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LEAN CONSTRUCTION AND SIMULATION

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ABSTRACT

This paper explores the relationship between simulation and the emerging topics of Lean Thinking and lean construction. The ideas which have motivated the evolution of lean construction concepts are presented. The use of simulation as a means of evaluating the benefit of using lean construction techniques is discussed. Two examples of lean thinking based re-design of common construction processes are described and evaluated using construction process simulation. The paper is designed to promote consideration of the similarities between simulation based process improvement and process re-design related to the application of the principles of lean construction.

1 INTRODUCTION

The topic of Lean Thinking has gained credence over the past decade. During the 1980s, the Institute of the Automobile at MIT did a comprehensive study of manufacturing processes in the automobile industry. This project and the concepts developed within the context of this initiative were documented in the book "The Machine that Changed the World (Womack, Jones, Roos 1991)." One of the major ideas which was developed as part of this work was called Lean Production.

The concepts of Lean Production were discussed by Koskela in a report generated at Stanford University in which he coined the term "lean construction (Koskela, 1992)." Lean thinking is a broader term which has come into the vocabulary as the title of a book which attempts to update and expand the concepts developed in the original automobile study (Womack and Jones 1996). Recently, the Lean Construction Institute (LCI) has begun to work to disseminate the concepts of "lean" to one of the most traditional and change resistant industries.

2 WHAT IS LEAN PRODUCTION / CONSTRUCTION

In general, lean concepts developed from initial work done by Deming and others targeting quality issues in the manufacturing sector. The quality movement as characterized by the Total Quality Management (TQM) mantra zeroed in on the need to study the manufacturing process to improve quality, meet the needs of the customer, and reduce cost due to non-value adding work tasks. Deming indicates that processes are key to satisfying the customer and that process improvement will lead to improved quality of the product.

The process approach is in contrast to the "end-item" approach which concentrates on the end objective rather than the means of achieving the objective. The end item approach is like the child which dreams of a puppy, visualizes a puppy, and then assumes that something will happen (e.g. Mom and Dad will get tired of being pestered) and a puppy will appear. The process approach focuses on the steps or sequence of events (process) which can be followed to obtain a puppy.

3 THE TRADITIONAL VERSUS THE LEAN APPROACH

Looking at the situation somewhat differently, if we are going to manufacture a product (e.g. a lawnmower, a refrigerator) and we know what resources are available (e.g. manpower, money, materials, machines, etc.) as well as have a clear idea of the appearance and performance characteristics of the item product, a transform can be found to link the resources to the end product. The management and production team can be tasked with the job of transforming the resources into the end product.

The problem is that the transform usually looks at existing processes and modifies them to generate the end product even though the existing processes are not optimal to the problem at hand. To make a mathematical analogy, a set of linear equations can be solved by inserting random values of x and y until the equations are satisfied. This is time consuming and inefficient, but if it works some people will accept it. The process is neglected since old methods, although inefficient, can be cobbled together.

The transform is like a "black box" with inputs on one side and the desired output on the other. What processes are in the black box which transform the inputs into the outputs are proposed based on previous means and methods. This leads to recycling and adaptation of old ideas and modification of the end item to fit the processes that can be modified and employed. There is a high probability that the processes assembled will not fit well and lead to inefficiencies impacting cost and quality of the end item.

4 USING A LEAN APPROACH

Lean thinking concentrates on going into the "black box" and studying the processes with the object of smoothing out interfaces, removing non-value adding activity, and in some cases completely rebuilding the processes or generating new processes. The assumption is that if the process is running smoothly, high quality products will be generated with a high level of productivity.

Existing management and production techniques concentrate on measuring what comes out of the black box. Cost control and scheduling in the construction industry are techniques designed to measure the output. If the output is in a given range, the process is accepted (even though it might not be optimal or even good). Only if the product is late or above cost expectations are the processes studied to determine how the end product criterion being violated can be achieved.

5 PRODUCT DRIVEN PROCESSES VERSUS PROCESS DRIVEN PRODUCTS

The trend in manufacturing is to make the product servant to the process since cost and quality improve. This generates a "culture of change" which simulates new methods and new products. Construction lacks the "culture of change" which drives other industries. Construction has for 5 thousand years visualized an end item and then generated methods or processes to achieve the end item. These processes have remained static and produced facilities which don't fully meet the needs of the user but are accepted since the means, materials and methods of building are entrenched.

Acceptance of the old processes leads to expensive buildings which are hard to build and hard to maintain. Research and development is almost non-existent since the owner or buyer is willing to pay for the inefficiencies of the old way. We still build buildings and facilities at the site as if we were hand constructing a 17^{th} century desk with inlaid marquetry for Louis XIV.

6 CONSTRUCTION SIMULATION AND LEAN CONSTRUCTION

Lean thinking focuses on studying processes with the objectives of improving flow of resources so that a product of high quality and acceptable cost can be produced. In fact, we have been studying construction processes using simulation for the past 20 years. Since the construction industry is totally *change and research* adverse, the mind set of viewing a construction project as the management and organization of a set of simple and complex processes has not gained purchase on the slippery slopes of expedience.

However, a few exceptions are worthy of note. Some large contractors (primarily in Europe and Japan) have begun to understand the advantage of redesigning the end item to allow the use of advanced construction processes such as precasting and automation.

In most cases, the differing perspectives of the designer who is visual and end item oriented and the constructor who is production oriented clash and block the improvement in both process and product. Since designers have until recently called the tune, the contractor has been content to follow the dictates of the design professional and build end items which require traditional and expensive processes in the field.

In the last 10 years, the concept of Design Build has begun to change the ancient paradigm of visualize and then develop production plan. Since the designer and constructor have common financial interests when working in a Design Build mode, the designer is under pressure to design for construction as well as for function. This begins to mimic the manufacturing sector where a refrigerator or lawn mower is designed to meet both functional requirements and production criteria keeping costs and quality in mind. The product is designed to use the most efficient production processes.

For many, lean thinking and simulation are very closely linked or even synonymous. Processes can be efficiently modeled and analyzed from a practical perspective using simulation. Therefore, the concepts of lean construction can be validated using simulation as means of testing lean concepts prior to actual field implementation.

7 SIMULATION AS A VALIDATION TOOL

Tommelein (1998) used simulation in order to compare different ways to sequence work area completion and material delivery to a construction site. Pipe spools were chosen to illustrate the effects of different sequencing since pipe spools are engineered products. Various sizes of pipe spools are normally only required in small quantities. The crew can only install pipe spools if they have the right ones at hand. This so-called matching-problem was simulated by Tommelein.

In the first situation, the pipe spool delivery and assembly on site were not coordinated. In this case, the crew has to work with whatever material is available to them and cannot work in sequence. In the second model, the delivery and the sequence of assembly were perfectly coordinated. The crew always has the required pipe spools at hand. The third model included a feedback mechanism. Material production and delivery were first executed in random order, but then priority was given to material that matched the area in which the crew was presently working. This material was "pulled" to site. All three models were simulated using STROBOSCOPE (Martinez 1996). The simulation results show that pull-techniques in material delivery are a useful tool to improve performance.

Balbontin-Bravo (1998) has reported on the use of simulation to improve process production in the manufacture of large precast elements and facilities consisting of large concrete elements. Dragados y Construcciones, one of the largest construction companies in Europe, has used simulation to analyze construction operations for 15 years. Many of their field processes have been re-designed using concepts related to lean thinking. His paper to this conference in 1998 noted major cost savings on operations as diverse as the prefabrication of floating caissons, placement of roller compacted concrete for construction of a dam, and train track renovation. In this application, the use of simulation allows for the identification of non-value adding activities. The savings achieved were on the order of \$200,000 per 100 man-hours of analysis and simulation.

8 LEAN CASE STUDY FOR WALL CONSTRUCTION

A number of small to mid-size companies are beginning to use process analysis and lean concepts to plan field operations. On a recent project, Messer Construction, a Cincinnati-based firm, used process analysis to improve the rate of installation of metal wall frames in a conventional multi-story frame structure. A simulation study was conducted to determine what, if any improvement in the rate of wall frame erection was achieved due to re-design using lean concepts.

As a first step, the building process was analyzed in order to identify all flow units and resources. The most important resources involved in the process of constructing the wall were the materials and the three laborers. The wall was about 65 m long and 3.20 m high. To facilitate assembly, the wall was divided into 10 separate elements that were erected in a linear fashion. The structural framework of the wall consisted of a steel frame and steel studs that are inserted into the frame every 41 cm. The original process design consisted of 4 basic activities: Preparation of the process, erecting the frame, inserting the studs and attaching the exterior board. Due to the division into 10 elements, the whole process can be seen as 10 cycles in which the four basic activities are repeated.

The CYCLONE model (Halpin and Riggs 1992) that was developed for conventional method erection durations for the work tasks is given in Figure 1. Work task times for a Beta distribution are given in Table 1.

Table 1: Durations for Activities in Hours – Conventional

Activity	Lowest value	Mean value	Highest value	Standard deviation
Preparation	1	1.5	2	0.17
Erect frames	2	3.5	5.5	0.58
Insert studs	3	4	5	0.33
Attach board	2	2.5	3.5	0.25

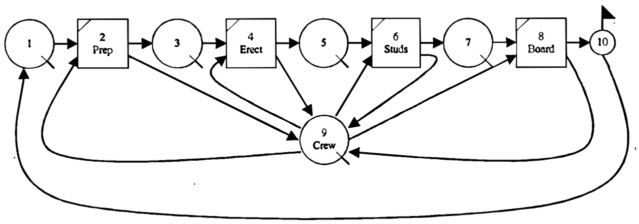

Figure 1: CYCLONE Model for the Examined Linear Construction Process – Conventional

The average cycle time for 10 cycles is 12.16 hours. For 100 simulation runs the average cycle time drops to 11.69 hours. The QUEUE nodes are all, as could be expected, occupied 0% of the time. The time the COMBI nodes are busy corresponds to the assigned durations for the activities. The individual cycle time for each wall segment falls between 12 and 12.9 hours. The variance on the construction site is often larger. The total time, however, matches the total production time of 120 hours that was anticipated for the job (12 hours × 10 wall segments).

Using lean construction concepts, Messer decided to better organize the material on site and to construct the wall without scaffolding. Construction of the wall without scaffolding meant the wall had to be assembled on the floor instead of in an upright position. Thus it was necessary to assemble the exterior frame, to insert the studs and to attach the exterior board while the element is lying on the floor. This made assembly easier, faster and more reliable. The elements were stood up and connected after assembly.

The re-design process was simulated using Micro-CYCLONE. The activities involved in the assembly of the wall were reduced to three for simulation purposes. The first activity involves getting the presorted material and the necessary tools to the site. The second activity includes assembly of the frame, insertion of the studs and braces and attaching the exterior board to the frame. The third activity is lifting, aligning and connecting the element. The durations that were assigned to each work task were obtained on the construction site and are summed up in Table 2. A beta distribution was assumed for the assembly activity. The changed CYCLONE model is presented in Figure 2.

Table 2: Durations for Activities in Hours – Lean

Activity	Lowest value	Mean value	Highest value	Standard deviation
Preparation	-	0.5	-	0
Assemble wall	2.5	3	3.5	0.17
Erect	-	0.5	-	0

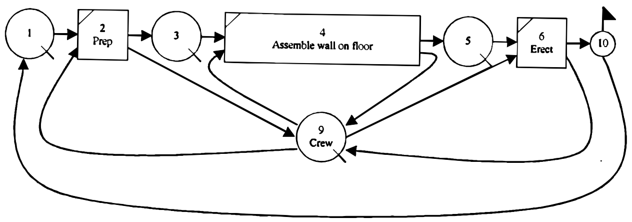

Figure 2: CYCLONE Model for the Examined Linear Construction Process – Lean

The average cycle time for 10 cycles is 4.10 hours/cycle. For 100 simulation runs the average cycle time increases to 4.28. The cycle times are very stable between 4.07 and 4.17 hours. The variability is therefore very small. The total time matches the real total production time of 40. By redesigning the process and applying lean thinking, the total production time was reduced from 120 hours to 40 hours. At the same time the total cost dropped from $20,000 to $7,000.

9 CASE STUDY – WASTE WATER TREATMENT PLANT

Bowen Engineering, an Indianapolis company, utilized Lean concepts in planning work for a waste water treatment plant being constructed in Lafayette, Indiana.

Due to the size of the project, several project managers are involved in the construction. About 60% of the labor and equipment cost spent on the project goes into concrete work, which makes it very attractive for optimization. Installation of formwork is often done in a linear fashion. The process that was selected for further analysis on the project is the construction of the ganged forms for one of the two digester tanks. Ganged forms are steel or aluminum braced formwork panels that are joined together with special hardware. Individual ganged forms are usually connected to form larger elements, or panels, prior to installation. The panels need cleaning and re-oiling after every use. Ganged forms produce a smooth concrete surface and can be assembled to form various shapes. Therefore they were chosen for the digester tanks. The first tank was completed in January 2002. As part of the preplanning, an operational plan was developed for the installation of the ganged forms and a detailed process setup was developed.

10 SIMULATION OF THE CHOSEN LINEAR CONSTRUCTION PROCESS

Two process setups were simulated with MicroCYCLONE: the as-planned process setup and an enhanced as-built setup. The data for the as-planned setup was extracted from planning documents and cycle times were slightly modified using data collected on the construction site (Cui and Lee 2001). The data for the enhanced as-built setup were taken from cycle time studies, process studies and interviews. The process has also been slightly modified to better meet Lean criteria.

The digester tank has a diameter of about 24 m and the outside walls of the tank are about 7 m high. The walls of the tank were divided into six concrete pours that are each about 12.5 m long. The framework for each pour consisted of six panels on the inside and six panels on the outside. The panels were about 7.5 m high and over 2 m wide. The main resources involved in the installation of the ganged forms were two carpenter foremen, two carpenters, one laborer, and a crane operator and a crane.

The following assumptions were made in order to build a model of the installation process:

- Every cycle involves the deinstallation and the installation of an element
- The cycle times for installation of outside and inside panels are all equal (the time data have been adjusted to accommodate this assumption)
- A small number of clean panels is stored in the cleaning area at the beginning of the simulation run
- The panels are installed without interruption for pouring
- Potential crane breakdown and obstructions are not considered.

In the as-planned process setup, all activities are performed while the crane is connected to the panel. Therefore there is only one major cycle – the crane is involved in all activities. At the beginning of the cycle, crew 1, one carpenter foreman and one carpenter, hooks the crane to a built-in panel to commence deinstallation. While the connection of the panel ensures that the built-in panel stays in place, crew 1 loosens the panel. When the panel is completely unsecured, it is lifted and swung to the cleaning area. Crew 2, one laborer, unhooks the dirty panel and the panel is stored. The crane swings to the next available clean panel and lifts it up and then flips it over after crew 2 has hooked the crane to the panel. The already cleaned panel is then oiled and swung to its new destination. Crew 3, one carpenter foreman and one carpenter, install the panel in its new destination while the crane remains attached to the panel until the installation is completed. The installation includes setting the panel in place, anchoring the bottom of the panel, anchoring the braces and pinning the panels. Pinning the panels is performed by crew 1, which unhooks the crane after the installation is completed. The crane then swings back to the installed panels. At the same time, crew 1 moves back to its original destination. This activity is therefore the only activity not including the crane. In simulation, the duration of this activity was assumed to be a fixed value. All other durations were assumed to be beta distributions. The durations for all activities (in seconds) are listed in Table 3. A CYCLONE model of the process is shown in Figure 3.

Table 3: Durations for Activities in Seconds (Original Installation Setup)

Activity	Lowest value	Mean value	Highest value	Stand. dev.
Hook (4)	20	35	50	5
Loosen, unsecure (5)	180	260	330	25
Swing & lie down (7)	90	105	125	5.83
Unhook panel (10)	10	15	20	1.67
Swing (12)	55	65	80	4.17
Hook (14)	15	30	50	5.83
Flip (15)	50	65	80	5
Oil (16)	110	130	150	6.67
Fly panel (17)	65	75	80	2.5
Dummy (20)[DET]	-	0	-	-
Set panel (21)	40	55	75	5.83
Anchor bottom (22)	100	110	120	3.33
Anchor braces (23)	100	120	140	6.67
Pin panels (26)	100	110	130	5
Unhook (28)	10	15	25	2.5
Move to old panel (29)	-	75	-	-
Swing (30)	50	60	75	4.17

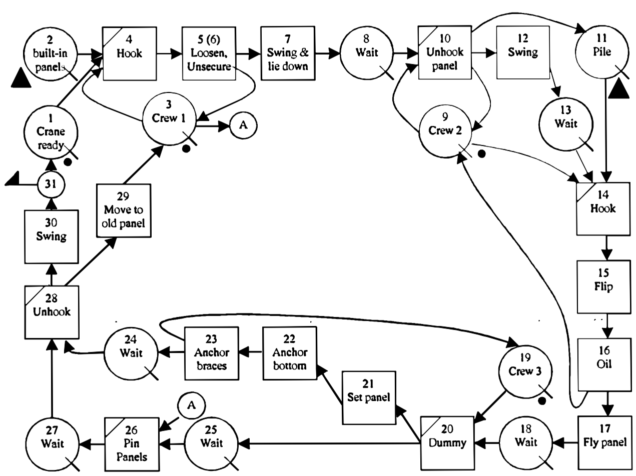

Figure 3: CYCLONE Model for the Original Installation Setup

A simulation run of 36 cycles was performed. The average cycle time for one complete wall panel (inside or outside) was 1175.6 seconds/cycle. The complete installation and deinstallation of one panel took about 19 ½ minutes, which leads to a productivity of 3.07 panels/hour. An analysis of the QUEUE nodes reveals that the crane is only idle 1.13% of the time, while crew 1 is idle 75.93%; crew 2 is idle 79.14% and crew 3 41.97%. The time the COMBI nodes are busy corresponds to the assigned durations for the activities. The shortest cycle time was 17 minutes and 20 seconds; the longest cycle time was almost 21 minutes.

Since the crane is obviously the critical resource, a second simulation run was conducted with two cranes. As a result, the productivity increased to 5.67 panels/hour. The productivity can be further be increased by adding cranes and adding crews if necessary. A sensitivity analysis was conducted and the most important results are shown in Table 4. However, due to limited availability of space, adding cranes would not have been a viable option. In addition, interferences between cranes and crews would very likely lead to longer durations of activities and therefore decrease productivity.

Table 4: Results of Sensitivity Analysis for 4 Cases (Original Setup)

Crane/ Crew 1/ 2 / 3	Prod. (pnl/ hr)	Idle (%)			
		Crane	Crew 1	Crew 2	Crew 3
1 / 1 / 1 / 1	3.07	1.13	75.39	79.14	41.97
2 / 1 / 1 / 1	5.67	3.62	52.68	59.77	1.63
3 / 2 / 1 / 1	8.31	6.17	30.06	39.23	34.43
4 / 2 / 1 / 1	10.68	11.25	13.36	25.15	9.03

An analysis of the simulation results shows that the key to increasing productivity is a reduction of the idle times of the crews and a reduction of the overall cycle time. Crew 1 and 2 are working less than 30% of the time; crew 3 is working less than 60% of the time. The three crews are working in different locations and if they were to move constantly, the crane would be slowed down and productivity reduced. However, some of the tasks can be performed without the crane. If the process is reorganized so that the crane only performs the necessary tasks, the total cycle time and the idle time of the crews will be reduced.

11 THE RE-DESIGNED PROCESS

In the second (as-built) process setup, some of the activities are separated from the crane. 4 resource cycles (crane, crew 1, crew 2, and crew 3) are created. In addition, crew 1 is now only responsible for the deinstallation of old panels.

The crane cycle remains the main cycle. An installed panel is hooked onto the crane (4), unsecured (5) and transported (7) to the cleaning area. The panel is unhooked (10) and the crane swings (12) to pick up a clean and oiled panel (16). This panel is transported to its new destination (17) and secured (20). When it is safe to unhook the crane, the crane is unhooked (20) and swings back to the built-in panels (22).

Crew 1 is busy with the deinstallation of the built-in panels. The duty of crew 1 is to hook the crane to the panel (4) and then release the panel (5). After the crew moves over to the next panel, the crane can then lift the panel. Crew 1 then starts to loosen (6) the connection of the next panel to a degree in which the panel still stays in place.

Crew 2 works in the cleaning and storing area, outside of the digester tank. Crew 2 unhooks panels from (10) and hooks panel to (16) the crane. Crew 2 also cleans and oils panels (14) and thereby prepares them for reinstallation.

Crew 3 first secures panels that are delivered by the crane (20). When it is safe to do so, the crew unhooks the panel from crane (21). Then the crew continues to connect the new panel to the one that was previously installed (23, 24).

The durations for all activities were obtained from onsite data collection. In simulation of this setup, the durations were assumed to follow the beta distribution. The durations for all activities (in seconds) are listed in Table 5. A CYCLONE model of the process is shown in Figure 4.

Table 5: Durations for Activities in Seconds (Enhanced Installation Setup)

Activity	Lowest value	Mean value	Highest value	Stand. dev.
Hook (4)	20	34	51	5.17
Unsecure (5)	39	50	69	5
Loosen (6)	150	210	270	20
Swing & lie down (7)	92	107	125	5.5
Unhook panel (10)	10	14	22	2
Swing (12)	57	67	78	3.5
Clean and oil (14)	110	130	150	6.67
Hook (16)	15	30	52	6.17
Pick and swing(17)	64	75	81	2.83
Secure (20)	120	180	270	25
Unhook (21)	10	16	28	3
Swing (22)	50	60	75	4.17
Anchor bottom (23)	45	85	125	13.33
Anchor braces (24)	50	90	135	14.17

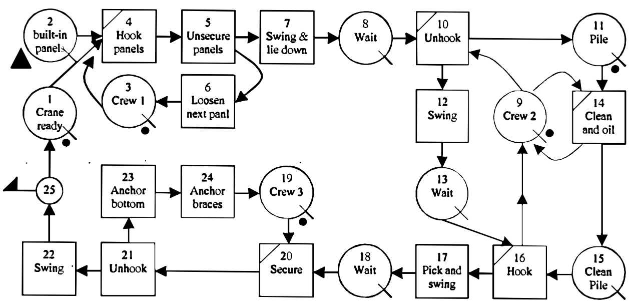

Figure 4: CYCLONE Model for the Enhanced Installation Setup

In simulation run of 6 cycles, the average cycle time for one complete wall dropped to 650.7 seconds/cycle, or 10 minutes and 50 seconds. The productivity therefore increased by 80% to 5.57 panels/hour. In the simulation run the crane was idle 0% of the time. Crew 1 was idle 53.48%, crew 2 61.65% and crew 3 was idle 41.08%. The shortest cycle time was 9 minutes and 20 seconds; the longest cycle time was 12 minutes and 30 seconds. A sensitivity analysis led to the results that are shown in Table 6.

Table 6: Results of Sensitivity Analysis for 3 Cases (Enhanced Setup)

Crane/ Crew 1/ 2 / 3	Prod. (pnl/ hr)	Idle (%)			
		Crane	Crew 1	Crew 2	Crew 3
1 / 1 / 1 / 1	5.57	0	53.48	61.65	41.08
2 / 1 / 1 / 1	9.12	2.31	21.45	35.49	2.82
2 / 1 / 1 / 2	10.52	7.50	9.43	26.15	80.98

Increasing the number of cranes could increase productivity, but the construction site does not allow for more than one crane. However, the productivity increase of 80% in comparison to the as-planned process setup is quite remarkable. In order to improve productivity further, the variability in the processes could be reduced. It is important to note that some of the variability is due to wind, a factor that cannot be eliminated. Since the panels are rather large, they are easily affected by wind. This will make it more difficult for the crane to swing with the panels and to position them and thus increase cycle times. Also, safety is top priority on the construction site. Therefore, conditions (wind) which require that the crane stays hooked to the panel will further reduce the productivity.

12 CONCLUSIONS

Lean construction is a result of the introduction of a new form of production management. Although lean construction is still evolving, the generic principles, techniques and tools of lean construction can already be applied. As described in this paper, lean construction can be used to yield very impressive gains in production on "bread and butter" processes such as wall erection and concrete forming.

Simulation offers a viable tool for evaluating the potential level of productivity gains which can be achieved using lean construction concepts. In some cases, such as projects reported by the Spanish firm Dragados, simulation can be used directly to introduce potential process modifications which can lead to improvement of production rates and reduction of production variability. In general, Lean thinking provides a structured format in which processes can be re-designed, and simulation offers a methodology for evaluating the benefits to be expected from process re-design.

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