THE ROLE OF CONCEPTUAL MODELING IN LEAN CONSTRUCTION SIMULATION

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ABSTRACT

Simulation can validate lean construction concepts prior to their field implementation. It enables efficient analysis of the impacts of lean construction theory on a project by supporting a variety of procedures including model sensitivity and scenario analyses. However, to date, the organization of the elements in lean construction simulation models has mainly followed the traditional perception of construction workarounds. They often assume the project will adhere to the work breakdown structure created by the planners before the execution phase. In order to implement the pull-driven approach, as one of the lean construction principles, managerial interventions during the project execution are inevitable and may include a change in the planned sequence of the work process. Hence, an efficient lean construction model has to explicitly capture the management feedback and decision linkages within the project. A review of the applied modeling approaches in lean construction simulation research indicates a weakness in this area. The methods do not apply a systematic framework that supports identifying the crucial elements of the project and includes the level of detail required in the model. This study investigates likely solutions to overcome the indicated shortage. It traces the roots of the deficiency back to the conceptual phase and investigates the implications of conceptual modeling in lean construction simulation research. It is demonstrated that undertaking a conceptual modeling stage can provide a good level of transparency about the elements that are necessary for abstracting the project reality. Therefore, this study suggests conceptual modeling as an effective solution to enhance the success of a lean construction simulation study.

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KEYWORDS
Simulation, Variability, Production, Process, Managerial Intervention.

INTRODUCTION

Construction operations are highly complex and dynamic, involving multiple interacting factors that produce unpredictable outcomes (AbouRizk et al., 2011). In such a complex environment, managerial decisions need to be carefully examined (Peña-Mora et al., 2008). An examination in a real project will be expensive, time-consuming and difficult to undertake (Al-Sudairi et al., 1999). Simulation can provide a low-cost, low-pressure alternative for experimenting with multiple scenarios. It assists in identifying the problematic areas and in defining possible solutions (González et al., 2013). Simulation models can represent the processes and their surrounding environment both quantitatively and logically, a capability which has proved to be valuable for analysis (AbouRizk et al., 2011). These analytical capabilities can be used in lean construction to test and estimate the achievements of its principles before their actual field implementation (Halpin and Kueckmann, 2002).

Despite its prospective capability, to date the use of simulation in lean construction projects has been limited (Farrar et al., 2004). This limitation can be attributed to the level of complexity and difficulty involved in the lean construction modeling process. We contend that such a level of complexity is the result of the mismatch between the fundamental principles of lean construction and the assumptions made in the traditional modeling approaches applied to construction processes.

Most construction simulation models are developed based on a traditional perspective about the organization of the project elements. They assume that the work breakdown structure of construction projects can be represented as a queuing system. In this system, crews of various trades move from one location to another to provide services and operate production processes. Their completed products are stationary and play the role of consumer of services for the next crew (Tommelein et al., 1999). In such a traditional approach, also known as a push system, the project will always adhere to the planned work structure. Therefore, each process passively waits to receive the planned input before starting its operation. Such strategy causes waste in production that takes the form of waiting time and slow work in some processes and overproduction in some others (Poshdar, 2015).

Lean construction contrarily strives to keep the waste minimized by pursuing pull techniques as a principle. Under this strategy, each process is supposed to acquire the required resources precisely as needed. The resources are pulled not only from the queues immediately preceding the activity but also from any other areas of the project that can supply the requirements (Tommelein, 1998). It offers a dynamic work breakdown structure, which may involve deliberate changes to the planned sequence of processes or the operations within a process. The managers decide the changes based upon feedback and decision links established between different parts of the project. An efficient lean construction modeling strategy should explicitly account for these links and the likely managerial interventions to implement the pull strategy. So far, no specific approach has been provided in lean construction simulation research that can support the modelers in recognizing the crucial elements and including the

level of detail that are necessary to build an efficient lean construction simulation model.

In order to address this issue, we first develop a critical review of the existing literature on lean construction simulation. Further, we identify the state of the art in simulation research in other areas. Afterward, the paper establishes a linkage between the systematic approaches developed in simulation research in other areas and the limitations found in the lean construction simulation studies. The study reveals conceptual modeling as a crucial process in simulation modeling that has received less attention from modelers. Accordingly, this paper proposes a systematic framework that can assist the modeler to move from a problem state to a solution that enables the development of a robust lean construction simulation model. Finally, we will demonstrate the utility of the proposed framework to model part of a real project involving the construction of a multi-story building.

SIMULATION RESEARCH IN LEAN CONSTRUCTION

As simulation can efficiently model and analyze production processes, for many, lean thinking and simulation are closely related (Halpin and Kueckmann, 2002). Tommelein (1997) utilized discrete-event simulation to generate system-level information about two construction projects. The study demonstrated the use of the information generated about the flow and conversion, and the effects of adopting different strategies of work sequencing in redesigning the construction processes and making them leaner. She discussed the use of simulation in understanding the so-called matching problem on construction sites. Many construction processes include an operation on unique materials in specific locations; materials and locations must match before the operation can take place (Tommelein, 1998). Al-Sudairi et al. (1999) examined the effects of five lean principles on a steel erection process based on a computer simulation analysis. Halpin and Kueckmann (2002) further explored the relationship between simulation and lean construction. They recommended that lean thinking provides a structured framework to redesign production processes while simulation offers a methodology for evaluating the benefits of it. Farrar et al. (2004) proposed a generic set of guidelines to test lean principles in a simulation model. Sacks et al. (2007) developed a game named LEAPCON based on a lean model for construction management of high-rise apartment buildings. The game simulates the execution of interior finishing activities required in a multi-story building with customized apartment designs. They used the computer simulation to validate the results of the live experiment; establish and implement an improved base plan; and test the marginal contribution of each lean intervention as well as the effects of variations on the management model. Mao and Zhang (2008) suggested a framework with eleven steps that provides guidelines to streamline the construction process and create innovative construction methods. They incorporated computer simulation techniques into their framework to assess the efficiency and effectiveness of the reengineered processes designed through the framework. González et al. (2009) proposed a generic simulation-optimization and multiobjective framework to design work-in-process buffers in repetitive projects using lean principles. Abbasian-Hosseini et al. (2014) used computer simulation to quantify and evaluate the results of applying lean principles in the bricklaying process. Nikakhtar et al. (2015) did the same to quantify the effects of lean principles on a reinforcement process.

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The review shows that lean construction simulation models often assume the project will keep the work breakdown the same as created by the planners before the execution phase. They model the systems, assess the potential gains from implementing lean construction concepts, and re-design the work breakdown to increase the potential gains overlooking the fact that often circumstances arise in the execution phase in which decisions need to be made about reallocation of resources and reorganization of processes. As such, a lean construction approach demands a dynamic work breakdown structure that may change based on managerial feedback and decision information during execution. Thus, the simulation modeling approach should be able to represent such dynamics. This necessity is confirmed by Peña-Mora et al. (2008), and AbouRizk et al. (2011) who emphasize the vital importance of robustness of simulation experiments and the significance of including all the influential factors that may arise during the execution phase. This paper proposes a systematic model development approach that can help to capture all the significant factors of the project, including likely managerial interventions in the execution phase, and enhance the robustness of the lean construction simulation experiment. To do so, it acquires a certain structure for developing the simulation experiment that has already been proved to be useful in other simulation research areas. The next section discusses the details of the established structure.

A SYSTEMATIC STRUCTURE TO DEVELOP SIMULATION STUDIES

According to Balci and Ormsby (2007), three major abstraction stages take place to develop a robust simulation. **Conceptual Model:** The conceptual model is a simplified, software independent representation of the real system. It enables the modeler(s) to move from a problem situation, through model requirements to a definition of the necessary elements of the model. This stage of modeling provides some advantages such as less demand for data, short development time, and more flexibility for future changes. **Model Design:** This stage involves specifying the paradigm that the model will follow. It also includes the selection of the simulation platform that will be used in the implementation stage. It can follow either object-oriented or procedural paradigms. The platform can be chosen to be a general or a special purpose package such as STROBOSCOPE (Martinez, 1996), or a programming language such as C, C++, or Java (Law, 2007). **Model Implementation:** The final phase involves implementing the designed model in the adopted simulation platform.

Revisiting the current lean construction simulation research shows that the models often focus on the design and implementation stages. However, a successful simulation process requires effective conceptual modeling (Robinson, 2014). Robinson (2014) argues that the importance of conceptual modeling is probably the least understood aspect of simulation modeling. Accordingly, in this paper, we explore the conceptual modeling stage in lean construction simulation research and its important role in building a robust model.

DEVELOPMENT OF A CONCEPTUAL MODEL

Three basic approaches can be identified for developing conceptual models

(Robinson, 2008a). **Providing principles of modeling:** A set of principles is provided that give general guidelines for building a conceptual model. The central theme is to start with simple models and gradually add scope and detail (Robinson, 2008a). **Methods of simplification:** These methods act primarily as a redesigning tool in contrast to a design approach (Robinson, 2008a). They aim to simplify the components of an existing model while a sufficient level of accuracy is maintained (Zeigler et al., 2000). **Modeling frameworks:** A framework provides specific steps for developing the conceptual model. The purpose is to provide a modeler with an understanding of the development process of a conceptual model.

The first approach is useful to provide some guidance to the conceptual model designer; however, it does not provide any details on developing the model. The second approach requires the model to be already available and focuses on its improvement. Only, the last approach supports extended guidelines to build a conceptual model from scratch (Robinson, 2014). A modeling framework provides a greater sense of discipline to the conceptual modeling activity. The higher discipline formalizes the basic tasks and can encourage greater creativity (Robinson, 2008b). However, when a conceptual modeling framework is utilized, its underlying assumptions can significantly affect the model as well as the consequent design and implementation of the model. Therefore, it is of particular interest to outline a conceptual framework in this paper that is able to effectively capture the fundamental concepts of lean construction and hence improve the quality of lean construction simulation.

A conceptual modeling framework for lean construction simulation

A conceptual model of lean construction must be able to represent all the elements that can take the job further than the queuing network arrangement underlying traditional approaches. Just recently, some researchers have discussed the role of conceptual modeling in testing the foundation stone of queuing networks in the simulation arena. In that respect, Robinson (2015) and Furian et al. (2015) proposed conceptual models that are not based on queuing networks and Furian et al. (2015) provide a framework for developing conceptual models with control structures that are not queue-based. They proposed a hierarchical control conceptual modeling framework that explicitly captures high-level policies and decision-making alongside typical operational control mechanisms. In this study, we will refine their framework by adding two post-modeling phases for presentation and validation. Figure 1 shows the organization of the proposed framework, which consists of six sequential phases.
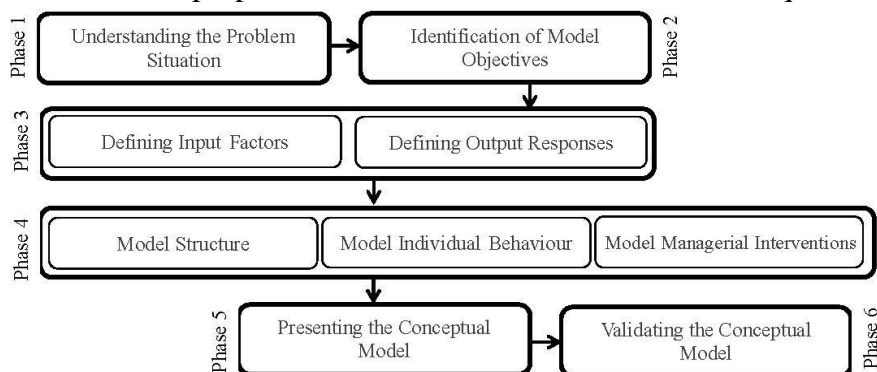

Figure 7. The Conceptual Modeling Framework

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In order to demonstrate the utility of the framework in practice, we also illustrate the application of each phase in the modeling of a real project. It involves a simplified version of the processes related to "fabricating doors and windows offsite and their installation in 17 apartments on site" (Figure 8). The offsite process includes fabricating four different types of products with specific dimensions, materials, and decorative designs. The onsite process involves installing the products into their corresponding wall openings (Figure 9). The processes are designed to complete the operations on each of the types of products in a certain order (shown in Figure 8). The potential contribution of the conceptual modeling process in developing robust lean construction simulation experiments is discussed as follows:
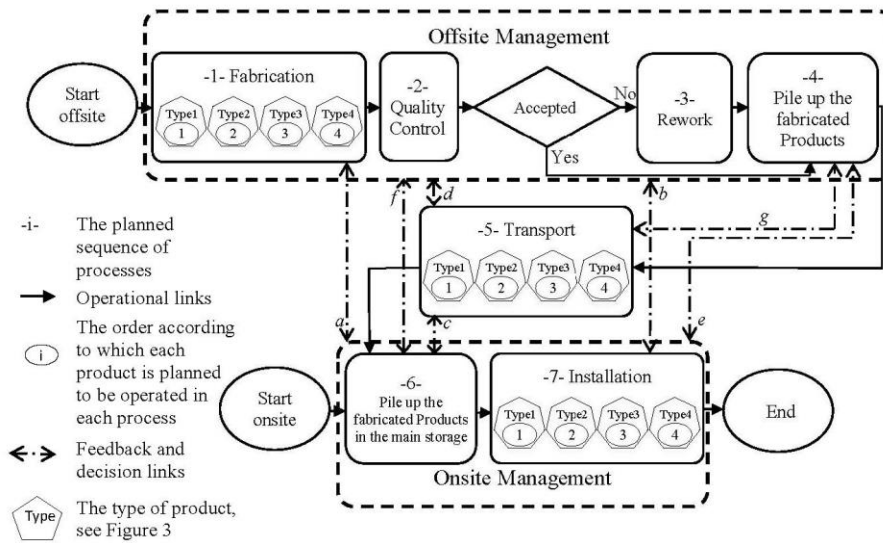

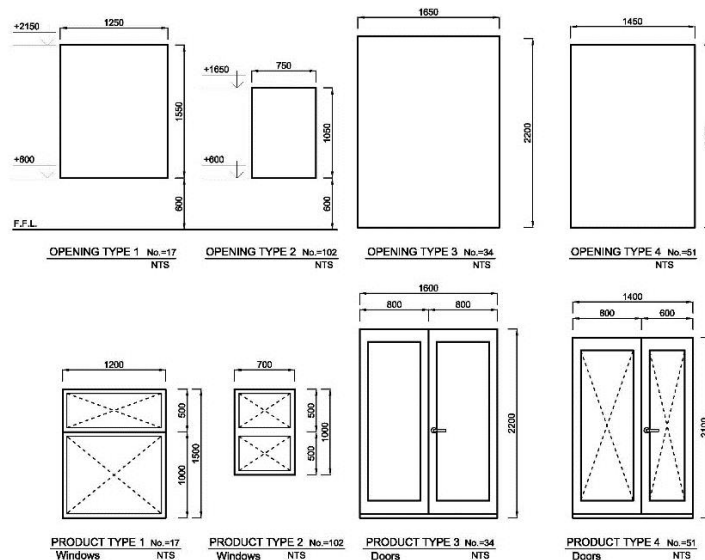Figure 8. An illustrative process flow diagram of the project

Figure 9. Four types of products offsite and their match openings on site

Phase 1: The starting point of any simulation study is to develop an understanding of the problem situation. This stage exposes any areas of limited knowledge and understanding that then necessitates making certain assumptions (Robinson, 2008b).

The case project: The project includes installation of four specific types of doors

and windows with certain characteristics specified in the architectural drawings. The prominent aspects of the problem are as follows: The product types and the available openings must match before installation can take place. In an actual case, however, the planned sequences of work are affected by unexpected conditions that can cause a mismatch between the fabricated products offsite and the available openings on site. The problems can include dimensional errors in the fabricated products or their corresponding openings on site, misaligned bottom plates, or imperfect floor leveling. A delay in the construction process of the wall openings can also be another reason for hampering the installation process. As a part of the management's actions that keep a pull strategy running, they may decide to change the planned sequence of processes or order of operations within a process.

Phase 2: A clear definition of the model objectives is the key to the development of a successful model. The objectives are concerned with the overall aim of the organization, and the specific modeling objectives (Robinson, 2008b).

The case project: The overall aim of the organization was to minimize the inventory, minimize project completion time, and maximize project productivity. In addition, the model needed to consider different constraints such as available space for product inventory. The specific objective of the simulation study was to make an accurate estimate of the likely contribution of applying a pull strategy in the project.

Phase 3: The third phase of the conceptual modeling process is to identify the experimental factors and responses as the primary inputs and outputs of the model.

The experimental factors are the model data that can be set as variables to achieve the modeling objectives. The responses typically are set to determine the extent to which the modeling objectives have been achieved and to identify the reasons for any failures (Robinson, 2008b).

The case project: The experimental factors of the project include the performance of different teams (measured by required time to complete an operation) and the size of the buffers utilized. A review of the key performance indicators as the model outputs could fulfill the specific objective of the project.

Phase 4: This phase involves the determination of the model contents. Robinson (2008b) suggests that simulation models may involve four types of components: entities, activities, queues, and resources. These four elements can properly model the push strategy applied by the traditional management approaches. As explained earlier, in traditional approaches the activities are intended to comply with the planned sequence of processes at the expense of a significant increase in waste.

In a pull system, the managers may give priority to some resources over others if they are known to match up with resources already available further downstream (Tommelein, 1997). Hence, in a pull-driven approach, the work breakdown structure of the processes may dynamically change. Therefore, it is not enough to model only the operational components, the management control policies must also be part of the model.

The case project: Table 1 summarizes the main components of the project model according to the definition by Robinson (2008b), which enables modeling of a traditional management approach.

As explained, in a pull-driven decision environment, the managers may change the planned work breakdown based on the project status. For instance, if the fabrication process operates ahead of the planned schedule, the on-site managers may decide to

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skip piling up the products in the main storage (process 6), and send them directly to the installation crew (process 7). It can help to avoid the waste of waiting in process 7, while also reducing the waste from production occurring too early in process 1. For this purpose, a feedback and decision link must be established between process 1 and the onsite management team (link *a* in Figure 8). Similarly, the establishment of a feedback tie between the offsite management team and process 7 (link *b* in Figure 8), enables adjustments to the fabrication operation with the completion of construction and availability of openings on site. Hence, the fabricators may change the planned sequence of production and give priority to a certain type of product that matches with the availabilities on site. The development of a conceptual model also can expose other potential connections for exchanging feedback between the project processes and management teams. The project managers may consider links *c* to *g* to transmit feedbacks and build up the pull system.

Table 1: Main operational components of the conceptual model

Process	Activity	Entities		Queues	Resources
		In	Out		
1	Fabrication	Drawings, Materials	Fabricated doors and windows	Design files, and materials	Fabrication Crew, Materials, Machinery
2	Quality Control	Fabricated doors and windows	(a) Accepted quality (b) Rejected quality	Fabricated doors and windows	Inspection Crew
3	Rework	Products with rejected quality	Corrected products	Rejected products	Fabrication Crew
4	Off-site warehousing	Products with acceptable quality, Corrected Products	Piled up and packed products	Products that are ready to be transported	Offsite storage Crew, Storing Area
5	Transport	Piled up products	Transported products	Piled up products	Transportation Crew, Machineries
6	On-site warehousing	Transported products	Piled up packs of products	Arrived packs of products	Onsite storage Crew, Storing area
7	Installation	Apartments ready for installation, products from item 6	Completed work	Ready apartments, and Piled up products	Installation Crew, Machinery

However, the inclusion of the additional links will increase the model complexity that has an inverse effect on usability and run-speed. Therefore, the modelers need to achieve a balance between the level of detail included in the model and its usability. Robinson (2008b) suggests referring to the judgment of the modeler, clients, and domain experts; experience; analysis of preliminary data about the system; or prototyping as some potential solutions to establish the proper balance.

Phase 5: The developed model should be expressed in a manner that can be communicated and understood by all parties involved in a simulation experiment. A range of methods has been proposed for representing and communicating simulation conceptual models. For instance process flow diagrams, activity cycle diagrams, Petri nets, event graphs, simulation activity diagrams, and tables describing the model rationale and content have been among the suggested approaches (Robinson, 2008b).

The case project: Figure 2 uses a basic outline of the components to enhance the transparency of the elements that are necessary for abstracting the project reality. Additional logic flow diagrams or pseudocode could elucidate the way in which the

feedback links *a* to *g* dynamically determine the flow of items in the system.

Phase 6: Once developed, the model has to be validated. It is a vital part of the process for the success of the simulation study. A validation process ensures fulfillment of the simulation objectives with the required accuracy (Robinson, 2014). It is, however, almost impossible to measure the accuracy of the conceptual model until at least a full computer representation becomes available. Before the computer modeling stage, validation of the conceptual model will be mainly based on the opinion of the modeler with additional support from the clients and the domain experts (Robinson, 2008b).

The case project: The feasibility and the extent of effectiveness of the designed links can be consulted with the project experts.

CONCLUSION

A systematic framework has been discussed for lean construction simulation modeling with three major abstraction phases including conceptual modeling, design, and implementation. Among them, the conceptual modeling phase has received the least attention from the simulation modelers in construction. This study revisited the conceptual modeling process as a vital part of the lean construction simulation procedure. A lean construction project involves managerial interventions during the execution phase. A model with a fixed queuing arrangement of the processes may be inadequate to represent a project with such interventions. Accordingly, a modeling framework was discussed that does not rely on a fixed work structure of activities. It involves the managerial decisions as an explicit part of the model. The framework provides the modeler with a good level of transparency about the decision links and effects. Hence, it enables modeling of the selective control utilized by the pull systems based on real-time information from project processes including downstream processes.

Further development of this research includes implementing the proposed structure in a real construction project and capturing the users' specific requirements.

ACKNOWLEDGMENTS

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