USING SYSTEM DYNAMICS MODELING AS A LEAN CONSTRUCTION WORK STRUCTURING TOOL

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ABSTRACT

Discrete Event Simulation has been advanced in the construction literature as a tool to design construction operations while incorporating performance variability to arrive at more realistic durations and cost estimates. This tool can enable Lean Construction work structuring (LWS), which is concerned with the selection and sequencing of work methods during the product design stage. LWS is "thinking production process during the product design stage". This paper introduces system dynamics as a quantitative approach for LWS wherein an operation is designed and analyzed for effectiveness of production strategies before implementation. System Dynamics evaluates the actions in terms of dependencies and feedback loops among process variables. The proposed modeling approach will be qualitatively demonstrated and discussed using a bricklaying operation to illustrate the benefits of the proposed methodology.

KEY WORDS

lean construction, lean work structuring, discrete event simulation, dynamic system modeling, simulation,

INTRODUCTION

During the second half of the 20th century, lean production principles have evolved and were successfully implemented by Toyota Motor Company. Toyota strived to work towards the ideal of 100% value-added work with zero (or minimum) waste. Popularized by the book *The Machine That Changed The World* (Womack et al. 1990), these lean principles are being increasingly employed in many other industrial sectors. Since 1992, ushered in by Koskela's seminal report (Koskela 1992), the adoption and adaptation of lean production concepts in the construction industry has been ongoing. An increasing number of construction academics and professionals have been storming the ramparts of conventional construction management in an effort to deliver better value to owners. As a result, lean-based tools have emerged and have been successfully applied to simple and complex construction projects. This collective development activity of both academics and practitioners has lead to the birth of Lean Construction as a practice and discipline that subsumes the transformation-dominated contemporary construction management.

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Lean Construction has escaped canonical definition mainly because lean principles defy simple characterization. A frequently referenced definition is that of the Lean Construction Institute (LCI). According to LCI, Lean Construction is a production management-based philosophy emphasizing the need to simultaneously design a facility and its production process while minimizing waste and maximizing value to owners throughout the project phases (including the post-construction phase) by improving performance at the total project level, using a conformance-based vs. a deviation-based performance control strategy, and improving the reliability of work flow among project participants.

According to Glen Ballard, co-founder of LCI, "Lean project delivery changes the job site concept of reliability, eliminating the 'systemic lying' that pervades traditional project management," and that "with Lean, control means insuring outcomes starting at the crew level. A project is truly under control when you do what you say you're going to do and minimize project disruptions." Greg Howell, also co-founder of LCI, believes that "Understanding the reliable work flow imperative in Lean production runs counter to the construction industry's 'can do' culture. But we must move beyond the deep cultural aspects of that mentality and create a system that cultivates judgment and reliability. We'll never trust each other if we don't become more reliable." (LCI 2001)

A number of construction companies have embarked on lean conversion initiatives and are starting to reap the benefits. One practitioner stated, "Lean lowers the 'hair-on-fire' index on our jobs." The Boldt Company, a national provider of construction, consulting and maintenance services with annual sales volume of $400-million is also embracing Lean Construction principles. Paul Reiser, Boldt's vice president for production process innovation, cites three reasons for being attracted to Lean: "First, Lean is simply systematically applied common sense. Second, it is counterintuitive. Unlike anything I've seen before, it causes us to rethink how we manage work. And, finally we saw it as an opportunity to deliver high value facilities to the marketplace in shorter time" (LCI 2001).

Lean Construction is concerned with the holistic pursuit of concurrent and continuous improvements in all dimensions of the built and natural environment: design, construction, activation, maintenance, salvaging, and recycling. To guide the implementation of lean construction on project-based production systems, the Lean Project Delivery System (LPDS) was developed. LPDS is a conceptual framework introduced by Ballard (2000), depicted as a model with 5 main phases, where each phase is comprised of three modules. The inter-dependence between the phases (e.g. that design of product and process should be performed concurrently) was represented by sharing one module between two subsequent phases. Production control and lean work structuring were both shown to extend throughout the 5 main phases. Learning or (post-occupancy evaluation) was introduced to underscore the need to document lessons learned from one engagement to another. The reader is referred to Ballard (2000) for a detailed account of the LPDS model.

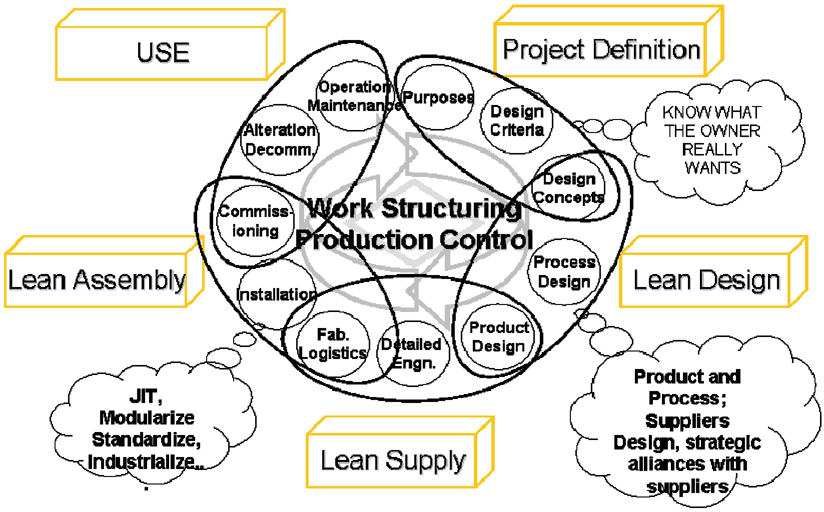

Figure 1. Lean Project Delivery System (modified from Ballard 2000)

Figure 1 represents the authors adaptation of the LPDS model original 'triad'-based illustration. This depiction is intended to accentuate the central role that Work Structuring and Production Control play throughout the LPDS phases. This paper is primarily concerned with the "Work Structuring" process.

"Lean Work Structuring" (LWS) is a term created by LCI to indicate the development of operation and process design in alignment with product design, the structure of supply chains, the allocation of resources, and design-for-assembly efforts, with the goal of making "work flow more reliable and quick while delivering value to the customer" (Ballard 2000). In essence, works structuring is *thinking production process during product design.*

LWS is different from Work Breakdown Structure (WBS) because the objective of LWS is to assure the best approximation of the lean ideal instead of defining each component that makes up the whole. In addition, WBS is looking at activities in an independent fashion in support of transformation thinking. WBS assumes that optimizing the part will optimize the whole – reduce the part cost and you will reduce the cost of the whole. WBS is useful to understand the entire scope and details of a project but not to plan and not to monitor production operations on site. It is worth noting also the difference between constructability reviews and LWS. Where constructability reviews merely react to designs and please with designers to reduce site construction issues, LWS will challenge and inform the design and go beyond to look at the supply chain as well.

According to Ballard (2000), work structuring is the most fundamental level of process design, answering the questions:

- In what chunks will work be assigned to specialist production units (PUs)?
- How will work chunks be sequenced through various PUs?

- In what chunks will work be released from one PU to the next?
- Where will decoupling buffers be needed and how should they be sized?
- When will the different chunks of work be done?

Work structuring decisions are made in all project phases, as new information becomes available and facts are revealed. For example, decisions regarding the supply chain structure that can best support the project and off-site fabrication may be made in the Lean Design phase, project definition phase, which will have an impact on workflow during the actual construction process.

Carrying out LWS requires tools and techniques. Most of these tools have existed prior to the birth of Lean Construction, but the distinction is in the way they are deployed. For example, critical path method scheduling is used in LWS to create a pull-based (not push-based) master and phase schedule that gives us the confidence in the intended construction sequence. Using BIM, first run studies, time studies, and work sampling are examples of tools used for LWS. Another important tool for LWS is computer simulation of construction operations. In this case, we don't just celebrate the inclusion of stochastic times in determining duration and cost of operations but we in fact seek to study and design a production system with less or no variability.

This paper is concerned with contrasting Discrete Event Simulation and System Dynamics approaches as tools for Lean Construction work structuring (LWS). While both approaches allow for designing effective operations before implementation, the paper posits that system dynamics provides added benefits in terms of inclusion of dependencies and feedback loops among process variables. The proposed system dynamics modelling approach will be demonstrated using a bricklaying operation to illustrate the benefits over discrete event simulation of the same operation.

COMPUTER SIMULATION OF CONSTRUCTION OPERATIONS

Computer simulation has been recognized as an efficient method to improve planning for construction projects (Halpin 1977; Martinez and Ioannou 1999). The primary motivation for the use of simulation in construction management is that it provides an inexpensive and relatively fast method to evaluate multiple operation design configurations without having to suffer the consequences of poor design selection (Back and Bell 1995). This process of production system design is conducted while incorporating stochastic durations to arrive at more realistic durations and cost estimates. It is particularly useful for evaluating the distinct impact of each one of a set of process changes (Farrar et al. 2004); however, given the likelihood of interactions and interdependence between changes, this is best done by running the simulations with all the changes and then eliminating each one in turn to evaluate its marginal contribut*ion*(Warszawski and Sacks 2003).

In the context of lean construction, simulation has been used to model the impact of pull-driven scheduling for process plant construction (Tommelein 1998), to model the impact of process changes for semiconductor plant delivery (Gil et al. 2004), and in other projects. Simulation has also been used in role-playing games that show lean construction principles, an approach widely utilized in lean manufacturing trainings (Verma 2003). For example, The "Parade of Trades" game illustrates the impact of variability on trade performance (Tommelein et al. 1999). The LEAPCON game *(*Sacks and Goldin 2007*)* has also been examined using simulation models. In addition, Computer simulation was used to enable Lean Construction work structuring (LWS).

DISCRETE EVENT SIMULATION MODELS

A discrete event simulation (DES) model can replicate the performance of an existing system very closely and provide decision-maker insights into how that system might perform if modified, or how a completely new system might perform. To achieve this fidelity to the performance of a real world process, a DES model requires accurate data on how the system operated in the past or accurate estimates on the operating characteristics of a proposed system.

In discrete event simulation, the operation of a system is represented as a chronological sequence of events. Each event occurs at a specific point in time and has a specific end as well. The transition from event to another marks a change in the state of the system being modeled. For example, if a backhoe operation is simulated, an event could be "swing bucket empty", with the resulting system state of "load bucket" and eventually (unless one chooses to simulate other details, like a breakdown) "swing bucket full", then "Empty load".

A common exercise in learning how to build discrete event simulations is to build an activity cycle diagram for the resources in the system and how these resources move through the system. A number of mechanisms have been proposed for carrying out discrete event simulation, among them are the event-based, activity-based, process-based and three-phase approaches (Lin and Lee 1993, Pidd 1998). Commercial simulation software packages typically follow the three-phase approach, and use graphical user interfaces making them quite user-friendly.

SYSTEM DYNAMICS

System dynamics is a continuous simulation techniques introduced by Forrester (1961), and has been used successfully in the study of organizational performance. System dynamics are simulation models used to understand the dynamic complexity in a system. It is an interdisciplinary area concerned with system behavior and "grounded in the theory of nonlinear dynamics and feedback control developed in mathematics, physics, and engineering" (Sterman 2000). System Dynamics is based on the paradigm of "system thinking". System thinking is a holistic, broad, long-term, dynamic view (Sterman 1994).

SD models often incorporate "fuzzy" qualitative aspects of behavior that, while difficult to quantify, might significantly affect the performance of a system. SD modelers, in practice, are comfortable than DES modelers with incorporating "best guesses" and expert opinion into their models. They tend to evaluate their models on the face validity of the model's output, and whether the model provides the user an increased understanding of the system.

The use of SD models is not necessarily ubiquitous across non-farm industries but it does have widespread application in manufacturing and high-tech companies, such as Boeing, BAE, Ford, Samsung, etc. Systems utilize SD for system integration issues as well as design and production simulations. During the past ten years, system dynamics has been applied successfully in research efforts in construction projects and construction organizations (Rodrigus and Bowers 1996, Ford and Sterman 1998, Park and Pena-Mora 2003). Earlier efforts identified six feedbacks in project construction including the labor, schedule, rework, work available, quality, and scope (Ford 1995). The six feedback structures are building blocks for modeling construction projects.

KEY SYSTEM DYNAMICS CONCEPTS

While discrete event simulation (DES) is similar in many respects to SD, SD has some unique terms and concepts. At a high level, SD is more focused on the analysis of systems as continuous processes. DES more often models particular processes and not entire systems, and best suited to modeling discrete processes.

A fundamental notion of system dynamics is the components and relationships among the components of a system determines performance. With a clear understanding of the linkages between people, organizations, processes, and resources, the system can be optimized to improve performance. The links between the objects in a system are modeled by feedback loops, where a change in one variable affects other variables in the system. DES methodology is a disciplined means of capturing the structure of an existing or proposed system that requires a great investment of time in data analysis and distribution fitting to ensure the model is statistically valid. In contrast, SD models frequently include "soft" variables, which may be difficult to empirically quantify. Identifying the system's structure is paramount in determining system performance.

Development of SD computer simulation

Both SD and DES routinely employ computer simulation. In SD, model building is an iterative process involving the model builder and the people who routinely work with the system under study. They begin by identifying the basic structure and relationships within the system (often referred to as "stocks" and "flows"), and then assign functions and numerical values to these relationships. Once the group has reached some agreement that the system under study has been adequately described in a causal loop diagram, a computer simulation is run of the model to see if the output reflects the group's intuitive understanding of the system. The model is then iteratively revised and re-run until the group feels comfortable that the important elements of the system are captured and the model's output reflects their view of reality. This part of system dynamics is much like discrete event simulation. Once the system under study is appropriately captured in a computer simulation it can be developed into a management "flight simulator."

SD AND DES MODELS: A BRICK LAYING PROCESS

To highlight the similarities and differences of the SD and DES models, the following example construction operations will be used (adapted from Halpin and Woodhead 1998):

- Eight masons are supported by two laborers. A mason removes one 15- brick packet from a stack position on the scaffold in about 1 min and places it in about 11 min. The laborers start supplying a brick packet to a stack position, when the preceding packet has been removed by the masons. Four stack positions are available near the working area of the masons. The average time for supplying one brick packet is 2 min, and 7.2 bricks are required for one square foot of the wall.

DES MODELLING

The simulation process begins with constructing of the models that represent the system being simulated. Figure 2 represents the DES model built using the simulation software EZSTROBE (a software package that uses STROBOSCOPE as its simulation engine and MS VISIO as its graphical user interface). The DES representation of the bricklaying system typically focuses on observable and measurable aspects of the workflow activities – shown as the rectangular elements in Figure 2, namely, re-supplying the stacks, picking up a packet, and placing bricks. The queues (circles in Figure 2) represent the resources utilized in the system. The activities have a clear beginning time and resource requirements, and an ending time. Entities move through the system in a linear fashion. There are no feedback loops.

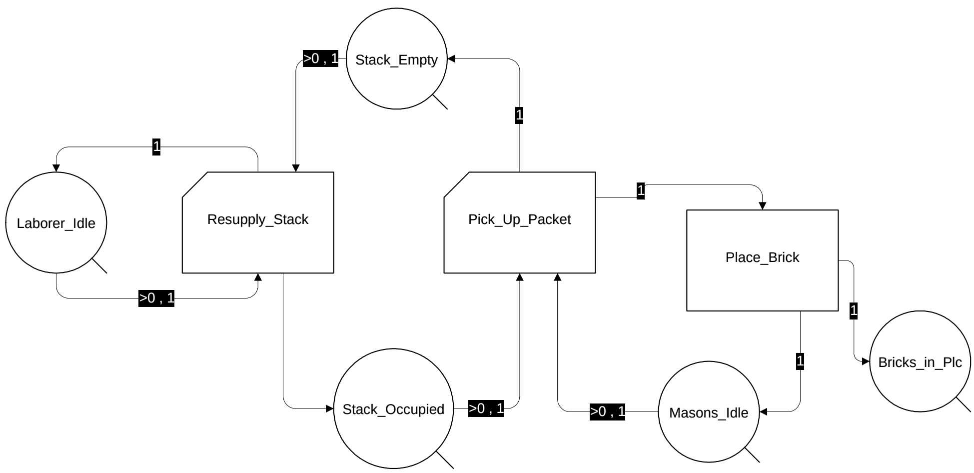

Figure 2: DES diagram of the bricklaying operation

Running the simulation using deterministic and/or stochastic timings, the following system properties can be computed:

- DES(a) Labor utilization
- DES(b) Mason utilization
- DES(c) Cycle time for: “Re-supply Stack”; “Pick-Up Packet”; “Place Brick”

The same modeling for this operation will be performed using SD and the two approaches will be contrasted.

SD MODELLING

Similar to Figure 2, an SD model for the same bricklaying operation is illustrated in Figure 3. In the SD model, the stocks (square elements in Figure 3: Supply, Move Brick; Stack; Blocks available at wall, Mason Queue, Wall, and Rework Solve Problem) and the flow between them represents the essence of the bricklaying process. The converters (the circular elements with a horizontal bar in Figure 3) act as valves that regulate the flow of the operation. However, in Figure 3, the converters are shown connected to the numerous factors (represented by the circular elements in Figure 3) that influence that flow. For instance, using a feedback loop (the arrows in Figure 3), schedule compression may have a negative effect on the brick laying rate. Note that it is also possible to show the factors influencing schedule compression itself, as shown in Figure 3 by the target schedule and schedule change nodes. The feedback loops from the various nodes and the rate at which they affect the flow between the stocks nodes can influence the brick lying life cycle (overall productivity).

The SD model in Figure 3 can be best characterized as a highly interdependent model that identifies the number of hard and soft rules (number of physical and human characteristics) that affect the overall flow of the work. This model is excellent at capturing the behavioral and qualitative relationships within the operation workflow. As mentioned before, it may be difficult to empirically verify the strength and intensity of some of the feedback loops.

It is expected that a significant difference between the results obtained from the SD model compared to those based on the DES approach are quite significant. The decisions that will follow will be entirely different, and the scenarios tested will also be different. The impact of not just the variability of performance is investigated, but the effect of the factors behind performance variability can also be tested.

CONCLUSION

This study has presented a qualitative comparison between a DES and SD simulation models. The two models (Figure 2 and Figure 3) reflect the drastically different approaches of each simulation methodology. The two approaches allow the consideration of a production system at two very different resolutions. The DES modeling approach is superior to SD in that it readily provides calculations of resource utilization measures (time and/or resource-based) and it can also allow for tracking an individual resource (e.g., each brick, mason, and/or laborer in the example used in the paper). A most significant difference is the extent the factors present in the SD model produce dynamic changes over time. The fact that these relationships may be difficult to quantify does not diminish their importance in understanding the system and predicting its behavior. However, the DES modeling approach will not allow such behavioral and qualitative relationships influencing the operation workflow. Celebrating the inclusion of these factors is not the goal. The experimentation with the production system design under various scenarios and allowing for the deliberate design of a production system that maximizes reliable workflow is the goal.

The implications of SD to Lean work structuring is it truly meets the goals that LWS attempt to achieve; thinking production during process design. The SD can also be used to understand the difference factors that impact workflow reliability during the construction process. For example, the constraints leading to not meeting 100% PPC for weekly production planning can not be investigated more closely and prioritized to their impact.

This paper considered the tip of the iceberg when it comes to the ever expanding and evolving area of System Dynamics modeling. Additional research is needed to investigate the implementation of SD modeling compared to DES modeling as an enabler for Lean Work Structuring.

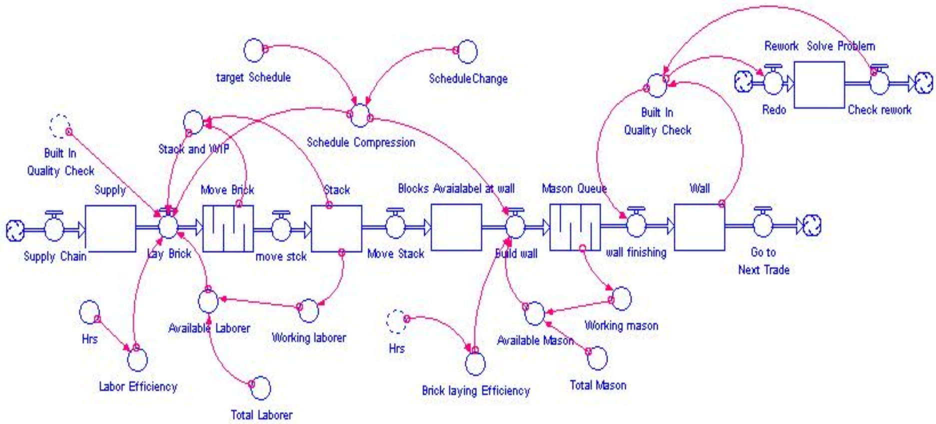

Figure 3: SD diagram with additional features impacting workflow

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