WORK STRUCTURING OF CONSTRUCTION CREWS: INSTALLATION OF LIGHT FIXTURES CASE STUDY

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ABSTRACT

The Lean Construction Institute defines Work Structuring as the fundamental level of production system design, which means developing a project's process design while trying to align engineering, design, supply chain, resource allocation, and assembly efforts. It's thinking construction during design - design of a production system before the start of construction operations. First run studies, computer simulation, and recently BIM have all been examples of techniques used to design production systems so that waste is minimized and system throughput improved. The design of crews has received less attention, and is typically considered adequate if the available resources are provisioned. This paper posits that crew design is an integral part in designing production systems. The purpose of this paper is to present *lean* rules to guide work structuring of construction crews. In this study, we focus on the crew design of a construction operation that has been well documented in prior research, namely, "Installation of Light Fixtures". The lean rules attempt to reach better crew design for the process of executing the construction operation. Discrete Event Simulation technique using EZStrobe program was used as an analytical tool for validating this study. The paper provides a demonstration of how to apply the rules and along with results of preliminary investigation efforts and finally concluding with propositions for future research.

KEYWORDS

Lean Construction, Production System Design, Work Crew Design, Lean Crew Design, People, Training and Development, Labor Issues

INTRODUCTION

The failure and inability of the conceptual models of construction management to deliver on the mantra of 'on-time, at budget, and at desired quality' is discussed at length in Koskela's seminal 1992 report and in Koskela (2000). Another paradigm-breaking anomaly was that observed by Ballard and Howell (1994). Analysis of project plan failures indicated that about 50% of weekly tasks were completed (Ballard and Howell 2003). The preceding observations have lead to the birth of Lean Construction as a discipline that subsumes the transformation-dominated contemporary construction management (Koskela 1999 and Koskela 2000).

The Lean Construction Institute defines Work Structuring as the fundamental level of production system design, which means developing a project's process design while trying to align engineering, design, supply chain, resource allocation, and assembly efforts (Tsao et al 2000). It's thinking construction during design - design of a production system before the start of construction operations. Work Structuring

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is to the construction operation what design is to the sizing of members. According to Howell and Ballard (1999), the design of work methods under a Lean Construction paradigm happens in two phases; the first involves structuring of work during the product design stage before the start of construction operations; and the second phase carries forward from master scheduling to weekly work production. In other words, work structuring is part and parcel of the Last Planner™ System.

Examples of techniques used for production system design during the design stage include first run studies, computer simulation, and recently BIM. These techniques are used to minimize waste and improve system throughput. However, the design of crews has received less attention, and is typically considered adequate if the available resources are provisioned.

A problem facing estimating and scheduling teams working on early stages of a construction project is the need to determine a reasonable number and composition of crews that can be effectively used in the construction process (Hassanein 1997). Can we choreographically design construction work crews, and how? This is the question that this paper takes on. Howell et al (1993) gave insights to this question when stating: "Operations can be continuously improved by moving from a tight-but-unbalanced state to loose-and-unbalanced to tight-and-balanced." However, in this study, we focus on developing lean rules for structuring crews involved in a construction operation. The lean rules are developed based on literature review and professional experience. As an example, the same light fixtures installation study, which was studied in Howell et al. (1993) in detail, was selected for this paper. Using computer simulation, specifically discrete event simulation, we systematically modeled and evaluated the lean rules against traditional crew set ups. Various impact parameters were evaluated as related to production system design such as unit cost, system throughput, resource utilization, and time of operations.

HYPOTHESIS

In this paper, it is hypothesized that the following lean-based rules should be used in designing crews. In designing a crew to execute a construction operation, the method and crew make-up should be decided so the following is achieved, or at least approached:

- No overproduction.
- "Flow where you can, pull where you must," Rother and Shook (1999).
- If waste is unavoidable, then it should be limited to one person (the water spider rule).
- Pride in end-product is maximized for all crew members.
- Learning is maximized for all crew members.
- System throughout is maximized; even at expense of resource utilization.

PROJECT BACKGROUND

The construction operation in this paper focuses on the installation of light fixtures by a construction crew. The data for this case was collected by interviews with the construction staff prior to commencement of the operations, as described in Howell et al (1993). The operation was monitored to keep a record of the initial durations, crew make-up, equipment used, design process of operation and other significant parameters involved during carrying out the operation.

The particular operation involved installation of 314 light fixtures. The crew was not familiar with the specific fixture type to be installed. The initial crew make-up for the installation operation consisted of 1 journeyman, 1 apprentice, and 1 scissor lift. The estimated productivity planned by the construction staff to carry out this operation was 2.5 fixtures per crew hour, or a total of 48 worker-minutes per fixture. The total time of operation was estimated to be 125.6 hours at the rate of 2.5 fixtures per crew hour. The hourly wages of the crew were $13.40 per hour for 1 journeyman, $6.00 per hour for 1 apprentice, and $1.50 per hour for the scissor lift.

The original installation operation was divided into four main tasks for each light fixture: assemble fixture, install fixture, wire & clip, and lamp & finish.

IMPLEMENTATION

In the remainder of this paper, the three different crew designs used in the installation of the 314 light fixtures will be outlined and discussed. We describe the various resources, crew make-up, process design and other assumptions considered by the construction staff to carry out the installation of 314 light fixtures. For the paper we used a total of 300 light fixtures for simulating and modeling the assembling and installation process.

INSTALLATION OF LIGHT FIXTURES: 1ST SCENARIO

In this scenario, only one light fixture at a time was assembled and installed by the crew. One apprentice was involved in assembling the light fixtures and one journeyman was responsible for installation, wire & clip, and lamp & finish of the light fixtures. Also one scissor lift was used by the journeyman to restock the assembled light fixture. In order to simulate the process, the original installation operation was modified and remodeled into the following tasks for each light fixture such as assemble fixture, restocking, lift going up, install fixture, wire & clip, and lamp & finish and lift going down. The task durations and process sequence has been modelled using EZStrobe (Martinez 1996))as shown in Figure 1.

Table 1: Simulation results of the process model of the original scenario (#1)

Parameters	Budgeted	1st Case
Time of Operation	125.60 hours	130.15 hours
Unit Cost of Installation	8.32 USD	9.06 USD
Apprentice Utilization	-	34.65%
Journeyman Utilization	-	89.88%
Lift Utilization	-	99.70%

Results from the simulation of the process model of the original scenario case of installing 300 light fixtures have been summarized in Table 1. The original scenario took 4.55 hours more than the budgeted 125.6 hours of operation. Also, the unit cost of installation of light fixture with the planned process design and crew makeup came out to be $0.72 more than the budgeted unit cost. The apprentice and journeyman utilization was not budgeted by the construction staff but from the results show the apprentice was being utilized only 34.65% throughout the operation. One benefit in this operation was the one light fixture at-a-time installation which would promote the quality of the installed light fixtures – if one is improperly installed or has a defect, it would be quickly identified. However, the assembly process was on-going and not based on a pull system between the journeyman and the apprentice, resulting in the need for a space for the piling inventory of assembled fixtures.

After evaluating the process design and simulation results of the original light fixture installation scenario, the hypothesized lean rules are evaluated as follows:

- Over production is high - Large intermediate inventory (AssmbldLitFix Queue)
- There is waste between both apprentice and journeyman.
- Continuous flow is not achieved (Howell et al (1993) called this tight-but-unbalanced)
- Pull is not used
- No team work/learning among crew
- Pride in the final outcome is limited to journeyman
- Learning is minimal to non-existent for the apprentice, except in assembling fixtures.

INSTALLATION OF LIGHT FIXTURES: REVISED CASE 2

The first improvement to the above crew make-up involved the following changes (Howell et al 1993): 1) Two journeymen with dedicated lifts were added; 2) A temporary rack developed by the crew held pieces for 16-20 fixtures- minimizing loading/restocking frequency; 3) The apprentice and one journeyman prepared the initial buffers of assembled fixtures while the other two journeymen modified the scissor-lifts. Hence, the total resources in this case were three journeymen, three scissor lifts, and one apprentice. In this case, each journeyman completed an entire process of the fixture (one did installation, the second completed wiring and clipping, and the third put the lamp and finished), while the apprentice was assembling the fixtures. Each of the 3 journeymen came down to restock after working on 15 fixtures. For simulation purposes, it was assumed that restocking required 3 minutes with lifts taking 1 minute each in going up and coming down. To save space, and be within the limit of the page numbers for the conference papers, the modified process design for the revised case 2 is not shown in this paper.

Results from the simulation of the process model of the 2nd case are shown in Table 2. The hours of operation were reduced from 125.60 hours to just 45.03 hours accounting to a saving of 80.57 hours or 64.14% of the budgeted hours. The unit cost of installation of light fixture was reduced to $7.61 from budgeted $8.32 saving 8.53% of the budgeted unit cost. The apprentice was now utilized 94.94% of its total capacity.

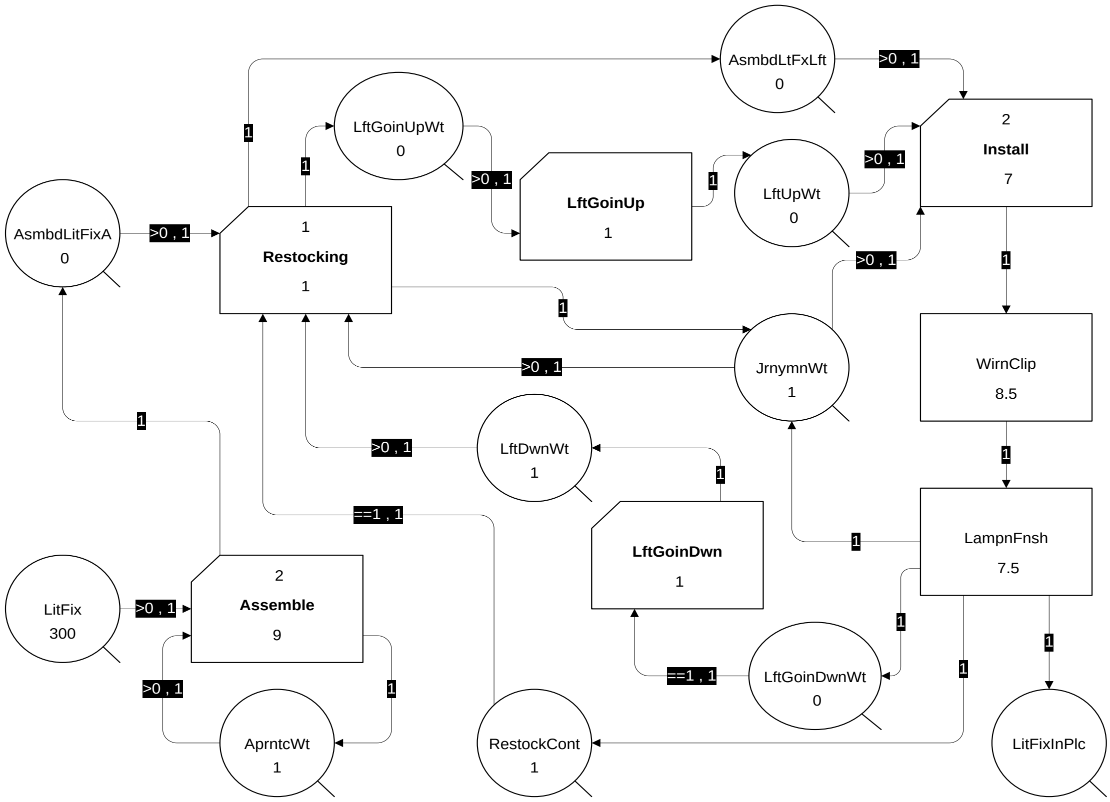

Figure 1: Simulation process model of the 1st scenario of installation of light fixtures

It is interesting to note here that the cycle times of Journeyman B (doing the wiring and clipping) is almost twice the cycle times of Journeymen A and C which leads to extra inventory for the Journeyman B and more waiting time for Journeyman C. This demonstrates a situation where high utilization of one crew member leads to low utilization of another.

Table 2: Simulation results of the process model of the revised 2nd case

Parameters	Budgeted	2nd Case
Time of Operation	125.60 hours	45.03 hours
Unit Cost of Installation	8.32 USD	7.61 USD
Apprentice Utilization	-	94.94%
Journeyman A Utilization	-	46.63%
Journeyman B Utilization	-	91.15%
Journeyman C Utilization	-	46.74%
Lift A Utilization	-	48.11%
Lift B Utilization	-	92.67%
Lift C Utilization	-	48.26%

Overall, in spite some of the waste, the 2nd case shows significant savings in hours of operation and unit cost along with better utilization of the resources. However, when evaluating the second case against the hypothesized lean rules, the following is found:

- Over production is high - the apprentice is still producing way more than the Journeymen A, B and C can process.
- There is waste, in the form of wait, for the apprentice, and journeyman A and C. In addition, there is also waste of transportation when all the 3 Journeymen go down to restock with the components of the light fixtures they are installing.
- Continuous flow is not achieved (Howell et al (1993) called this loose-but-unbalanced)
- Pull is not used
- No team work/learning among crew
- Pride in the final outcome is now lost to all involved.
- Learning is minimal to non-existent for the apprentice, except in assembling fixtures.

INSTALLATION OF LIGHT FIXTURES: LEAN CASE

In Howell et al (1993), it is stated that "Operations can be continuously improved by moving from a tight-but-unbalanced state to loose-and-unbalanced to tight-and-balanced." The first case modeled above was an example of tight-but-unbalanced operation, and the second was an example of loose-and-unbalanced. If performance variation of the production units is minimized, then lower buffers can be used giving a tightly balanced system. This may be plausible, but the interest in this paper is to investigate if the proposed lean rules can guide the process of crew selection and makeup.

Following the lean rule, a 3-person crew (2 Apprentices, and 1 Journeyman) and 2 scissor lifts are used. One Apprentice (the experienced one out of the two) is made responsible for assembling light fixtures and the other Apprentice worked along with the Journeyman on the scissor lift where they both completed the install, wire and clip, and lamp and finish of the fixtures. All light fixtures were assembled and installed one at a time. Restocking was done by the Apprentice A on the ground using his own scissor lift. Again, for space economy, the revised process model after structuring the work to follow the "lean" case is not shown in this paper. Results from the simulation of the process model of the lean case are summarized in Table 3.

In the lean case, the hours of operation were reduced from 125.60 hours to 60.17 hours accounting to a saving of 60.17 hours or 52.09% of the budgeted hours. The unit cost of installation of a light fixture was reduced to \$5.69 from budgeted \$8.32 saving 31.61% of the budgeted unit cost. Labor utilizations were increased to above 90% with an average equipment utilization of 60.24%.

In this lean case, the problem with overproduction and large intermediate inventory has been controlled. This was achieved by balancing the variation in cycle times of the assembling and installation activities coming out to be 12 minutes and 11.5 minutes respectively. As soon as the Apprentice A finishes assembling, Journeyman A and Apprentice B receive their restocking. This assembling and installation of single fixture at a time also leads to better quality of installation. Also the reduced variation in cycle times leads to the increased utilization of above 90% for all the workers in the crew, with only one lift being underutilized because it is only used when journeyman A is ready to restock the crew.

Table 3: Simulation results of the process model of the lean case.

Parameters	Budgeted	Lean Case
Time of Operation	125.60 hours	60.17 hours
Unit Cost of Installation	8.32 USD	5.69 USD
Apprentice A Utilization	-	92.19%
Apprentice B Utilization	-	95.55%
Journeyman Utilization	-	95.55%
Lift A Utilization	-	24.92%
Lift B Utilization	-	95.56%

Evaluating this lean case against the hypothesized lean rules, the following is found:

- Over production is controlled because the journeyman on the ground can read the situation and anticipate when more fixtures will be needed as well as the restocking needs.
- Waste is limited to the journeyman on the ground (going up and down for restocking).
- Continuous flow is approached, albeit not achieved. Pull is used.
- Pride in the final outcome between two people.
- Learning and real team work present

LEAN CREW DESIGN ANALYSIS

Crew Design – Make-up and Size

The initial crew make-up for the installation operation as planned by the construction staff consisted of 1 journeyman, 1 apprentice, and 1 scissor lift. The apprentice was responsible for assembling the light fixtures and the journeyman was executing the installation activities such as install, wire and clip and lamp and finish using a scissor lift. This initial make-up and size was modified based on the rules reported in Howell et al (1993). Then a case was designed to satisfy the lean rules. The crew variation for the cases is shown below in Table 4.

Table 4: Crew make-up and size for installation of light fixtures

	Budgeted	1st Case	2nd Case	Lean Case
Apprentice	1	1	1	2
Journeyman	1	1	3	1
Scissor lift	1	1	3	2

Unit Cost and Time of Operation

The variation and savings in the unit cost and time of operations bases on all the cases tested is shown in Table 5. The lean case is lower in cost but is 15 hours longer than the second case.

Reducing Waste and Maximizing Value

According to Ballard and Tommelein (1999), the objective of achieving continuous flow is maximizing the throughput of the system while minimizing resource idle time and work in progress. In this case study, the original crew and process of executing the installation of light fixtures as planned by the construction staff went from tight-but-unbalanced to loose-but-unbalanced. Comparing both cases 1 and 2 to the lean case, resource wait times and work in progress is higher, and it appears as though the lean case is more of a tight-and- balanced system. The resource idle time, work in progress, operation production rate, and operation production to maximum production rate have been shown in Table 5.

Table 5: Detailed simulation results

		1st Case	2nd Case	Lean Case	Savings/ Improvements
Unit cost		\$9.06	\$7.61	\$5.69	37.19%
Time of operations		130.15	45.03	60.17	53.77%
Avg. Resource idle time (min)	Apprentice	16.97	0.48	1.02	93.99%
	Journeyman	1.01	4.49, 0.00, 4.47	0.53	47.52%
Avg. Work (Fixtures) in progress (WIP)		97.64	28.29	0.00	97.64%
Operation production rate		2.31 Fixtures/ Hr	6.67 Fixtures/ Hr	4.98 Fixtures/ Hr	53.61%
Operation production to maximum production rate		34.63%	99.85%	99.60%	

From Table 5, it is evident that by modifying the crew make-up and size, substantial improvements could be made to a construction operation. The average idle time for both the apprentice and the journeyman were reduced by 93.99% and 47.52% respectively. Also the average work in progress was reduced significantly from 97.64 to 0 accounting to a 97.64% improvement and the operation production rate was also improved by 53.61 %.

In the lean case, the batch size was reduced to one fixture at a time and crew make make-up and size was modified to balance the cycle times of the assembling and installation activities leading to a more continuous flow of operation from one activity to another leading to significant reduction in labor and equipment resource idle times and zero work in progress.

The cycle times for assembling and installation activities for the three cases is shown in Table 6. The Restocking activity here includes 3 tasks such as restock, lift going up and lift going down and the times for restocking activity have been included in either assembling activity or installation activity depending on whether it is coming in assembling activity cycle or installation activity cycle.

Table 6 illustrates that in the lean case, the cycle times for assembling and installation activities are almost balanced and hence all the light fixtures assembled are processed and installed without any resource wait time in the queues or having work in progress.

In addition, in the lean case, reducing the batch size to only one fixture at a time the lean issue of over production has also been controlled in the lean case. The batch size was reduced to match the assembly and installation capacity of the apprentice and journeyman in order to generate a high throughput of the operation. The light fixtures in the lean case were only pulled by the journeyman and apprentice as needed for installation. This way the assembled light fixtures did not wait in the queue to be installed.

Table 6: Simulation results showing the cycle times of assembling and installation activities

Activity	Task	1st Case		2nd Case		Lean Case	
Assembling	Assemble	9 min		9 min		9 min	12 min
	Restocking	3 min		5 min		3 min	
Installation	Install	7 min	26 min	4 min	21 min	3.5	11.5 min
	Wire & Clip	8.5 min		8 min		4.25	
	Lamp & Finish	7.5 min		4 min		3.75	

As mentioned earlier, the lean case is lower in cost but is 15 hours longer than the second case. However, the benefits of having better quality, or at least less re-work compared to case2, as well as the learning and shared pride in the final product are all likely to tip the scale in favor of the lean case, on the long run.

CONCLUSIONS

This paper presented *lean* rules to guide work structuring of construction crews. A demonstration example was used to contrast the results of using the lean rules against a well documented construction operation from prior research. Promising results have been found in support of the lean rules.

This paper has ventured into the area of construction crew design in the hope of enticing more research into this topic. Additional research is needed to investigate the implementation of the proposed lean rules in other trades as well as in first run studies to better assess the veracity of the rules. Some researchers may consider computational methods as well. In general, focus on the design of crew composition and choreographing the process will add to the knowledge base in the area of construction operations design.

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