AN ENGINEERING PERSPECTIVE ON LEAN CONSTRUCTION THEORY

Anders Björnfot[1]

ABSTRACT

The diversity of Lean Construction research and applications is extensive. Due to this diversity, it can be argued that Lean Construction theory has been overextended and lost some of its fundamental ideas. Even though much theoretical progress has been achieved, theoretical development shows inadequate relation to practical construction. Therefore, theory development is of limited interest for the construction community.

The aim of this paper is to make Lean Construction more accessible for construction participants who are interested in learning more about the advances of Lean Construction theory, but are unable to do so due to the vast availability of associated theories. The view of the engineer, representing such a construction participant, is used to revivify and organise Lean Construction theory through a classic structural engineering problem, the column-buckling case.

Similar to the engineering case, the delivery team should consider four dimensions when designing a stable production system; these dimensions are product standardisation, process standardisation, workload reduction, and organisation strength. Application of these aspects in a systematic manner has potential to reduce variation while improving system stability and control.

KEY WORDS

lean construction, construction theory, production system design, engineering design,

INTRODUCTION

Beginning as recent as the early 1990's, Lean theory for construction has been developed and shaped. Adaptation of Lean ideas to construction, based on the manufacturing-oriented five principles of Lean Thinking (value, value stream, flow, pull, perfection), began by addition of flow and value theories to the traditional transformation view of construction. This formed the Transformation-Flow-Value (TFV) theory of production (Koskela 2000), a theory that has reached acceptance and application within the Lean Construction research community.

Since the introduction of the TFV-theory of production, many additional theories have been related to Lean Construction. Examples of significant theories adding depth to our understanding of production in construction is supply chain management, quality management, organisational theories, economical theories, etc. As a matter of fact, the diversity of Lean Construction research is much more extensive than this; Alves and Tsao (2007) revealed that a total of 17 clusters of key words

1 PhD, Civil and Environmental Engineering, Structural Engineering – Timber Structures, Luleå University of Technology, 97187 Luleå, Sweden, Phone +46 920 492067, anbjo@ltu.se

often are used to define Lean Construction research.

Due to this diversity, it can on one hand easily be argued that Lean Construction theory has been overextended and has lost some of its fundamental ideas and meaning, resulting in a theory that some academics and practitioner find impoverished and alien. On the other hand, it can be argued that Lean Construction theory has fulfilled (one of) its goals, i.e., to provide a foundation for diverse innovative research striving to improve construction in every aspect.

However, even though much theoretical progress has been achieved in construction, work remains in order to create a cohesive theoretical foundation. Recently, attempts have been made to revivify construction theory by introducing new theories, such as *metaphysics* (Koskela and Kagioglou 2005) and the "*method of analysis*" (Codinhoto et al. 2007). For example, Koskela et al. (2007) attempted to revivify the TFV-theory of production by describing and distinguishing this theory through the metaphysics framework.

The benefit of these theories for the construction community as a whole can be discussed because they sometime show inadequate relation to practical construction. Therefore it can be understood why theory development is of limited interest for the construction community. However, the importance of these theoretical insights can not be denied! After all, science is a continuous search for information, information that, as Graziano and Raulin (1996) write, must be better structured to become useful.

Even though much research has been performed in order to distinguish Lean theory, it is still appropriate to ask the question Howell (1999) put forward; what is Lean Construction? The aim of this paper is to make Lean Construction more accessible for construction participants who are interested in learning more about the advances of Lean Construction theory, but are unable to do so due to the vast availability of associated theories. The view of the engineer, representing such a construction participant, is used to revivify and organise Lean Construction theory.

CHARACTERISTICS OF THE ENGINEER

McCready (1998) wrote that an Engineer is a person who "*understands how to use techniques of engineering analysis to design (i.e., synthesize) substances, devices and processes even though they have an imperfect understanding of important physical, chemical or biological issues. Furthermore engineers operate under constraints caused by a need to produce a product or service that is timely, competitive, reliable, and consistent with the philosophy and within the financial means of their company.*"

Consequently, it is not what engineers' do that makes them stand out; it is who they are, or in other words - ***how they think about the world*** (McCready 1998). The Engineer employ all that he/she knows to construct an answer to a problem, the best answer! McCready (1998) further argues that as an Engineer, you are expected to have a defined view the world, a defined way of relating to occurring events around you, and certain "engineering tools" that you employ to solve problems.

The perspective of the Engineer as a problem-solving person is the most distinctive view, but there are also darker views of the Engineer as Gambetta and Hertog (2007, p.59) writes that the Engineer is a person who fails to "*understand individuals and their world as the outcome of a social process in which spontaneous behaviours and interactions play a significant part*". Gambetta and Hertog (2007) further argue that this narrow-minded view of the world makes engineers prone to think that "*societies should operate orderly akin to well-functioning machines*". The mindset of a general Engineer is probably a mix of the stated views. To summarise the above discussion, characteristic traits of the Engineer can be stated as:

- Attempts to simplify complex situations
- Orderly view of the world
- Problem-solving & Goal-oriented attitudes
- Experimental mindset
- Expected to produce an "answer"

In relation to the TFV theory of production, the engineer clearly has a transformation view, while the flow and value views are only briefly regarded. This is the view of the world an engineer use when analysing the construction process in general and the construction production system specifically. To further describe the mindset of the engineer, the engineers work is exemplified through a classic structural engineering problem – the column-buckling case – that will be used as a filter when organising and analysing Lean Construction theory and applications.

A CLASSIC STRUCTURAL ENGINEERING PROBLEM

In the column-buckling case the column (illustrated in Figure 1) is represented by a rectangular straight beam of length (L), width (W) and height (H). In the real case, this beam is often homogenous and made out of a specific material (such as wood, concrete, steel, etc.) with specific strength (S) associated with the choice of material. Examples of typical applications of this type of structural engineering system are as columns or load-carrying members of rafters in buildings, or as studs in single- or multi-storey housing.

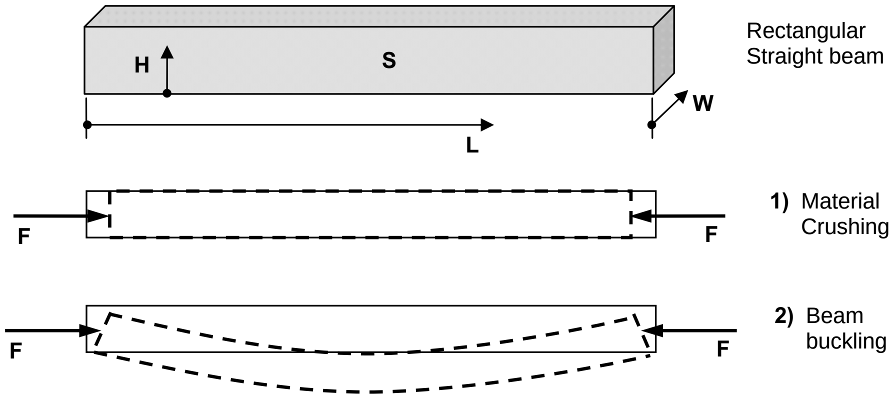

Figure 1: Illustration of the column buckling case and the two prevailing failure modes; 1) crushing of the material and 2) beam buckling (system instability)

When a perpendicular force (F) is applied to this beam (Figure 1), failure can occur in two ways; 1) by exceeding the material strength leading to crushing of the material, or 2) by buckling of the beam, an instability phenomenon severely reducing beam strength. Instability should, by all means possible, be avoided because in this failure mode the capacity of the beam to carry the applied force is often severely reduced resulting in premature failure and system collapse. To recap, buckling of the system is governed by:

- Height (H) and width (W) ratio; buckling will occur in the weakest direction
- Beam length (L); the longer the beam, the larger is the risk of buckling
- Material (S); a stronger material reduces the risk of buckling
- Beam rotation (R); hampering beam edge rotation reduces the risk of buckling
- Combinations of the above mechanisms

AN ENGINEERING PROBLEM SOLVING METHODOLOGY

In the design of a column, as with most kinds of engineering designs, the Engineer must consider a number of ***target parameters***. A fundamental demand on construction design is human safety from structural collapse, as regulated by the government (building codes) on all constructed buildings. Therefore, buildings generally tend to be structurally optimised with material cost as the main target parameter (Björnfot and Stehn 2007a). Another important target parameter in design is constructability; Tsao et al. (2004) revealed tolerance issues emanating from poor constructability decisions in design while Björnfot and Stehn (2005) related constructability issues to poor working conditions.

A cost sub-optimised structural design may lead to poor constructability decisions with subsequent waste. Therefore, an important task for the Engineer is to design a column by taking in regard all of the above described target parameters. Commonly this work is done by first firmly assessing the system limitations, such as applied load and its direction, building code demand on load-carrying capacity and limitations to geometry (cross-section) emanating from the relation of the studied system to the rest of the structure. Design of the beam according to the specified target parameters are performed by optimising beam dimensions, improving material strength, decreasing beam length or hampering beam rotation. These ***dependant variables*** (Table 1) are chosen and designed in such a way that the whole system is optimised.

Table 1: Impact of dependant parameters on target parameters and on system design

Variable	Explanation	Design challenge
L	Length of beam	*Reduced* as much as possible through system analysis
H	Height of beam	Height/Width ratio is optimised for minimal *material cost*
W	Width of beam	
F	Applied force	*Reduced* as much as possible through system analysis
S	Strength of material	Material choice is dependant on beam application and beam geometry (low *material cost* is target parameter)
R	Rotation of Beam	Depending on beam application, hampering rotation may not be possible due to *constructability* reasons

THE CONSTRUCTION PRODUCTION SYSTEM

What is the purpose of construction? The goal of construction should be to produce value for its customers. Consequently, the goal of the construction production system is to design and make a construction product (“*a ready to use object*” such as a single family home, or a free-spanning bridge, etc.) in a continuous process from initial idea to finished product that is of value for both the customer and the delivery team (Björnfot and Sardén 2006). Thus, construction is about producing precisely what the customer(s) wants (external values) using minimal amount of time and resources while providing a working environment of trust and learning (internal values).

Still today, the most common production system in construction seems to be the traditional site-based production system where most of the work is performed on the construction site. Other production systems steadily becoming more and more competitive and popular are the element and the volume production systems (Figure 2) where an increasing amount of construction products are prefabricated inside factories (and hence the amount of factory performed work is increasing in relation to construction site work).

Figure 2: Illustration of the element and volume production system (Björnfot and Sardén 2006)

There is no generic production system for construction that can produce every type of construction product with maximum value in every occasion. Even industrial production systems that rely on a high degree of prefabrication, such as the element and volume production systems illustrated above, can greatly differ from each other even if they produce similar products. This difference depends on for example company history and fixed production units already invested in (such as factories and machinery). In Table 2 general objectives of the production system are summarised.

The inputs to the production system are for example designers or sub-contractors (the people making the work), legislations and regulations (providing important system limitations), as well as project related inputs such as construction documentation and client demands. The goal of the production system is then to transform these limitations into a construction product of value for all involved; examples of values strived for are durability, flexibility, profitability, independence (see e.g., Bertelsen and Emmitt 2005, Cuperus and Napolitano 2005).

Table 2: The three aspects (input, transformation and output) of the production system

Aspect	Explanation & objectives
Input	Assigns work, limitations, resources and goals for production
Transformation	Work performed that makes use of inputs to provide expected outputs
Output	Produced value for all involved participants (customers and supply chain)

Due to the variation between how construction is performed it does, from a theoretical point of view, make sense to model the construction process as a *"black-box"* which goal is to transform inputs into outputs (Figure 3). Ballard et al. (2001) and Halpin and Kueckmann (2002), as well as many other authors, used this abstract view of the production system. This basic model of reality is henceforth in this paper used to illustrate the production system. Consequently, there will be no attempt to distinguish individual unique production systems.

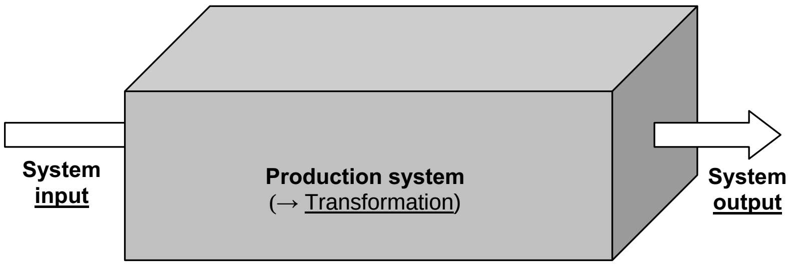

Figure 3: A *"black-box"* illustration of the production system transforming inputs into outputs

AN ENGINEERING VIEW ON THEORETICAL LEAN ADVANCEMENTS

The most accepted theoretical foundation for construction is the TFV-theory of production that, together with the principles of Lean Thinking, provides a general framework for developing Lean Construction theory and applications. Björnfot and Stehn (2007b) argued that a fundamental aim of Lean Construction is to aid in the delivery of external value by managing the internal value generation process. In Lean Construction, value generation is generally facilitated through theoretical advances such as work flow control, value stream mapping, just-in-time production, etc.

It is common to associate these theories with *"Lean toolkits"* used to attain Lean practices in practice, such as the Last planner system of production control providing work flow control in site-based production (Knapp et al. 2006). However, as has previously mentioned, Lean construction research and applications is more extensive than this. Extracted from Alves and Tsao (2007), the most common theoretical advances in the Lean Construction community can be summarised as in Table 3.

Table 3: General frameworks associated to the most common theoretical advances in Lean Construction (from Alves and Tsao 2007) and an engineering analysis of these theories

Theory field	Framework	Engineering view
Design management	Involves transformation of intangible resources into outputs of design data, so constraints can be identified and managed	The goal is to design a product that is easy to understand for all involved participants, i.e., a *product standardisation* effort
Information technology	Development of tools to support implementation of Lean Construction and design, planning, procurement, etc.	The goal is to create a process where information is understood by everyone involved, i.e., a *process standardisation* effort
Project management	Stabilizing work flow by the management of projects through scheduling, planning, reducing complexity, etc.	The goal is to create a process where variation and complexity is reduced and managed, i.e., a *process standardisation* effort
Supply chain management	Aims at explaining how construction supply chains work, how actors in a specific supply chain interact, good practices, etc.	The goal is to better manage the supply chain so that a flow of resources can be created, i.e., a *value stream standardisation* effort
Production management	Works with methods and tools for measuring and improving production, e.g., safety, scheduling, planning, etc.	The goal is to better manage variation, quality, complexity, etc. within the production system, i.e., a *process standardisation* effort
Value management	Describes methods that help define customer value and the generation and balancing of value for all involved participants	The goal is to better manage customer values and to establish the link to product design, a *product standardisation* effort
Culture & human aspects	Research involves competencies necessary for implementing Lean Construction and investigations in project cultures	The goal is to improve the ability of organisations in providing a working environment of trust and learning, i.e., *organisation strength*

AN ENGINEERING VIEW ON PRODUCTION SYSTEM DESIGN

The many different Lean Construction theories make it difficult to comprehend what Lean Construction is all about. An engineer, with a problem-solving attitude, strives to reduce what seems complex to smaller and easier to manage parts. Through the engineering view (seeing the world through the eyes of an engineer), the core aim of each theory is expressed as a standardisation effort (Table 3) which further emphasise the link between different theories. This simplified and orderly view of Lean Construction can make its theory more readily understandable by an engineer.

The column in the structural engineering case can be seen as a representation of the production system while the applied forces is a representation of the system inputs and outputs as illustrated in Figure 3. To continue the modelling of the production system, it can, from the presented engineering view of Lean Construction theoretical advances in Table 3, be deducted that these theories can be structured around four main dimensions as illustrated in Figure 4:

- **Process standardisation.** Theories and tools for process standardisation have the goal of reducing the variation of performed work throughout the whole production system by developing and utilising practices for standard work
- **Product standardisation.** Theories and tools for product standardisation have the goal of reducing the variation of the production system output by limiting the number of unique products produced or by reducing the amount of unique parts that these products are composed of.
- **Value stream standardisation.** Theories and tools for the value stream have the goal of preventive reduction of variation within a chain of processes by striving to reduce the amount of unique independent activities performed
- **Organisation strength.** Theories and tools for organisation strength have the goal of improving the rigidity of the organisation to change, i.e., improving the culture and the flexibility of the workforce to change

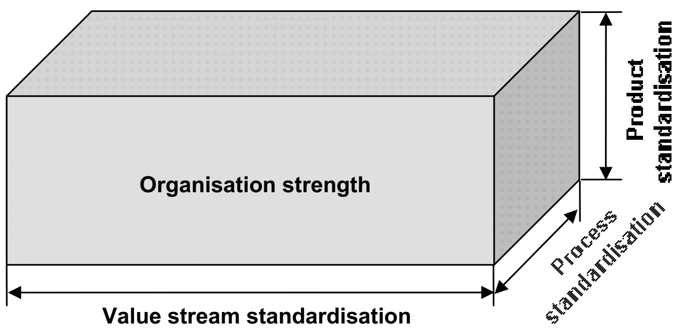

Figure 4: A structural engineering illustration of production system design and improvement

Based on the failure modes of the structural engineering case (Figure 1), there are similar "failures modes" of the production system, failure as in waste generation when the production system becomes unstable. Such "failures" can occur if, for example, too much work is assigned, i.e., assigned work can not be finished resulting in too much pressure on the production system. That waste generation is related to variation and that variation leads to poor production control is not new. For example Henrich et al. (2006) relates for a number of sources of variation that leads to poor production control, e.g., project uncertainty, type of contract, production control methods, project typology, space availability on site, tasks interrelationship, decision-making, etc.

Thus, similar to the structural engineering case, the goal of a company, or delivery team, is to design a stable production system (beam) with as little variation as possible. This task should be performed by minimizing risk of system instability. Ideally, the production system should be able to handle as much variation as possible while producing a flexible output (targeted to multiple customers), i.e., similar to increasing the capacity to carry applied force in the structural engineering case.

Comparing the structural engineering case (Table 1) to the model of the production system, improved stability of the system should be reached by reducing the amount of workload (length of system), by processes standardisation (width of system) and by product standardisation (height of system). Also, stability is improved by making the organisation less susceptible to change (choice of material) or by reducing the variation of inputs and outputs (hamper rotation). In Table 4, the impact of the dependant parameters (Figure 4) on production system design are summarised.

Table 4: Dependant parameters and their impact on production system design (compare with variables for the engineering system design in Table 1)

Variable	Explanation	Design goal and challenge
L	Workload reduction	Determine what is of value, take control of the value chain and focus on value-adding activities
H	Product standardisation	Balancing of product variety and standard work – neglecting either process or product standardisation leads to waste as the system becomes unstable
W	Process standardisation	
F	System Inputs/outputs	Reduce *amount* of system inputs and outputs. For example, see the development of *"product offers"* (see Björnfot and Stehn 2007b)
S	Organisation strength	Change the culture of the workforce so that learning motivation, and trust will fight variation from inside
R	Input/output variation	Limiting the *variation* in system inputs and outputs facilitates a better controlled production process

DISCUSSION AND CONCLUSION

A problem of spreading Lean Construction theory further within the construction industry was recognized. It was argued that construction participants have problems identifying with Lean Construction theory. The proposed production system model (Figure 4) represents a unified and simplified perspective of Lean Construction that should make its theory more accessible for the structural engineer since it is based on a problem the structural engineer can readily identify with. The model also represents a common physics problem that other engineering professions can identify with.

The results from this paper indicate that structural engineering knowledge obtained from a traditional structural engineering problem (the column-buckling case) can be applied to deepen the understanding of mechanisms (Table 4) for efficient production system design, especially how methods and tools for Lean Construction can be applied to these production systems so that variation is reduced while system stability and control is improved.

So far the ideas presented in this paper are only theoretical as the relation between production system parameters has not been empirically verified. To predict behaviour, production system performance must be understood and measured. Therefore, the next challenge in better understanding production system design is to verify dependant parameters and then to measure target parameters; product and process standardisation (and their relation), workload reduction and organisational strength.

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