INTERPLAY OF PROJECT COMPLEXITY AND LEAN PRODUCTION METHODS

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ABSTRACT

Recent studies have demonstrated the potential of lean production methods for improving the effectiveness of construction processes. This study investigates the effect of lean production principles on construction projects that manifest different degrees of structural complexity. The importance of specific lean principles (specify value, rethink your operating methods, focus on actual objects, release resources for delivery just when needed and strive for perfection) is evaluated using discrete event simulation for three different structural steel projects. The projects' configurations range from simple to complex and include a small commercial building, a mid-rise office building and a hospital expansion. Results of simulation analysis indicate that the more complex projects exhibit increased "lean" process improvement when compared to the simpler projects. Our results also indicate that traditional production planning methods are more effective on simpler projects. In addition, domain uncertainty and project complexity are highly coupled as regards the improvements that are realized by applying lean principles. In short, project characteristics play a significant role on the impact of lean production theory when it is applied to construction processes. It is possible that hybrid construction process design approaches, such as a push-pull system, will behave better than a pure pull system. There is a need for a better understanding of how to apply lean principles to maximize improvement to construction systems.

KEY WORDS

Lean principles, process simulation, project characteristics, complexity, volatility, buffer size

INTRODUCTION

Recent studies have demonstrated the potential of lean production methods for improving the effectiveness of construction processes (Kartam et al. 1995, Tommelein 1998, Alsudairi et al. 1999). However, transferring lean production principles to the construction industry requires a careful examination due to the inherent peculiarities of the industry. The main objective of this study is to investigate the effect of lean production principles on construction projects that manifest different degrees of project complexity. The importance of specific lean principles (specify value, rethink your

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operating methods, focus on actual objects, release resources for delivery just when needed, and strive for perfection (Womack 1996)) is evaluated using discrete event simulation.

This paper examines three structural steel projects out of a set of ten such projects evaluated. The projects' configurations range from simple to complex and include a small commercial building (referred to as Louisville project), a mid-rise office building (referred to as Denver Project) and a hospital expansion (referred to as Longmont project). This study is a continuation of the authors’ work presented at the IGLC-7 (Alsudairi et al. 1999).

The erection processes for the three projects were modeled in a simulation package called Extend (Imagine That, Inc. 1997). The simulation results for the three projects demonstrate that project characteristics do influence the effect of lean principles. Also the behavior of the lean models of the three projects changed dramatically in response to simulated exogenous disruptions to the lean process. In general, we found application of lean practices made the case study processes more efficient and more fragile in proportion to the process complexity.

CASE STUDIES

Louisville Project

The Louisville project is the simplest case study of the three. The fabricator is located within the city limits. The project site is fairly large with good accessibility and can accommodate one third of the total number of steel members. The members are highly interchangeable; i.e. the steel members are mainly equal in size and shape, which made erection and fabrication easier when compared to the other case studies. The likelihood for mismatches to occur among delivered materials and their erection sequence is low.

The erection process contains sub-processes of unloading, shake out, and erection. In practice, the unload and shake-out activities were combined with each other most of the time during the erection process.

Denver Project

The Denver project is the moderate complexity case study. The fabricator is located within the city limits. However, the project is located in Denver Technology Center, which is one of the busiest areas in the city which made material deliveries prone to delays. The project site exhibits fair accessibility and can accommodate 11% of the total number of steel members. The members are not as interchangeable as they were on the previous project. Thus, the need to coordinate delivery of materials between the fabricator and the erector is crucial. In practice, materials were delivered by levels in a sequence that did not match erection progress. The likelihood for mismatches to occur is high.

The erection process contains all major sub-processes of unloading, shake out, and erection. Due to the weak coordination between the fabricator and the erector, the non-adding activities consumed almost 40% of the erection crew time; non-value adding activities are those which create no value and are either required by the product development, e.g. unload materials, or not, e.g. rework. When delivered steel members did not match erection sequence, they were stockpiled on the site. The material yard was so congested that double handling was inevitable.

Longmont Project

The Longmont project is the most complex case study of the three. It is a hospital building with seven stories and a complicated floor plan. The fabricator is located outside the limits of Longmont. The project site is limited in area, it contains existing buildings with limited accessibility, and can accommodate 5% of the total number of steel members. Most of the steel members were designed for a specific location in the building, which made erection and fabrication more difficult when compared to the other case studies. The characteristic of interchangeability in the previous case studies almost disappeared in the Longmont project.

The erection process contains sub-processes of unloading, shake out, and erection. In practice, steel members were delivered to the site by levels. On average, every level contained more than 300 pieces of different sizes and shapes which made matching and inventory a tedious and time-consuming job. Almost 45% of the erection crew time was utilized in non-value adding activities.

Table 1 lists the project characteristics that were used to describe project complexity. Most of these characteristics, which are divided into three sub-categories, are adopted from Eraso and Slaughter (1994), Eraso (1995), Slaughter and Eraso (1997), and Thomas at al. 1989). Each characteristic has a subjective score that varies from 1 to 4, where a score of "1" means excellent/no effect and a score of "4" means bad/large effect. Accordingly, a total score approaching 32 indicates a complex project. A total score approaching 8 indicates a simple project. Thus, the Louisville project is the simplest among the three with a score of 11, the Longmont project is the most complex one with a score of 28, and the Denver project lies in between with a score of 20.

Table-1: Comparing the three projects in terms of their characteristics (1=good, 4=bad).

Project Characteristics	**Louisville**	**Denver**	**Longmont**
1- Site Characteristics			
• Accessibility	1	2	3
• Material yard	1	2	4
• Presence of existing structure	1	3	4
• Fabricator location	1	2	4
2- Material Management			
• Material Handling	2	3	3
3- Design Characteristics			
• Regularity of structure	2	3	3
• Weight of member	2	3	3
• Number of bays per floor	1	2	4
Total Score	**11**	**20**	**28**

The first sub-category of site characteristics includes accessibility, material yard, presence of existing structures and fabricator location. For example, a site with very limited access for materials handling and little space around existing structures would be expected to have significantly longer construction durations than a more accessible site (Slaughter and Eraso 1997). The Louisville project has good characteristics according to the relative score and the Longmont project has bad site characteristics.

The second sub-category is material management, which describes how the erection crew organizes materials in the project site in accordance to erection sequence. Previous study concluded that material management has a crucial role in improving project performance. A related work by Thomas et al. (1989) indicated: considerable time was spent in moving the steel and other materials in search of the required pieces; this is because steel was randomly delivered and unloaded. Tommelein (1997) also emphasized the need to plan materials location for storage and staging their path for movement in order to avoid unnecessary handling of them, especially because many of them are heavy and bulky. These factors were considered in the modeling design so that one can study their impact on construction processes.

All three projects were ineffective with respect to material handling. The Louisville project had a better score because the number of steel members was small which made organizing them easier than on the other projects. Additionally, the material yard was big which made material organization easier than on the other projects.

The last sub-category is design characteristics, which includes regularity of structure, weight of members and number of bays per floor. A study by Slaughter and Eraso (1997) emphasized that the more regular or rectilinear the structure, the more standardized the connections, and the lighter and more maneuverable the members, the faster the connection can proceed. The Longmont project exhibits complicated design characteristics where bays have irregular shapes. This made steel members less interchangeable than on the other two projects.

To illustrate the differences among these three case studies, data of the "as is" models are compared (Figures-1). Crew utilization is the ratio of the time the crew spent in value adding activities to the total time. The utilization rates are 66%, 60% and 55% for Louisville, Denver and Longmont projects respectively. The average daily throughput (member/day) is 41.5, 36.3 and 34.4 for Louisville, Denver and Longmont projects respectively. The average total cost to erect a steel member is $36, $44 and $53 for Louisville, Denver and Longmont projects respectively. The total time to erect a steel member is 10.9 minutes, 13 minutes and 14.3 minutes for Louisville, Denver and Longmont projects respectively.

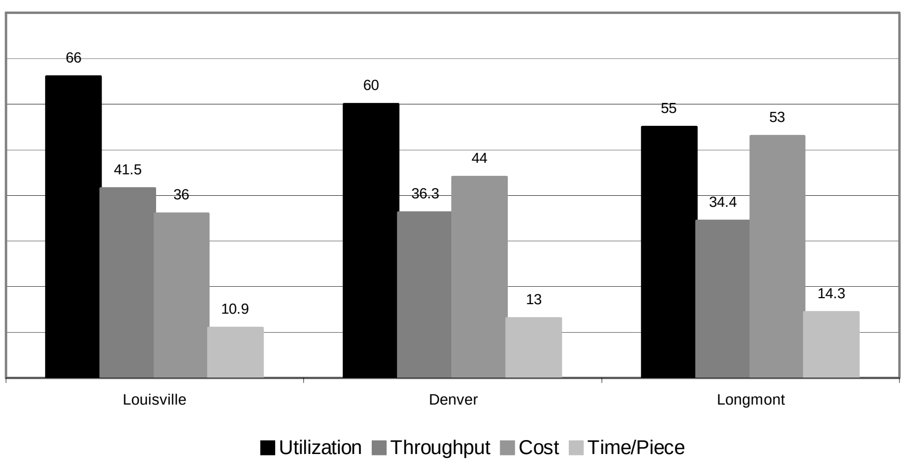

Figure-1: Comparing utilization rate, throughput and cost for Louisville, Denver and Longmont projects.

Clearly, the Louisville project exhibits better "as is" performance than either the Denver or the Longmont projects. However, from the utilization metric shown in Figure-

1, it is apparent all three projects contain significant waste. Rework, existence of non-value adding activities, delays of materials and disruption of work caused by unplanned tasks such as deliveries of materials all caused waste.

IMPLEMENTING LEAN PRINCIPLES

Before implementation, processes and statistical data for every case study were modeled/collected by means of field observations. The data were used as basis for modeling and simulating the real system. Each model was verified and validated to be certain that the models were error free and unbiased (Alsudairi et al. 1999).

Lean manufacturing theory is founded in 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 (Womack and Jones 1996). Table-2 summarizes interpretations of these principles when implemented in the three case studies.

Table-2: Presents lean principles and how they are used to change construction processes (Alsudairi et al. 1999).

PRINCIPLE	**CHANGES TO “AS IS” MODEL**
1- Specify Value	Materials were specified by BAYS instead of LEVELS.
2- Eliminate *Muda*	Reduce contributory activities by combining unload activities to shake out activities.
3- Rethink Your Operating Methods	Buffer size is changed from big to medium.
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.
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.
6- Form a Picture of Perfection	All the aforementioned changes besides unload and shake out activities were eliminated and rework rate was set to zero.

For this research the six lean principles were individually implemented to study their impact. After verifying and validating the “as-is” models for the three case studies, lean principles presented in Table 2 are separately introduced to the “as-is” model for every case study (Alsudairi Forthcoming). Figure 2 depicts the improvement in cycle time, i.e., the time to finish the whole project. It is clear that the more complex the project, the more influence lean principles have on construction processes, which is consistent with Tommelein's (1998) study that presented 'matching problem'. In Tommelein (1998) scenario with interchangeable pipe spools, pull will have no effect on performance. Pull is useful when matching problems exist, which are one characteristic to describe complexity.

The first three principles in Figure 2 did not make a significant improvement to the simple Louisville project. In fact, the third principle, rethink your operating methods, had a negative impact. Reducing the buffer size did not reduce double handling because the material yard could carry materials for one floor very easily. In fact, reducing the buffer size indirectly increases the possibility of mismatch of delivered materials and the erection sequence. In the Denver and the Longmont projects reducing buffer size contributed significantly to reducing double handling. On the other hand, reducing the buffer size diminished fabricator/erector coordination. However, the benefits gained from reducing double handling compensate for the weakened coordination. A similar study found that relative small buffers were easier to manage than bigger ones (Thomas et al. 1989).

Implementing one or few lean principles is not enough. Improvement varies from one principle to another. That is to say waste is still encountered in the first five principles in all cases even though there is an improvement (Figure 2). In fact, previous study proved that focusing on one aspect of a process or an organization will not lead to a complete elimination of waste; lean principles should be addressed wherever the value existed (Womack and Jones 1996). This is because lean theory adopts a system view where integration among its principles is very crucial (Tommelein 1998).

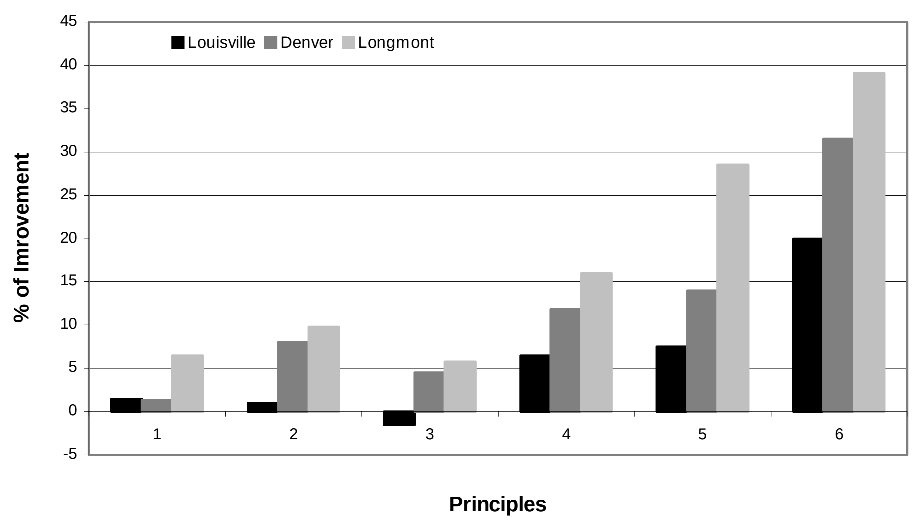

Figure-2: Showing improvements in cycle time after implementing individual lean principles for the three projects.

One major drawback to implementing lean principles is that they make construction processes more volatile; i.e., they will alter their robustness (Alsudairi et al. 1999 and Naim et al. 1999). One major lean principle is to 'pull value'. That is to say big buffers or safety stocks are waste because they require more non-value adding activities (Womack et al. 1990, Womack and Jones 1996). On the contrary, it is preferable to have big buffers (Howell and Ballard 1998). The next section will discuss the question of buffer in more detail.

FROM LEAN PRODUCTION TO LEAN CONSTRUCTION

Three models are used for every case study the "as-is" model, the "lean" model and the "semi-lean" model. The "as-is" model refers to the observed field conditions. The "lean" model includes changes that refer to the first five principles shown in Table 2. In summary, the changes are steel members were specified by bays, non-value adding activities were reduced from the erection process and steel members were pulled from the fabricator yard at the right time in the right quantity to the erection site. The next sections will compare the three models in more details.

All three models encountered rework to approximately 10% of the members where they needed adjustment to fit properly (Table 3). In terms of the buffer size the "as-is" model has a buffer that is oversized where steel members are stockpiled. The buffer size of the semi-lean model is large to an extent that it requires reduced or no double handling. In the lean model the buffer size is designed to optimize material deliveries, to minimize inventory work, and to meet the demand of downstream activities. In other words, materials are pulled into and through the process on a part-by-part in small quantities only when required by the next work station (Akintoye 1995). Coordination between the fabricator and the erector is carefully designed in both the semi-lean model and the lean model. In the "as-is" model steel members were delivered by levels in a sequence that does not match erection sequence. For instance, erection crew may receive materials for bay-20 of the third level while working on bay-7 of the same level or even for a different level.

Another difference among the three models is the relationship between fabrication and erection processes (Table 3). The "as-is" model has the worst synchronization where materials are delivered to the site in huge quantities with no or weak coordination. The erection crew has to interrupt the flow of erection work and move to unload materials that might be used in the next week. Because such deliveries were not planned to meet erection sequence trucks carrying materials sometimes spent more time waiting than the time to unload materials. In the lean model the flow of materials is designed so that it is released from the fabricator's yard when needed with optimized quantities as previously discussed. Most of the time the work of the erection crew in the lean model goes uninterrupted. This tends to minimize lot size, queues, and work-in-process (Akintoye 1995). The semi-lean model lies in between where materials released in accordance to erection sequence as in the lean model but relatively in larger quantities that may interrupt erection flow.

Table 3: Summarizes the meaning of the "as-is" model, the semi-lean model, and the lean model

	Rework	**Inventory Size**	**Delivery Sequence**	**Relationship Among Different Processes**
As-Is	Encountered	Over Sized	Random	Not Synchronized
Semi-Lean	Encountered	Reasonably Sized	Perfectly Coordinated	Statically Synchronized
Lean	Encountered	Optimized	Perfectly Coordinated	Dynamically Synchronized

Thus, from the previous sections one can tell that the "as-is" model is a push system, the lean model is a pull system, and the semi-lean model is neither a push system nor a pull system. That is to say it is like a push system because materials were maintained in large quantities and stored at the erection site. Likewise, the semi-lean model is like a pull system because materials were carefully selected from the fabricator yard and delivered in a sequence that matches the erection sequence.

Simulation results show that releasing resources just when needed, i.e. keeping small buffers, made construction processes very efficient. Materials are not stockpiled on the site so that they do not require double handling or increase the time to unload/shake-out delivered materials. This is consistent with a study by Pheng and Hui (1999) where JIT lead to a neater site with more space for workers to work in and clear space for mobile plant (for example, mobile cranes, forklifts, and dumpers) to move about on site. Figure 3 presents the average time to erecting a steel member for the three case studies. The ideal values shown in Figure 3 resulted from a hypothetical scenario where there are no non-value adding activities and zero rework. One may notice that lean principles improved performance differently for each level of project complexities.

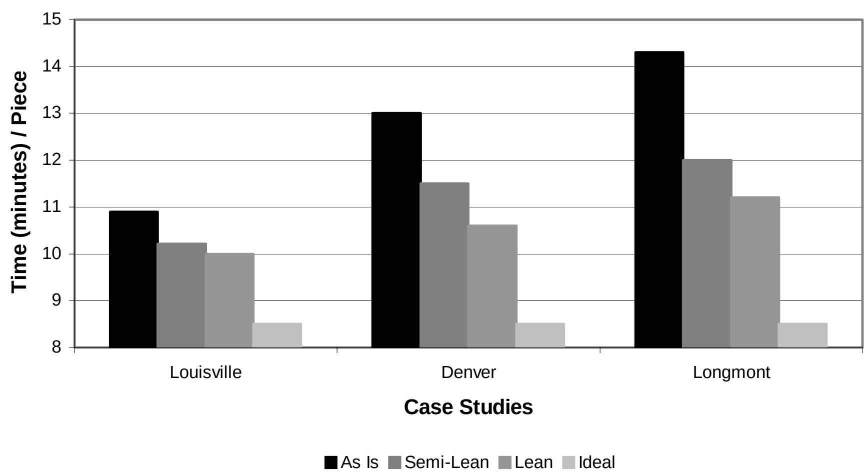

Figure-3: Average time to erect a steel member when volatility factors are not considered.

The simulated models (i.e., the "as-is", the semi-lean, and the lean) did not include fundamental factors such as design issues, rework rates and so on, which are not the same among the three case studies. To approach ideal performance lean theory must be addressed at a broader scope; e.g. at fabrication/design phases. In fact, one principle of the lean theory is to 'look at the whole' (Womack 1999b).

A study by Tommelein and Weissenberger (1999) investigated the location of buffers in the steel industry using JIT approach. This study investigates the impact of volatility and different project complexities on the application of lean principles. Thus, combining the two studies could be one possible way to further examine buffers and their locations.

Volatility

The results from Figure 3 are when exogenous factors are not considered. Exogenous factors are conditions beyond the control of the contractor that cause volatility in the process performance. Exogenous factors may include variation in activities' duration, traffic conditions and errors in material sequence (Alsudairi et al. 1999). Most construction projects will encounter all or some of these factors. Figure 4 shows the same results presented in Figure 3 when volatility conditions are considered. When traffic is bad or when delivery errors occur, the "semi-lean" model behaves better than the "lean" model; this is because in the pull systems responding to unexpected demands is not possible (Pheng and Tan 1997). Indeed this is what happened in the lean model when delivered materials do not match erection sequence. The erection crew has to wait for the right materials which increased the total time to have a steel member erected. The bars on the "semi-lean" and the "lean" results in figure-4 show the increase in time to erect a steel member due to exogenous factors. In fact, both the "semi-lean" model and the "as-is" model were not affected significantly by such factors; it is only the "lean" model that was affected by exogenous factors. Also notice how volatility is proportional to project complexity.

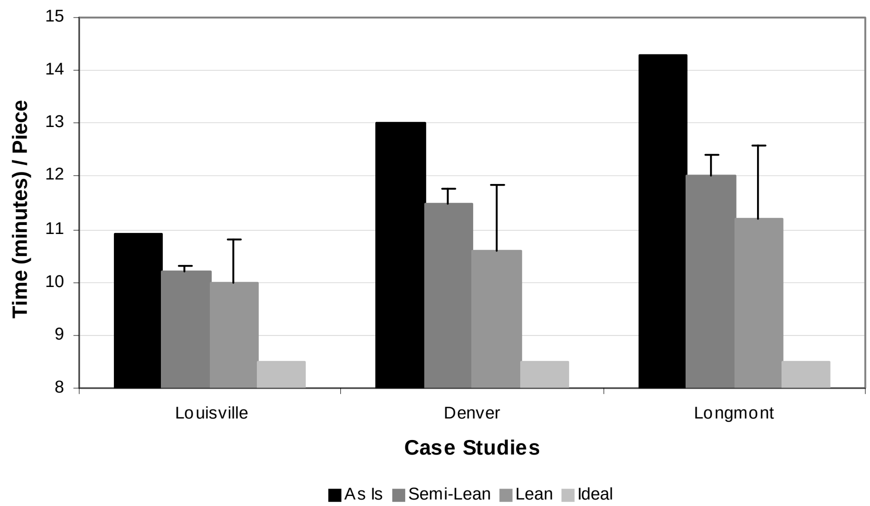

Figure-4: Showing the change in average time to erect a steel member when volatility factors are considered.

Another method to evaluate the effect of exogenous factors in the Louisville project is to calculate a confidence interval. A 95% confidence interval for the difference in cycle time for the "as-is" model and the "semi-lean" model is 0.62 day to 0.71 day. Such an interval tells that the "semi-lean" model is superior to the "as-is" model even after volatility factors are included. Likewise, the 95% confidence interval for the difference in cycle time for the "as-is" model and the "lean" model is 0.06 day to 0.18 day, which is very close to zero. In other words, improvement gained from implementing lean principles is very marginal when project characteristics are simple. The small marginal improvement results from a simple "as-is" erection process where most of the characteristics remained unchanged.

Push systems increase non-value adding activities such as double handling even though they protect downstream activities from uncertainty. Pure pull systems are very efficient but they increase the fragility of construction processes. However, the "semi-lean" model, which is a push-pull system, improvement can be achieved in all three cases before and after the inclusion of volatility factors; i.e., it combines the efficiency of the pull system and the stability of the push system.

Figure-5 shows the impact of buffer size on project performance, which was measured by the total cycle time of the project, when all volatility factors are considered. It ranges from very small buffers to very big buffers. The black dots in figure-5 reflect independent runs for a specific buffer size. Notice how variable the outcomes are when buffer size is small. To a certain extent the larger the buffer size the less variable and the better the outcome. When the buffer size is large, variability becomes smaller however performance decreases. For a system with large buffers, arriving materials are stockpiled on the site, which becomes very congested. Due to increased site congestion, more time is required to look for the right material, hook it and lift it for erection. When the buffer size is moderate one may notice that the system reaches its optimum performance.

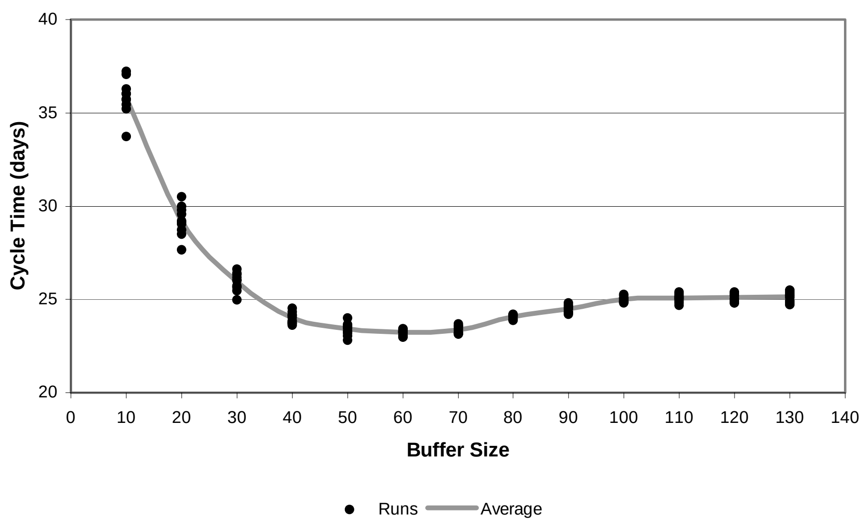

Figure-5: Showing the effect of buffer size on project performance for Denver project when all exogenous factors are considered.

The question is now, what is the optimum buffer size and where should they be located. It is very difficult to answer such a question when every project is essentially unique (Womack 1999a). In steel projects buffers could be located at fabricator's yard either as raw or prefabricated materials or at erector's yard as previously discussed. However, it is better to keep the buffer size as small as possible, while still shielding downstream activities from uncertainty caused by volatility factors. Sometimes the minimum safe buffer size will be quite small depending upon the site and design characteristics, for instance on the Louisville project. Other times the safe buffer size will be large, for instance the Longmont project.

One great lesson is that there is a need to better understand of how to apply lean principles to maximize improvement to construction systems.

CONCLUSION

The potential of lean theory is manifested by studying its impact on three steel projects with different characteristics, i.e. ranging from simple to complex. Results of simulation showed that application of lean theory improved performance of the three projects in proportion to their complexity. Complex projects exhibited increased lean process improvement when compared to simpler projects.

However, implementing lean principles did not bring different construction processes to the same level of performance. There are several reasons behind such a difference in performance. First, there are internal factors that were not dealt with during simulation such as rework. All three projects encountered rework at different percentages. Previous studies proved that mistakes follow certain patterns and hence can be avoided or reduced. Second lean theory was limited to only construction processes. Widening the scope of the study to include design and fabrication could be considered in order to minimize project complexity.

The behavior of lean models were sensitive to uncontrollable factors such as traffic. Adopting a pull system altered the robustness of construction processes. On the other hand, keeping a push system made construction system very inefficient, where non-value adding activities were inevitable. It is possible that hybrid construction process design approaches, such as a push-pull system, will behave better than a pure pull system. There is a need for a better understanding of how to apply lean principles to maximize improvement to construction systems.

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