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INVESTIGATING AND SIMULATING COLLABORATION AMONG THE LPS PHASES

Elyar Pourrahimian[1], Lynn Shehab[2], and Farook Hamzeh[3]

ABSTRACT

Although heavily studied, collaboration in construction is still perceived as an elusive or intangible aspect because of its complex nature. Its complexity roots in the unfeasibility of quantifying it or its impacts on the performance of a construction project. While some studies acknowledged the need to evaluate or assess collaboration, empirical and numerical methods that pertain to direct quantification of either collaboration or the impacts of collaboration on the performance of a project are still unaddressed. This paper aims to address this gap from a Lean perspective by investigating the effects of collaboration throughout the different phases of the Last Planner System. After a thorough analysis of the collaborative points occurring in each phase, computer simulation is employed to model the progression of a construction project from pull planning to lookahead planning and finally to execution while also modelling collaboration among the project members. Findings on how collaboration during each phase impacts the project performance differently are presented. This study's contribution lies in highlighting the importance of early collaboration in construction projects and emphasizing the need for accurate quantification of such qualitative aspects.

KEYWORDS

Collaboration, Last Planner® System, agent-based modelling, and simulation.

INTRODUCTION

Construction projects are often described as unique and complex due to their ever-changing methods, distinctive objectives, and uncontrollable factors (Howell 1999). Among these are labor factors such as supervision, incentive schemes, leadership skills, overtime, and worker interactions (Jarkas and Bitar 2014). Interaction in construction includes collaboration and cooperation, which (Schöttle et al. 2014) attempted to distinguish between. Their study described collaboration as "an inter-organizational relationship with a common vision." In contrast, cooperation was described as "an inter-organizational relationship among participants of a project, which are not commonly related by vision or mission". This paper will address collaboration, where project participants collectively strive to successfully complete the project.

One of the significant enablers of collaboration is Lean construction, along with its tools and techniques. The Last Planner® System (LPS) is one Lean tool (Ballard 2000) that not only fosters but also entails collaboration as a vital component for the success of its implementation. Developed to improve workflow and increase reliability in construction planning, the LPS is a production control system widely used in construction projects (Ballard 2000; Ballard and

[1] Ph.D. Candidate, Hole School of Construction Engineering, University of Alberta, Edmonton, Canada, elyar@ualberta.ca, orcid.org/0000-0003-0035-2324

[2] Ph.D. Student, Hole School of Construction Engineering, University of Alberta, Edmonton, Canada, lshehab@ualberta.ca, orcid.org/0000-0002-2708-3550

[3] Associate Professor, Hole School of Construction Engineering, University of Alberta, Edmonton, Canada, hamzeh@ualberta.ca, orcid.org/0000-0002-3986-9534

Howell 2003). It may be described as a mechanism for transforming work that "should" be done into work that "can" be done, then into work that was actually "done" (El Samad et al. 2017). LPS includes four main planning phases: (1) Master Scheduling, (2) Pull Planning, (3) Lookahead Planning, and (4) Weekly Work Planning (WWP).

While collaboration in construction generally and the LPS specifically has been frequently promoted, attempts in quantifying it have been limited to identifying its influencing factors through surveys and questionnaires. However, the direct quantification of either collaboration or the impacts of collaboration on project performance is still unaddressed. Therefore, this paper aims to highlight (1) the importance of investigating and accurately quantifying the impacts of collaboration on construction projects, (2) the change in the impacts of collaboration when occurring during the different LPS phases, and (3) the importance of early collaboration in construction projects. To achieve these objectives, a discussion over how collaborative points manifest in the different LPS phases is carried out, followed by agent-based modelling and simulation of the project members and tasks during the progression of a construction project from pull planning to lookahead planning and finally to execution. In the simulation model, collaboration among the project members throughout the different phases is also modelled and manipulated to study its impacts on performance. Finally, an analysis and discussion of the results are presented, and conclusions and future recommendations are suggested.

RESEARCH METHODOLOGY

A simulation-based research (SBR) approach is adopted to achieve the mentioned objectives. SBR may be divided into two methodologies: (1) research on the efficacy of simulation as a training methodology and (2) research using simulation as an investigative methodology (Cheng et al. 2014). This study follows the latter methodology to address research questions whose answers are unattainable through real-life experimentation without being too expensive or time-consuming. Therefore, after a rigorous discussion of the collaborative points in construction planning and in the LPS, collaboration is modelled through computer simulation and its influencing factors identified in the literature. Different scenarios depicting the different collaborative practices along the LPS phases are simulated, and their results are analyzed to deduce where collaboration has the most substantial impact on the project.

COLLABORATION IN CONSTRUCTION PLANNING

As collaboration is one of the "Five Big Ideas" presented by (Macomber 2004), along with optimizing the whole, coupling learning with action, viewing projects as networks of commitment, and increasing relatedness, collaboration must be investigated through the context of LPS to weave and embed its implementation from within. (Schöttle et al. 2014) defined collaboration and compared it against cooperation sometimes used interchangeably with the former. Among the presented definitions of collaboration was the phrase "the process of shared creation" (Schrage 1995), where several individuals with "complementary skills" engage in an interaction that creates a newly achieved understanding (Schöttle et al. 2014). Other researchers have defined collaboration as "a process of joint decision-making among key stakeholders" (Gray 1989).

Several studies investigated key strategies for effective collaboration in construction, such as one by (Shelbourn et al. 2007), who identified people, business, process and procedure, and technology as driving factors for successful collaborations. Moreover, a sense of familiarity, willingness, and level of engagement were described by (Skinnarland and Yndesdal 2010) as a set of collaboration indicators that describe the collaborative development process. Based on their study, all three indicators may have a positive functional relationship with the degree of collaboration in construction projects.

Collaboration has been a topic of interest for several researchers, each addressing it from a unique perspective, as it is essential for the success of any construction project. A study by (Jara et al. 2009) adapted a methodology called Extreme Collaboration in an AEC project to accelerate the design process of a multidisciplinary team that must optimize the architecture, structure design, energy efficiency, and cost of wood houses simultaneously. They also suggested a methodology for integrating Extreme Collaboration in the Pull Planning phase. Another study reviewed and analyzed the experiences of project managers and foremen with implementing the Last Planner System on a construction project from a collaborative perspective (Skinnarland 2012). They found that one of the most prominent outcomes of the LPS implementation was the establishment of an arena for collaboration. (Schöttle and Gehbauer 2012) showed the importance of a working incentive system to foster collaboration among project members and presented a model for managing such a system. (Abdirad and Pishdad-Bozorgi 2014) highlighted the importance of collaboration on participants' success in an Integrated Project Delivery (IPD) system depends. They proposed developing a framework of metrics to assess collaboration in IPD by investigating the traits of collaboration in IPD and linking them with respective metrics. Most recently, (Malvik 2022) viewed collaboration from an entirely different lens by putting the collaborative style of a successful football team in a Lean construction context. They conceptualized the ideas a famous football coach brought forward by viewing them from a Lean construction perspective and investigated whether collaboration techniques from another performance environment can inspire the Lean construction theory.

MEANS TO MEASURE COLLABORATION IN CONSTRUCTION

Collaboration may be perceived as an intangible or qualitative concept whose measurement may not be as feasible as other concepts in a construction project, such as productivity, budget, schedule, accident rates, and so on. However, some attempts at measuring or quantifying collaboration in construction were introduced, such as the one by (Abdirad and Pishdad-Bozorgi 2014), where collaborative traits within Integrated Project Delivery (IPD) are investigated and linked with respective metrics. A framework based on the identified traits and metrics is developed to achieve a proactive collaboration assessment within IPD. Identified traits included co-location of the project team members, diversity in skills, education, or organization roles, team productivity, the cost impact of collaboration, training, communication methods, and individual human aspects such as absence rate and turnover. Another study by (Marek et al. 2015) recognized the need for evaluating collaboration and presented a seven-factor model of effective collaboration alongside the Collaboration Assessment Tool (CAT), which the U.S. Department of Agriculture developed to evaluate partnership processes and identify key factors to successful collaboration. The seven factors were adopted from a study by (Mattessich and Monsey 1992) and included Context, Members, Process and Organization, Communication, Function, Resources, and Leadership. The developed model included a Likert-scale questionnaire, where participants were asked to rate several items of the identified factors. (Thomson et al. 2009) also relied on a questionnaire-based approach to "measure" collaboration among organization directors. Their guiding dimensions were Governance, Administration, Organizational Autonomy, Mutuality, and Norms. Collaborative planning is a vital aspect of construction projects, and Elsayegh et al. (2021) introduced the Collaborative Planning Index (CPI), a holistic rating system that considers all factors influencing collaborative planning. The CPI offers tailored experiences and strategies to improve collaborative planning practices, contributing to the body of knowledge on the subject. Partially implementing LPS can also yield positive results, as observed by Priven and Sacks (2013), who found that LPS fosters social networks among subcontractors, enhancing communication, reliability, trust, and coordination. Duva et al. (2022) compared the network topologies of two Architectural, Engineering, and

Construction (AEC) project teams to identify how network parameters impact knowledge transfer and project outcomes. Additionally, Cisterna et al. (2018) examined the suitability of Social Network Analysis (SNA) in the AEC industry and identified the influence of project complexity and cultural aspects. Lastly, Lagos et al. (2022) studied the LPS adoption levels, team collaboration, and project performance by comparing two Chilean construction projects, finding that mature LPS adoption significantly aids collaboration and performance. While these studies introduced a much-needed perspective on how collaboration may be assessed and evaluated, empirical and numerical methods that pertain to the direct quantification of either collaboration or the impacts of collaboration on the performance of a project are still unaddressed.

COLLABORATIVE ACTIONS IN THE LAST PLANNER SYSTEM

This section will discuss the LPS phases and the various tasks that constitute each LPS phase, followed by an investigation of the different collaborative actions that enable each task's success and effectiveness. The Master Schedule phase is a crucial aspect of the Last Planner System (LPS) in construction project management. This phase involves creating a high-level project schedule that provides an overview of the entire project. This schedule aims to help the project team understand the critical path and identify potential constraints that could impact the project timeline. The Master Schedule is typically created at the start of the project and is based on the project scope, resources, and constraints. It shows a high-level view of the project timeline, including major activity start and end dates and dependencies between activities. During this phase, the project team should also identify the critical path and any constraints that could affect the project timeline. The Master Schedule is then used as the basis for the Pull Planning and Lookahead Planning phases of the LPS. As one main principle in the LPS is planning in greater detail as you get closer to execution (Hamzeh and Aridi 2013), Master Scheduling includes setting major project milestones and highlighting deliverables to release once the milestone is complete. It also ensures that the perspectives of various project partners for each milestone are aligned (Hamzeh et al. 2009). It is important to align the perspectives of various project partners for each milestone to ensure this phase's effectiveness. This can be achieved by engaging all relevant stakeholders in creating the schedule. The Master Schedule should include major project milestones and highlight deliverables to be released once the milestone is complete. It should also identify potential constraints that could impact the project timeline so that the project team can take steps to mitigate these risks. The Master Schedule should be used to monitor project progress and ensure that the project is on track to meet its deadline. It provides a high-level overview of the entire project, including major activity start and end dates and dependencies between activities, so the project team can better understand the critical path. By engaging the project team, including all relevant stakeholders, the Master Schedule ensures that everyone clearly understands the project timeline and their respective roles and responsibilities.

In the Pull Planning phase of LPS, the project team comes together to plan the work that needs to be done in the next two to four weeks, creating a detailed and accurate plan for the work to be executed. This phase is crucial for the project's success, as it enables the team to identify and resolve any issues before they become problems and complete the project on time and within budget. During the Pull Planning phase, the project team identifies the work to be performed, determines the resources required, and sequences the activities in the most efficient manner possible. The team also engages project stakeholders to ensure that everyone is on the same page and that the plan is feasible. By working together, the team can coordinate their efforts and ensure that the project is executed smoothly and efficiently. One important aspect of Pull Planning is the identification of potential bottlenecks or risks and the development of contingency plans to mitigate these risks. This is crucial for the project's success, as it helps the team anticipate and resolve problems before they occur. In addition, the team regularly reviews the work that has been completed, assesses the status of the work in progress, and identifies any changes to the work plan. This helps to ensure that the project stays on track and that the timeline is updated as necessary (Hamzeh et al. 2009). Another key aspect of Pull Planning is the engagement of the project team, including all relevant stakeholders, which ensures that everyone clearly understands their respective roles and responsibilities and that everyone is working together towards a common goal. By working together, the team can create a detailed plan for the next four weeks, including the work to be performed, the resources required, and the sequence of activities. This allows the team to coordinate their efforts and ensures that the project is executed smoothly and efficiently. Pull Planning is a critical phase in the Last Planner System. It enables the project team to identify and resolve issues, coordinate their efforts, and ensure that the project is executed smoothly and efficiently. By working together, the team can complete the project on time and within budget while ensuring that everyone is on the same page and that the project timeline is updated as necessary.

The Lookahead Planning phase is a crucial aspect of construction project management utilizing the LPS. This phase is dedicated to creating a comprehensive plan for the upcoming work period based on the current state of the project and any potential changes that may impact the schedule or scope of work. This phase aims to ensure that the project is progressing smoothly and efficiently and that the team is prepared to execute the work as planned. The process of Lookahead Planning starts with the project team meeting to review completed work, assess the status of work in progress, and identify changes to the work plan. The team then collaborates to develop a detailed plan for the next four weeks, including the work to be performed, the resources required, and the sequence of activities. This plan is crucial in ensuring that the project is executed efficiently and effectively, as it provides a roadmap for the team to follow. One of the key benefits of Lookahead Planning is its ability to anticipate and resolve problems before they occur. This proactive approach ensures that the project remains on schedule and that the team is prepared to handle any challenges. The team can identify potential bottlenecks or risks and develop contingency plans to mitigate these risks. This level of preparation and foresight is essential in construction project management, as it helps to minimize the risk of delays and ensures that the project is completed on time and within budget. To further ensure the project's success, the team reviews the plan with project stakeholders to ensure its feasibility and ensure everyone is on the same page. By involving all stakeholders in the process, the team can ensure that everyone knows the project's goals and objectives and understands the work that needs to be done. This level of transparency and collaboration is critical in ensuring that the project stays on track and that all parties are aligned in their efforts (Sheikhkhoshkar et al. 2023). Lookahead Planning provides a comprehensive plan for the following work period and ensures that the team is prepared to execute the work as planned. By anticipating and resolving problems before they occur, the project remains on schedule, and the team can coordinate their efforts efficiently. Through regular meetings and collaboration with project stakeholders, the team can ensure that the project is executed smoothly and that everyone is aligned in their efforts toward its success (Hamzeh et al. 2009).

The Weekly Work Planning (WWP) phase of the LPS in construction project management is crucial to ensure the successful execution of the project. This phase involves creating a detailed plan for the work to be performed in the upcoming week based on the Lookahead Plan and the project's current state. In the WWP, extensive collaboration is required to aid each other in executing tasks and among workers and their superintendents to obtain instructions and directions. Also, deviations from the schedule are detected, analyzed, and addressed by all participating project members, and handoffs among different trades and members are handled and finalized, necessitating continuous and thorough discussions and collaboration (Hamzeh et al. 2009; Seppänen et al. 2010). The first step in the WWP phase is a meeting between the project team to review completed work, assess the status of work in progress, and identify changes to the work plan. The team then develops a detailed plan for the work to be performed in the upcoming week, including work, resources, and activity sequence. Through these collaborative efforts, the WWP phase aims to ensure that the project is progressing efficiently and that the team is prepared to execute the work as planned. By planning the work every week, the team can coordinate their efforts, ensure that the work is performed as planned, and identify and resolve any potential issues before they become problems. Finally, the weekly work plan is reviewed with stakeholders to ensure that everyone is on the same page and that the work plan is feasible. Day-to-day collaboration on site is key, either to abide by the plan or to adjust to the plan when necessary. Through these collaborative efforts, the Weekly Work Planning phase of the Last Planner System helps to ensure the successful and efficient execution of the construction project. The discussed collaborative actions are classified into the different LPS phases and represented in Table 1 below. While Table 1 is not exhaustive, and some additional collaborative actions might occur during the LPS phases, it exhibits the main actions that require collaboration among the project members during the planning and execution phases of a construction project.

Table 1: Collaboration Actions in the LPS

Master Scheduling	Pull Planning	Lookahead Planning	Weekly Work Planning
Aligning perspectives	Understanding the scope	Reviewing completed work	Reviewing completed work
Setting major project milestones	Identifying activities	Assessing work in progress	Assessing work in progress
Identifying potential constraints	Sequencing activities	Identifying work plan change	Identifying work plan change
Providing a high-level overview	Identifying required activity resources	Developing a detailed plan for the lookahead period	Developing a weekly work plan
Engaging the project team	Allocating resources	Assigning task responsibilities	Reviewing weekly work plan
	Agreeing on planned activity dates	Reviewing the plan with project stakeholders	Analyzing constraints
	Identifying critical activities	Sharing knowledge to identify constraints	Resolving potential issues
	Designing successful handoffs	Agreeing on which risks are allocated and which risks are shared	Addressing schedule deviations
			Sharing efforts and instructions to execute tasks
			Discussing handoffs finalization

AGENT-BASED MODELLING AND SIMULATION OF COLLABORATION DURING THE LPS

In order to investigate the impacts of collaboration carried out at different phases throughout a construction project, an agent-based simulation model was built using AnyLogic v. 8.7.10. The model included two agent populations: tasks and members. Data from a sample project were used. Agent-based modeling (ABM) is a computational modeling that focuses on simulating the actions of individual agents and how they interact with one another and their environment. ABM is useful for studying multi-interacting complex systems, such as social, economic, and ecological systems.

Model Description

The task population included 14 agents representing 14 individual tasks. It was assumed that the project included five trades, so each modelled task was randomly assigned to one of the five trades. Each task agent was assigned a set of attributes, including an ID number, a trade it belongs to, a planned duration, a planned date for pull planning, a planned date for lookahead planning, a planned date for execution, and a set of predecessors. It also included a statechart, where the task agent moves from one state to another based on its progress. The statechart was divided into three main sections representing (1) pull planning, (2) lookahead planning, and (3) weekly work planning, each containing parameters that specify the required number of superintendents, the required number of workers, the required number of collaborations among superintendents, and the required number of collaborations among workers.

Conditions and functions in the model drove the behavior and progress of the task agents along the different states. The overall behavior of each task agent is described as follows: Once a task's pull planning date is due, it moves from the "not_due_yet" state to the "plan_pull" state, where it starts preparing for its pull planning phase by checking that all superintendents are idle. Once checked, the task agent sends all superintendents messages to start pull planning and moves to the "start_pull" state. Once the number of completed collaborations among the superintendents reaches the required number of collaborations, the task agent moves to the "wait_for_lookahead" state, where it waits for one week after its actual pull planning start date. It then moves to the "plan_lookahead" state, where is starts preparing for the lookahead planning phase by checking that the superintendent of the trade it belongs to and another superintendent for another trade are idle. Once checked, it moves to the "Start_Assigning" state, where it assigns several worker agents based on the prespecified required number of workers belonging to the same trade. Once the required number of workers is achieved, is moves to the "start_lookahead" phase until the number of completed collaborations among superintendents and number of completed collaborations among workers reach the required values. Afterwards, the task agent waits for one week after its actual lookahead planning start date to pass before going through the "Weekly Work Planning" phase states, which are identical to those of the "Lookahead Planning" phase, except for the values of the required numbers of workers and superintendents and the required number of collaborations among workers and superintendents, which vary based on each phase. Once the required collaborations are achieved, the task agent moves to the final "complete" state and notifies the tasks that follow it that they may start. The simulation is stopped once all 14 tasks are completed.

As for the members agent population, it included five superintendents (one for each trade) and several workers. Each member agent was given an ID, a role specifying whether they are superintendents or workers, and a trade they belong to. Each member was also given "willingness" to collaborate, "engagement" in the process, and "scope familiarity" parameter values. These parameters were used to calculate each member agent's "probability of collaboration". They were chosen based on the literature review carried out in the previous sections, proving that positive functional relationships may exist between the three factors and collaboration. The values of these three parameters vary among the different scenarios, which will guide the analysis process in this study. Finally, the probability of collaborating for each member agent is calculated as the average of the aforementioned three parameters. During each phase, if the member agent's probability to collaborate is higher than 5, they collaborate. Otherwise, they do not. In this case, they return to their phase and increase their probability to collaborate by a specified value. Member agents moves between the "Idle" state and the three states of the different phases, i.e. "pull planning", "lookahead planning", and "execution", based on messages received from the task agents to start or stop working on a specified phase.

SIMULATION SCENARIOS

Various scenarios were simulated to investigate the impact of collaboration on the different LPS phases. The scenarios were driven by the changing values of the modelled factors impacting the chance of collaboration among agents, which are each agent's "willingness" to collaborate, "familiarity" with the scope of the tasks in hand, and "engagement" in the process. The different modelled scenarios are shown in Table 2. The terms "high" and "low" refer to the modelled probability of collaboration among agents during the different phases. For example, in scenario 1, member agents were assigned low ranges of factor (willingness, engagement, and familiarity) values to decrease the probability of collaboration among all LPS phases.

Table 2: Modelled Scenarios and Their Assigned Collaboration Probabilities

Scenario	Pull planning	Lookahead	WWP
1	Low	Low	Low
2	High	Low	Low
3	Low	High	Low
4	Low	Low	High
5	High	High	High
6	Low	High	High
7	High	Low	High
8	High	High	Low
9	Average	Average	High
10	Average	Average	Low

ANALYSIS AND DISCUSSION

The model was run for various scenarios as outlined in Table 2, and the results are displayed in **Error! Reference source not found.**(a) and **Error! Reference source not found.**. These figures illustrate the obtained durations (in days) based on the different scenarios in the simulation model. The study variables represent the level of collaboration in the pull planning, look-ahead planning, and weekly work planning phases. For a methodical analysis of the different scenarios and results, the two extremes in the levels of collaboration are examined as a first step: high collaboration in all phases (referred to as “best” scenario) and low collaboration in all phases (referred to as “worst” scenario). Doubtlessly, the highest level of collaboration in all three phases leads to the shortest project duration (86 days), emphasizing the vital role of collaboration in each stage of the LPS, while low collaboration in all three phases leads to the longest project duration (168 days), stressing the need for collaboration throughout the entire LPS and the involvement of all stakeholders in the planning and execution process.

When collaboration is high in the pull planning and look-ahead phases but low in the weekly work planning phase, the project duration extends slightly (94 days) compared to the best scenario, highlighting the importance of collaboration in the weekly work planning phase for maintaining project momentum and ensuring that all team members are on the same page. However, this scenario generated the second shortest duration among all scenarios, implying that despite the lack of collaboration during execution, the undertaken collaboration attempts early on in the project during the planning phases guaranteed a safe degree of satisfactory duration results.

On the other hand, when comparing this 94-day result with its neighbouring and high 116-day result obtained by only decreasing the level of collaboration in the pull planning, we can deduce the significance of collaboration carried out in the early stages of the project. This result indicates that early involvement is crucial for an efficient performance and a successful construction project.

The second longest duration among all scenarios was obtained from the one with low collaboration in pull planning and lookahead planning but high collaboration in the weekly work planning (142 days). This result indicates that despite collaborative efforts being exerted during execution, the lack of early collaboration during the planning phases rendered the early project completion near impossible. To further reinforce this hypothesis, by analysing the scenario right above it, which is obtained by only increasing the collaboration level in the pull planning phase, a 103-day duration was obtained, showing a significant reduction in the duration of the project by enforcing collaboration in the early pull planning phase.

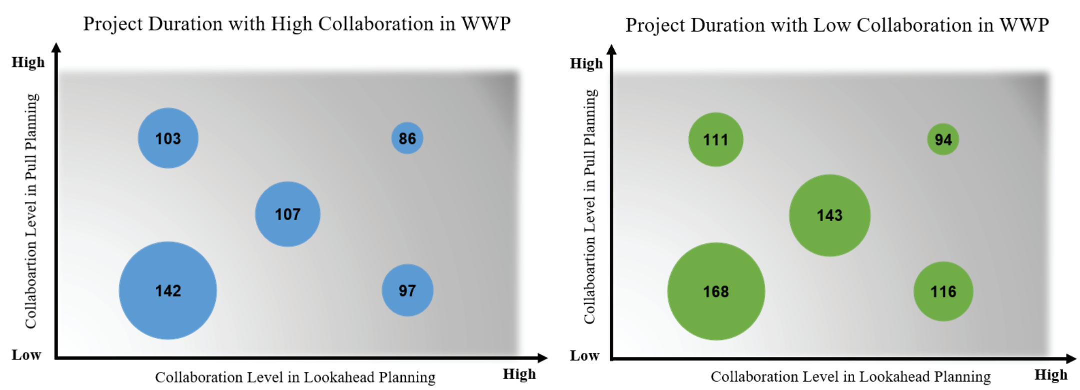

Figure 1: The project duration in case of high, average, and low collaboration in pull planning and lookahead planning with (a) high collaboration in the WWP and (b) low collaboration in the WWP

Figure shows the percent increase in project duration for different scenarios compared to the "best" scenario with high collaboration in all phases. As the level of collaboration decreases, the difference from the best result increases. For example, when collaboration is low in all three phases, the difference from the best result is 95% (168), which highlights the importance of collaboration in all phases of the LPS for a successful and efficient construction project. When collaboration is high in the pull planning and lookahead phases but low in the weekly work plan phase, the difference from the best result is only 9% (94), which further reinforces the importance of early collaboration.

The difference from the best result serves as a measure of the impact of collaboration on project duration and demonstrates that high collaboration results in shorter project durations. The difference from the best result is a useful benchmark for assessing the impact of collaboration on construction projects using the Last Planner System. It demonstrates the importance of collaboration in all phases of the LPS for a successful and efficient project outcome.

This study emphasizes the complexity of collaboration in construction, underlining the need for accurate quantification of its impact on project performance. Effective implementation of LPS relies on fostering a culture of communication and collaboration among all stakeholders involved in the construction project. LPS has been proven to be an effective way of improving workflow in construction production systems and creating a social network among subcontractors, which enhances coordination among trade crews. Thorough implementation of LPS can strengthen social networks, contributing to improved coordination among construction teams and building relationships. However, the success of LPS is dependent on the whole system's thinking and learning culture. Avoiding excessive centrality in LPS meetings is important, as this can affect the necessary distribution of connections and responsibilities. While social network metrics such as network density, average degree, diameter, and average path length are significant factors in project performance (Castillo et al. 2017, 2018; Priven and Sacks 2015a; b), the quality of communication and relationships among team members in different phases of LPS should also be considered.

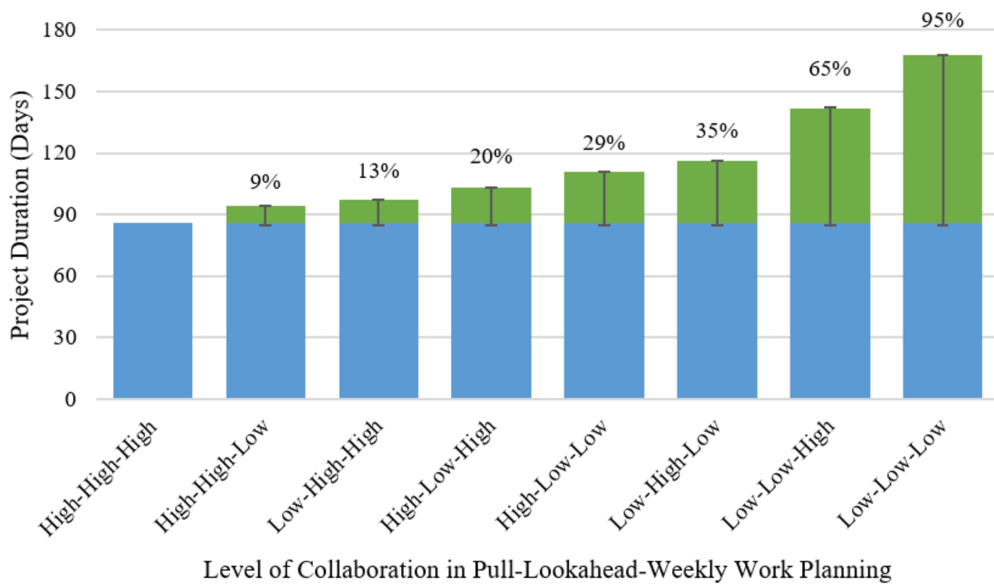

Figure 2: Percent Increase of Project Duration in Each Scenario Compared to "Best" Scenario

CONCLUSION

The findings of this study emphasize the critical role of collaboration in various phases of the LPS in ensuring successful and efficient construction projects. Clearly enough, high collaboration in all three phases of the LPS was found to result in the shortest project duration, while low collaboration in all phases resulted in the longest duration. Simulation results also highlighted the significance of early involvement of project members in the collaboration process, as scenarios with high collaboration in the planning phases resulted in short durations, while those with low collaboration in the early pull planning phase resulted in longer durations, despite having high collaboration in the later stages. The difference from the best result serves as a valuable benchmark for evaluating the impact of collaboration on project duration, emphasizing the need for prioritizing communication and cooperation among all stakeholders in the LPS.

The varying duration results prove the importance of investigating and accurately quantifying the impacts of collaboration on construction projects. They also demonstrate how changes in the levels of collaboration during the different LPS phase have different impacts on the durations, which proves that impacts of collaborative efforts vary depending on when they are being exerted. Finally, the importance of early collaboration in construction projects is clearly manifested in the conducted comparison and analysis.

The study sheds light on the complexity of collaboration in the construction and the need for precise quantification of its impacts on project performance. The study aimed to address this gap by investigating the impact of collaboration in different phases of the LPS and utilizing computer simulation to model collaboration among project members. The conclusion highlights the importance of early collaboration in construction projects and the need for further research to accurately quantify qualitative aspects of collaboration in construction.

The limitations of the study include the lack of detailed investigation into the specific factors that influence collaboration on project performance. The study does not account for individual factors that may impact collaboration, such as a member's familiarity change with the project scope and their role within the construction team. For instance, the study did not investigate the varying degrees of engagement between a superintendent and a construction worker during different phases of the project. Future research could address studying the impacts of individual factors that influence collaboration on performance.

REFERENCES

Abdirad, H., and P. Pishdad-Bozorgi. 2014. "Developing a Framework of Metrics to Assess Collaboration in Integrated Project Delivery." *Proceedings of the 50th Annual International Conference of the Associated Schools of Construction, Virginia Polytechnic Institute and State University*, 1–9. VA, US.

Ballard, G. 2000. *The Last Planner System of production control. Ph.D. dissertation, Faculty of Engineerimg, The University of Birmingham, UK*.

Ballard, G., and G. Howell. 2003. "An update on last planner." *In: Annual Conference of the International Group for Lean Construction, 11, 2003, Blacksburg*, 1–10.

Castillo, T., ; Luis, F. Alarcón, A. Alarcón, A. M. Asce, and J. L. Salvatierra. 2017. "Effects of Last Planner System Practices on Social Networks and the Performance of Construction Projects." *J Constr Eng Manag*, 144 (3): 04017120. American Society of Civil Engineers. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001443.

Castillo, T., ; Luis, F. Alarcón, M. Asce, and E. Pellicer. 2018. "Influence of Organizational Characteristics on Construction Project Performance Using Corporate Social Networks." *Journal of Management in Engineering*, 34 (4): 04018013. American Society of Civil Engineers. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000612.

Cheng, A., M. Auerbach, E. A. Hunt, T. P. Chang, M. Pusic, V. Nadkarni, and D. Kessler. 2014. "Designing and conducting simulation-based research." *Pediatrics*, 133 (6): 1091–1101. https://doi.org/10.1542/peds.2013-3267.

Cisterna, D., J. Von Heyl, D. M. Alarcón, R. F. Herrera, and L. F. Alarcón. 2018. "Application of Social Network Analysis in Lean and Infrastructure Projects." *IGLC 2018 - Proceedings of the 26th Annual Conference of the International Group for Lean Construction: Evolving Lean Construction Towards Mature Production Management Across Cultures and Frontiers*, 1: 412–421. The International Group for Lean Construction. https://doi.org/10.24928/2018/0483.

Duva, M., S. Mollaoglu, D. Zhao, and K. A. Frank. 2022. "Network Topologies and Team Performance: A Comparative Study of AEC Projects." *Construction Research Congress 2022: Project Management and Delivery, Controls, and Design and Materials - Selected Papers from Construction Research Congress 2022*, 3–C: 1062–1071. American Society of Civil Engineers. https://doi.org/10.1061/9780784483978.108.

Elsayegh, A., S. M. Asce, I. H. El-Adaway, and F. Asce. 2021. "Collaborative Planning Index: A Novel Comprehensive Benchmark for Collaboration in Construction Projects." *Journal of Management in Engineering*, 37 (5): 04021057. American Society of Civil Engineers. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000953.

Gray, B. 1989. *Collaborating: Finding common ground for multiparty problems.* Jossey-Bass, San Francisco.

Hamzeh, F. R., and O. Z. Aridi. 2013. "Modeling the Last Planner System Metrics: A Case Study of an AEZ Company." *Annual Conference of the International Group for Lean Contruction IGLC*, 599–608. Fortaleza, Brazil.

Hamzeh, F. R., G. Ballard, and I. D. Tommelein. 2009. “Is the Last Planner System applicable to design? A case study.” *Proceedings of IGLC17: 17th Annual Conference of the International Group for Lean Construction*, 165–176.
Howell, G. A. 1999. “What is lean construction?” *Proc. 7th Annual Conference of the International Group for Lean Construction (IGLC)*. Berkeley, California, USA.
Jara, C., L. F. Alarcón, and C. Mourgues. 2009. “Accelerating interactions in project design through extreme collaboration and commitment management - A case study.” *Proceedings of IGLC17: 17th Annual Conference of the International Group for Lean Construction*, 477–488.
Jarkas, A. M., and C. G. Bitar. 2014. “Factors affecting construction labor productivity in Kuwait.” *J Constr Eng Manag*, 138 (7): 811–820. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000501.
Lagos, C. I., R. F. Herrera, J. Muñoz, and L. F. Alarcón. 2022. “Influence of Last Planner® System Adoption Level on Project Management and Communication.” *Proc. 30th Annual Conference of the International Group for Lean Construction (IGLC)*, 211–222. International Group for Lean Construction. https://doi.org/10.24928/2022/0124.
Macomber, H. 2004. *Putting the Five Big Ideas to Work*. Lean Project Consulting, White.
Malvik, T. O. 2022. “Putting the Collaborative Style of a Successful Football Team in a Lean Construction Context.” *Proc. 30th Annual Conference of the International Group for Lean Construction (IGLC)*, 295–306. https://doi.org/10.24928/2022/0131.
Marek, L. I., D. J. P. Brock, and J. Savla. 2015. “Evaluating Collaboration for Effectiveness: Conceptualization and Measurement.” *American Journal of Evaluation*, 36 (1): 67–85. https://doi.org/10.1177/1098214014531068.
Mattessich, P. W., and B. R. Monsey. 1992. *Collaboration: what makes it work. A review of research literature on factors influencing successful collaboration*. *Amherst H. Wilder Foundation*.
Priven, V., and R. Sacks. 2013. “Social Network Development in Last Planner System Implementations.”
Priven, V., and R. Sacks. 2015a. “Effects of the Last Planner System on Social Networks among Construction Trade Crews.” *J Constr Eng Manag*, 141 (6): 04015006. American Society of Civil Engineers. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000975.
Priven, V., and R. Sacks. 2015b. “Effects of the Last Planner System on Social Networks among Construction Trade Crews.” *J Constr Eng Manag*, 141 (6): 04015006. American Society of Civil Engineers. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000975.
El Samad, G., F. Hamzeh, and S. Emdanat. 2017. “Last Planner System – the Need for New Metrics.” *Proceedings of the 25th Annual Conference of the International Group for Lean Construction*, 637–644. Heraklion, Greece.
Schöttle, A., and F. Gehbauer. 2012. “Incentive systems to support collaboration in construction projects.” *IGLC 2012 - 20th Conference of the International Group for Lean Construction*.
Schöttle, A., S. Haghsheno, and F. Gehbauer. 2014. “Defining cooperation and collaboration in the context of lean construction.” *22nd Annual Conference of the International Group for Lean Construction: Understanding and Improving Project Based Production, IGLC 2014*, 49 (0): 1269–1280.
Schrage, M. 1995. *“No more teams!: Mastering the dynamics of creative collaboration.”* Currency Doubleday, New York.
Seppänen, O., G. Ballard, and S. Pesonen. 2010. “The combination of last planner system and location-based management system.” *Lean Construction Journal*, 43–54.
Shelbourn, M., N. M. Bouchlaghem, C. Anumba, and P. Carrillo. 2007. “Planning and implementation of effective collaboration in construction projects.” *Construction*

Innovation, 7 (4): 357–377. https://doi.org/10.1108/14714170710780101.
Skinnarland, S. 2012. “Norwegian project managers and foremen’s experiences of collaborative planning.” *IGLC 2012 - 20th Conference of the International Group for Lean Construction*, (Ballard 2000).
Skinnarland, S., and S. Yndesdal. 2010. “Exploring the development of collaboration in construction projects: A case study.” *18th Annual Conference of the International Group for Lean Construction, IGLC 18*, 356–365. Haifa, Israel.
Thomson, A. M., J. L. Perry, and T. K. Miller. 2009. “Conceptualizing and measuring collaboration.” *Journal of Public Administration Research and Theory*, 19 (1): 23–56. https://doi.org/10.1093/jopart/mum036.