SIMULATION OF CONSTRUCTION PROCESSES: TRADITIONAL PRACTICES VERSUS LEAN PRINCIPLES

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ABSTRACT

Lean manufacturing theory is founded on several key principles: specify value by product, rethink your operating methods, focus on actual objects from beginning to completion, release resources for delivery just when needed and strive for perfection. Transferring these principles from manufacturing to the construction domain is of ongoing interest for construction researchers. However, modifying real construction processes is expensive, time consuming and difficult. This paper reports interim results of a study to evaluate lean principles when applied to construction using computer simulation.

Data for a structural steel erection process was modeled in Extend® to form the experimental tool for evaluating lean principles. In all cases, the simulated principles improved project performance. Performance improved dramatically when all principles are simultaneously applied.

However, the erection process became volatile and fragile when it was subjected to changes and uncertainties from outside of the process. Maintaining a zero buffer at the erection site made the process extremely fragile. This study demonstrates the need for a broad systems view when one is considering lean modifications to a construction process.

KEY WORDS

Lean principles, lean construction, process simulation, buffer size, volatility.

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INTRODUCTION

Recently lean manufacturing theory has been introduced to the construction industry. In the last two decades, great improvements in performance have been observed in manufacturing. In particular, lean automobile manufacturing is now using less of everything: half the manufacturing space, half the human effort in factory, half the product development time, half the investments in tools (Alarcon 1997). Production is "lean" because it uses less of everything compared with mass production (Womack 1990).

The lean producer combines the advantages of craft and mass production, while avoiding the high cost of the former and the rigidity of the latter (Table 1). Towards this end, lean producers employ teams of multi-skilled workers at all levels of the organization and use highly flexible, increasingly automated machines to produce high volume products in enormous variety. Perhaps the most striking difference between mass production and lean production lies in their ultimate objectives. Mass-producers set a limited goal for themselves-"good enough", which translates into an acceptable number of defects. Lean-producers, on the other hand, set their sights explicitly on perfection.

Table 1: Comparing the Three Types of Production

Production Type	Worker's Skill	Technology
Craft	High	Simple
Mass	Unskilled/semiskilled	High-rigid
Lean	Multi-skilled	High and Flexible

Comparing construction to the three types of production, construction is more like craft production. The question now is can the construction industry learn from the developments in manufacturing industry and move to lean production? This study explores this question and investigates the applicability of lean principles to the construction domain. Investigating the applicability of lean principles implies several questions:

- Are lean principles applicable to construction?
  - Which are most effective?
  - What are the intended and unintended consequences of applying lean theory?
- Are construction buffers effective?
  - Do they add value or waste?
  - Do they or can they support better flow?

This work is founded on three hypotheses; lean principles will improve project performance, lean principles will make construction processes more volatile, and managing construction buffers is a key to moving to leaner processes. To test these hypotheses, field observations of structural steel frames were conducted to provide the basis for a simulated erection model. This paper discusses case study results for simulating the steel erection process using both static (studying its logic, flowchart of activities and decisions) and dynamic (using computer simulation) models.

RESEARCH METHODOLOGY

Figure 1 depicts the methodology of this study. The modeling portion consists of three major parts, which are adopted from Slaughter and Eraso (1997). First the process flow, detailed tasks, sequences and decisions are identified. Second, specific design elements, resources and the characteristics of the operating conditions, e.g., site characteristics, are specified. Third, the dynamic aspects of the process are modeled using computer simulation to allow experimentation to verify the research hypotheses.

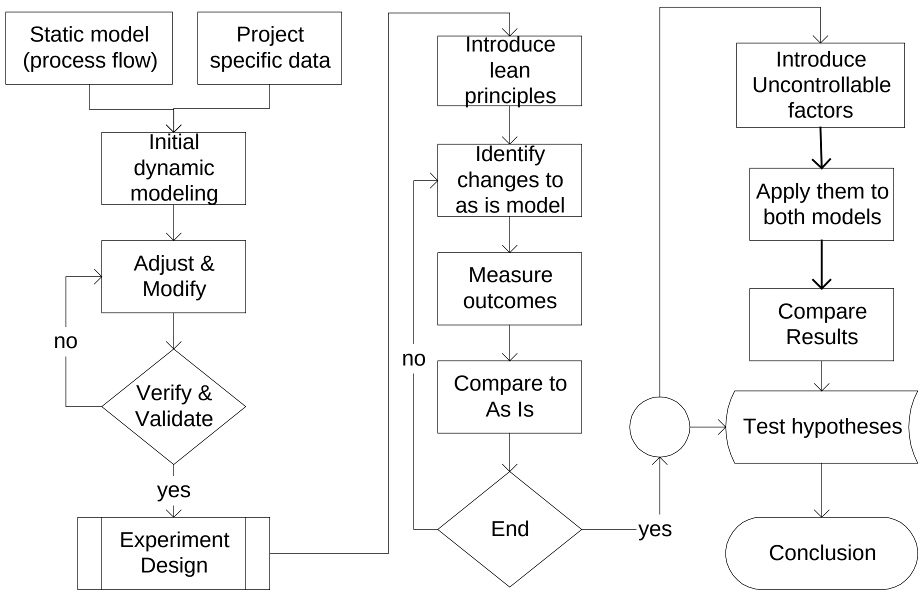

Figure 1: Flowchart of the Research Methodology

Before experimenting with lean principles, it is necessary to verify and validate the dynamic model. Verification means that every portion in the model operates as expected, i.e. no logical errors. Using features offered in Extend+BPR, which is an object oriented simulation package, such as animation, generating reports, tracing command and certain debugging blocks, the authors reached a confidence level that the model is functioning properly. Validation, on the other hand, means that the model accurately represents the real system. Daily throughput, productivity, crew utilization and cycle time for both actual data and empirical data were compared using t-test to make sure that the later data are significantly representative. A comparison of the actual steel erection process' throughput (members/crew-day) and the simulated system's throughput is shown in Figure 2. In addition, a comparison of other process metrics is shown in Tables 2 and 3. Notice the close correspondence between the behavior of the actual system and the simulated system. Table 3 summarizes results of a t-test, which was used as a validation tool. It is clear that at any value of alpha the model is valid.

To study the impact of lean principles, each principle was individually introduced to the actual system model. The results of the simulation are compared using the process metrics: average throughput, utilization of resources, cycle time and productivity. Additionally, factors beyond the control of the lean contractor that are identified as “uncontrollable” factors. Testing the impact of the “uncontrollable” factors on system behavior indicates the sensitivity (volatility) of the system to exogenous changes.

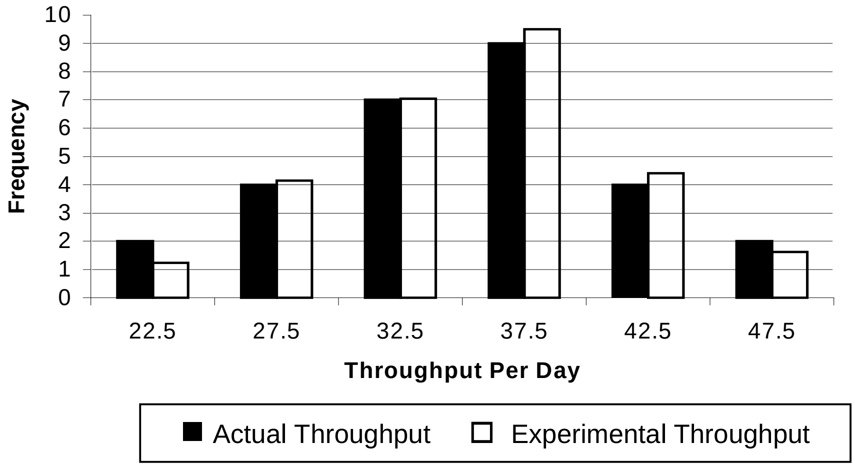

Figure 2: Comparing the Actual Throughput to the Experimented Throughput

Table 2: Comparing Other Process Metrics of Both Actual and Experimental Data

	Statistical Data	Actual	Experimental
Productivity	μ	1.25	1.20
	σ	0.584	0.31
Utilization	μ	0.62	0.59
	σ	0.13	0.085
Throughput	μ	35.71	36.50
	σ	7.44	7.15

Table 3: T-Test Results for Both Actual and Experimental Data at Alpha = 0.05

Process Metric	**Test Statistic Value**	$t_{\alpha/2, \nu}$
Productivity	0.16	2.02
Utilization	1.703	2.014
Throughput	0.405	2.006

LEAN THINKING AND SIMULATION

Lean production theory can be summarized in five principles: precisely specify value by specific product, identify the value stream for each product, make value flow without interruptions, let the customer pull value from the producer, and pursue perfection (Womack and Jones 1996). Figure 3 depicts the conceptual framework for such a theory that was

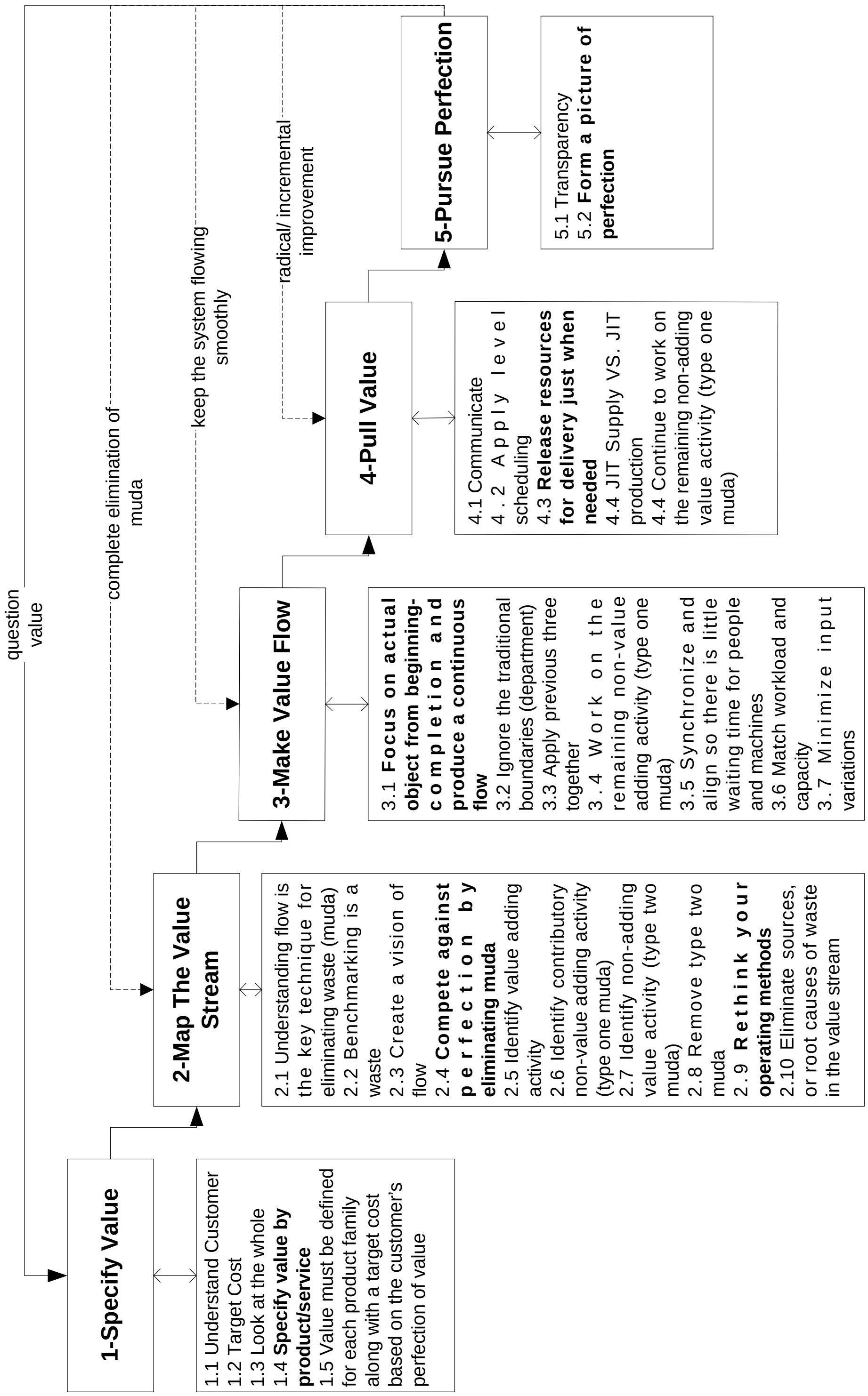

Figure 3: Conceptual Framework of Lean Production Theory with Highlighted Implemented Principles

adopted by the authors to evaluate lean principles as applied to a construction process. A primary challenge was to incorporate the principles highlighted in Figure 3 into our base case simulation model to demonstrate the effects of lean behavior.

The five principles together constitute the lean production theory. That is to say dealing with waste and flow are one aspect of such a theory. It's true that lean means shifting the focal plane of management to differentiate value from waste (Womack 1999a). However, such a shift requires the implementation of lean principles wherever a value flows in order to make sure that there is no waste. That is to say, management has to go beyond its own boundaries by establishing lean enterprise, which is an organizational model where group of individuals and functions that are legally separate but operationally synchronized (Mariotti 1996). This is because many failure-to-complete situations are caused by up-stream partners, so situation must be analyzed *as a whole* (Womack 1999b). Using simulation lean principles were implemented to the base case individually in order to study their impact. After that all lean principles were simulated and compared to those principles implemented individually.

EXPERIMENTAL DESIGN

A designed experiment is an approach to systematically vary the controllable input factors and observe the effect these factors have on the output product parameters (Montgomery 1997). Experimentation is a research method in which conditions are controlled so that one or more independent variables can be manipulated to test a hypothesis about dependent variables. A dependent variable is the outcome of an experiment and is often a quality characteristic or a measure of performance of the process. On the other hand, the independent variable is deliberately varied or changed in a controlled manner in an experiment to observe its impact on the dependent variable.

$$Y \text{ (project performance)} = f\,[X_{1\text{-}N} \text{ (project related decisions-which may be lean oriented)}, \; X_{2\text{-}N} \text{ (volatility factors)}]$$

Table 4 and 5 lists the lean decisions and factors that influence the dependent variable, project performance. Each decision may be categories into two or three levels. The buffer size decision could be big (>80 steel members), medium (<=80 and >30) or small (<=30). The process design could be traditional or lean. For example, a lean process is where unloading and shake out activities are combined. A radical lean process design is where unload and shake out activities are eliminated so that erection starts directly from the truck. The decision related to coordination could be weak or strong. Strong coordination means that steel members are released from the fabricator yard to the job site in a sequence that matches erection progress as opposed to weak coordination where materials are released by levels.

Table 4: List of Decisions that Management Could Have Control Over

LEAN DECISIONS	DECISIONS OUTCOME
How big is the buffer size?	Big, Medium, Small
What is the process design?	Traditional, Lean
What is the degree of coordination?	Weak, Strong

Table 5: List of Volatility Factors that Could Influence Project Behavior

VOLATILITY FACTORS
Traffic
Error in material sequence
Variation in activities' duration

From the three generic decisions twelve different scenarios can be generated. Table 6 lists the details of all twelve scenarios. These scenarios represent all possible ways of managing the project that has been selected as a case study. Accordingly, many scenarios may be traditional such as 1 and 2, some are semi lean such as 8 and 10 and only one lean scenario which is 12. In table 7 some of the twelve scenarios were reorganized from a lean point of view, which is going to be discussed in the coming section.

Table 6: Showing Different Scenarios of the "as is/base" Case Study

SCENARIO	**DECISIONS**		
	BUFFER SIZE	PROCESS DESIGN	COORDINATION
1 (Base)	**Big**	**Traditional**	**Weak**
2	Big	Traditional	Strong
3	Big	Lean	Weak
4	Big	Lean	Strong
5	Medium	Traditional	Weak
6	Medium	Traditional	Strong
7	Medium	Lean	Weak
8	Medium	Lean	Strong
9	Small	Traditional	Weak
10	Small	Traditional	Strong
11	Small	Lean	Weak
12	Small	Lean	Strong

Experimentally, changes were incorporated into the base case simulation model to represent changes to the process if lean principles were applied. The "specify value" principle was accomplished by reordering the delivery sequence to accommodate the erector's needs rather than the fabricator's. "Eliminate muda" was accomplished by changing the material delivery and shakeout activities to reduce double handling. "Re-thinking methods" was achieved by eliminating the unloading and shakeout activities altogether. "Focus on objects" evaluated the flow consequences of changes to delivery sequence and buffer size. "Release resources" was incorporated by pulling materials from the fabricator's yard just in time to support construction. Finally, the "strive for perfection" principle was accomplished by combining all of the previous improvements and reducing the models re-work rate to zero.

RESULTS AND ANALYSIS

Table 7 summarizes the changes to the process metrics (cycle time, productivity, utilization, throughput) caused by the inclusion of the "lean principles" into the base case model. Table 8 ranks the results for all possible scenarios. Improvement to cycle time, productivity, utilization and throughput due to the application of lean principles is calculated by comparing the outcome of each principle to the base case. Remaining waste is calculated by comparing the least erection cycle time, which resulted from "strive for perfection" model, to the cycle time of the other principles.

All principles implemented demonstrate improvements; i.e. the first hypothesis, which is lean principles will improve project performance, is fundamentally true. However, improvement varies from one principle to another and waste is still encountered in all first five principles (Table 7).

Table 7: Changes and Improvements to "as is" Model when Lean Principles Implemented

PRINCIPLE	CHANGES TO "AS IS" MODEL	IMPROVEMENTS	REMAINING WASTE
1- Specify Value	Materials were specified by BAYS instead of LEVELS.	Cycle time by 1.3% Productivity by 1.67% Utilization by 0.53% Throughput by 1.29%	30.29%
2- Eliminate *Muda*	Reduce contributory activities by combining unload activities to shake out activities.	Cycle time by 9.79% Productivity by 9.17% Utilization by 9.4% Throughput by 10.86%	21.76%
3- Rethink Your Operating Methods	Buffer size is changed from big to medium.	Cycle time by 4.68% Productivity by 6.67% Utilization by 6.56% Throughput by 4.91%	26.88%
4- Focus on Actual objects from beginning to completion	Similar to changes in principle-1, the difference is that value is observed within erection process with small buffer size and strong coordination.	Cycle time by 11.76% Productivity by 12.5% Utilization by 7.14% Throughput by 11.77%	17.41%
5- Release Resources for delivery just when needed	Materials are pulled from fabricator yard at the right time in the right quantity to the erection site.	Cycle time by 13.96% Productivity by 20.41% Utilization by 21.95% Throughput by 16.24%	11.35%
6- Form a Picture of Perfection	All the aforementioned changes besides that unload and shake out activities were eliminated and rework rate was assumed to be zero.	Cycle time by 31.45% Productivity by 37.17% Utilization by 59.17% Throughput by 45.88%	~ 0.00%

The volatility and buffer size questions are illustrated by examining the just-in-time principle (i.e., principle 5). Just-in-time releases resources for delivery just when needed. Table 8 shows that implementing this principle provides good results and has the least waste.

However, is it the most effective principle? What unintended consequences result from applying just-in-time delivery methods? As previously mentioned, one portion of the study is to evaluate the impacts of exogenous factors such as traffic and errors in delivery sequence on system performance, particularly as buffer sizes vary. Table 9 reorganizes research results according to the buffer size. Notice that the smaller the buffer size the more variable a system becomes. For example, when the buffer size is small cycle time ranges from 22.00 days to 31.70 days as opposed to when the buffer size is big cycle time ranges from 24.34 days to 27.57 days. Does this mean that big buffers add value to construction projects or do they add volatility? The answer to this question is controversial because big buffers shield downstream activities from uncertainty, e.g., errors of materials delivery. On the contrary big buffers may become obstacles against improvement, as they require more activities and muda.

Table 8: Showing Results for all Possible Scenarios

Scenario	**Best to Worst**	**Cycle Time**	**Productivity**	**Utilization**	**T-put**
12	1	22.00	0.893	80.87	45.45
10	2	23.72	0.955	73.29	42.16
8	3	23.81	0.973	72.15	42
4	4	24.34	1.015	67.82	41.08
7	5	24.57	1.05	66.30	40.70
3	6	24.87	1.09	65.85	40.21
6	7	25.53	1.10	65.30	39.17
5	8	26.28	1.12	64.04	38.05
2	9	27.22	1.18	60.42	36.74
1 (Base)	**10**	**27.57**	**1.20**	**60.10**	**36.27**
11	11	29.35	1.23	59.20	34.10
9	12	31.70	1.25	58.80	32.13

Table 9: Effect of Buffer Size on Cycle Time

Scenarios	**Buffer Size**	**Cycle Time**			
1, 2, 3, and 4	Big	24.34	24.87	27.22	27.57
5, 6, 7, and 8	Medium	23.81	24.87	25.53	26.28
9, 10, 11, and 12	Small	22.00	23.72	29.35	31.70

An alternative analysis of buffers is shown in Figure 4 that graphs the daily output/input ratio for the base case and scenarios 8 (case 2) and 12 (case 3). The buffer size in the base case and case 2 is relatively large and hence the flow of steel members is not continuous. In other words, the members that are erected at any point are substantially less than the members that are on-site, in storage, e.g., output/input ratio is 26% and 45% for the base case and case 2, respectively. Regarding case 3, the output-input ratio is close to 100% which means that there is a continuous flow and virtually no stockpile. This means that there are few interruptions to the iron crew to unload and shakeout steel. Consequently, productivity is enhanced substantially. Figure 4 demonstrates that materials can flow if management moves toward lean construction.

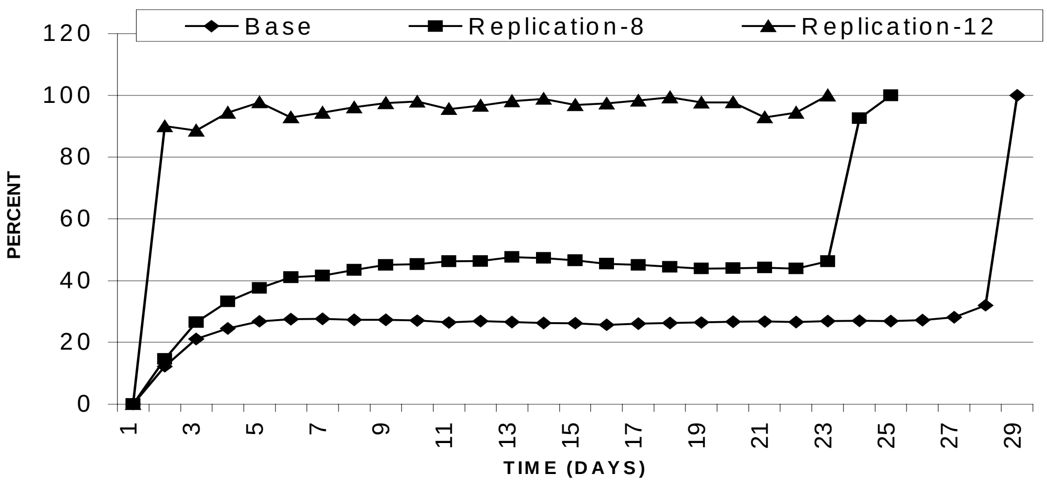

Figure 4: Showing Output Input Ratio Per Day for Base Case and Cases 2 and 3

For the sake of clarity only three scenarios have been chosen for the remaining analyses: the base case, replication-8 (i.e. case 2) and replication-12 (i.e. case 3). These cases vary in terms of buffer size, i.e. big, medium and small. Experimenting with lean principles, case 3 was the leanest because buffer size was small and contributory activities are smallest. However, introducing exogenous factors to the model effects the behavior of the leanest scenario dramatically. It is true that maintaining a zero buffer leads to an efficient process, yet at the same time it causes the process to become fragile. Figures 5, 6, and 7 demonstrate 500 simulation runs which introduce variation in the models. Introducing just one uncontrollable change, e.g., delivery errors that affects material delivery times increases the average cycle time by 1.25 days (Figure 6). The cumulative impact of additional changes is illustrated in Figure 7. Delivery errors and traffic delays increase cycle time by 2.5 days.

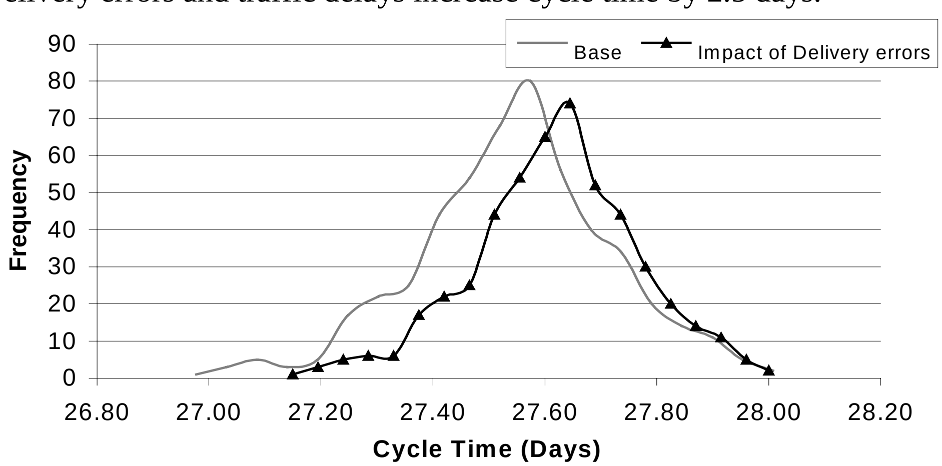

Figure 5: Volatility Experimentation for Base Case

This demonstrates that lean principles increase volatility in construction processes. However, for this particular case study the lean outcomes still demonstrate better results even after incorporating volatility factors.

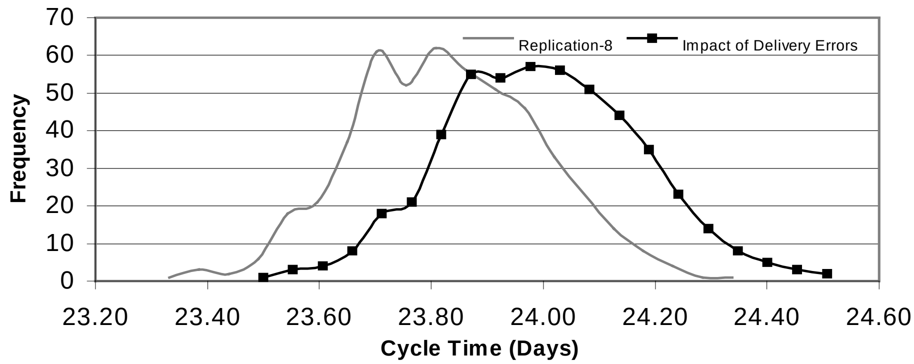

Figure 6: Showing the Shift of Cycle Time of Case 2 When Delivery Errors Could Happen

Therefore, the hypothesis that “managing construction buffers is a key to moving towards leaner processes” also appears to be true. However, buffer size depends on the degree of influence management has over uncontrollable factors that affect a project. In other words, when a buffer size is moderate an optimum balance between improvement and stability is achieved.

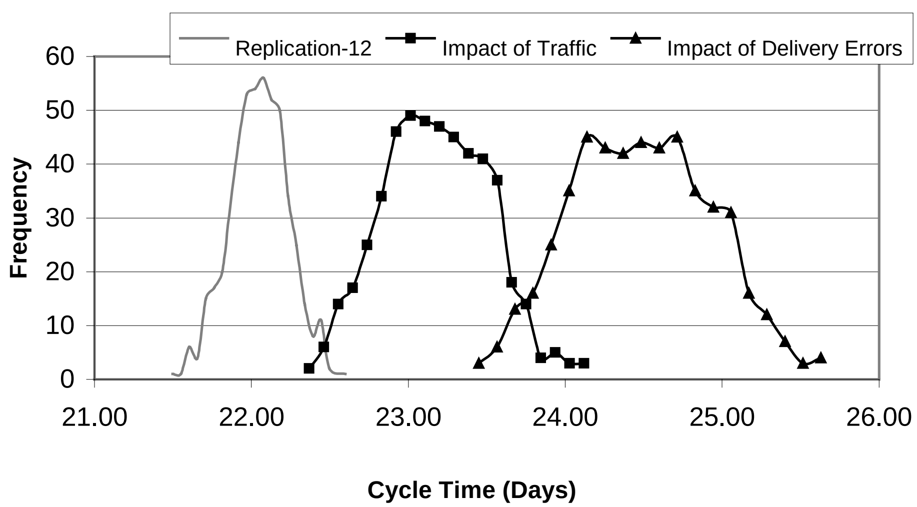

Figure 7: Showing How Volatile Case-3, Traffic and Delivery Sequence are Bad

CONCLUSION

This study implements the five principles of lean production to a traditional steel erection process using computer simulation. The principles are specify value by a product, rethink your operating methods, focus on actual objects from beginning to completion, release resources for delivery just when needed and strive for perfection. The simulated principles improved project performance and the erection process became exceedingly efficient when all principles are used simultaneously.

However, implementing lean principles increases volatility of the erection process. According to lean production theory big buffers are waste and should be reduced or eliminated from the value stream. However, maintaining a zero buffer at the erection site made the process highly volatile and sensitive to variances in reliability. Maintaining large buffers causes significant contributory activities that influence production efficiency. Therefore, managing buffer size is a critical component for implementing lean principles in construction processes.

It was clear from volatility experimentation that moving from traditional construction to lean construction, construction processes became fragile and management will not get full benefit from isolated implementation of production theory. This suggests that a systems view for value-creating activities in the construction industry is critical and is consistent with current lean thinking (Tommelein 1998).

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