. They conclude that the standard needs revision. They also provide critique in Antony et al. (2021) where a range of cross sector Lean Six Sigma Experts were interviewed as to the pros and cons of 18404. They concluded the standard is "not fit for purpose". Oudrhiri et al. (2022) rebutted Antony et al. (2021) with an in-depth explanation of how 18404 works in practice, noting the Antony et al. (2021) work was based on significant general experience with lean six sigma, but no specific experience with the application of 18404. Oudrhiri et al. (2022) provide explanations and information regarding how the standard works in practice by people familiar with its application. Related to the requirement for the systemic change called for by Peltokorpi et al. (2021), Ward and Mossman (2023) explored the business case for Integrated Project Delivery (IPD). They carried out a benchmarking study of project performance and noted that Project Alliancing represents a system change and positive shift in performance but does not focus on lean. When lean processes and leadership are built onto Alliancing a further significant shift in performance is gained as shown in Figure 1.

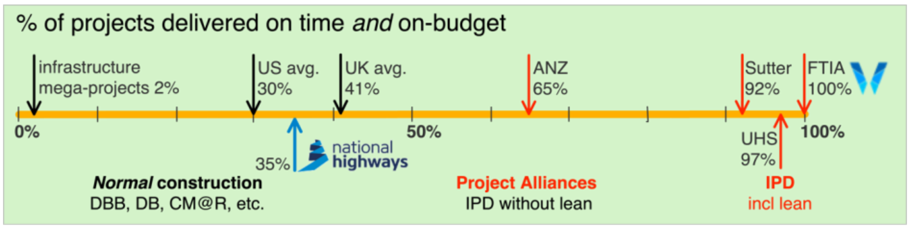

Figure 1: Percentage of projects on time and on budget or better (Ward & Mossman, 2023)

RESEARCH METHODOLOGY

The methodology was a single Case Study (Fellows and Liu, 2003; Yin 2018). Data were collected from many primary and tertiary sources including lean strategy development and review workshops, lean workshops, 18404 management reviews, leadership team meetings, internal and external 18404 and Highways Excellence Lean Maturity Assessment (HELMA) audits, contract documents and annexes, diary notes, interviews, observations and a survey of the ISO 18404 Lean Practitioner/Leader Candidates and Sponsors. Data were analysed and framed using content/thematic analysis techniques advocated by Braun & Clarke (2006) and Boyatzis (1998) employing a sliding 7-point numerical scale (Nunnally, 1978).

Survey Data

A survey was conducted with those who were 'involved' in 18404 deployment (n=58) rather than the approach taken to review the standard by Antony et al. (2023) where the respondents who reviewed 18404 had little practical knowledge of it. 'Involved' meant they had either gone through the RSS approved training, were pursuing individual certification or were one of the 18404 Sponsors. Approximately 10% had left or were leaving the Alliance. The response rate was 60% (n=35/58) with the distribution of respondents aligned to respondents' roles as shown on Table 3. There were four questions. Questions 1 & 2 were quantitative with the average response shown below. Questions 3 & 4 were qualitative with the analysis in and after Table 2.

1. As an individual, what value have you got from involvement in ISO 18404 to date where 1 = no value and 7 = high value? Average was 5.89
2. How effective is ISO 18404 as a model for Organisational Lean Transformation and Business Improvement where 1 = not effective and 7 = very effective? Average was 6.0
3. Please state your key thoughts on ISO 18404 as an approach to embed a culture of sustainable continuous improvement in an organisation.
4. Please state your key thoughts how 18404 has or has not impacted lean culture, production and/or benefits realisation such as efficiencies or any of the Six Outcomes.

Table 1 replicates Ward's (2015) Critical Success Factors (CSFs) for lean interventions. The CSF references in the left column of Table 1 are mapped to the sub-themes of right column in Table 2 to show the correlation between the results of the thematic survey analysis with Ward's (2015) CSFs. Table 2 also outlines additional insights not found by Ward and Caklais (2019). Many examples of CSFs correlating to the four Themes exist. For example, Theme one in Table 2 'Org Structure' relates to the Alliance Model which correlates to the CSFs 'no blame culture' (23) and 'long term relationship or work stream required' (19) in Table 1. Table 2 shows the broad distribution of 221 mentions (taken from 126 statements) relative to Ward and Caklais'(2019) four Themes. Most statements typically fell into several Sub-Themes. The analysis was conducted using a simple tally chart to capture the no. of mentions of each Sub-Theme.

Table 1: CSFs Significant Hypotheses (after Ward, 2015)

CSF Reference #	Critical Success Factor (CSF)	Confidence Level
21	The facilitator is critical to success	>99%
18	More than one tool required for success	>99%
10	Management must stay focused on efforts to improve	>99%
17	Relevant data is available or is created	>99%
11	Lean training is required	>99%
14	Staff time out required to focus on improvements	>99%
2	Buy-in from improvement team required	>99%
19	Long term client relationship or work stream required	>95%
8	Lean capability in management required	>95%
23	No blame culture required	>95%
3	Senior management buy-in required	>90%
9	Direct senior management involvement required	>90%
13	Closing actions by improvement team required	>90%

Table 2: Thematic Analysis of Survey Responses (n=35) Mapped to Ward's CSFs

#	Theme	Sub-Theme	No. of Mentions	Ward's (2015) CSF Reference #
1	'Org Structure'	Alliance Model	2	23, 19
2	'Roadmaps & Clarity of Concepts' (n=39)	18404 provides a model/structure/consistency	22	N/A
		Adaptation of lean tools and techniques req'd	9	21, 18, 11
		18404 aligns with org strategy	8	17
3	(Lean) 'Leadership' (& Culture & Community) (n=55)	Mindset and culture change	25	10, 2, 23, 3, 9
		Lean leadership and sponsorship	16	10, 8, 23, 3, 9
		Sense of lean community	14	21, 18, 11, 14, 2, 8, 23, 3, 9, 13
4	'Change by Force' Conditions)	(External Market	0	N/A
4 a	Lean as Business as Usual (BAU) (n=98)	Better lean knowledge, tools and competency	41	21, 18, 17, 11, 14, 2, 8, 23, 3, 9
		Realisation of benefits and outcomes	38	10, 17, 11, 14, 19, 23, 13
		Focused lean training & team capability	13	21, 18, 17, 11, 14, 2, 8, 23, 3, 9, 13
		Availability & use of lean support	6	21, 11, 2, 8, 3, 9
5	ISO 18404:2015 Standard (n=22)	Positive view of 18404	14	N/A
		Maturity of 18404 standard	5	N/A
		Certification benefits	2	N/A
		Negative/indifferent view of 18404	1	N/A
6	Concerns	Organisation Change Challenges & Portfolio process & evidence collection	6	N/A

REFLECTION ON SURVEY THEMES & DATA COLLECTED

Ward's CSFs in Table 1 were correlated to the survey analysis in Table 2 as one could argue that a lean transformation is a series of interventions, and the CSFs are appropriate to both. Below is some discussion around the qualitative data supporting Table 2's Themes and Sub-Themes with the number of mentions from Table 2 denoted in the brackets after each heading. Table 3 outlines the distribution of survey responses from the demographics of those 'involved' in 18404 deployment. These are known as 'Key Personnel' in ISO 18404:2015.

Table 3: Demographics of ISO 18404 Key Personnel (N=48) and Survey Responses (N=35)

# 18404 Trained	Role	Survey Responses
2	Sponsor (Alliance/Programme Leadership Team)	7
4	Sub-Programme Leadership	6
7	Construction Manager/Director	4
4	Site Agent	3
8	Design Manager/Lead	1
3	Supply Partner Manager	2
2	Planner	2
13	Production Hub (Back Office)	8
5	Lean Coach	4

THEME 1: ORGANISATIONAL STRUCTURE (N=2)

A single reference to 'Org Structure' was made by a Planner who thought "18404 has added to the collaborative approach of the Alliance and team members feel reassured working slightly out of their normal routines (e.g., a less commercial mindset)". There was another positive reference about the Alliance by a Sponsor. The Alliance is an Enterprise Model built around Infrastructure Client Group (2017) Project 13 concepts which has helped develop long term relationships, inform the development of the Vision, Mission, and Six Outcomes in Figure 2, and encourage role modelling 'Trust' as one of the Alliance's Six Behaviours. The Alliance model supports Ward's (2015) 'no blame culture' and 'long term relationships or workstreams' CSFs and Ward and Mossman's (2023) move towards IPD. The scarcity of comments relating to org structure suggests that Alliancing is conducive to lean transformation and ISO 18404.

THEME 2: ROADMAPS FOR LEAN AND CLARIFICATION OF CONCEPTS (N=39)

This was broken down into three broad areas and was alluded to in some format by every demographic in Table 3 except for the Planners.

The structure, framework, and consistency of ISO 18404 (n=22)

30% of this Sub-Theme's references were from the Sponsors or Programme Leadership and the remaining were spread across the other demographics. One of the Lean Coaches referred to 18404 as a "powerful transformational model".

Adaptation of lean tools and techniques (n=9)

References were made to the agnostic nature of 18404 and the need to interpret it relative to infrastructure and job roles. Additionally, as the 18404 course was specifically tailored to lean in the construction sector, there were several remarks about how the ideas and tools taught had changed the Alliance's approach to delivery. Some statements argued the 18404 competencies were catalysts for change – like Deutschman's (2007) conundrum of 'Change or Die'.

Alignment of lean strategy with organisation strategy (n=8)

Whilst there was not an abundance of statements specifically regarding strategy alignment there were many mentions related to how 18404 was supporting the realisation of benefits and outcomes (n=38). This infers that 18404 is beginning to impact strategic goals. The Hoshin Plan discussed in the Case Study was designed to support realisation of all Alliance Outcomes.

THEME 3: LEAN LEADERSHIP, CULTURE & COMMUNITY (N=55)

Ward and Caklais' (2019) Theme of 'Leadership' was expanded to reflect the statements.

Mindset & Culture Change (n=25)

The difficulties getting buy-in to a lean culture and the impact of 18404 to "win over" mid-senior level leadership and embed large scale change was recognised.

Lean Leadership & Sponsorship (n=16)

The Leadership engagement and the Sponsor role helped generate lean deployment momentum.

Community of Practice & Cohort Selection (n=14)

The positive impact of the diverse selection of Key Personnel trained (including leadership) along with the lean coaching availability and support structure was as another important factor.

CHANGE BY FORCE (N=0)

There were no comments related to change by force. However, the specific requirements for lean contained in the Contract Annex (G) which included a requirement for annual Highways Excellence Lean Maturity Assessments (HELMA) audits (National Highways, 2024), combined with a tender commitment 'to lead the Alliance to ISO 18404 Accreditation' provided external force. HELMA 'forced' the Alliance to collect appropriate evidence albeit from a 'show us your best homework' lens. The Alliance scored 1.7/4 in 2021 and jumped 35% year on year to 3.1/4 in 2023. The moderators noted "since the 2022 HELMA the Alliance have put considerable effort into expanding their lean deployment and building sustainable capability using ISO 18404 as the main method. This has delivered considerable success and there has been a real step change in performance and capability." Furthermore, the BSI ISO 18404 Stage 1 and 2 Audits in February and March 2024 did 'force' many good practices such as the release of the Alliance Policy (combined quality & lean), establishing the Lean Deployment Plan and Dashboard, and helping structure lean deployment vs. an ad hoc lean intervention approach.

LEAN AS BUSINESS AS USUAL (BAU) (N=98)

An underlying theme that emerged in 2023 through the Sponsor sessions, discussions, and strategy updates was that lean was no longer a "buzz word" (Crisp, 2023) and was now part of the Alliance DNA (Slater & Grimm, 2023). The Alliance 2023-2025 Strategy and Production Delivery Plan were published in July '23 with 27 implicit and 7 explicit references to lean. The high proportion of mentions relative to lean as Business as Usual (98/221), suggests the people and lean competency development approach played a significant factor in normalising lean. As reported by the respondents: "this is the way we deliver projects in the Alliance… [lean] supports us realising our Six Outcomes… the [lean] benefits are felt right across the Alliance".

THE CASE STUDY – OVERVIEW, RESULTS & DISCUSSION

The case study examines a UK Framework Alliance with six partner organisations who provided programme management, digitally enabled design, and on-site assembly services for highway upgrades. The Alliance then pre-procured a supplier network, to deliver enhancements to positively impact safety, environment, congestion, and asset condition using the Six Outcomes in Figure 2 as shared goals to support the vision and mission.

Figure 2: Alliance Vision, Mission and Outcomes

The Alliance NEC4 contract model is IPDish (Ward & Mossman, 2023) with a single approach to shared risk and reward. The Alliance model supports Table 2's Theme 1 requirement for the right 'Organisational Structure' and Theme 4's 'Change by Force' for lean transformation.

Lean requirements were specified in the Contract Annex (G) and included requirements such as lean leadership, learning and sharing current best practices and adopting key lean tools such as the Last Planner System (LPS) - known as Collaborative Planning in the UK, Visual Management, and lean maturity assessments. Fundamentally, Annex G required a coherent lean strategy and deployment plan to support realising Client Safety, Customer and Delivery imperatives. The client moderated and scored lean deployment through annual HELMA audits (Highways England, 2020; National Highways, 2024) which have been in use since 2009 (Williams, 2023). HELMA was initially reported by Drysdale (2013) under the guise of HALMAT (Highways Agency Lean Maturity Assessment Tool) and alluded to by Nesensohn (2014) in his Lean Construction Maturity Model. Annex G also supports Theme 2's 'Roadmaps & Clarity of Concepts' and Theme 3's 'Leadership' requirements for a lean transformation.

Since inception and throughout the life of the Alliance, a complex set of challenges were faced, including COVID-19 impacts, changing standards and technologies, and changing Government requirements, all of which impacted scope and increased the number and complexity of projects. With respect to lean deployment the biggest initial challenge was to increase lean support capacity and the lean capability of leadership, individuals, and teams. The biggest challenge not overcome was to establish a physical Big Room environment 3 years into the Alliance (Ward & Mossman, 2023) – this was largely due to mobilising in a pandemic, and the dispersed nature of teams and individuals across the framework in the UK, Europe, and India. The countermeasure was pulse-based co-location combined with Big Room workshops as required and digital solutions such as Dashboards and 'Home Visual Board' to visualise performance (Szyperski et al., 2023).

Researchers Background, Experience and Roles

The Researchers (A & B) are Certified ISO 18404 Lean Experts. 'A' became certified as a Lean Expert in 2024 and 'B' in 2017. The 18404 Lean Expert qualification is like that of a Fellow within a Chartered Organisation and requires assessing every three years with evidence no more than five years old. 'A' and 'B's' lean experience totals c.40 years and construction experience c.70 years. 'A' instigated ISO 18404 in the Alliance acting as an internal Lean Coach and chaired the Lean Production Steering Committee. 'B' provided external ISO 18404 expertise during the initial bid and after 18404 Business Case approval, having supported two companies through 18404 Certification. The Lean Production Steering Committee had representation from across the Alliance and 113 years of lean experience when established in September 2022.

ISO 18404

The Business Case for ISO 18404 was approved by the Alliance Board in November 2022. The funding was primarily to support c.40 Key Personnel participate in an Approved RSS 18404 Lean Practitioner Course, develop their lean portfolios, and attend their external assessment. A relatively smaller funding envelope supported the auditing and certification process by BSI (British Standards Institute), 24 months of external 18404 coaching for the Lean Production Steering Committee and support for Ward and Mossman's (2023) IPD study.

For organisational certification to ISO 18404:2015 the link between day-to-day lean improvements and strategic objectives' realisation must be demonstrated. This broadly focuses effort on two areas:

- Individual Lean Competencies according to Tables B1 & B2 in the standard which require people to demonstrate application of a mixture of soft and hard competencies.
- Organisation conformance to Clauses 4 – 6 normative to ISO 9001:2015 to demonstrate alignment across strategy, architecture, and (quantified) continuous improvement.

ISO 18404 Strategy & Hoshin Planning

The Lean Production Steering Committee was responsible for co-creating, revising, and coordinating the deployment of the Alliance Lean Strategy through regular meetings and workshops to support deployment of the wider Alliance Strategy & Production Delivery Plan.

The purpose (why) of the Lean Strategy was "to embed a culture of sustainable continuous improvement by March 2025". The original breakthrough goals (what's) were to:

1. Achieve ISO 18404 Accreditation by March 2024
2. Ensure 80% of people approved to work on the Alliance were at a level of lean competency appropriate to their role by March 2025
3. Achieve 5% efficiency savings through Lean Improvement Projects by March 2025

The 3 what's were revised in February 2024 to reflect an updated Alliance Strategy to include:

4. Improving LEI (Lookahead Execution Index) from 44% to 70% by March 2025
5. Effectively measure RfT (Right first Time) Quality by March 2025

The breakthrough goals (what's), were originally to be realised through 14 initiatives (how's) which are summarised under three headings:

1. Developing lean competency through training, coaching and the application of lean
2. Excelling at core lean tools such as the LPS, VM, and Direct Work Observations
3. Sharing and embedding current best practices and lesson learned

ISO 18404:2015 requires demonstrating the link between organisational strategic goals and continuous improvement so the Lean Strategy was revised to reflect a leadership focus on Right first Time. Countless debates occurred on how to measure this which resulted in an even more focused approach to a full LPS adoption and the introduction of a new 'snag free PPC' metric TRiFT (Tasks Right First Time) to screen weekly promises for rework and capture reasons why. The original 14 how's were not all discrete initiatives or interventions. Some did not progress as initially anticipated. They increased to 16 in Feb 2024 when the Lean Strategy was updated to reflect current state lean deployment - less relevant how's were removed and new ones added.

ISO 18404 ARCHITECTURE (KEY PERSONNEL, REVIEWS & TOOLS)

The Steering Committee co-created the ISO 18404 architecture and largely codified this as the Alliance Lean Production System. This was a combination of the most relevant of 16 How's in the Lean Strategy plus any emergent best practices such as ELMO (Enough Let's Move On). The lean system was rolled out in the pre-assembly (design) and assembly (construction) phases of all programmes and projects to develop people, excel at core lean tools and realise benefits. A snapshot of the Deployment Plan is in Figure 4. Elmo emoji denotes his deployment date.

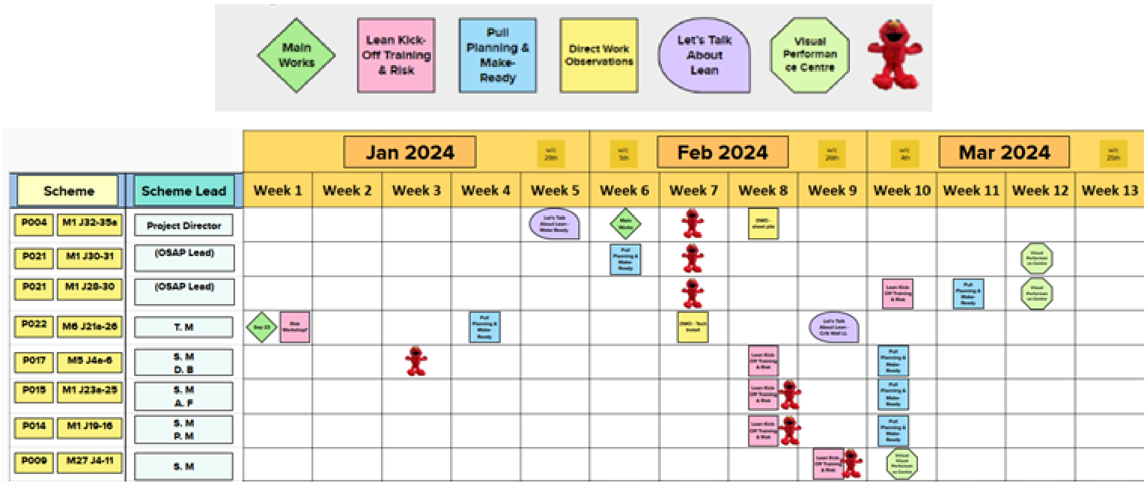

Figure 4: Alliance Lean Production System (ALPS) Deployment Plan (sample of projects)

The ISO 18404:2015 standard requires an appropriate level of Key Personnel to deploy an organisations lean management system (architecture) in pursuit of strategic objectives. A 5-level lean training and coaching programme was developed and deployed. Levels 3-5 were to ISO 18404:2015 Tables B1 & B2 competency requirements whilst levels 1 & 2 were tailored for lean awareness and day-to-day application. 48 people completed the ISO 18404 training over 12 months in 4 Cohorts with 1 Lean Expert, 3 Lean Leaders and 2 Lean Practitioners certified by March 2024. 26 of the remaining candidates committed to be assessed as ISO 18404 Lean Practitioners (Level 3) by December '24 upon completion of their portfolio of evidence.

18404 Practitioner portfolios were focused on delivering improvement projects and/or deploying core tools and techniques as defined in the strategy. The 18404 Key Personnel were all thoughtfully selected mid-senior level leadership as listed in Table 3. Pull vs. Push was the final factor in selection. The Key Personnel championed lean deployment at local levels to identify and support improvement activities within their programmes and projects to directly improve performance by seeking out and resolving problems collaboratively, making people feel safe to highlight, prevent and learn from mistakes and prevent reoccurrences. The result of this top-down approach to lean deployment was demonstrated in Table 2 where 'Lean Leadership, Culture & Community' and 'Lean as Business as Usual' featured heavily.

The biggest challenge developing the 18404 Key Personnel was the preparation of portfolios. Course feedback of 92% averaged across the cohorts, however, portfolio progress was slow. One of the original 'how's' in the strategy was to certify 20 18404 Key Personnel by March 2024 but by July 2023 it was clear that a countermeasure was required if this was to be achieved. From December 2023, a Sponsor role for the 18404 Candidates was introduced by distributing Candidates across the Alliance Leadership Team. The Managing Director personally sponsored three 18404 Lean Practitioners. In hindsight, this was a top-down strategic approach to sustainable lean deployment. In parallel, monthly 'Portfolio Coaching Clinics' were held to coach people through the competencies and develop action plans to demonstrate the application of 18404 competencies to their role. The Alliance's 18404 architecture was further supported through a Lean Comms Plan shown in Figure 5 using various mediums such as networking and knowledge-sharing events such as 'Let's Talk About Lean' monthly webinars and annual 7ogether conferences, internal bi-annual Connec7 magazines (SMP Alliance, 2023a, 2023b), and LinkedIn posts that spread the understanding of new initiatives and applications of lean.

	Monthly	Quarterly	Annually
Touchpoints	Single Slide Update	10mins Strategy Update	
Let's Talk About Lean		Current Best Practice Share	
Digest	Strategy and/or scheme deployment article		
Connec7 Magazine			4 Page Lean 7imes bi-annually
Events	Supply Network F2F, 7ogether, International Group for Lean Construction (IGLC), NH Lean Practitioner, Highways UK		
LinkedIn	Approx bi-weekly - all of the above e.g., 18404 kick-off, Make-Ready Post, Pull Planning, Training & Coaching		

Figure 5: Lean Comms Plan

Additionally, 18404:2015 normative to ISO 9001 requires internal audits and management reviews. Monthly Leadership Governance and Project Performance Reviews through ALPS Dashboards and quarterly site visits helped demonstrate compliance and identify opportunities.

Organisational Certification requires independent two stage auditing of the Alliance Lean Production System (ALPS), processes, and software normative to ISO 9001. These were defined by the Alliance in Hoshin Plans but recorded formally in Alliance Integrated Management System documentation. In February 2024, the auditor noted zero non-conformances at Stage 1 and during the wrap up the Alliance Managing Director noted "we are embedding lean as 'the' thing not 'a' thing we do to help us achieve our vision, mission and outcomes (strategy), lean is now part of our DNA and next time we start an Alliance it has got to be from day one, we are now setting a new benchmark for infrastructure performance, every project before us overran". The Auditor noted it was his third organisation to audit 18404, but he also provided consultancy for another organisation. He noted the systems were "as good or even better than he had seen before". During the March 2024 Stage 2 Audit the Auditor met with multiple project teams to understand their role in lean deployment to see the results of 18404 deployment. A common theme was how shared understanding (Pasquire, 2012), and detailed knowledge of how to do the work (Spear & Bowen, 1999) significantly improved when using the Alliance Lean Production System. Highlights were one project delivered four weeks early (approx. 10%) which was unprecedented in highways and another project delivered five Emergency Areas (extra safety laybys) within the same time originally allowed to complete three, or a 66% productivity improvement. No non-conformances were found by the BSI and the Alliance was recommended for certification to ISO 18404 by the Auditor in March '24.

CONCLUSIONS

Systemic change is required to enable sustainable lean improvement. Bolting lean onto a broken system only yields superficial results. The focus here is effective lean construction transformation (systemic change) and whether ISO 18404 is helpful in this regard. Project and Framework Alliancing represent a system change and ISO 18404 also contributes to this by providing a repeatable business strategy for effectively deploying lean that is properly linked with project delivery needs. In the case study presented, Ward & Caklais' four Themes are clearly present and the additional theme of Lean as Business as Usual together with the positive quantitative survey responses to Questions 1 & 2 provide evidence of sustainable improvement.

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INSTITUTE FOR LEAN CONSTRUCTION EXCELLENCE LEAN MATURITY MODEL (ILMM) – A LEAN MATURITY MODEL FOR INDIAN CONSTRUCTION

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ABSTRACT

In the construction industry, sustained implementation of lean practices is vital for enhancing efficiency and outcomes for projects and organisations. Having a maturity model is one way to assess sustained implementation. This paper identifies the need and describes a comprehensive maturity model framework to gauge and improve project and organisational lean maturity in the Indian construction context – Institute for Lean Construction Excellence Lean Maturity Model (ILMM). The model introduces a distinctive 4x3 matrix, with four levels – Bronze, Silver, Gold, and Platinum – each further divided into three sublevels – Low, Medium, and High. The assessment is done on five dimensions – top management support, process, people & partners, methods & tools, and technology. Field data collection has been done on two projects to see if data on the proposed assessment dimensions can be gathered and an appropriate rating provided to the project along with guidelines on how to improve the maturity.

This research advances lean construction practices by providing a practical framework for continuous improvement and organisational excellence tailored to local construction contexts. In the next phase, the authors plan to do a more elaborate assessment across a broader range of projects and modify the ILMM framework as needed based on their experience.

KEYWORDS

Lean Construction, Lean Maturity Model, Lean Culture, Continuous Improvement, Assessment Framework.

INTRODUCTION

In the dynamic world of construction, variability is constant. Lean construction aims to minimise waste and maximise value, offering a toolkit of methods and tools developed over nearly three decades. Technology, particularly in project information management, has also evolved, providing digitisation as a means to reduce waste. As a result, organisations undertaking lean transformation now have various options, but the specific approach depends on individual projects or organisations. As projects and organisations progress in their lean adoption journey, guided by their awareness and experience, they face challenges in understanding how to sustain implementation and ensure continuous improvement. This

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observation and feedback are particularly notable in the Indian construction industry, which has embraced lean construction practices and technology solutions over the past decade. This paper addresses this critical gap by proposing a maturity model for projects and/or organisations as a means to sustain their lean adoption initiatives.

India has seen significant investment in real estate and infrastructure for the past decade, and this trend is expected to continue (*Infrastructure Development in India: Market Size, Investments, Govt Initiatives | IBEF*, n.d.). As the industry grows, the industry is evolving in its professionalism and is seeing varying levels of adoption of processes like lean construction and technology, including building information modelling (BIM), digitisation of various processes, etc., for the past decade or so (Giridhar et al., 2018; Kalyan et al., 2018; Karanjawala & Baretto, 2018; Ravi et al., 2018; Vaidyanathan et al., 2016). However, our research and interactions with the industry indicate that while there are pockets of adoption and understanding of individual tools and technologies, there has not been a planned, organic, and transformative change that has been effected in any organisation. On the contrary, after a decade of adopting lean construction practices in the country by a few organisations, there is a sense of saturation. The authors realise that as the adoption of lean construction practices grows, so must the tools to assess the level of adoption, provide a roadmap to deepen the adoption and offer an actionable direction to improve the adoption. There is a conspicuous absence of any applicable framework that can benchmark the level of adoption tailored to local intricacies. The proposed maturity model bridges this gap for the Indian construction industry.

The rest of the paper is organised as follows. The next section provides a literature review of available maturity models and a comparison of their strengths and applicability. The third section describes the need for a maturity model identified for the stakeholders in the local Indian construction industry. The fourth section describes the ILMM framework and describes the assessment framework. The fifth section describes the pilot assessment studies done on two projects using the ILMM framework. The last section provides some conclusions and a way forward for the ILMM framework.

LITERATURE REVIEW

A literature review of both available lean maturity models has been done. That helped identify the strengths of each of the models and the motivations behind their evolution. That review coupled with the need in the industry, helped the authors create a maturity model framework that addresses the needs of the local industry while taking into account some of the best practices in the existing models (

Table 1). This literature review is divided into six prominent frameworks across Lean Construction and broader organisational excellence, as outlined below.

LEAN CONSTRUCTION MATURITY MODEL FRAMEWORKS:

LESAT

The MIT - Lean Evaluation of Systems and Tactics (LESAT) helps analyse project outcomes through stakeholder interviews and robust data analysis. It utilises Lean performance indicators (LPIs) to evaluate the impact of Lean practices on project goals. Its four levels – Fragmented, Emerging, Integrated, Continuous Improvement – are based on objective data, revealing valuable insights into project performance. However, LESAT's data-driven nature requires significant resources and time, making it less suitable for quick assessments. Additionally, its project-centric focus might neglect the bigger picture of organisational transformation (Massachusetts Institute of Technology, 2012).

HELMA

The Highways England Lean Maturity Assessment Toolkit (HELMA) was developed for infrastructure projects in the UK. HELMA employs a gap analysis approach, comparing your current state with established best practices. Its five levels – Basic, Emerging, Intermediate, Advanced, and Leading – pinpoint areas for improvement and offer resources specifically designed for infrastructure projects. HELMA has been successfully used in this domain, but it might not translate well to other sectors, and its detailed scoring system can be daunting for newcomers (Highways England, 2018).

LCMR

The Lean Construction Maturity Rating (LCMR) offers a Framework for the Progressive Evaluation of Lean Construction Maturity Using a Multi-Dimensional Matrix (FPE-LCMM). Its spider radar charts and bar graphs provide a holistic and dynamic view. It analyses both project-specific and organizational-level factors, guiding you through three strategic stages: Initiation, Integration, and Optimization. While its intricate calculations require expert guidance, the FPE-LCMM provides a comprehensive picture of your lean maturity journey (Sainath et al., 2018).

Nesensohn LCMM

The Nesensohn Lean Construction Maturity Model (LCMM) is a guided step-by-step methodology to help assess the lean implementation path for organisations. This framework focuses on adopting specific tools and techniques, offering a self-assessment questionnaire with four defined levels: Awareness, Initiation, Integration, and Continuous Improvement. Post-assessment provides clear action plans towards mastering key lean practices. However, Nesensohn LCMM's framework and assessment methodology pressed the need for generalisation of the emergent elements of Lean Construction maturity as well as the 11 Key Attributes articulated in the LCMM, which can be confirmed or disconfirmed through further empirical evidence (Claus Nesensohn et al., 2016). Hence, it proves challenging to adapt these concepts to the Indian context, especially considering that the Indian industry is still in the nascent stage of embracing professionalism and incorporating tools and technologies. This underscores the importance of studying the key attributes applicable to Indian contexts, a necessity that must be verified with industry practitioners.

LCI Lean Maturity Model

The LCI Lean Construction Institute Lean Maturity model is an established framework that utilises a familiar self-assessment survey with five levels: Beginner, Aware, Focused, Advanced, and Lean Enterprise. Its binary scoring system offers a baseline for benchmarking and comparing your progress with others. While the LCI model's widespread recognition makes it a valuable tool, its rigidity might not capture the nuances of incremental progress within each level (*Organization Lean Assessment | Lean Construction Institute*, n.d.).

ISO 18404

The ISO 18404 standard offers a comprehensive framework for defining competencies in Six Sigma, Lean, and "Lean & Six Sigma," ensuring clarity and alignment. Structured guidelines and clear definitions facilitate effective implementation. At the same time, its complexity and resource-intensive nature may pose challenges for smaller organisations, potentially limiting inclusivity and hindering complete understanding and implementation (International Organization for Standardization, 2015). Antony et al., (2021) uncovered that the current standard requires improvement to align with industry needs. So, it underscores the importance of consulting industry experts to establish the appropriate dimensions, assessment levels, and criteria for standardizing lean maturity assessments across projects and organisations.

Table 1: Comparison of Lean Maturity Models

Framework	Focus	Methodology	Scoring	Strengths	Weaknesses
LESAT	Project-based assessment for enterprise	Stakeholder interviews and data analysis	Lean performance indicators (LPIs) mapped to maturity levels	Rigorous and data-driven focus on outcomes	High resource requirement, not ideal for quick assessments
HELMA	Infrastructure project context	Gap analysis between current state and desired state	Scoring based on specific criteria for each maturity level	Tailored for infrastructure projects, clear action plans	Not suitable for other sectors, complexity in scoring
LCMR	Multi-dimensional evaluation	Weighted factor model based on spider radar and bar charts	Lean scores mapped to maturity progression curve	Holistic and dynamic, considers project and organisational levels	Requires complex calculations and expertise
LCMM	Organisation-wide lean evaluation	Self-assessment questionnaire with scoring based on adoption levels	Scoring across four levels: Awareness, Initiation, Integration, and Continuous Improvement	Practical and easy to use, suitable for beginners	Limited scope, focuses mainly on 11 key cultural attributes
LCI-LMM	Organisational level assessment	Self-assessment survey with weighted scoring	Five levels: Beginner, Aware, Focused, Advanced, and Lean Enterprise.	Widely used and recognised, suitable for benchmarking	Limited flexibility, binary scoring system
ISO 18404	Organisational & Individual level assessment	Assessment based on personnel and process documentation	Green, Black, and Master Black belts	Structured guidelines to facilitate effective implementation, enhancing education, training, and experience levels for personnel	It is too complex for the Indian context and does not cover technology and other aspects.

POINT OF DEPARTURE

The literature review of various maturity models reveals that each model has its strengths and has been developed for the context in which it has been developed. Applying the model beyond the context and assumptions to which it has been developed will not yield the desired results. In fact, models likely cannot be developed in a very widely applicable framework for it to be effective. Beyond that first point of realisation, the authors realised that there is a need to document the context in which we are trying to develop a maturity model. Based on the authors' experience in trying to drive lean construction practices in the Indian construction industry over the past nearly fifteen years, the following have been observed:

- Projects or organisations adopt one or more of the processes of the basic lean toolset – Last Planner System™, Value Stream Mapping, Work Sampling, and 5S.
- Adoption set and level of adoption is dependent on the team and organisation.
- Some or most organisations have or are adopting digitisation technology solutions for project collaboration and control, 3D BIM modelling, etc.
- While motivated organisations continue to adopt some combination of the methods and tools and technology solutions, they are unable to proceed to the next level of transformation, leading them to reach a level of saturation.
- Projects and/or organisations are also unable to benchmark themselves with respect to each other to motivate themselves to go to the next level.

Based on the above observations, the authors posit that any maturity model developed for the Indian construction context has to incorporate the following into the framework.

1. Be applicable to the local industry context.
2. Provide flexibility to let organisations decide whether lean adoption should be project-based, organization-based, or hybrid.
3. Provide the ability for teams to make relative comparisons.
4. Data collection and assessment methodology has to be simple, practical, and something that can be easily taught to other assessors.
5. Be objective so the results are unbiased and process, not people-dependent.
6. Be somewhat prescriptive to give organisations a guided roadmap to driving lean transformation over time in a structured fashion.

The proposed model incrementally becomes more comprehensive, allowing objective data collection and evaluation and allowing the adoption to be project- and/or organization-based. However, it has to evolve to meet the above needs with the methodology described below.

RESEARCH METHODOLOGY

From the research method perspective, we are still in an exploratory stage of developing the Lean maturity model. Based on testing the outcomes from this exploratory stage, more rigorous research will be utilized to develop/ refine the ILMM. For developing the Lean Maturity Model for the construction industry in the Indian context involves an evolution from what we learned about the development of the LCMR model. Applied qualitative research methods instrumented for synthesising best practices from literature, conducting brainstorming sessions, presenting to stakeholders at conferences, and conducting pilot studies to develop the framework. This section outlines the systematic process of refining and validating the framework components.

FRAMEWORK EVOLUTION

The core framework for the maturity model evolved from adapting and adopting the best practices from the existing models reviewed and ideating the rest of the framework based on the needs identified as described above. So, while the foundation of our research was laid through the extensive literature review focusing on maturity models within the field of construction and across other industries, the basic tenets of the framework were evolved through collaborative discussion and ideation between the authors.

BRAINSTORMING SESSIONS

Once the basic framework of the model was in place, the authors conducted several unstructured brainstorming sessions with academic researchers and industry professionals. These collaborative discussions aimed to get feedback on the model proposed from industry professionals on its applicability, adoptability by the industry, ease of assessment and other criteria discussed above. The same with academic researchers aimed to question the assumptions that the authors had built into the model, modify the criteria for assessment, and provide a certain level of academic rigor to the proposed approach for periodic and continuous evaluation to get the desired outcomes. All of the conversations also sought to understand and brainstorm the model's applicability to the Indian construction context and any potential limitations to its adoption by the industry. The model presented in the next section results from that iterative dialogue and exchange of insights.

PRESENTATION AND FEEDBACK

Once the model was finalised through the brainstorming sessions above, the proposed model was presented to a wider set of stakeholders at multiple forums. These included the Indian Lean Construction Conference (ILCC) in 2022 and 2023. These presentations served as platforms to solicit feedback from a diverse audience comprising researchers, practitioners, and stakeholders. The input received during these sessions helped refine the model and validate its relevance and effectiveness in addressing industry challenges.

PILOT STUDIES

To validate the practical utility of the developed model, an initial pilot study has been conducted across two construction projects in India. These studies aimed to assess the model's ability to measure the current status of lean maturity within projects and/or organisations and provide actionable insights for improvement to the next level of maturity. More importantly, the project teams accepted the assessment methodology as a benchmark of where they stand and guidance on where they need to go.

In summary, our research methodology integrated theoretical insights, collaborative engagement, stakeholder feedback, and empirical validation to develop ILMM tailored to the specific needs and dynamics of the Indian construction industry. This iterative and inclusive approach ensured the creation of a model that is not only theoretically sound but also practical and actionable in driving organisational transformation. The authors are aware that the model is evolving and will evolve as more assessments are done, but they believe that the current version is ready for industry-wide deployment.

PROPOSED FRAMEWORK

The Institute for Lean Construction Excellence Lean Maturity Model (ILMM) consists of twelve levels as described below and summarised in

Table 2 graphically depicted in Figure 1 below. The assessment methodology to determine the level at which each project and/or organisation encompasses a modified Plan-Do-Check-Act (PDCA) approach is described below.

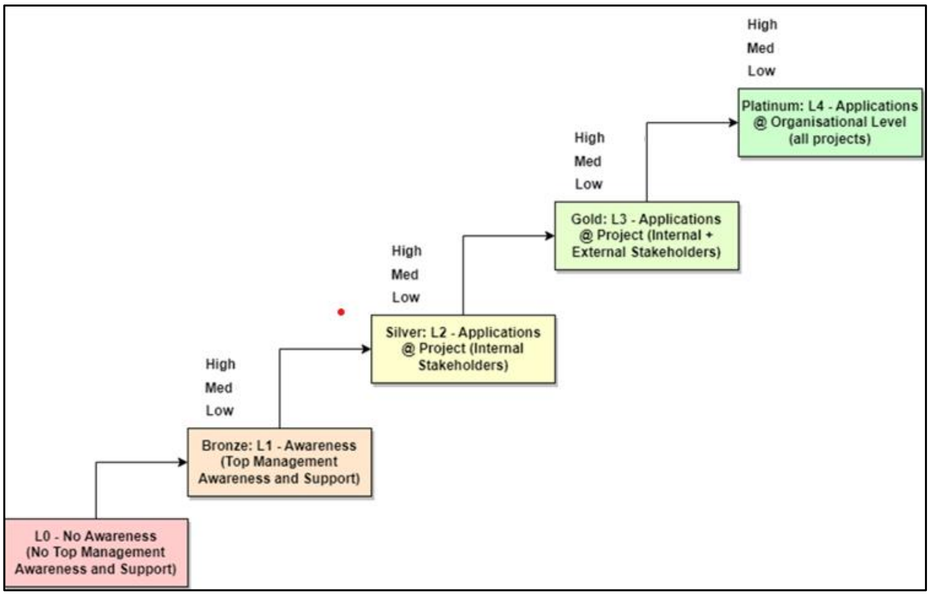

Figure 1: ILCE Lean Maturity Model (ILMM)

ILMM consists of four levels of maturity. Each level provides a significant leap in lean adoption from the previous level. Within each level, the model allows sub-categorization of 3 sub-levels: Low (L), Medium (M), or High (H). These sub-categorizations allow for the measurement of incremental improvement within the maturity level in a relatively smaller time horizon, allowing projects and/or organisations to grow organically to the next level. The four major levels of maturity and their sub-levels are summarised in the table and described briefly below:

7. **L0: NO Awareness**: This level indicates a general lack of awareness and support of lean practices at all levels of the organisation, including the top management. There is no concrete evidence of Lean initiatives in the project and/or organisation at this stage.
8. **L1 – Bronze**: At this level, there is Top Management Awareness of lean, and they commit resources in the form of a lean champion to drive the awareness within the various department heads with increasing adoption among them as they move from Low, Medium, and High as described in the table below.
9. **L2 – Silver**: At this level, lean adoption is done with internal stakeholders of the organisation at the project level driven by a corporate strategy. As the project teams move from Low, Medium, and High, there is an increasing level of adoption among the internal stakeholders, as described in the table below.
10. **L3 – Gold**: At this level, lean adoption is again extended to external stakeholders, driven by a corporate strategy. As project teams move from Low, Medium, and High, there is an increasing level of adoption among the external stakeholders driven by the project team, as described in the table below.
11. **L4 – Platinum**: At this level, lean adoption is happening at the portfolio or business unit level with increasing levels of adoption as described in Table 2 below.

Table 2: ILCE Lean Maturity Model

Maturity Level	Low	Medium	High
L0: No Awareness	Not Applicable	Not Applicable	Not Applicable
L1 – Bronze: Basic Awareness at Top Management Level	**Bronze – Low** No concrete evidence, but there is a Top management awareness	**Bronze – Medium** Top management and a FEW HODs attended Lean Awareness Sessions Part-time Lean champion to drive initiatives	**Bronze – High** Top management and ALL HODs attended Lean Awareness Sessions Full-time Lean champion to drive initiatives
L2 – Silver: Lean Application at Project Level with Internal Stakeholders	**Silver – Low** Corporate Strategy to adopt Lean practices Education and Training to a FEW Internal stakeholders Setting Operational targets for ONE internal department to adopt basic lean tools	**Silver – Medium** Execution of basic lean tool adoption in ONE internal department Education and Training to ALL Internal stakeholders Setting Operational targets for the adoption of basic lean tools with ALL internal departments	**Silver – High** Execution of basic lean tool adoption in ALL internal departments Continual Education and Training to ALL Internal stakeholders
L3 – Gold: Lean Application at Project Level with Internal and External Stakeholders	**Gold – Low** Corporate Strategy to adopt Lean practices to the next level Education and Training to a FEW External stakeholders Setting Operational targets for ONE External department to adopt basic lean tools	**Gold – Medium** Execution of basic lean tool adoption in ONE External department Education and Training to ALL External stakeholders Setting Operational targets for ALL Internal departments to adopt basic lean tools	**Gold – High** Execution of basic lean tool adoption in ALL External departments Continual Education and Training to ALL External stakeholders
L4 – Platinum: Lean Application at Portfolio and Organization Level	**Platinum – Low** Corporate Strategy to adopt Lean practices to the next level At least 20% of the projects at Gold - High	**Platinum – Medium** At least 40% of the projects at Gold-High	**Platinum – High** At least 80% of the projects at Gold-High

It is assumed that broadly, a project team will take around 2 to 2 ½ years to go from one maturity level to another, and they will move from one sub-level to another to another during that period. The lean strategy document that each project team will write provides the flexibility that the team(s) and organisation (s) need to adopt their path to lean transformation. Each could adopt a strategy depending on whether their internal organisational structure is de-centralized (project-based) or, centralised (shared functions), or a hybrid between the two. But within each strategy document, the ILMM model expects that they cover their strategy to adopt lean along five dimensions as discussed below:

1. *Top Management Support:* Based on the author's experience, pursuing lean initiatives without top management support and, consequently, a lack of resources is challenging.

Hence, the authors strongly believe this needs to be aligned before any project team or organisation takes any lean initiatives.

2. *Process*: Understanding and documenting processes is another principle aspect of lean. Documenting processes help identify waste and create pathways for continuous improvement. It also helps benchmark where a project (or organisation) stands on a process and helps them realise how and what to improve and the potential benefits gained through any interventions.
3. *People & Partners*: The authors' experience driving lean awareness and adoption in the Indian construction industry has made them intimately realise that a lot of the success of lean adoption happens after people and teams realise that it is the culture that needs to be changed and transformed – the culture of accountability, trust and transparency among stakeholders (both within and outside organisation), proactive information sharing, and putting project's needs above organisational constraints (sometimes) are critical for the long-term success of lean initiatives. This cultural transformation is critical for the sustained implementation of lean initiatives.
4. *Methods & Tools*: The lean construction research community has created or adopted several lean methods and tools over the past nearly thirty years. But the authors' believe the basic lean toolset is – Last Planner System™ (LPS), Value Stream Mapping, 5S, and Work Sampling. The authors recommend adopting these in the initial phase of lean adoption. The other methods and tools can be adopted organically as understanding and maturity grow. However, the basic tools are necessary to realise the benefits of lean adoption.
5. *Technology*: Technology has always served the purpose of improving productivity and eliminating wasteful processes, including data entry duplication and simplifying project information sharing, collaboration, and control. The authors' believe that adopting technology solutions with a lean mindset of productivity improvement and waste elimination is a better roadmap for technology adoption that makes them more sustainable.

Each level within the ILMM framework is associated with specific criteria along each of the five dimensions outlined above. By providing flexibility but governing it through fixed parameters, the authors believe they can give organisations the flexibility to adopt their own path but, at the overall industry level, provide some level of uniformity during the maturity assessment. That uniformity is critical to allow project teams and organisations to benchmark themselves and figure out how they measure up against the industry. The sub-categorization allows teams to make incremental progress without waiting for long periods and is expected to provide intrinsic motivation.

The assessment of project teams to benchmark them to a certain level of maturity is done through a survey. The assessment methodology is a modified PDCA methodology as outlined below:

- *Plan – Assessment Readiness:* Herein, the project teams and assessors agree to the basics and logistics of the assessment, allowing project teams to prepare the evidence.
- *Do – Assessment*: This is the actual onsite assessment done by the assessors. It is an in-person assessment with the assessors interviewing all the project departments, including the project team members. The assessors are expected to talk not only to the leaders in the functions but also to the supervisors, last planners, storekeepers, engineering document coordinators, billing engineers, etc. Individual interviews and surveys are done with each of the departments. Actual site walk-throughs are to be done by the assessors to gather information through visual inspection in addition to documentary evidence.
- *Check – Reporting & Assessment Action Plan*: Post the onsite visit, the assessors are expected to write a report documenting the current as-is of each department,

highlighting their strengths, the evidence gathered, etc. Based on this, the assessors benchmark the team to a certain maturity level and justify the same based on the evidence collected and gaps identified. The authors are working on a standard template report and are in the early stages of the same. The pilot studies (see below) show how it has evolved as of date.

- *Act – Implement Improvement Action Plan*: This is the implementation phase wherein the project teams implement the recommendations given by the assessors over time, document improvements and advance to the next level of maturity.

The actual assessment is done as a survey. The authors have developed standardised questions for each maturity level (and sub-level) along the five dimensions outlined above. The assessment is expected to take two working days, with the assessors visiting the project teams onsite. The responses to the assessment survey are the evidence that the team provides. The evidence is expected to be documentary evidence (like a certification for having attended a training course, a VSM document, etc.), a visible manifestation of a lean process (for example, a site store organised keeping 5S principles in mind or a Big Room wherein the teams have displayed their lookahead constraints, weekly work plans, PPC etc.) or an interview with individuals of the project teams (for example, What is waste, what is value etc.). The authors have developed an expected set of answers to each survey question. The survey and the expected answers provide some standardisation and objective assessment to the maturity assessment process. As outlined above, the post-assessment report benchmarks the project at a certain level of maturity. It provides actionable recommendations for the team to reach the next sub-level(s) or major maturity level. Finally, with the intent to scale, the authors recommend that the project teams do quarterly self-assessments to ensure that they are making incremental progress and have external assessors do an annual assessment to ensure that major progress is assessed and benchmarked. The next section shows how the methodology was applied on two project sites as a pilot study.

PILOT STUDY

Project: Cement Grinding Unit

The first pilot study was done on a Cement Grinding Unit project. The assessment was done with the main civil contractor whose contractual value in the project is Rs. 85 Crores. The project duration is about 30 months and the site had been functioning for about 18 months when the assessment was done. The project exhibits several strengths in its lean implementation, including robust top management support from the site and head office. There are limited yet documented process maps and no evidence of initial lean awareness training for 25% of the project team members. The site shows a strong adoption of 5S across several departments, including stores, quality, safety, time office, etc. The team has implemented LPS in the critical facilities of the project but not across all the facilities in the contractor's scope. The contractor has also implemented a web-enabled ERP system for data management across some functions, including accounting, finance, and HR.

Based on the outcome of the assessment, the authors, as assessors, have marked the project at a *Bronze – Medium* level of maturity. The recommendations to get to the next level of maturity include filling the gaps and completing some of the incomplete implementations of lean processes. Although the detailed action report is not in the scope of this paper, the main recommendations include items like exhaustive documentation of processes, thorough implementation of LPS, comprehensive lean training for the rest of the project teams, and adoption of other basic lean tools. To get the project team to further their maturity level, they also need to evaluate their technology strategy and deepen the complementary nature of technology and process. Finally, the organisation must develop a lean strategy document outlining how to operationalise their lean adoption (and hence maturity) through the project and/or organisation.

Project: Underground Metro Construction

The second pilot study was done on an Underground Metro construction project. The assessment was done with the main EPC contractor whose contractual value in the project is Rs. 1,526 Crores. The project duration is about 42 months and the site had been functioning for about 24 months when the assessment was done. From the assessment, it is evident that the project enjoys robust top management support both from the HO and site offices. The team has spent significant effort documenting processes in certain departments like Planning and QA/QC. All the site office personnel had undergone lean training as part of their corporate learning & development process. On an as-needed basis, the team has adopted LPS and constraint identification. At least in the stores, the team had adopted sophisticated technology solutions to monitor and manage material consumption and avoid pilferage. There were dedicated lean champions at the HO level who constantly ideated and drove lean initiatives across various project sites (including this one).

Based on the outcome of the assessment, the authors, as assessors, have marked the project at a *Bronze – Medium* level of maturity. The recommendations include comprehensive lean training for all the field project team members, a more rigorous and continuous adoption of LPS, the basic adoption of other basic lean methods and tools, and the extension of the documentation of processes to the other departments. Although the detailed action report is not in the scope of this paper, the main recommendations to get the project team to further their maturity level included the comments discussed above. Here, the assessors also recommend that the organisation develop a lean strategy document that outlines how they plan to operationalise their lean adoption and complementary digitisation strategy evolution (and hence maturity) through the project and/or organisation.

CONCLUSIONS

In conclusion, the authors have presented a maturity model that addresses the needs for the Indian construction industry. The model is currently the first version of the maturity model, and the authors believe that the model will evolve as more assessments are done. It should be noted that both the pilot project sites were done with organisations that had been practising lean in various forms for the past few years and had reached a sort of saturation point. The outcome of the assessment report has been presented to the project teams and organisations. The objective is to give organisations a concrete set of actions to implement and a guideline for adopting and growing their lean adoption to the next level.

One of the limitations of the current model and pilot studies is that it is not clear how the model will perform on a portfolio of projects within the same organisation and how the outcomes will interplay when assessment is done on various projects within the same organisation. The authors are aiming to address this in their next phase of research and potentially modify the maturity model based on the learning that comes out of that study. In the next phase, the authors are also looking to run pilot studies on projects and organisations that have not started on their lean transformation journey. Finally, the authors are looking to do a second assessment on the existing project sites and see if the maturity levels do advance (assuming the project teams did implement the recommendations from the current assessment) and if that increase in maturity levels translates to measurable improvement in project performance.

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LEAN CONSTRUCTION 4.0 AND SOCIETY 5.0, HOW CLOSE ARE THEY?

Eric Forcael[1]

ABSTRACT

The rapid advent of technological progress has triggered many industries to modify how they perform their tasks. The construction industry has not been immune to this reality. In this sense, Lean Construction 4.0 was recently born from the fusion of Lean principles and Construction 4.0. Similarly, concepts such as Industry 5.0 and Society 5.0 have also emerged in recent years, intending to put human beings at the center of companies' work. Thus, this article addresses how close Lean Construction 4.0 and Society 5.0 are. After analyzing both approaches, it is feasible to say that the relationship between both views is sensitively close, specifically under a human-centered approach and, therefore, it cannot be ignored as a process that also deals with the transformation of society through technology.

KEYWORDS

Lean Construction 4.0, Society 5.0, Human-centered approach, People-Process-Technology.

INTRODUCTION

According to Hamzeh *et al.* (2021) and González *et al.* (2023), Lean Construction 4.0 can be defined as the necessary combination of Lean principles and the implementation of technologies that make up Industry 4.0 in the construction industry, also known as Construction 4.0. In this sense, Lean Construction is inspired by the postulates originally proposed by Lauri Koskela (1992), aimed to meet customer needs better while using less of everything, based on production management principles, and resulting in a new project delivery system that can be applied to any construction but particularly suited for complex, uncertain, and quick projects (Aziz & Hafez, 2013; Howell, 1999). Similarly, based on Industry 4.0, the concept of Construction 4.0 was born, essentially made up of the digitization of the construction industry and industrialization of construction processes (Forcael *et al.*, 2020), and characterized by robotics, Internet of Things, digital twins, 4D printing, cloud augmented and virtual reality, blockchain, artificial intelligence, machine learning, and deep learning (Baduge *et al.*, 2022).

On the other hand, Society 5.0 is a model to spread to industry and the general public how governments envision a society in the future, based on a people-centric society founded on merging cyberspace and physical space (Deguchi *et al.*, 2020) to balance economic advancement with the solution of social problems (Huang *et al.*, 2022). In other words, Society 5.0 states a system of systems connected to mitigate both local and global major social problems (productivity, competitiveness, networking, and well-being), focused on humans to balance the growth of Big Data, Internet of Things, and Artificial Intelligence, and maximize human use of the current and future technological transformation and digitization (Narvaez Rojas *et al.*, 2021).

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Thus, on the one hand, a new perspective arises that connects Lean Construction with the technologies of Construction 4.0, while another perspective known as Society 5.0 seeks to put people at the center in the face of deploying those technologies typical of Industry 4.0. This paper tries to answer the question of how close both views are. Regarding the rules of exclusion or inclusion of dimensions for the critical and comparative analysis between Lean Construction 4.0 and Society 5.0, the main criterion was to consider some of the most cited bibliographical sources related to both topics, accordingly included in the present research.

LEAN CONSTRUCTION 4.0

LEAN CONSTRUCTION

According to Koskela *et al.* (2019), from an epistemological point of view, there can be two interpretations of Lean Construction: a Platonic one that considers a static body of knowledge applied to practical situations or an Aristotelian one that contemplates a dynamic body of knowledge that is born from discoveries that come from practical situations. As a consequence of this reflection, Lean Construction could be defined as a combination of a circumstantial production model arising from trying to solve specific issues in the construction industry by implementing generic lean production principles, tools, and methods from the automobile manufacturing industry (Koskela, 2020).

In this sense, authors such as Womack & Jones (2003) and Pessôa & Trabasso (2017) have established that the Lean principles correspond to specifying value, identifying the stream value, guaranteeing the flow, pulling the value, and seeking perfection. According to Aziz & Hafez (2013), lean thinking can be summarized into eleven principles: reduce the share of non-value-adding activities (waste); reduce variability; minimize the number of steps, parts, and linkages; increase process transparency; focus control on the complete process; balance flow improvement with conversion improvement, to mention a few (Koskela, 1992), while the Construction Industry Institute (Ballard *et al.*, 2007) considers fourteen principles organized in four categories (4P of the lean way): Philosophy, Process, People and Partners, and Problem-Solving, including decisions based on long-term philosophy even over short-term financial objectives, developing extraordinary work teams committed to the enterprise philosophy, going through a company that learns from deep and continuous cogitation and improvement.

On the other hand, from a lean perspective, Dave *et al.* (2008) state that people, process, and technology —essential aspects of Lean Construction— can be summarized as a) People: the core driving force behind the process and technology, where a poorly implemented information system may jeopardize to reach a higher efficiency; b) Process: a task-based approach where variability is inherent within the processes and wastes have to be eliminated or reduced; c) Technology: including information and communication technology (ICT) systems such as CAD, estimating, scheduling and productivity software, 3D modeling, and BIM, among other tools. Accordingly, the TFV theory establishes that Transformation (T), Flow (F), and Value (V) influence People, Processes, and Information Systems (Dave *et al.*, 2008; Koskela, 2000), including the problem-solving ambit from the 4P of the lean way (Ballard *et al.*, 2007).

Thus, the last 30 years have brought with them a series of advances in rethinking the construction industry based on technology, processes, and people interaction, integrating partnering practices, databases, new construction methods, new financial and cost models, and quality management practices, helping practitioners to think about construction as a manufacturing process (Tzortzopoulos *et al.*, 2020).

CONSTRUCTION 4.0

During this first quarter of the 21st Century, significant technological and scientific progress has been evidenced in terms of Industry 4.0, which mainly focuses on computer and cyber-physical systems (Boyes *et al.*, 2018). On the other hand, the construction industry has also taken advantage of these advances, converging in what is known as Construction 4.0, a term first mentioned in 2016 by Roland Berger, which emphasizes that the digitization of the construction industry, encompassing digital data, automation, connectivity, and digital access (Roland Berger, 2016). Accordingly, Sawhney *et al.* (2020) establish that Construction 4.0 is a framework where industrial production and construction, cyber-physical systems, and digital technologies occur. Forcael *et al.* (2020) mention some technologies of Construction 4.0, such as BIM, drones, virtual and augmented reality, new materials, cloud-based project management, blockchain and cybersecurity, artificial intelligence, Big data, laser scanners, robotics and automation, wearable sensors, Internet of Things, actuators, additive manufacturing, offsite and on-site construction; technologies that may help define Construction 4.0 as the industrialization of the construction processes and digitalization of the construction industry.

Recent investigations also establish that Construction 4.0 has diverse variants focused on the broader ambit of the asset/product/property of the realm of construction and going beyond the general concepts of Industry 4.0, including but not limited to lean construction, digital building ecosystems, Internet of Things, and smart cities (Siriwardhana & Moehler, 2023). Similarly, according to Muñoz-La Rivera *et al.* (2021), Construction 4.0 can be categorized into (a) Automation (to integrate digital end-to-end engineering based on technologies to automate the physical manufacturing environment), (b) Simulations and Modelling (implements to design, build, and operate infrastructures and buildings through simulation and modeling), and (c) Digitalization and Virtualization (implements for products and industrial processes, digitally and virtually). In other words, Construction 4.0 is an extension of Industry 4.0 that focuses specifically on the construction industry, emphasizing automation, dematerialization of buildings (usually linked to “smart” homes), and the interdisciplinary nature of new construction (Forcael *et al.*, 2020).

LEAN CONSTRUCTION 4.0 FUNDAMENTALS

Essentially, the concept of Lean Construction 4.0 is a framework that integrates the principles of Lean Construction and the technologies associated with Industry 4.0 (Hatoum & Nassereddine, 2023). Accordingly, Hamzeh *et al.* (2021) suggest that Lean Construction has to seize the changes triggered by Industry 4.0 while keeping the people-processes-technology in the center, where a turnaround to Lean Construction 4.0 requires focusing on the combined benefits between digital/smart technologies and production management theory. On the other hand, based on the three crucial aspects of Lean Construction: people, process, and technology (Dave *et al.*, 2008; Koskela, 2000), there is an inherent connection between technology and Industry 4.0, or even more specifically, Construction 4.0. Nevertheless, given that Lean Construction 4.0 focuses on integrating ICT into the construction industry, it will not be easy to transform the current construction business model if all construction participants do not incorporate innovative technologies and techniques (Musa *et al.*, 2023).

Notwithstanding the relevance of the previously emphasized relationship between Lean principles and Construction 4.0, it is crucial to consider the power of people as the foundations needed to successfully attain the Lean Construction 4.0 vision of the Architecture, Engineering, and Construction (AEC) Industry (Hatoum & Nassereddine, 2023). In other words, since the resistance of a chain is given by the resistance of its weakest link, it is not possible to talk about process and technology leaving people behind, especially when one expects to have a robust chain made of people-process-technology.

In terms of applications, despite the incipient nature of the concept, some initiatives of Lean Construction 4.0 are already evidenced, such as the feasibility of implementing it in multi-family projects to improve the decision-making experience using digital twins of building works (Lara Ramirez *et al.*, 2022). Another example concerns evaluating the usability of a cloud-based tool called LeanBuild after the design stage and assessing the exhaustiveness of the software design flow, showing that considering data privacy and security, modules for designing and tracking offsite construction, sustainability tools, and artificial intelligence enhance its use and bring more value to end-users (Musa *et al.*, 2023).

In summary, Lean Construction 4.0 can be graphically represented through Figure 1, adapted from González *et al.* (2023) and Forcael *et al.* (2020).

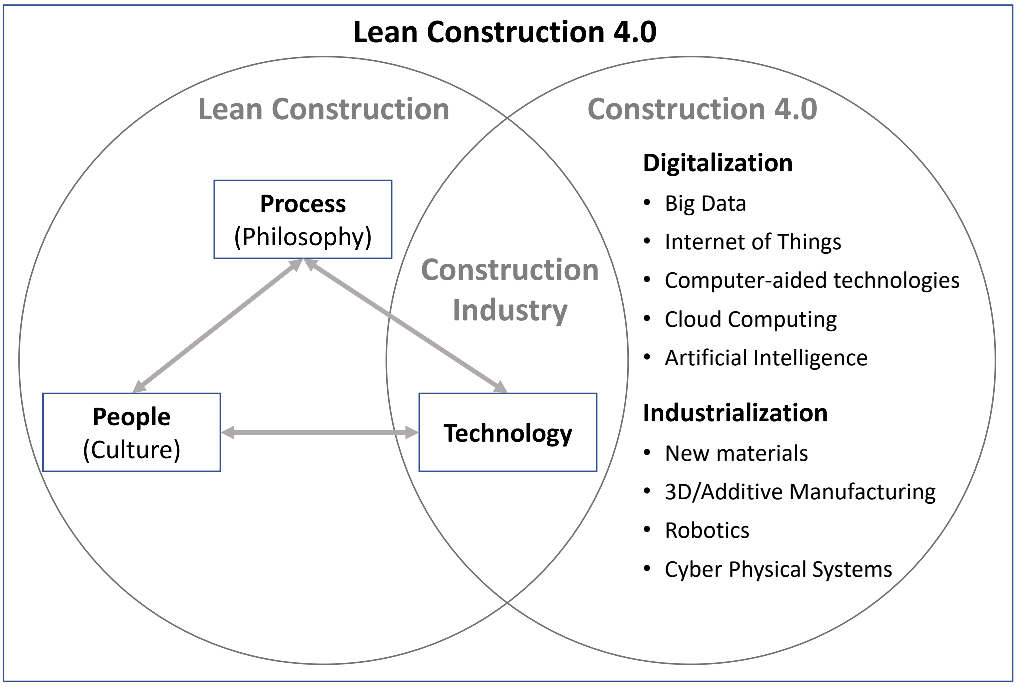

Figure 1: Lean Construction 4.0 (adapted from González *et al.* (2023) and Forcael *et al.* (2020))

SOCIETY 5.0

The term "Society 5.0" was proposed in January 2016 by the Japanese government as part of the 2016-2020 Fifth Basic Plan for Science and Technology, aimed at merging the physical space (real world) and cyberspace by fully leveraging ICT, based on a "super smart society" that brings wealth to the people (Council for Science Technology and Innovation Cabinet Office Government of Japan, 2015). From a chronological point of view, Society 1.0 corresponds to the hunter-gatherer human, Society 2.0 is related to the agrarian human, Society 3.0 is centered on an industrial human, Society 4.0 regards an information-based human, and finally, it is found to a superintelligent society known as Society 5.0 (Deguchi *et al.*, 2020).

According to Narvaez-Rojas *et al.* (2021), Society 5.0, as a Japanese concept for a "superintelligent society," is focused on human beings at the core of transformations, economic growth, technological development, and sustainability, allowing for the development of sustainable technology without restricting prosperity. In other words, Society 5.0 consists of finding solutions for the current society's obstacles based on a modern super-smart society, where people may benefit from a high-quality and enjoyable life by amalgamating cyberspace and physical space through fully utilizing ICT (Huang *et al.*, 2022).

Also, taking into account the relevance of placing the human being at the center of the work of every company, Industry 5.0 came up as a vision from a technological Industry 4.0 to an industry centered on people and the workers' well-being but keeping up productive performance (Alves *et al.*, 2023). Comparatively speaking, Industry 5.0 was launched by the European Commission looking for a sustainable, human-centric, and resilient European industry, while Japan suggested Society 5.0 to equilibrate economic progress and social issues solutions within the Japanese society (Huang *et al.*, 2022).

Thus, Society 5.0 should be sustainable and resilient against threats and unpredictable and uncertain conditions, ensuring people's safety, security, and well-being (Council for Science Technology and Innovation Cabinet Office Government of Japan, 2021). This vision toward a people-centric society, which looks to merge cyberspace with physical space, based on a knowledge-intensive and data-driven society, can be schematically summarized in Figure 2.

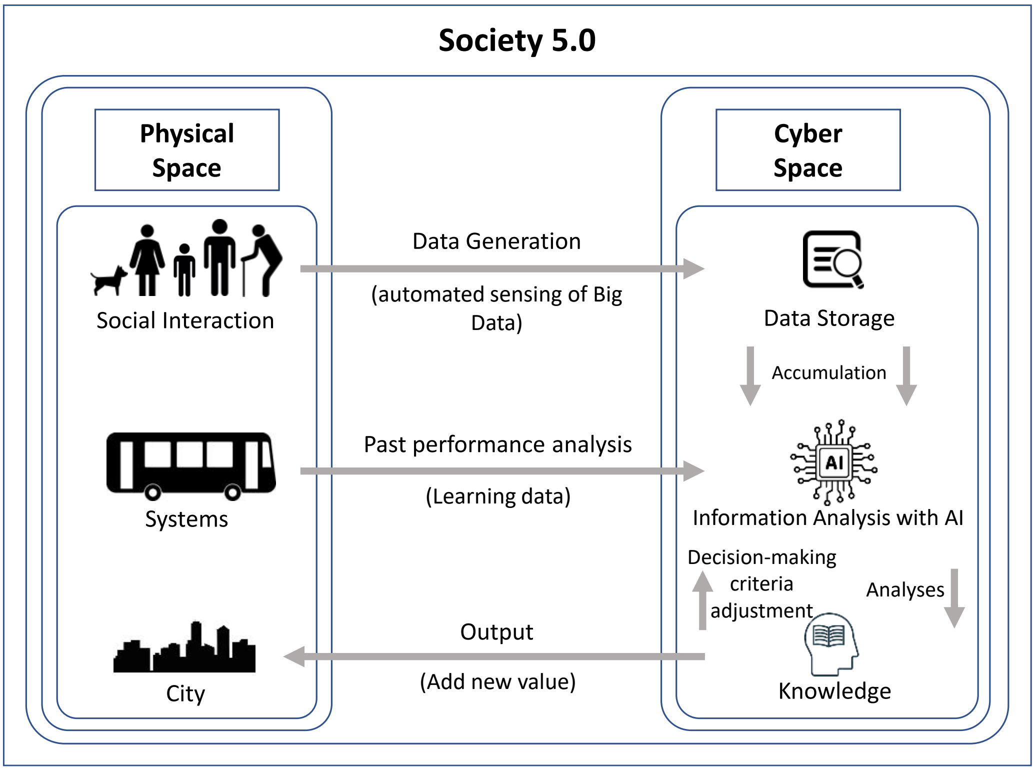

Figure 2: Society 5.0 (adapted from Deguchi *et al.* (2020))

RELATIONSHIP BETWEEN LEAN CONSTRUCTION 4.0 AND SOCIETY 5.0

Based on all of the above, it will be increasingly necessary to consider those aspects behind the technologies associated with Lean Construction 4.0 and Society 5.0, such as digital manufacturing, Internet of Things, cybersecurity, artificial intelligence, big data, cyber-physical systems, maker culture, among others, but also those topics related to professional ethics, environmental and social sustainability, decision-making under challenging situations, and the promotion of creative problem solving, thereby focusing on people. To achieve this, it would be good, for example, to look back to the model of the ancient engineers, who built fortifications and ports, channeled rivers, designed machines, and traveled to discover the world to successfully face and solve the increasingly demanding needs of a society that was becoming increasingly globalized (Cámara & Revuelta, 2016).

Tomorrow then involves implementing the technologies behind Lean Construction 4.0 but properly managing humanity's most precious resource, people; also worrying about their comprehensive training, including professionals not only from the AEC but also talent from diverse fields of knowledge: philosophers, sociologists, linguists, biologists, economists, jurists, scientists from various areas and even politicians. All of this, along with a more accentuated role of people, will provide the flexibility, plurality of approaches, and dynamism necessary to face the dizzying technological changes that the future holds for the construction industry.

In this way, it is interesting to consider how Lean Construction 4.0 principles and Society 5.0 are connected, as schematically shown in Figure 3 and discussed in the following section.

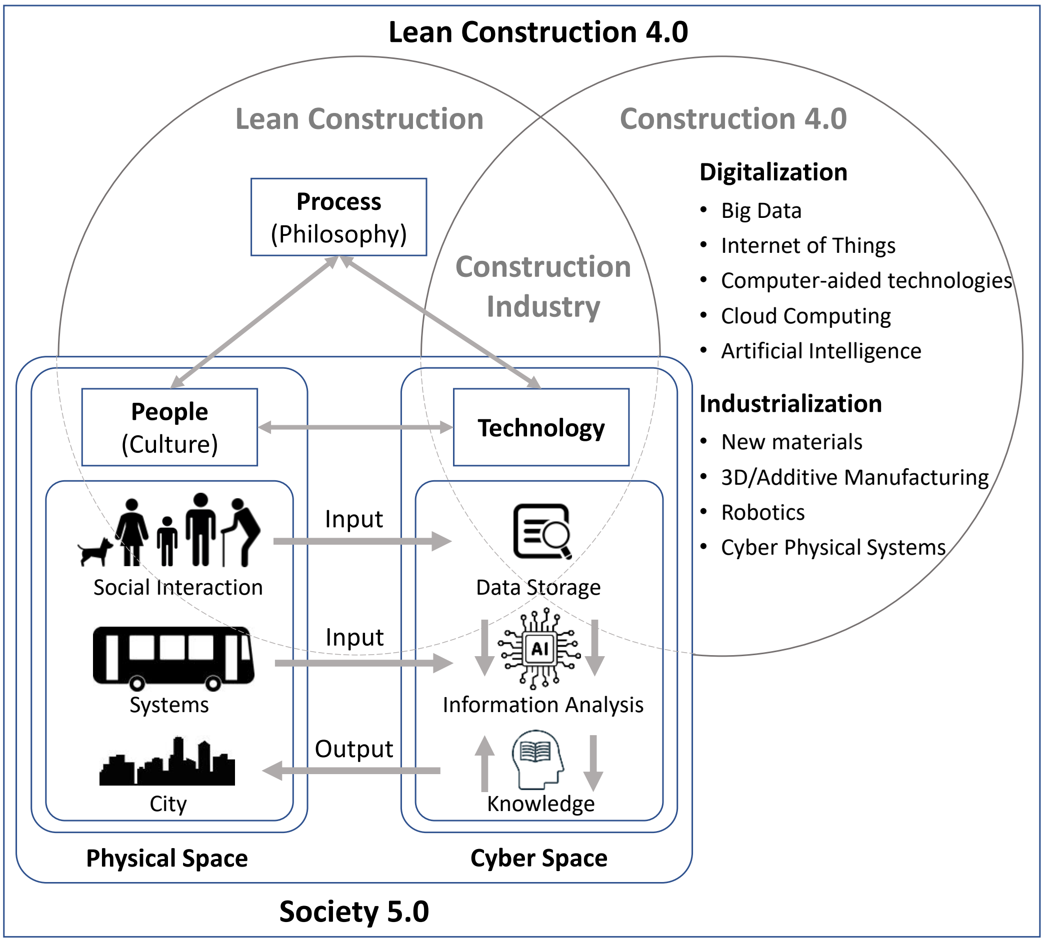

Figure 3: Lean Construction 4.0 and Society 5.0.

DISCUSSION

NEW CHALLENGES FOR A LEAN CONSTRUCTION 4.0 BASED ON SOCIETY' NEEDS

Due to the extensive scientific-technological growth, construction professionals could easily take on the legacy of the ancient engineers, characterized by their ability to face the most varied intellectual, productive, and even artistic challenges, always considering the technical aspects of their tasks but without leaving behind the human perspective in their performance (Cámara & Revuelta, 2016), capable of learning and reinventing themselves throughout life, with global projection and vocation, aware of the challenges of working with professionals from other countries and cultures, to deal with the challenges for sustainable growth of society.

These construction professionals, with solid technical and technological knowledge, are called to build a new humanism for the 21st Century (Bokova, 2014), given that they occupy positions of responsibility in all areas of the construction industry; therefore, with the ability to make decisions based on the Lean Construction 4.0 view but in total harmony with Society 5.0.

In this sense, this new approach of Lean Construction 4.0 must also be involved in the decision-making processes that affect society since the construction industry is linked primarily to technical or technological problems and overlooks its impact outside its immediate operational environment. In developing any construction project, considering environmental and social aspects is essential to the change and must be motivated by academia and industry.

It is for all these reasons that the path to the future requires a construction industry better prepared to continue developing and guiding the technological advances that are rewriting the present and that include the development of supermaterials, global communication networks, the widespread use of nanotechnology, and the exponential growth of artificial intelligence, among others. New Lean Construction 4.0 development schemes are necessary to combine the fundamentals of construction and new technological challenges, becoming more stable, specialized, and dynamic, thus aligning the performance of the construction industry with the needs of this new paradigm of Society 5.0.

The construction industry of the future must be able to learn along its way and adapt to today's rapid technological changes, continually preparing to reinvent its professional work, assuming the possibility that certain construction areas or constructive processes will disappear —the disuse of formworks with the advent of 3D concrete printing methods (Forcael *et al.*, 2021), or drones replacing people in the structural inspection of bridges (Jeong *et al.*, 2020) —, bringing the challenge of defining and linking to new business sectors.

PREPARING THE CONSTRUCTION INDUSTRY FOR THIS NEW PARADIGM THAT COMBINES LEAN CONSTRUCTION 4.0 AND SOCIETY 5.0

The ability to learn and adapt during the life of a company is a crucial competence for its survival, where conventional practices in the construction industry will require to be redesigned to adapt to the new changes brought by Industry 4.0 and boost growth successfully (Alaloul *et al.,* 2020). In this sense, taking into account that technological revolutions occur without pause and that these will affect the role of any company in society, learning to learn and adapt over time is increasingly necessary. This adaptative skill must be actively promoted within the construction industry through strategies that include increasing collaboration between academia and industry (Falcone *et al.*, 2019), establishing research and training collaborations between higher education institutions and local communities, developing continuing training programs for construction professionals, and creating mechanisms for the increment of significant learning in diverse contexts (cultural, social, technological).

Thus, the solution to different social challenges and the adaptation to the radical changes that are coming will require a more complex construction industry, which transcends traditional practices, including aspects such as the ability to implement and work in multidisciplinary and international teams, an interest in delving into cultural, social, political, and historical aspects, as a complement to purely scientific-technological ones, and a basis for mutual understanding between countries and cultures, and awareness of globalization as a fundamental key towards the new perspective of Lean Construction 4.0 and Society 5.0, which improves social cohesion and access to opportunities.

On the other hand, an adequate adaptation of the construction industry is necessary to solve the needs demanded by Lean Construction 4.0 in a dynamic and personalized way based on greater legislative dynamism and simplifying procedures and bureaucracies focused on data, moving towards human-centered systems. In this sense, it is also crucial that the construction industry assumes the role of accompanying its workers to turn them into the leaders of the future, with adequate training in aspects related to personal and professional growth, the management of technological, economic, and human resources, further promoting graduate training in construction. In other words, the industrial revolutions in which society is involved demand the attention of organizations to develop and train human resources for the future growth of the nations (Man, 2020). Lean Construction 4.0 and Society 5.0 cannot be absent in this challenge.

Finally, in terms of competitiveness in the era of Industry 4.0 and Society 5.0, it will be required to count on sensitive human resources who are fervent to find opportunities and dare to produce changes to stay in the game against competitors (Ellitan, 2020).

MERGING OF LEAN CONSTRUCTION 4.0 AND SOCIETY 5.0

As known, Industry 4.0 was defined more than ten years ago, mainly driven by a comprehensive set of interconnected innovative technologies (intelligent factories, artificial intelligence, rapid prototyping, additive manufacturing, big data, cloud computing, and robotics, among others), moving from the third to a cyber-systems-based industrial revolution (Kagermann *et al.*, 2011). Although the topics belonging to Industry 4.0 have been a matter of permanent interest, the number "5.0" has been more related to research and development of processes, products, and systems performed as "4.0 Technologies," which have been moving towards Society 5.0 (Cabinet Office of the Government of Japan, 2024). Consequently, "Industry 5.0" has been born as the effect of implementing the technologies from Industry 4.0 and their diverse derivations into the "Society 5.0" approach (Gürdür Broo *et al.*, 2022; Habash, 2022).

Thus, "5.0" will be significant in the future construction industry since its fundamental mission is to generate and apply innovative knowledge in traditional construction. In this sense, if society moves towards Industry 4.0, the construction industry must advance even faster, not only thinking about current challenges but also implementing new technological advances that allow it to reach the productivity levels of other industries. Consequently, Lean Construction 4.0 and Society 5.0 should converge on systems and methodologies beyond conventional construction's current and already obsolete models.

Ethical and Social Aspects Behind Lean Construction 4.0 and Society 5.0

As the construction industry is considered unethical, including but not limited to nepotism, interest conflicts, bribes, or contract awarding for political reasons (Owusu *et al.*, 2019), there is a challenge to meet the conduct codes and avoid corrupt practices within the construction industry (Amoah & Steyn, 2023). Therefore, based on the people-process-technology triad, it becomes essential to motivate the construction industry to be ethical when developing construction projects, going beyond the purely procedural or technological aspects (process-technology) and considering the harmful effects of unethical practices on the social fabric (people). In this sense, the construction industry must encourage reliable and committed behavior in its professionals to work under high ethical standards, understand the social responsibility of their actions, and incorporate an attitude of service towards people in each constructive project they carry out (Forcael *et al.*, 2013; Rupnow *et al.*, 2018).

In this sense, it becomes very relevant to understand the construction industry as a social activity that must reach the highest ethical standards. This principle implies that the construction industry must realize that it does not only work with equipment and machinery but also with people fundamentally. Therefore, it has to be prepared to face its work's potential ethical and social impacts. Consequently, the merging of Lean Construction 4.0 and Society 5.0 will require each construction project throughout its entire life cycle to contemplate the study of the social effects and ethical challenges present in the industry. Fortunately, professional ethics and social responsibility have been systematically incorporated into the construction industry.

Despite the previous facts and the complex societal and technological challenges that are coming, this industry's future is promising and full of opportunities, where the accomplishment of the highest ethical standards by the construction industry will be more effortless after materializing a mutually beneficial merging of Lean Construction 4.0 and Society 5.0.

A reframing view of Lean Construction 4.0 and Society 5.0

The rapid and constant transformations in the construction industry will demand less dogmatism, open-mindedness, dynamism, foresight, the ability to adapt to vertiginous changes, and the capability to face new scenarios with humbleness. This new perspective will give the modern construction industry —which will successfully implement technological advances in its work—, a relevant role in reshaping society towards a less threatening future based on the quality of life through technology.

From this perspective, a Lean Construction 4.0 vision without strong moral and scientific postulates that put society at the center is doomed. The traditional ways of the construction industry will no longer be a rigid dogma; they must be adjusted to include the contemporary and ongoing technological revolutions from Industry 4.0, primarily related to the Construction 4.0 technologies, but without ignoring the human factor. However, disruptive technologies, such as artificial intelligence or humanoid robots, may bring uncertainty to people due to the recurrent fear that machines will replace humans sooner or later. Therefore, a Lean Construction 4.0 vision that strongly emphasizes the role of people by merging with the Society 5.0 approach will play a fundamental role in the modern construction industry.

Thus, the vision of a construction industry that strives to incorporate technology and innovation into its processes to bring comfort, well-being, and economic growth without harming the environment and respecting people is more significant than ever.

IMPLICATIONS FOR LEAN PRACTITIONERS

Below are some recommended practices for Lean practitioners that can help jointly implement Lean Construction 4.0 and Society 5.0, as a way to impact society through this integration:

It is unnecessary to look for intricate definitions of these two concepts. Lean Construction 4.0 combines Lean principles and technologies from Construction 4.0, while Society 5.0 is essentially a model to publicly spread how governments envision a future based on a human-centered view that balances new technologies and solutions to social problems.

After the discussion, there might be the feeling that using ICT is the end goal, but it is not. Although supporting effective practices via software raises the value of technological outputs rapidly, "waiting for Superman" is a recurrent problem of technology —the next iteration or version will be the response—. However, the reality is that today's generation has more software than ever, and productivity remains at a standstill. The solution is not technology itself but people driving technology to improve society.

Construction professionals must strengthen their ability to face broader intellectual, constructive, technological, social, and cultural demands without leaving behind the people-centric view. They must be capable of learning and reinventing themselves throughout life, with a worldwide vision for working with people from other countries and cultures through making decisions based on the Lean Construction 4.0 principles and Society 5.0.

The construction industry must actively promote learning to learn and adapt faster than ever, including research and training collaborations with higher education institutions. This action will increase significant learning in diverse contexts (cultural, social, technological, political, and historical), facilitating access to opportunities and cultivating social cohesion.

Construction has to solve the needs demanded by Lean Construction 4.0 in a flexible way challenged by greater legislative vigor and streamlining procedures and bureaucracy, moving on the road to people-centric systems through leaders with appropriate training in aspects related to personal and professional growth, the management of financial, technological, and human resources, based on sensitive people who are fervent to dare to produce changes.

Finally, merging Lean Construction 4.0 and Society 5.0 will require each construction project's development to contemplate studying the industry's social effects and ethical challenges throughout its life cycle.

CONCLUSIONS

The present research was focused on the merging of Lean Construction and Society 5.0, based on the construction industry's role in using new technologies to face increasingly complex construction projects and their impact on people. In this context, the construction industry needs to be closely connected with people looking to impact society by using technology and information analyses that provide a quality life for all.

This new perspective requires highlighting the relevance of counting on an updated construction industry capable of gathering the best technological aspects from Construction 4.0, including how the incorporation and implementation of technology into constructive processes emphasize the privileged position of human beings and ethical principles as crucial elements of the modern construction industry. To put it differently, new ways of envisioning a construction sector that considers the best of technological advances and people's perspectives but takes into account multiple social contexts and interactions today.

Finally, the current Society 5.0 approach, based on social interaction with systems that generate valuable data to be analyzed by different means (e.g., AI), has to merge into a new technological vision that leverages the best of the Lean Construction 4.0 emphasizing the need for linking the physical and digital worlds and the relevance of human's role in technology utilization (González *et al.*, 2023). Thus, after analyzing both views, while Lean Construction 4.0 needs to develop its processes through technology and considering people, and Society 5.0 searches for the better use of technology to improve the human's physical world, it is feasible to say that the relationship between both paradigms is sensitively close, specifically under a human-centered approach and, therefore, it cannot be ignored as a process that also deals with the transformation of society through technology, a phenomenon that the human race has been facing from its origins but today more than ever.

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LEAN CONSTRUCTION ENTERPRISE MANAGEMENT: THE VALUE AND POTENTIAL OF THE MERIT GAME SIMULATION

Matt Stevens[1] and Mani Poshdar[2]

ABSTRACT

A Lean Enterprise Construction-aligned learning game is an opportunity to meet the industry's needs and wants. Competitive Simulation can offer such an alignment by using an online system as a medium to instruct. Learning three critical components: vocabulary, concepts, and processes, as well as game-based learning, allows students to acquire knowledge and skills through an interactive and entertaining learning experience to achieve the purpose of real-time teaching. As a result, many educators have adopted gamification in various disciplines in the tertiary sector to enhance learning and teaching. This paper will discuss applying the MERIT game to Lean Construction Learning through a case study within a leading Australian university. The case study incorporates the Merit Game and relevant organisational management content into an undergraduate construction management program. Its focus is Lean Enterprise principles and concepts. Overall, students reported a positive learning experience with higher-order learning outcomes while identifying good practices incorporated into future delivery programs. The case study findings will inform academics and training professionals about the potential of the MERIT game, if tailored, for teaching Lean Construction at the enterprise level.

KEYWORDS

Gamification, Online Simulation, Project Management, Construction Portfolio Management

INTRODUCTION

Introducing Lean Construction (LC) through an online game with peer competition offers a robust approach to educating emerging professionals. Effective learning games motivate students to apply principles that expose them to the content and enhance their situational thinking. The adoption of gamification in higher education has become commonplace, with an increasing number of educators embracing it across various subjects to enhance student engagement and performance (Gómez-Carrasco et al., 2019; Swacha, 2021). Nevertheless, the incorporation of gamification into Lean Construction education and its community remains a developing area.

One of the seminal works in the Lean movement was Womack and Jones' (1996) book, "*Lean Thinking: Banish waste and create wealth in your corporation*." This publication signalled the critical nature of enterprises in minimising waste and producing higher value.

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Lean Construction Enterprise (LCE) dynamics are primary lessons in the MERIT Game experience. According to Tsigskas (2022), knowledge capture about LCE should be:

- Production and administration processes driven solely by complementarity of activities to increase profit.
- Flow of work, material, information, and cash through digitisation.
- Adaptation strategies and methods to changing market conditions.

These three understandings provide the learner with a starting point to build upon. They can progress their mastery to more nuanced and powerful ideas that scaffold from these foundations.

MERIT GAME AND EQUIPPING STUDENTS WITH PRACTICAL SKILLS

There is a small but significant threat to tertiary education if relevant skills are not reliably captured by their graduates. Business Insider (2024) reports that 37% made progress in skills-based hiring, including Walmart, Apple, and Target, and 45%, took college requirements out of job postings such as Bank of America, Amazon, and Lockheed Martin. Still, they failed to institute actual changes in their formal process and hiring documentation. However, it may be an emerging signal from the market about the value and hunger for relevant skills.

Recognising the importance of equipping students with practical skills, one construction management program (WSU 2020) has integrated the MERIT game into its curriculum. This game-based approach aligns with the evolving needs of the construction industry and offers students hands-on experience in managing project portfolios. By bridging the gap between theoretical knowledge and practical application, the program aims to prepare students for the dynamic challenges of the construction sector. Additionally, the MERIT game addresses challenges in direct labour management. This feature resonates with the prevailing market reality that approximately ¾ of construction firms are characterized as non-subcontract yet labour-intensive entities (Stevens and Smolders 2023a).

PROJECT PORTFOLIO DYNAMICS

Modern construction projects' larger size and increased complexity have catalysed the development of improved leadership and management training methods for leaders and managers – matriculating or working (Ahmed et al. 2014). Educational games such as MERIT simulate the intricacies and interdependencies in real-world project management, making it an excellent platform for conveying complex concepts and promoting deeper understanding. The MERIT game's foundational work is manifested in Modern Construction Management (Harris et al., 2021) and its seven editions, first published in 1983. The book focused on construction organisational leadership and the many simultaneous projects that are ongoing at any one time. The MERIT game was published, and its first competition was held in 1989.

Constructing a project is a linear one-off process in which every mistake affects two or more tasks downstream – early mistakes are especially pernicious. A contractor's business involves managing several critical paths and their myriad of tasks to produce cash flow, profit and a good reputation. Risk is well-managed when a company is sensitive to incorrect or tardy task executions (Stevens and Smolders 2023)

Building upon the educational benefits of gamification, particularly demonstrated through the MERIT game, it is essential to explore the broader dynamics of project management, specifically focusing on Project Portfolio Management (PPM). By integrating game-based learning experiences like the MERIT game with discussions on PPM, students can understand the complexities and challenges involved in managing multiple projects within an organisational context.

The MERIT game effectively simulates the challenges and opportunities inherent in PPM, a strategic framework integral to effective project management that aligns multiple projects with an organisation's broader strategic objectives (Project Management Institute, 2000). Effective PPM needs a structured process, including risk assessment, estimated profitability and an overall strategic fit to the corporate goals (Bilgin et al., 2023). PPM focuses on dovetailing projects into a time and resource demand framework unique to the constructor and requires a vastly different approach than project management (Oltman, 2008).

As an example, the staffing of projects is not primarily for the site manager to decide but typically a home office executive who balances all the current project's demands. The Lean project production practice of Percent Plan Complete, as described by Stevens (2015), may not align with realism. For educators, a solid grasp of PPM is essential for students in the construction industry, where managing multiple interrelated projects as a Project Manager or as a Managing Director is a certainty.

PPM's strength lies in its ability to handle the uncertainties and complexities often encountered in projects. It offers a flexible approach that can adapt to changes and unforeseen challenges, ensuring project success (Cooper et al., 2000). One significant advantage of PPM is its approach to understanding and managing the interconnections between different projects. Managing these connections in environments where projects are closely linked regarding resources and goals is vital for resource efficiency, avoiding delays and cost overruns (Engwall & Jerbrant, 2003).

Moreover, PPM significantly contributes to enhancing project success rates. Effective PPM involves regular portfolio reviews, strict schedule adherence, and a readiness to allocate additional resources when necessary, resulting in more successful project outcomes (Unger et al., 2012). Furthermore, effective PPM helps mitigate counterproductive practices such as overburdening teams and thinly stretching financial resources across numerous projects, which can lead to poor quality and project failure. Instead, PPM advocates for a balanced distribution of resources, ensuring that each project receives the necessary support to thrive (Levine, 2005). Additionally, PPM aligns projects with the organisation's long-term goals. Organisations can direct their efforts towards achieving broader objectives by selecting and prioritising projects based on their strategic value (Archer & Ghasemzadeh, 1999). Thus, PPM offers numerous advantages for organisations seeking to optimise project outcomes and align them with overall strategic goals. Its application provides a comprehensive framework for addressing uncertainties, managing interdependencies, improving success rates, ensuring balanced resource allocation, and aligning projects with strategic objectives.

This paper utilises the Introduction, Methods, Results, and Discussion (IMRAD) framework to examine opportunities and assert reasoned directions for the effective use of gamification in construction management teaching and learning.

METHOD

This research employed a case study approach, utilising the MERIT Game online simulation within an elective subject, Construction Business Management, at Western Sydney University (WSU). The researchers utilised this simulation to collect and analyse data, including direct observations. The study collected data from the most recent two years of weekly competition results, as well as post-competition student reflection papers.

THE MERIT GAME STRUCTURE AND PROCESS

The MERIT game places each student as a board member for a publicly held and prime construction contractor employing direct labour. The simulation encompasses six specialised management areas.: a) Financial b) Overhead c) Estimating d) Bidding e) Personnel and f) Construction. Typically, teams are comprised of 4 students and self-regulate.

Three- to six-person groups are created at the start of the subject – some self-form, while unattached students are assigned. It is recommended that each student be assigned responsibility for two of the six areas – finance, overhead, estimating, bidding, personnel, and construction. This is an intended overlap to prompt members' decision-making and interaction. Each member is encouraged to add their perspectives in the decision-making process for unassigned areas.

From the first to the fourth week of the semester, the instructor narrates the purpose (the "why"), vocabulary, concepts, and preferred process for successfully engaging the game. The teaching intent is to encourage new approaches or, at minimum, iterative improvements to engage the game successfully.

A 20-question assessment is given to individual students. Afterwards, groups are expected to enter their decisions in a 2-week trialling period for students to familiarise themselves with the program. Each class period is spent with two to three groups entering their decisions into the program while sharing their screen with all attendees. Subsequently, an 8-period competition follows. Teams who earn at or above 2,000 points receive full marks, and those scoring less are given a prorated score. After the trialling period, another more detailed online quiz is given. It is equal to the first but demands more mastery for a passing mark. This serves indirectly as a self-check for student preparation before the competition starts.

The simulation starts in the fifth period after the previous board exits. This means the flow of work and follow-on outcomes are somewhat uncontrollable for the student groups. Previous decisions affect the current opportunities. This downstream ripple effect is realistic for the industry. For each period, an analysis of the results has to be conducted. This limits planning options and informs the students of the stubborn linkage between earlier decisions, current outcomes, and future possible actions. The previous board effect (and their decisions) shows one dimension of uncontrollable factors present in construction. In this way, projects can be viewed as income-expense flows and critical path management challenges.

A reflection paper is required from all student groups as their final assessment. Four areas of inquiry are expected to be answered:

1. Individual student's expectations
2. Previous Assessments' Value and Lessons Learnt Individually and as a Team
3. Strategies and Decision-Making in Each Period
4. Reflection and Conclusions
    a) What were the challenges of working individually and as a group?
    b) What skills did you and your group acquire or strengthen?
    c) What were your individual and group lessons learnt
    d) What are your group's suggestions for future participants?

There is an intended overlap of each query's content disclosure. The researchers have found that prompting answers in the template encourages expansive and complete reflection. So, a template is provided so teams will answer the core questions and ponder "what if" and lessons learnt.

THE MERIT GAME SCORING

The MERIT Game total scoring is multifactor. Based on ten metrics, groups decrease or increase their starting 1000 points after weekly decisions. See Figure 1. The emphasis is on a balanced approach to the construction of work. Construction PPM has little room to focus on a single or a few outcomes. In the opinion of the MERIT game creators, this will lead to a deterioration of the firm's viability. Additionally, the weighted approach of the outputs guides the boards of directors to be more sensitive to transcendent results, such as client satisfaction and less so, such as operating to turnover. Of course, financial stresses will show seminal importance as the subject company is restricted in tendering and bidding options.

Performance Indicators

Period	Total	Turnover	Gross Profit to Turnover	Operating Profit to Turnover	Company Value	Capital Employed	Contract Completion	Forward Workload	Forward Margin	Share Price	Client Satisfaction
4	1000	80	75	60	120	100	120	80	120	120	125

Figure 1. Assessment Report of Individual Components Showing the Starting Point Total

Construction contracting involves early collection and confirmation of information for each project built. Excellent pre-project planning is contingent on this (Stevens et al. 2023). Effective PPM requires capturing, analysing, and distilling project and organisational data into actions. There are over three dozen reports to view and digest. See Figure 2.

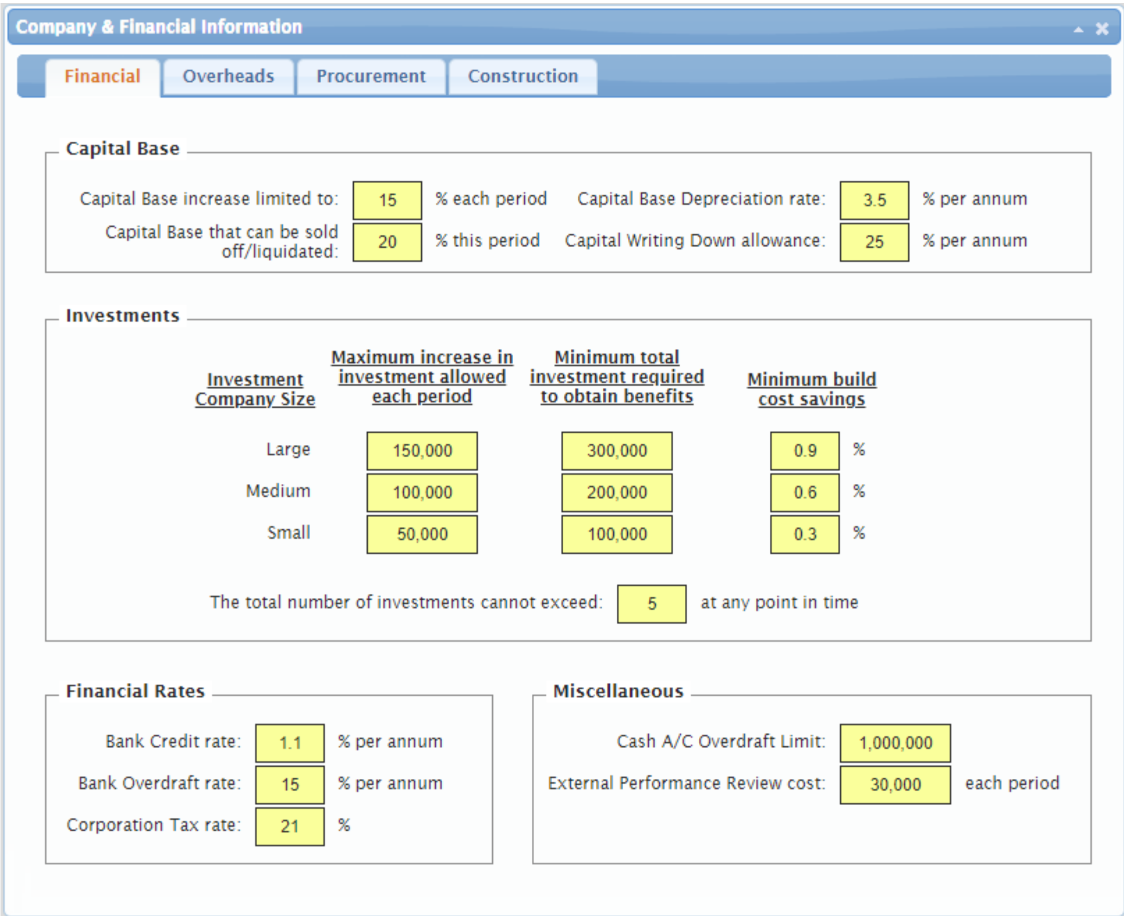

Figure 2. One Example of the More than Three Dozen Reports and Ratio Guidelines

Lean Construction Application

At the start of the semester, we propose that students capture key concepts and reorient their thinking by applying Lean Concepts to the dynamics of construction contracting PPM. Indeed, the basics will start the process of rethinking productivity in construction contracting. This change is relatively minor to the subject's content.

1. Lean Thinking versus Muda. One role of Lean leadership is teaching people how to see waste. Lean philosophy makes it a priority for stakeholders to suggest methods to convert waste into value.
    a. Type 1 Muda - Necessary but, non-value-creating practices, such as client meetings (where project results are physically evident and outstanding issues can be documented without interpersonal contact) or multiparty approval (practised in a bureaucracy).
    b. Type 2 Muda - Non-value creating and unnecessary, such as amenities (supports operations and does not directly produce work), and marketing activities (completed work done well is the best sales practice)
2. Value - Value creation can be defined as results sought by clients in which they will pay per an income schedule. Certainly, after several projects, those contractors that have consistently met safety, quality, cost and schedule demands can tender and win at a higher proposed price than the average competitor.
3. The Value Stream - In Value Streaming, many project tasks are interrelated and ordered, and when executed well, they positively affect safety, quality, cost, and schedule. Of course, clients may add environmental, economic, and social metrics to their requirements.
    a. Many steps will be found to create value unambiguously.
    b. Other steps will be found not to create value but are necessary due to current technology and production assets – Type 1 Muda
    c. On an average project, it has been found that several steps create no value and are immediately avoidable – Type 2 Muda

It is critical to explain to students that three tasks are involved in Value Streaming

- Problem-solving Task – taking information and designing an action involving a product.
- Information management Task – collection and confirmation of project facts distilled into planning through detailed scheduling to delivery.
- Transformation Task – product and labour to install the specified item on the job.

Identifying the entire value stream for each action/installation means a team understands and can improve. What is not understood cannot be improved.

4. Flow - Flow must be a priority focus by the team in construction. The demand of resources for the work available is synchronised (Single Piece Flow) Using "chaku chaku" or "load load," one worker or manager takes a task from the information gathering stage to completion as practicable—the opposite of batch and queue.
5. Pull - a formalised trigger of work ready to install determines the short-term allocation of resources for a specific task – in construction, it may be a building floor or infrastructure area.
6. Perfection - The improvement journey is inefficient and frustrating if you find "just good enough" rather than perfection. The constant striving to reach a process error and defect-free state motivates employees steadily and specifically.

Table 1: Proposed Conversion of the MERIT Game Vocabulary and Concepts to Align with Lean Construction

MERIT Game Concept	Explanation	Lean Construction Concept
Hiring and Layoffs of Managers and Workers Increase Costs.	Forecast resource demand for the current and future demand across the portfolio of projects to increase utilisation and lessen waste and resulting crises. This includes co-locating cells of production. In construction contracting, equipment shops next to tendering and PM departments cause people to communicate face-to-face, which lessens conflict and increases social and business interaction.	"Heijunka" or Levelled Workload
Governing Structure – Executive Structure Allocates Resources Among Projects	This is a critical component of portfolio management, a strategic planning tool that requires executive management to select three to five objectives – all others are deselected (Juran 1995).	"Hoshin Kanri" or Executive Level Resource Allocation
Redundant Systems and Double-Checking Keep Errors Minimised	Mistake-proofing and Trouble-blocking methods limit or eliminate potential rework and crises. (Tommelain 2008). A customised spreadsheet is recommended for students to minimise math and calculator mistakes. See Figure 3.	"Poka-yoke" ("Baka Yoke") or mistake-proofing
Construction Decision-Making	Construction Contractor must set the production rate (cycle time) to exceed customer demand due to the industry's many uncontrollable factors causing unforeseen delays. It is a core principle of LC. Meeting Takt Time assures that the project fulfils all functional requirements within the set time, positively influencing cost and quality. It must be planned and verified by a structured process, managerially driven from the tender stage and pre-mobilization planning to practical completion	"Takt Time" or Customer Required Delivery Time
Supporting Spreadsheet	The pre-programmed spreadsheet represents a simple ITC application to assist teams with rapidly calculating critical numbers. This supplants a hand calculator approach and frees up more time for iterating improvement ideas.	LC's 8th principle, "Use only reliable, thoroughly tested technology that serves your people and process"
13 Class Sessions of Trialling and Competition	The instructor selects two student teams each class session during the last 12 weeks (each team is present watching and listening) Review the previous week's decisions and results Points out key insights and suggests ideas for improvement	Kaizen

At first, students may not appreciate the structure and decision-making process needed to succeed in the MERIT game. The game produces over three dozen metrics that indicate critical strategic and operational direction from the previous period. Many indicate a strengthening, static or weakening company position. Measures such as utilisation percentage, on-site cost per worker, and estimating confidence alert the teams of deficiency or perfect optimisation. This consistent reality that collecting and confirming a myriad of information items affects the next period's decision-making is a realistic pressure. See Figure 3.

Job #	Estimating Confidence	Current Total Site Cost	Current Per Person Site Cost	Overstaff Limit	Period 4 Labour Needed	Period 5 Labour Needed	Period 6 Labour Needed	Period 7 Labour Needed	Period 8 Labour Needed	Period 9 Labour Needed	Cost Based on Current Performance	Lay Off	Billing Projected	Cash Needed Next Period
3	Extremely High	657,138	10,268	45.00%	64	64					657,138		$3,587,908	$3,493,581
10	Extremely High	74,890	14,978	35.00%	5	9					134,802		$840,835	$456,896
12	Extremely High	175,034	17,503	25.00%	10	15					175,034		$1,590,390	$1,039,471
19	Extremely High	0	#DIV/0!	45.00%	0	42					#DIV/0!		#DIV/0!	$0
20	Extremely High	0	#DIV/0!	45.00%	0	81					#DIV/0!		#DIV/0!	$0

Figure 3. Spreadsheet Critical to Organising Inputs and Calculating Outputs

DISCUSSION

Trends in construction education point to emerging opportunities and threats. Employers appear to be starting to embrace skill-based hiring criteria. Students with general management degrees without an understanding of current issues may be losing their perceived value to contractors. The largest employers from several industries are signalling dissatisfaction with graduates.

PPM is a reality for construction contractors and their managing directors. Teaching this skill will often serve future corporate leaders and their project managers. Since most contractors, including specialist contractors, manage labour directly to complete projects, the scopes they agree on are a fraction of the total project size, so PMs manage multiple jobs.

Construction contracting is a VUCA business, i.e., volatile, uncertain, complex and ambiguous, a phrase and concept created by Bennis and Nanus (1986). There is a critical need to use a proven system to attain alignment of the many contractor functions. Lean Construction has proven to beneficially guide the dozens of decisions that need to be made that affect safety, quality, cost, and schedule. Said differently, there is more certainty and speed when all decisions dovetail efficiently. It is vital since poor decisions negatively impact follow-up tasks.

In construction contracting, factorials show us the complexity dimension from an increased number of projects, i.e., this leads to a disproportionately more significant number of possible combinations and, thus, risk event probabilities. Each project varies under the conditions it is built, such as client expectations, design uniqueness, material required, contract terms, and site conditions; therefore, it contains many new variables. Additionally, multiple projects have different work-in-process percentages, undocumented promises, dozens of interrelated tasks and differing specifications. This PPM challenge is significant. So, comparing two portfolios – a) four projects to b) eight projects, i.e., possible combinations are written as n! so,

a. 4! projects means that there are 24 interconnections, i.e. 1x2x3x4
b. 8! projects translate into 40,320 interconnections, i.e. 1x2x3x4x5x6x7x8

Projects demand shared resources such as craftworkers, project managers, site supervisors, cash, and equipment. However, people are the "wild card" in the construction business. Project managers and site supervisors are unique, and when they interact with others, the predictability of positive results decreases. So, if an executive can keep the variability in people (employees, clients, and stakeholders) less, the probability of risk events manifesting is lower. Contrast this to manufacturing; for example, if a company has produced 100,000 of a product, making one more is less costly and risky than creating the first one. No other industry is exposed to this factorial dynamic. Thus, error rates trend higher than others, meaning mistake-proofing has value in reducing rework and its disproportional cost.

Presently, Information and Communication Technology (ICT) is a default option for universities' education challenges. The MERIT game can be viewed as a mature educational product. It reflects LC's 8th principle, "Use only reliable, thoroughly tested technology that serves your people and process". It has been on the market for over 30 years and is based on a textbook in its seventh edition. Refreshing its content, structure, and process will extend its useful life. This paper suggests that the Lean Construction approach can be embedded as an electronic game to further construction management education.

For the continued relevance of construction management graduates, their programs should continue to evolve in content and delivery. The MERIT Game reflects the industry's realities, especially those subcontractors comprising ¾ of the industry and main contractors constructing smaller projects.

CONCLUSIONS

The Lean Enterprise approach to construction contracting is efficient for achieving high scores in the MERIT Game, thus a beginning competent understanding of PPM dynamics. Increasing project complexity and size continue to challenge constructors. Lean Construction is a proven answer.

The researchers envision changing labels and instructions for the present MERIT game to become a useful Lean Construction teaching tool for the Community. This would be a second product that the game creators should consider. It would involve less time and expense than a bespoke one. Lean thinking is a mainstream and valuable approach to raising value and eliminating waste.

Based on the researchers' career experience and observations, PPM is not consistently taught in universities' construction management curricula. This is a misalignment with industry realities. Many graduates will become project managers who lead more than one site at a time. A smaller percentage will become construction company owners. PPM mastery is the challenge. There is little reason for educators not to confront this reality. The good news is that a ready application exists to start from. Iterative improvement can be pursued quickly.

"Business as Usual" is not acceptable in construction education, given the significant project complexity and size increases. Educators must match this rising intensity. If not, contractors may be likely to discount the value of graduates and hire more under-21 recruits with good mental, emotional, and spiritual composition and train them in needed skills. Said differently, utilising new ways of educating while covering critical gaps should keep pace with industry demands.

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THE REPAIR-CO GAME: A ROADMAP TO DEMONSTRATE THE IMPORTANCE OF PROBLEM-SOLVING CAPABILITIES OF LEAN TOOLS

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ABSTRACT

Lean Construction facilitators use the Repair-Co Game to introduce new stakeholders to the need for Lean. The game heightens participant awareness of the futility of impulsive finger-pointing to individual workers when an existing management system may instead be principally responsible for a company's inability to reach its expressed goals. Although this current gaming approach has been shown to be effective, the authors of this paper observed that the Repair-Co Game can also be expanded to introduce players to the usefulness of Lean tools that can identify root causes and effective countermeasures. These tools include the Ishikawa Fishbone Diagram, Pareto Chart, 5 Whys Root Cause Analysis, Big Room Meetings, and Collective Kaizen, which are implemented during Big Room meetings. This expanded version of the Repair-Co Simulation has been tested with 35 graduate students at Texas A&M University, 45 students at CEPT University, and 33 members of the URC construction company. Despite the different locations of the test grounds and make-up of players, results from initial experimental sessions have been shown to be remarkably similar in some ways but also different in others, demonstrating the important nuances of an individual context. Qualitative feedback from participants demonstrate the potential of the game in helping participants solve problems at their root cause.

KEYWORDS

Lean Simulations, Repair-Co Game, Ishikawa Fishbone (Cause-and-Effect) Diagram, Pareto Chart, 5-Whys Root Cause Analysis, Continuous Improvement (PDCA).

INTRODUCTION

In contrast to manufacturing, the construction industry is widely recognized for its fragmentation, silo-ization of OAEC[5] (Owner, Architecture, Engineering, and Construction)

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[5] This paper uses the acronym OAEC to signify Owner – Architect – Engineer – Constructor, where the Owner is placed in the primary position to remind other stakeholders that fulfilling the Owner's conditions of satisfaction is paramount in Lean.

stakeholders and high levels of variability. Prabaharan and Shanmugapriya (2022) investigated barriers to adopting Lean in Indian construction industries. They discovered that one of the critical barriers to the implementation of Lean is the "perceived complexity of learning and implementing Lean concepts" (p. 11). Furthermore, similar findings can be found throughout the literature, indicating that a "lack of knowledge and understanding of Lean principles and the intricacy of Lean philosophy and terminology" persists as a potential hindrance to the incorporation of Lean practices within the construction industry (Demirkesen et al. 2019, p. 7-8).

Lean simulation games serve as highly reliable training tools to help professionals learn Lean concepts through hands-on experiences. Lean games help bridge the gap between a concept and its application (Bhatnagar and Devkar 2021). Lean simulation games serve a pivotal role in helping OAEC professionals to dispel misconceptions and enhance their understanding of Lean concepts (Rybkowski et al. 2021). Lean simulation games are regarded as an influential way to teach Lean concepts clearly and effectively (Hamzeh et al. 2017; Rybkowski et al. 2018). Over the past decade, there has been a steady rise in the adoption of Lean simulation games within the OAEC industry (Bhatnagar et al. 2022). As firms progress in their Lean initiatives, they can incorporate a training program with simulation games targeted to address specific Lean processes and tools. For Lean training workshops, especially those catering to working professionals, specific Lean simulation games must be designed and tested to ensure that they are effective in communicating desired objectives.

This research paper reports on results from implementing the Repair-Co Game in three different locations with different populations,[6] namely: (i) graduate students of construction engineering and management at CEPT University in Ahmedabad, India, (ii) graduate students of construction science at Texas A&M University in College Station, Texas, USA, and (iii) URC Construction[7] practitioners, including craftworkers, and licensed engineers and architects in Chennai, India. Because so much of Lean arguably reflects common sense, students may initially question the need for Lean principles at the beginning of a course on Lean. Therefore, it is helpful to share evidence of the poor performance of the OAEC sector, but also how Lean has been shown to help (McKinsey 2017). Prior to the rounds of play described in this paper, the Repair-Co Game had already been facilitated in its original incarnation in numerous settings and in various locations. However, results from the Repair-Co Game have not been published in peer-reviewed literature in either its (a) original or (b) extended versions, which offers additional lessons. The intent of this paper is to fill this gap.

LITERATURE REVIEW

PART I: THE GENESIS OF THE REPAIR-CO GAME

The Repair-Co Game is popularly used in the classroom and professional training programs to open the minds of students and professionals about the challenges the construction industry faces, and the need for a better approach such as Lean. This simulation game is relatively simple to administer in diverse settings thanks to limited physical demands. The authors of this paper have used the Repair-Co Game in the classroom setting for several years. The version played is based on a PowerPoint™ instructional guide prepared and openly shared by Alan Mossman (2020). In this guide, Mossman credits John Seddon, Vanguard Consulting, UK, for inspiring the game (Seddon n.d.). The authors of this paper searched for the roots of this game and discovered that the stated mission of the consulting firm echoes the spirit of the Repair-Co Game. The website title, "Bursting bureaucracy in home repairs," provided contextual

[6] Readers may wish to contact the authors of this paper to learn specifics about facilitation of Repair-Co in multiple settings.
[7] URC Construction is a general contractor headquartered in Erode, India, specializing in infrastructure construction with approximately 2,000 employees.

information about the Repair-Co Game. A 20-minute podcast by Seddon (2020) was transcribed by the authors to understand the genesis of the Repair-Co Game. In his podcast, John Seddon argues that "95% of the influences on performance are in the system, and only 5% are due to the people who actually serve customers" (Seddon 2020). This is the fundamental message conveyed by the Repair-Co Game. To illustrate his point, Seddon used the example of a repair person who is called to fix washing machines. He chose repair companies as examples of service organizations because most people can readily relate to them (Seddon 2020).

Mossman developed the Repair-Co Game from Seddon's exercise. The game starts with a narrative about a Repair-Company's call centre that receives service requests from customers. The call centre personnel notifies a repairperson who is then dispatched throughout a specified geographic area according to logistics established by the call centre. The repairperson travels the route dictated by the logistics map. The repairperson's sequence of daily activities is informed by individuals such as the call centre receptionist, logistics personnel, and a manager. Mossman's graphics support Seddon's vision that helps players focus on the facts of the narrative (Figure 1).

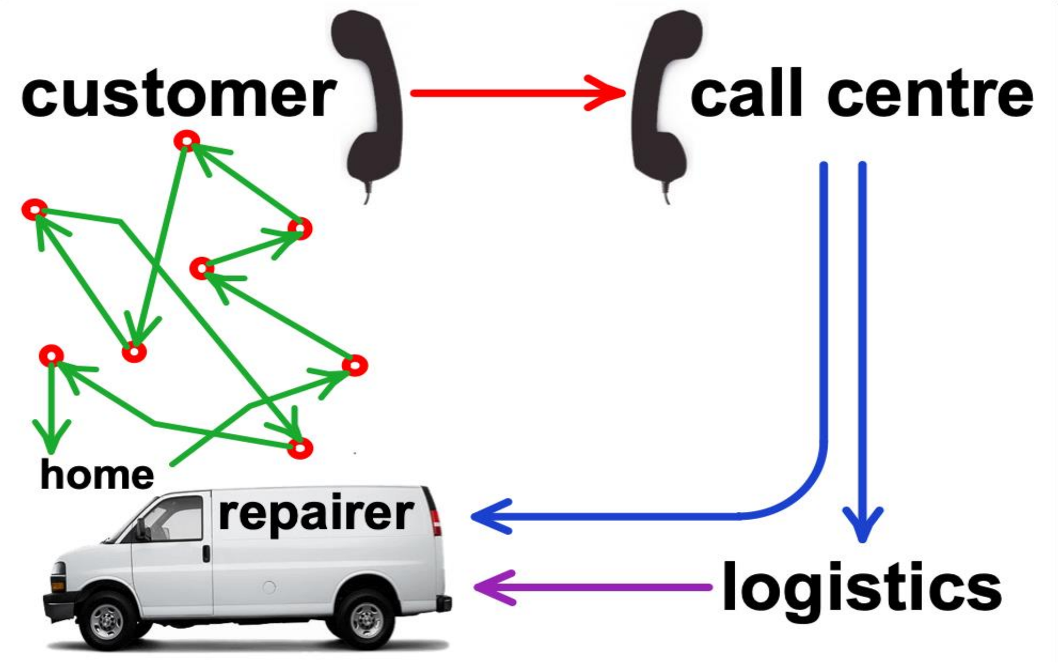

Figure 1: Repair-Co Game setup.
Graphic reprinted from Mossman (2020), with permission.

Once a facilitator describes the scenario, participants are shown the diagram in Figure 2 and asked the following questions: According to the manager's weekly schedule, how many daily repair visits are expected during a typical workweek? (e.g. 8). How many visits, on average, are actually made each day during a typical week? (e.g. 5.5). Once participants openly respond to these two questions, they are invited to individually, and then collectively in a group, brainstorm possible reasons the repairperson's schedule varies. The facilitator projects an Excel spreadsheet onto a wall for all to see; a hand-drawn table on a whiteboard or flip chart also works. In the left-hand column, the facilitator lists each brainstormed response separately. While the group is asked to collectively share at least ten possible reasons for the variability, a large and/or highly engaged group may generate quite a few more. With brainstorming complete, the facilitator writes "repairperson" in the heading of the column to the immediate right of the potential "reasons" column and "system" atop the farthest right-hand column. The facilitator then directs participant attention to the table and then asks: "What is the main cause of the variation? Is it primarily the fault of the repairperson or the system?" After moving down the list and marking participant responses, the facilitator then asks: "Yet where is the blame often placed?" While some variation is arguably due to the person or both the person and the system, most reasons for varied performance are discovered to be outside the control of the repairperson and are instead due to a fault of the system. In the Seddon version of the Repair-Co Game, the game stops here. The original intent is to give participants an "aha" realization that it is often not the individual alone who is the main culprit. In other words, the game convincingly demonstrates that it is often the *system* that first and foremost needs to be fixed with the help of those performing the work.

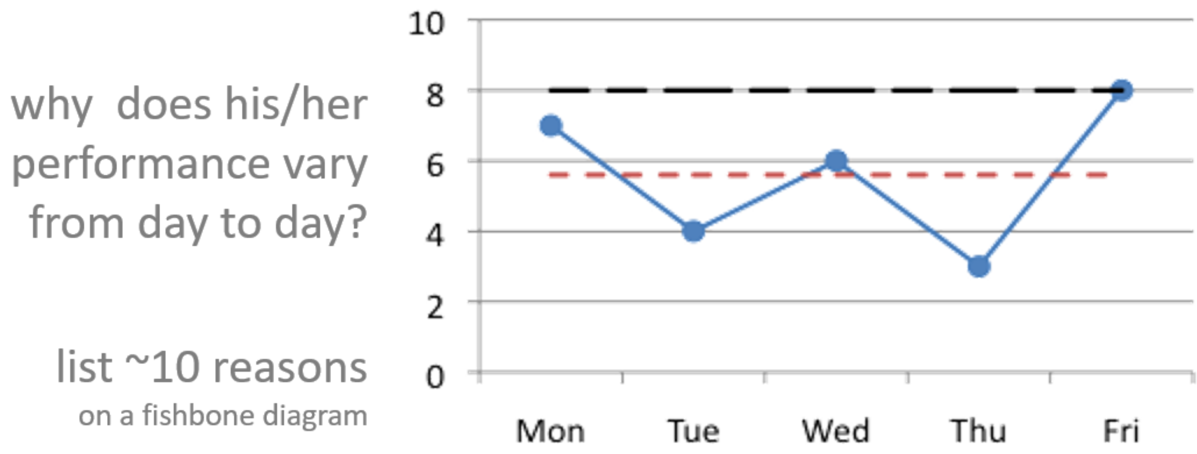

Figure 2: Performance characteristics of the repair person during a typical workweek. The graphic is reprinted from Mossman (2020) with permission.

Individuals can be myopic. One takeaway of the Repair-Co Game is that collective brainstorming during a Big Room meeting can help a manager identify numerous potential causes of a challenging problem s/he may not have considered when contemplating the problem alone. Brainstorming with others within an organization often helps ideas emerge that might otherwise be overlooked.

PART II. EXTENDING REPAIR-CO: THE POTENCY OF THREE LEAN TOOLS

The original intent of playing the Repair-Co Game has been to heighten participant awareness of the need for Lean to fix an organization's system with the help of the people in the organization. While the game continues to serve effectively in this capacity, it can further be used as an illustration to show how three additional Lean tools can be used to solve an organization's challenges. These three tools are the Ishikawa Fish Bone (cause and effect) diagram, the Pareto Chart, and the Five-Whys Root Cause Analysis.

Following Part I, which helps participants to appreciate the system as a key area of improvement rather than primarily blaming the repairperson, the facilitator invites participants to consider two different contexts: a large city and a small town. Participants are then provided with a blank template of Ishikawa Fish Bone diagram showing different "bones," that can be used to organize various causes under six categories: measurement, manpower, environment, machines, methods, and materials. The participants are then asked to insert the "reasons for varied performance" they had previously brainstormed into the Ishikawa Fish Bone diagram. One advantage of the fishbone structure is that the categories can help prompt participants to identify causes they may not have previously considered. For example, under "measurement," did the group give thought to the possibility that the repair person's daily performance may not have been accurately measured and recorded? The Ishikawa Diagram reminds us to consider this, as one of the six categorical "bones" of the "fish." To help identify additional causes, the facilitator can also invite participants to assume different roles such as customer, call centre personnel, repairperson, manager, etc. (Bono n.d.).

In reality, not all potential reasons shown in the fishbone diagram are equally responsible for a problem. Typically, a small proportion of causes (i.e. 20%) create the lion's share (80%) of a problem/effect. The identified causes by the participants are entered into a spreadsheet, and the participants are asked to consider the likelihood of the occurrence of each of these causes. The participants are asked to raise their hands if they feel a possible cause can occur in the context of a specific large city—and subsequently—a small town. The raised hands are counted by the facilitator, and this number is entered into the spreadsheet. This process is repeated for each brainstormed reason. This tabulated information is then graphed in the spreadsheet and depicted as a Pareto Chart (i.e., the frequency of reasons is sequenced from left to right, from largest to smallest). As this process of seeking inputs is conducted for both big cities and small towns, two Pareto Charts should be separately generated by the end of this exercise. The ranked histogram format of a Pareto Chart helps viewers readily identify primary culprits (i.e. reasons for performance variability) and focus on a countermeasure to resolve the primary cause(s) first.

The final step is to subject the primary cause(s) identified on the Pareto Chart to a Five-Whys Root Cause Analysis (Liker 2004). The Five-Whys process aims to systematically drill down to identify the ultimate root cause of a problem to ensure that a selected countermeasure will solve the problem permanently. In Five-Whys, a manager sequentially asks, "Why?" a problem has occurred until s/he reaches the last actionable cause. In the Five Whys table of *The Toyota Way* (Liker 2004), the investigator begins with the puddle of oil on the shop floor and asks why it occurred. If one simply wipes up the puddle, the problem will reoccur. However, by repeatedly asking "Why?" the manager discovers the leak is due to a gasket made of inferior material. Why? The purchasing agent is evaluated on short-term cost savings. Once the last actionable cause is identified, the problem can permanently be resolved at its underlying root by applying a countermeasure to change the evaluation policy for purchasing agents. In a similar manner, when participants start their journey to investigate the root cause and develop a countermeasure, they experience, again with greater clarity, that it is typically a "system" that is at fault for the poor performance of the repairman. The process also helps to appreciate one of the key principles of the Toyota Production System (TPS), which is to make decisions slowly by consensus because time taken during collaborative decision-making enables fast, efficient, and often error-free implementation. While conducting the 5 Whys Analysis, participants are urged to avoid arriving at immediate conclusions. Instead, they are invited to delve more deeply into the brainstorming process to identify with fellow participants the final actionable root cause and to suggest a viable countermeasure.

These three simple tools, the Ishikawa Fish Bone Diagram, the Pareto Chart, and the 5-Whys Root Cause Analysis—when implemented during a Big Room Meeting—help Lean managers engage in the plan-do-check-act (PDCA) cycle of continuous improvement where countermeasures to root causes are used to permanently resolve a problem at its core. Using PDCA, the effects of the change are measured, and if successful, the change is standardized. This is the stairstep of continuous improvement (Figure 3). The extended version of the Repair-Co Game also highlights to the managers that during their journey of continuous process improvement, it is important to judiciously select and apply relevant Lean tools during the process of building consensus. For instance, there is a sound rationale for applying the earlier-mentioned Lean tools in a specific sequence.

REPAIR-CO: FIRST RUN STUDIES OF THE THREE LEAN TOOLS

To test the progressive application of the three tools mentioned above in our first-run studies, the authors played the Repair-Co Game with three different audiences in three separate locations. The participants were asked to imagine the Repair-Co scenario in two different contexts: one in a large city with significant urban sprawl and the other in a small town. The purpose of introducing two locations was to help illustrate how problems and their solutions are context-dependent. In other words, the manager must systematically investigate causes for poor performance in a given context rather than arriving at unfounded conclusions and suggesting remedies as a "one size fits all" approach. The rationale behind the addition of these processes is to help students and professionals understand how Lean tools can be helpful for not only analyzing the causes of poor performance but also for suggesting routes to continuous improvement while collaboratively engaging the members of an organization. Images of these tools and processes are depicted in Figure 4.

RESEARCH METHODOLOGY

INDUSTRY WORKSHOP SETUP

Although there are slight variations in how the Repair-Co Game is facilitated, one example for each of the three settings will be presented and discussed for clarity.

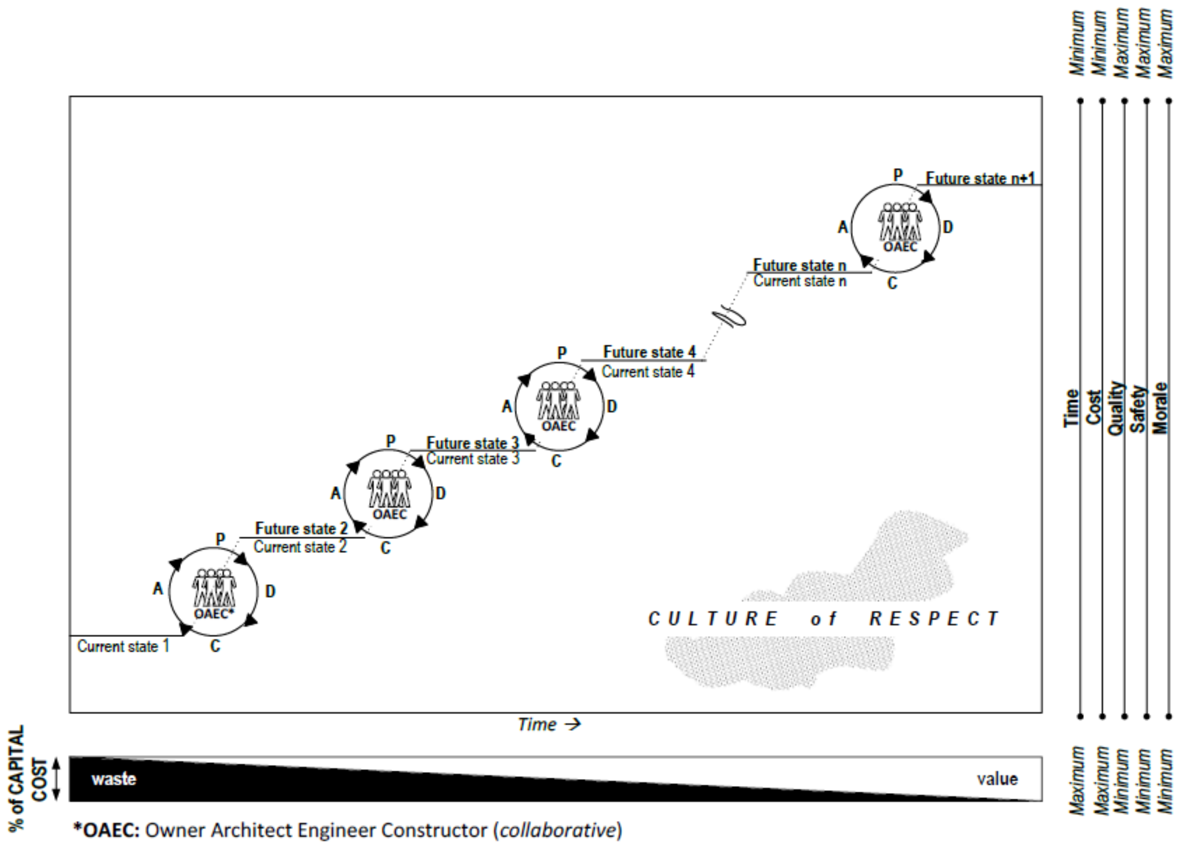

Figure 3: Lean's stairstep of Continuous Improvement (Rybkowski 2013).

The first research setting was a general contractor in India. This company began its Lean transformation journey in 2012 with the support of the Institute for Lean Construction Excellence (ILCE). The contractor had joined ILCE as a chartered member. The human resources department for this contracting organization went through extensive capacity upgrading sessions in the form of training programs and on-site guidance focusing on Lean concepts, principles, and tools. The sessions resulted in the implementation of Lean principles on several projects, with wide-scale adoption of the Last Planner® System of Production

Control (LPS), Value Stream Mapping (VSM), 5S, Work Sampling, and Big Room Meetings. The organization experienced impressive results with the application of Lean concepts and tools in the execution stage of its projects. In the recent past, the organization won prominent Engineering, Procurement, and Construction (EPC) projects, and there was a growing realization that it needed to align its design teams with the growing Lean ethos of the organization. The senior management became aware that Lean principles would reap fruits in a true sense most effectively when the seeds of Lean principles are sown in the early stages of a project's lifecycle, which was the design phase in this organization. The company's Research and Development (R&D) personnel were tasked with disseminating Lean principles and tools to the functional departments involved in the design process. The design departments included: Structural, Architectural, and MEPF. In addition to being applied to construction activities, Lean principles can and should be implemented throughout all phases of project delivery, including design, project accounting, etc. The R&D division crafted a roadmap to align with this goal. The first step involved a brainstorming session with functional heads of the design departments focusing on the identification of current design challenges. Based on these interactions, the organization reached out to CEPT University to help conduct research on the identified challenges and to guide the organization in ways to streamline its design processes. "Lean Champions" were identified from each design department (Architecture, Structural, and MEPF) to facilitate the dissemination and application of Lean principles and tools to their respective departments. The R&D Team conducted a one-day workshop with the theme of "Lean Design." Two authors of this paper served as facilitators and designed and conducted the workshop targeted to specifically assist the organization's design professionals. Because the event marked an important milestone for the organization, the facilitators carefully tailored the workshop agenda to align with the organization's expressed needs. The program was designed by interconnecting two components: Discussion about Lean principles in design processes and facilitation of Lean simulation games. The managing director was especially keen to engage young professionals in the company's design departments. The workshop was held during a weekend (Saturday) in a conference room that enabled participants to sit in groups around tables; the flexibility of the selected space was conducive to keeping participants engaged and focused.

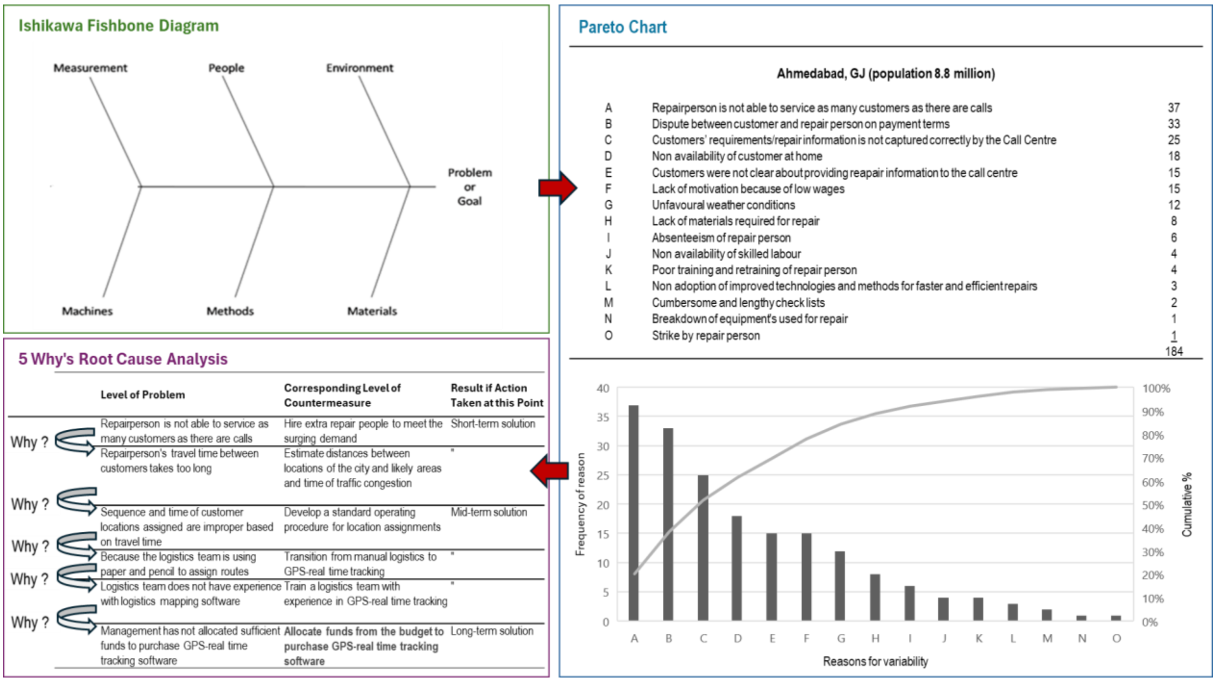

Figure 4: Sequencing of tool application runs clockwise, starting from upper left (in order: Ishikawa Fishbone Diagram, Pareto Chart, 5-Whys Root Cause Analysis table).

ACADEMIC INSTITUTES

In addition to Lean champions in practice and industry, Lean simulation games have been used worldwide by those in academia to impart knowledge of Lean principles to students. The academic settings described in this paper comprised two graduate-level courses focusing on Lean Construction: one in India and one in the US. The co-authors of this paper have been using Lean simulation games as an integral part of their teaching pedagogy in their courses on Lean Construction for a number of years.

FACILITATION OF THE REPAIR-CO-GAME

INDUSTRY WORKSHOP

On the day of the workshop, 33 design personnel in total came to participate. This number was encouraging given the hectic schedule of construction industry professionals. Included in these 33 participants were three (3) heads of each department, two (2) R&D team members, the Managing Director of the approximately 1500-member organization, and the Technical Secretary of ILCE.

The workshop was attended by professionals from multiple disciplines and departments: Architecture (3 No.), Structural (16 No.), MEPF (mechanical, electrical, plumbing, and fire protection) (11 No.), Research and Development (2 No.), and Human Resources (1 No.). The workshop began with self-introductions by participants and facilitators, followed by a playing of the Repair-Co Game in its extended version. The workshop facilitators identified two cities – one large and one small from the state where the headquarters of this organization was located. The purpose of choosing specific cities was to help the participants easily connect with the context. The steps described earlier about the Repair-Co Game in its extended version were followed, and the participants were requested to give their feedback digitally using a Plus-Delta form (Google Form®) at the end of the workshop (LCI 2024).

ACADEMIC INSTITUTES

Out of two academic settings for the facilitation of the extended Repair-Co Game, one consisted of 45 graduate students of the Construction Engineering and Management Program at CEPT University in India while the second involved 35 graduate students of a Construction Science program at Texas A&M University in the US. Before the facilitation of this simulation, the authors collected data on the demographic background of the students. In both settings, most of the students had previously experienced large and small cities. In the Indian University, approximately 20% of the students held an undergraduate qualification in Architecture while 80% of the students held an undergraduate qualification in Civil Engineering. Several had prior work experience as well. In the US-based university, approximately 95% of the graduate students had previously earned undergraduate degrees in Civil / Construction Engineering and had experienced both large and small cities. Facilitation steps described in an earlier section were followed. After finishing the facilitation of the Repair-Co simulation game, post-simulation discussions focused on lessons learned from playing the game.

RESULTS & DISCUSSION

The underlying common thread in the three settings where the Repair-Co Game was facilitated was the context of a large city versus a small town. In the case of the workshop facilitated for URC Construction Company, the large city was Chennai, Tamil Nadu State, India, and the small town was Coimbatore, located in Tamil Nadu State. The academic setting in India considered Ahmedabad and Morbi as large and small cities, respectively, located in the Gujarat State. Houston and College Station in the state of Texas were considered as large and small cities, respectively, for the academic setting in the US. These settings provided fertile grounds to compare and analyse potential causes of variability in the performance of the repairperson in different contexts. It was interesting to observe how game participants primarily attributed their brainstormed causes to the "management system" instead of the "repairperson" during the first phase of the game as was the intent of the original version of the Repair-Co Game. In the extended version of the Repair-Co Game, participants appeared to develop an understanding of the usefulness and interconnectedness of Lean tools as a means to analyse root causes and develop effective countermeasures to address underperformance. In the process of identification of potential reasons for poor performance, suggested causes in the context of a large city were identified, followed by suggested potential causes in a small town.

An analysis of reasons behind variable performance indicated a similarity in the identification of "traffic" as a likely primary cause for the repairperson's variable performance in large cities. After their identification of this potential cause, participants were shown a Google Map™ screenshot with traffic patterns during rush hour (i.e. 5:00 pm; Figure 5). These screenshots supported participant hunches that traffic may indeed represent a key inhibiting factor in large cities. It also strengthened the case that the causes identified by the game participants are not random, but informed by the participants' prior experience with large cities. The students also felt that with the advent of innovative technologies such as GPS and other forms of transport scheduling software, traffic challenges could potentially be addressed by generating more efficient routing of repair calls. Additional suggestions included making repair calls outside of rush hour or hiring and stationing additional repairpersons to service geographically defined zones of a city. "Traffic" did not appear in the list of potential causes for variable performance in small towns, likely because of the lower populations and more sparse distribution of occupants in these regions. The students were shown traffic maps of screen prints during rush hour in smaller towns, indicating significantly lower levels of congestion. The intent of sharing these maps was to impress upon participants the importance of not only generating a hunch but also of seeking evidence to validate the hunch before implementing a countermeasure to resolve the suspected problem.

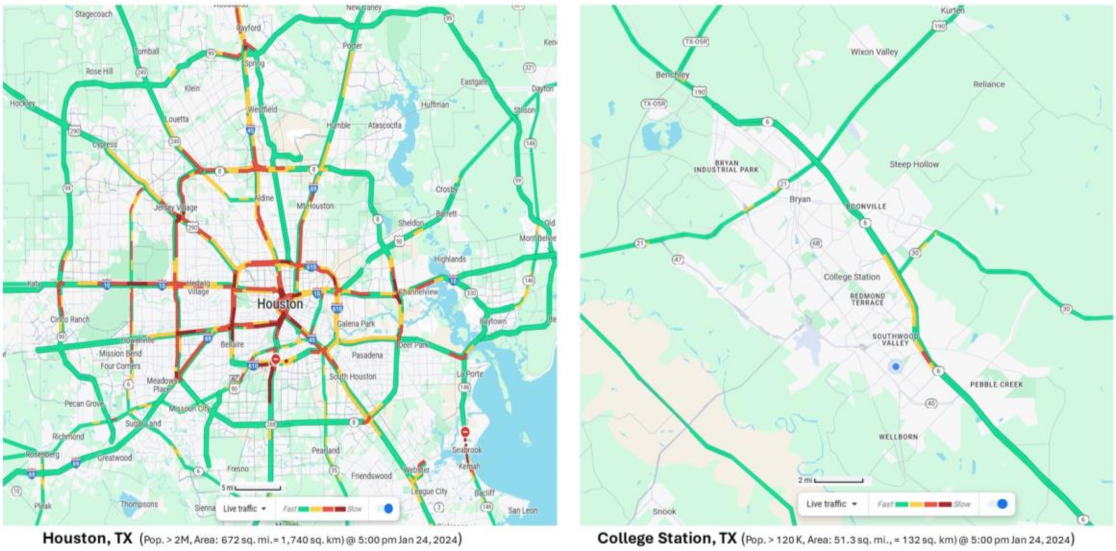

Figure 5: Traffic Pattern in Houston (left) and College Station (right) shown to participants during a trial playing of the Repair-Co Game in the US. Screenshots were taken from Google Maps™ at 5:00 pm in both locations.

For the three smaller cities, "insufficient customer demand" and "non-availability of skilled manpower" for repair work emerged as prominent proposed causes in all three test settings.

These outcomes indicated a commonality in the thought process among the game participants across three different settings. The purpose of presenting the context of two cities, both large and small, within the extended Repair-Co Game, was to impress upon participants that the context surrounding an activity plays an influencing role. Therefore, managers should make systematic efforts to decipher a context and identify “causes” behind poor performance within that given context. In other words, there is no “one size fits all” when seeking solutions to a problem. After all, implementing a countermeasure to post employees in different locations throughout a region or servicing customers outside of rush hour makes sense for large cities where heavy traffic is a primary constraint. However, a different countermeasure for a company to add additional capabilities to their repertoire would make sense for a small town where there is limited need for washing machine repair. Finally, when a manager invites diverse and multiple members within an organization to brainstorm potential causes of a problem that needs to be resolved, the probability that primary causes will be identified increases—reinforcing the importance of implementing these tools during Big Room Meetings with those who do the work.

In both the original and extended versions of the Repair-Co simulation, game participants expressed appreciation that Lean principles not only offer opportunities for systematically analysing causes but also for arriving at potential solutions. During the game, participants embraced the collaborative spirit required to brainstorm potential causes. They also appeared to respond to the thoroughness provided by categorizing causes under different arms (Manpower, Machines, Methods, Measurement, Materials, and Environment) in the Ishikawa Diagram. As managers often have limited resources to improve a given problem context, there is a need to focus on resolving the primary causes for maximum benefit. Generating Pareto Charts for each of the two cities helped participants (and ultimately managers) prioritize their efforts on the most impactful causes. Finally, using a 5-Why analysis to identify a root cause ensures a problem does not recur once resolved.

During the conduct of these three workshops, the work facilitators keenly observed the interactions and behaviour of game participants. As the game participants were seated in groups, the workshop facilitators reached out to members surrounding each table and listened to the conversation of participants over the course of this game. It appeared that improvements occurred through a social process, facilitated by interactions and diverse perspectives. Additionally, their responses suggest that participants experienced a desired “aha” moment in terms of analysis of “system” vs “person,” as well as an understanding of the importance of prioritizing the “vital few” versus “trivial many” causes revealed by a Pareto Chart analysis. Importantly, participants experienced how Lean philosophy and principles have given rise to practical analysis and process improvements armed with Lean tools.

It should also be acknowledged that the Repair-Co game is typically facilitated within a larger context which can affect participant receptivity to specific ideas. For example, to motivate participation in these sessions, participants were often awarded plastic tokens that could be converted to book prizes or grades at the end of the workshop and academic courses, respectively. These sessions were considered effective based on “plus-delta” feedback from participants and students. However, one limitation of this research is that a separate rating for the Repair-Co Game was never asked of participants. Future research should be done to consider what works well and what could be improved, if anything, to the structure of the Repair-Co Game.

CONCLUSION

The Repair-Co Game appears to serve as a valuable tool for introducing stakeholders to the principles of Lean Construction. By highlighting the systemic nature of inefficiencies and the need for collective problem-solving, the game effectively demonstrates the usefulness of Lean methodologies. Moreover, its adaptability allows for expansion to incorporate additional Lean tools such as the Ishikawa Fishbone Diagram, Pareto Chart, and 5 Whys Root Cause Analysis, further enhancing participants' understanding of Lean concepts. Testing the extended version of the game across different locations and participant groups yielded consistent results, indicating its potential for widespread application. However, feedback from participants still suggests areas for improvement, including the need for clearer communication and the inclusion of more design-related examples. In general, the Repair-Co Game presents a promising avenue for promoting Lean practices within the construction industry, facilitating continuous improvement and problem-solving at its core. Finally, the extended version of the Repair-Co simulation further enhanced learning outcomes and helped to drive home a message about the need for a systematic approach to consistent improvement in organizational systems with the collaborative application of selected Lean tools.

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DESIGNING AN EFFECTIVE TRAINING PROGRAM FOR SYSTEMATIC LEAN CONSTRUCTION IMPLEMENTATION

Eder Martinez[1], Louis Pfister[2] and Luis F. Alarcón[3]

ABSTRACT

Training and education stand out as pivotal factors for the successful implementation of lean construction. Despite their critical role, current literature lacks comprehensive guidance on the development and implementation of lean training programs within the context of construction organizations. This paper aims to addresses this gap by presenting the case study of a multinational construction service provider developing and implementing a training program aimed at fostering a broader and sustainable integration of lean construction practices within the organization. The analysis includes the insights and perspectives of 95 trainees, gathered through an electronic survey. The results show a positive evaluation of different components of the program after 2 years of implementation. The case study emphasizes the significance of a collaborative approach to find an adequate balance of standardization and flexibility required to effectively deploy a unified training program across diverse local contexts and construction operations within the organization. The valuable insights derived from this case study serve as a resource for both researchers and practitioners, providing practical guidance for those looking to implement training programs. Furthermore, it supports in identifying best practices and potential pitfalls that warrant careful consideration in similar initiatives.

KEYWORDS

Lean construction, Training, Education program.

INTRODUCTION

Lean construction principles, derived from lean manufacturing and the Toyota Production System, have gained widespread recognition in the construction industry for their potential to enhance efficiency, reduce waste, and optimize project outcomes (Ballard, 2000; Koskela, 1992). Central to the successful implementation of lean practices is the imperative for adequate training programs tailored to the specific needs of construction professionals.

Despite the importance of training in achieving overall success in lean construction implementation, there is a lack of literature and documentation providing examples of training approaches aiming to sustainably support its adoption in corporate environments (Tsao et al., 2012). Notably, most of the literature refer to education in university setups with a lack of focus

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on how these concepts could be implemented in corporate environments (Alves et al., 2016; Rybkowski et al., 2018).

This paper aims to contribute to this area by presenting a case study of a structured approach to lean construction training program developed and implemented in a large European construction service provider. The authors describe the training program development and analyze the results up to date considering 2 years of effective implementation. The authors also build upon trainees' survey to include the perspective of participant in the case study.

RELATED LITERATURE

Lean construction aims to optimize project delivery by minimizing waste, improving collaboration, and enhancing value for all stakeholders involved. Achieving these objectives requires a paradigm shift in the organizational culture, requiring a workforce that is well-versed in lean principles and practices (Koskela et al., 2002).

Literature emphasizes that skilled professionals and workforce are essential for successful lean construction implementation (e.g., Aslam et al., 2020). Adequate lean construction trainings serve as a vehicle for skill acquisition, providing practitioners with the necessary knowledge to apply lean concepts, fostering a network of capable construction professionals able to execute lean practices at the different phases of the project lifecycle. The transformative impact of lean construction training has the potential to extend beyond individual skill development to encompass a positive organizational culture development. Scholars argue that lean implementation requires a cultural shift towards continuous improvement and collaboration (Ballard & Howell, 1998; Koskela et al., 2002). Therefore, training initiatives contribute to this cultural transformation by instilling a mindset of learning and adaptability, vital components for the sustained success of lean practices within an organization.

Several studies have identified the lack of adequate lean awareness and understanding as critical barriers in successful lean construction implementation (Sarhan & Fox, 2013). According to Watfa and Sawalha (2021), the successful implementation of lean construction requires a certain level of technical proficiency in the tools and techniques essential for its proper execution. In fact, the Lean Construction Journal has recently launched a special issue call for lean education devoted to consolidating best practices and simulations for enhancing lean education (Lean Construction Journal, 2023).

Researchers have dedicated significant attention to lean construction education, offering comprehensive guidelines for the development and implementation of training programs. For instance, Hirota and Formoso (1998) offered guidance in developing lean construction training programs. The authors highlight the ease with which trainees can grasp fundamental concepts like processes, operations, conversion, flow activities, and the overarching notion of waste. However, they also emphasize the challenge trainees face in fully comprehending and seamlessly integrating lean construction principles and approaches. Based on several years of experience, Tsao et al. (2012) provide different perspectives and lessons learned in lean training and education. The authors provide guidelines for developing adequate training that considers a good mix of learning modules, case studies, simulations, and field trips. Similarly, Pellicer and Ponz-Tienda (2014) outline the approach and outcomes of a lean construction course established at as part of a master program in civil engineering. The proposed approach covers key aspects of lean construction, including its historical evolution, value stream mapping, pull production, The Last Planner® system (LPS), standardization, optimization of construction operations, Building Information Modelling (BIM), and Integrated Project Delivery (IPD). The authors credit the course's success to its dynamic approach, which integrates lectures, exercises, classroom games, and a term project. In a similar direction, Nofera et al. (2015) provide detailed descriptions of a teaching approach for lean construction targeted at university students. The authors also offered feedback on the effectiveness of the approach and suggests potential areas for improvement. Only a few studies have addressed lean construction education in corporate environments. For instance, Alarcón et. al (2006) and Pavez and Alarcon (2008) report critical factors, barriers, and recommendations for the implementation of lean in construction organizations. The authors highlight that professionals' adequate social and technical competences are essential for efficient lean construction implementation.

Previous research in lean training and education provides valuable insights and guidance for the formulation of effective training programmes. However, a significant proportion of this literature focuses predominantly on the higher education environment (Tsao et al., 2012). Applying the results of these studies may become challenging when trying to use them directly in corporate settings, where professionals have diverse profiles. Furthermore, literature highlights the variability in the approaches adopted by construction industry companies in relation to lean construction training (Forbes et al., 2018). This variability is attributed to differences in organisational structures and strategic priorities. In particular, the translation of lean training programmes into corporate settings faces additional challenges, including resistance to change and the need to align training initiatives with the operational priorities of professionals tasked with project delivery. This paper aims to address this gap contributing to knowledge by presenting a practical case study of an organisation developing and implementing a training programme aimed at fostering lean construction skills among its professionals.

RESEARCH METHODOLOGY

This research uses case study approach. Case study is an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between the phenomenon and context are not clear (Yin, 2014). The authors use different sources of data to describe and analyze the case study. This includes observations, documents produced by people involved in the case study, and surveys. An online survey was conducted at the end of the study to collect feedback and perspectives from individuals who successfully completed the training program. The authors triangulate data from the different sources to build a comprehensive understanding of the case and derive the insights and conclusion of the study.

CASE STUDY

BACKGROUND

The case study involves the development and implementation of a lean construction training program in a multinational construction services provider based in Switzerland. In addition to its presence in Switzerland, the organization conducts active operations across various central European countries, including Germany, France, Austria, Norway, and Sweden.

The main challenges the organization aims to address are related to scalability of lean construction implementation and sustaining lean practices in the long term. Prior to implementing the program, the organization conducted a series of lean construction pilot projects where lean construction specialists acted as coaches, actively supporting the different project teams. Lean construction specialists were centrally recruited by the organization and strategically positioned to provide dedicated support to project teams. The organization soon realized 2 main challenges in this approach. The first relates to resource constraints to efficiently broaden lean implementation. Depending on project complexity, lean construction specialists could only manage a handful of projects simultaneously. Scaling up lean construction implementation to a wider number of projects in different locations would require hiring an important number of additional specialists. The second challenge relates to the transfer of knowledge from one project to another and the dissemination of learnings within the organization. In many cases, people involved in the pilot projects learned the application of a specific tool and method in a given context without having a broader understanding of the fundamentals and principles of lean construction. Furthermore, this project-based approach generated in many cases ad hoc implementation of different tools and methods defaulting the establishment of a certain level of standardization and systematization that supports leveraging learning across different projects.

Consequently, the organization opted for a transition from a project-centric strategy to a more "enabling approach." This involved the training and activation of a supplementary layer of lean construction champions, specifically targeting individuals in closer proximity to operations, such as project managers and site engineers. This strategic shift aimed to cultivate greater autonomy in lean construction implementation, reducing dependence on central designated lean construction specialists and promoting long-term scalability.

LEAN TRAINING PROGRAM DEVELOPMENT

The development of the lean training program involved 3 distinct phases: identification of requirements, development of the training program, and implementation.

Requirements

The program's organizational learning objectives aim to help trainees to gaining the knowledge, skills, and competencies required to implement lean construction independently and effectively. These overreaching objectives guided the creation of the training concept and materials, ensuring a consistent approach in teaching lean principles and methods. By standardizing the training, the organization seeks to improve efficiency and benefit from the shared expertise of participants.

Nevertheless, reaching this standardization posed some challenges considering the broad range of requirements. Along with operating in different countries (different cultures and languages), the organization also executes various types of complex infrastructure projects covering a large variety of construction services including roads, bridges, special foundations, and tunnels. Thereby, the first step in developing the program was to reach a level of understanding of the needs of local contexts and types of projects. For this purpose, the authors conducted semi-structured interviews and workshops with local stakeholders in different locations to capture requirements to steer the training program development. These included target audience, delivery approach (e.g., online, face to face), duration, as well as the relevant specific lean subjects, tools, and methods to be prioritized.

Program development

The overall structure of the program, as well as the content of the different training modules was developed collaboratively by all lean construction specialists involved in previous pilot projects. The content from pre-existing lean construction training modules within the organization was consolidated, enhanced, and supplemented with additional materials to fulfill the specified requirements. This was based on a structured plan to continually review and enhance the program's design and content using a Plan Do Check Act (PDCA) cycle.

Figure 1 depicts the overall program design consisting of 6 phases. The initial phase involves the nomination of employees for the training program. This involves selecting individuals from various business units, either through nominations or volunteering, in collaboration with management. This approach aims to ensure that the participants have the local support to invest time in the program and the personal willingness and commitment of different individuals to participate in the training. The second phase is onboarding and kickoff, where participants are introduced to the components of the program, including scheduling the different training sessions and workshops. In general, the program operates on a yearly basis, with local country units (e.g., Norway, Germany) defining their training schedules according to the local context. This aims to provide the flexibility to adjust the program according to the constraints and planning of the local organization.

Figure 1: Lean training program design

The third phase involves the delivery of different training modules. Except for the module "lean principles," the sequence in training delivery relies on local planning based on business and operational needs. For instance, country units focusing on tunneling construction may prioritize and focus on different modules than units building bridges. Thus, local lean specialists responsible for conducting the trainings are provided with significant flexibility in delivering and adapting module content to meet specific needs.

The next phase considers the execution of a "live case" on an individual basis. During the live case, trainees are tasked with identifying improvement opportunities and applying the knowledge gained from the training to tackle those challenges. In this way, along with the training they can experience the problem-solving approach experimenting with new tools and methods for continuous improvement. Live cases are documented based on the structure provided by the A3 report. Close to the end of the program, trainees in a country unit (or region) get together and present their cases in peer feedback sessions. This provides them with the opportunity to share and exchange their cases and lessons learned with peers, gather feedback, and improve their approach.

At the end of the program, trainees complete a standard proficiency test to receive an external certification. This provides them with the opportunity to obtain proof of their training completion and competences in lean. To finalize the program, all trainees gather for a one-day event/conference organized at the company's central office where they receive their official certificate. In this event, selected cases are presented in parallel sessions (in a conference mode), so trainees can also exchange and learn from cases developed by colleagues in other countries. The event also includes a field visit to partner organizations where they can see lean implementation in other contexts (e.g., manufacturing contexts or other projects). Different networking events are organized after program completion aiming to keep the community active, engaged, and exchanging ideas about continuous improvement.

PROGRAM RESULTS

The results of the program presented in this section correspond to an online survey distributed to trainees at the end of the program. The purpose of this survey is twofold. First, to ensure quality in the delivery of the different modules, as well as to understand the value it delivers to participants in performing their work. Second, identify opportunities for improvement in different areas of the program (e.g., content, timing, organization, etc.). The survey considers a comprehensive analysis of 95 responses, including 38 inputs from the initial program implementation in 2022 and 57 from the subsequent training cohort in 2023.

In Figure 2, participants were initially asked about the overall rating for the training program and how likely they would recommend it to their colleagues. On average, participants rate the program with a 4.3 score (1 – very poor, and 5 – excellent). Similarly, the average score for recommending the program to a colleague is 4.4 (Figure 2).

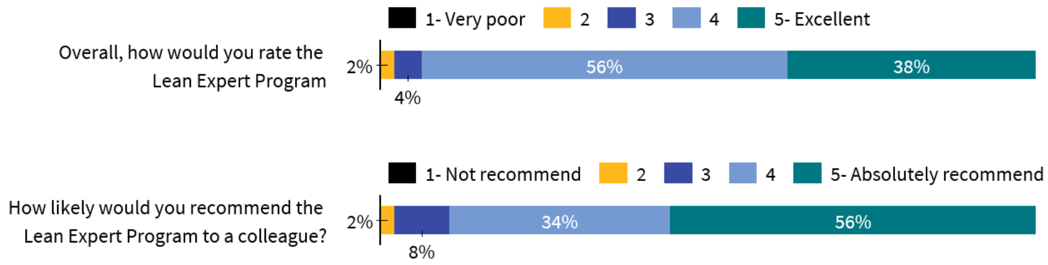

Figure 2: Overall lean training program evaluation

Following a similar approach, Figure 3 summarizes feedback from different aspects of the program. Overall, the program received positive evaluations in all dimensions, especially regarding the knowledge and capabilities of the trainer, as well as the interactive approach to deliver the content.

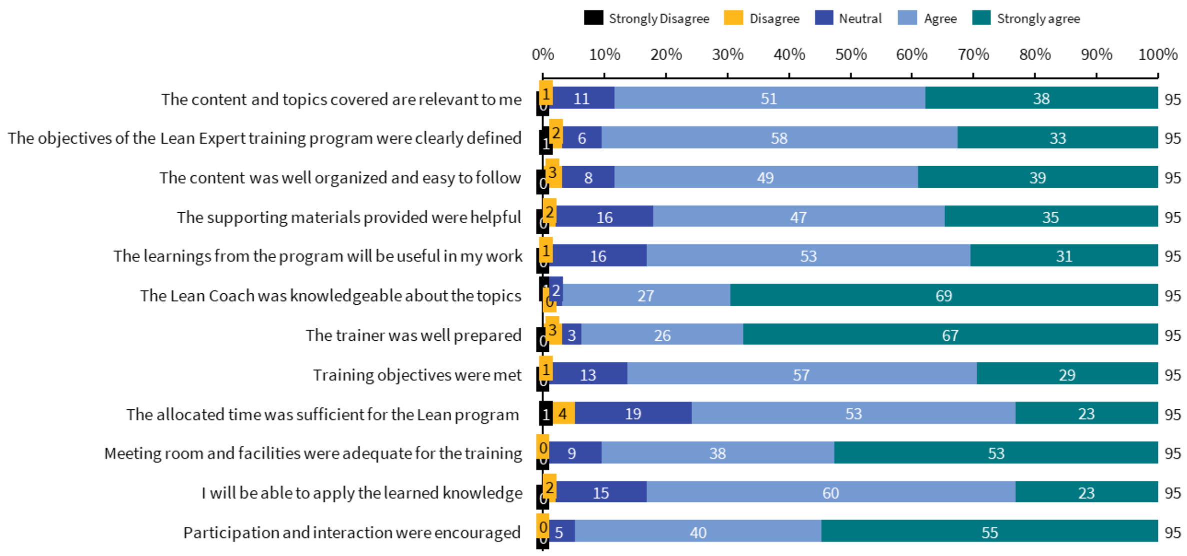

Figure 3: Training program evaluation

Following the plus and delta approach, survey participants were asked to offer written insights regarding the program's strengths and areas for improvement. On the positive side, numerous responses underscored the value of exchanging ideas and experiences with colleagues from diverse business divisions during various training sessions and the program's closing event. Another highlighted aspect is the hands-on approach to training, incorporating real-case implementations and simulations to illustrate the practical application of lean principles. While this aspect received positive evaluations, participants expressed a strong desire for even more hands-on involvement and real-life examples to demonstrate the significance of these principles in their daily work. For instance, some inputs indicate that certain sessions were "still too theoretical and not applicable 1 to 1 to construction operations." Other inputs indicate that "sometimes it was hard to transfer all of the examples to actual situations on site." Further opportunities for improvement relate to the time availability for people to undertake the program and the challenge to balance this with their daily operations. This aligns with the dimension “the allocated time was sufficient for the lean program” in Figure 3 which received the highest “disagree” and “neutral” inputs. Some people indicate that the time required for the program was “difficult to combine during an ongoing project.” Others indicate having “'…little time parallel to work.”

DISCUSSION

The authors build the discussion section triangulating learnings and results of the case study organizing them into 2 main areas: program development and implementation (including survey results).

PROGRAM DEVELOPMENT

Internal vs external training

At the beginning of the process the authors were confronted with the discussion of developing an internal vs external training program. In-house training utilizes internal resources, tailoring content to organizational needs, while external training, leverages external industry experts and practices (e.g., Abhishek et al., 2018). The organization already explored external trainings with dissimilar results. Most of the feedback for this was the lack of practical examples to assimilate the concept and a limited range of practical tools provided in these trainings. For instance, most examples were related to high rise building construction using takt planning but not too related to complex infrastructure (e.g., road, tunnel construction). Furthermore, organizing a training in different countries and languages proved to be complicated with an external provider/consultant, thus the decision was made to develop an in-house training. This approach required significant investment at the beginning of the process. The experience shows that a tailored approach for the organization pays off contributing to increased buy-in from participants. Another positive aspect of an internal training is the flexibility to continuously improve the program based on real case examples and learnings from operations (e.g., incorporating live cases as best practices).

Standardization versus flexibility

The program balances both standardization and flexibility by incorporating in the design modules which can be organized and delivered in the training according to the local operational context of a regional/country unit. The delivery of foundational modules related to lean construction principles and basics is mandatory for all units, while certain method/tool-oriented sessions are emphasized according to the local context. For instance, a region working with different subcontractors and difficult interfaces may emphasize coordination via LPS, while other units working on tunneling projects place more emphasis on Value Stream Mapping to support adequate material flows in critical supply chains. Accommodating the needs of different countries and operations required an intense collaborative development process gathering requirements and building consensus among the lean construction specialists (trainers) to design the training program.

IMPLEMENTATION

Building a strong network and the “multiplier” effect

Along with providing trainees with skills to implement lean construction more independently, the program allows the creation of an additional network of people capable and willing to experiment with new methodologies for continuous improvement. This additional network creates a “multiplier” effect supporting the scalability and transfer of good practices from one project to another. Although not the case for all trainees, the experience shows that in many cases trainees started implementing their learnings (e.g., a lean tool or method) in new projects with little, or no support from a designated lean construction specialist. This is a positive effect that was originally one of the goals of the program. The experience also demonstrates that, in order to keep this network active, it is very important to consider the organization of regular exchanges where trainees can keep exchanging ideas and knowledge.

Quality of live cases

A critical component of the training program is the live case, where trainees can identify opportunities for improvement and put in practice learnings in a structured approach to problem solving documented in an A3. This allows the identification and consolidation of various ideas and approaches to problem solving realized by trainees. However, there is a considerable variation in the quality of the cases in terms of both approach and content. While some live cases are executed exceptionally well, others merely meet the minimum requirements to pass the program. Our experience indicates that the issue lies not so much on the quality of the training but rather on the time availability of participants to invest in their live cases and the accessibility of local trainers to provide support and coaching. Working on the live case demands time and dedication, often underestimated by participants. Therefore, it is advised to recommend trainees to start with the problem formulation of their live case right at the beginning the program and to introduce the basic problem-solving processes as early as possible. As per our experience, participants tend to postpone the live case till the end of the program, prioritizing daily business/operations. This also matches the “time allocation” feedback collected in the survey. Another option could involve facilitating pair or group live cases to encourage collaboration and teamwork in the problem-solving approach simultaneously.

Participants dropping out

While the trainee nomination phase involves aligning with local management and conducting personal discussions to assess both management support and individuals' interest in the training, the program still encounters instances of participants dropping out. Our experience shows that this has something to do with priorities defined by participants. When they have urgent matters to solve at the project level, they prioritize this over the program. When a participant has missed too many sessions, they are asked to leave the program, or alternatively to resume the following year. The time factor and balancing program participation versus daily business activities again plays an important role. The attendance rate for trainings is best when training dates are defined collaboratively involving trainees at the beginning of the program.

Practice-oriented sessions

One of the most important aspects highlighted by the trainees is the inclusion of hands-on sessions and real-life implementation cases. Most of the modules include different types of simulations to support the learning experience. Similarly, the collective and bottom-up approach allowed the identification and centralization of good practices which are shared in the different training modules. The inclusion of these internal success stories demonstrates to trainees the applicability of lean in real context, while at the same time serving as inspiration of good practices to be implemented in projects. These current state best practices, templates and supporting materials to implement are consolidated and shared company-wide via an internal SharePoint “toolbox” website. As highlighted in the survey, trainees express a desire for more real-life cases. In response, the third round of the program incorporates the involvement of past trainees as guest speakers in various modules. These former trainees share insights into their experiences and the practical implementation of lean methodologies in their projects. Incorporating colleagues or peers into discussions on lean implementation not only cultivates participant buy-in, as they observe firsthand how their peers apply lean principles in real-world scenarios, but also enriches the sessions by addressing the challenges encountered during the implementation of specific methodologies in projects.

LIMITATIONS AND FUTURE WORK

The findings of this study should be considered within the following limitations. In particular, the case study considers the specific context of a single organization. While recognizing the potential challenges associated with directly extrapolating the findings to other contexts, the authors assert that the empirical insights gained from this study offer valuable perspectives. These insights are relevant to researchers and practitioners involved in the design and delivery of lean training programs and contribute to a broader understanding of effective practices in similar efforts.

In terms of future work, a post-training survey 12+ months after completing the program would provide insights into whether the training has been integrated into daily operations and sustained. This is something that the authors envision to implement in the next years.

CONCLUSIONS

This paper presents an innovative training program to scale up and support a sustainable implementation of lean construction in a multinational construction service provider. The positive evaluation of the program's various components is based on feedback from 95 trainees who have undergone the program over the 2 years since its effective implementation.

In terms of development, the collaborative and bottom-up approach to training development facilitated the creation of a program that effectively balances the need for standardization and flexibility. This approach ensures the implementation of a training program that leverages internal knowledge while meeting the diverse requirements of an international organization operating in differing geographies and construction-operation contexts. Insights gained through the implementation process highlight the importance of integrating real-life case studies and hands-on sessions into the training methods, fostering a more effective assimilation of various lean concepts. The delicate equilibrium between daily operational demands and the time commitment necessary for program participation also emerges as a pivotal consideration, as it significantly impacts the quality of participant engagement and involvement in the program.

The insights presented in this case study act as a valuable resource for researchers and practitioners alike, offering practical guidance for those aiming to execute training programs. Additionally, it assists in recognizing optimal approaches and potential challenges that require thoughtful consideration in similar initiatives.

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