RESOURCE OPTIMIZATION FOR MODULAR CONSTRUCTION THROUGH VALUE STREAM MAP IMPROVEMENT

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ABSTRACT

Implementation of Lean manufacturing begins with the development of value stream maps, which depict process flow in the production line. However, the application of value stream mapping (VSM) in modular manufacturing has various shortcomings, due to the variety of products and the level of customization demanded. One of the challenges is assessing the production rate variations in modular manufacturing activities and resource movements within work stations along the production line. VSM also falls short of verifying prior to implementation that the proposed state will meet the efficiency demands for a variety of products. This research presents a model of resource optimization to develop the VSM, considering variety as an inevitable element in modular construction, and also evaluates the value stream prior to implementation. The methodology provides an efficient method to formulate a set of rules to quantify productivity rate, probabilistic duration, and resource requirements for fabrication of wall components. A simulation model is also generated in order to evaluate the proposed VSM. Current- and future-state maps of the factory production line are compared to prove the effectiveness of the proposed methodology. The proposed methodology is validated by a case study – a residential modular factory located in Edmonton, AB, Canada.

KEYWORDS

Modular Building, Lean, Production Line, Value Stream Mapping, Product Variation, Resource Optimization, Simulation

INTRODUCTION

The current on-site (stick-built) construction process is hampered by inefficiency and material and process waste. The process also limits opportunities for technological and productivity innovations, thereby encumbering discipline-specific professionals in their efforts to communicate information and knowledge. Modular manufacturing is superior to the current on-site construction system in terms of efficiency and cost-effectiveness, but current manufacturing-based approach does not meet the potential productivity offers by modular building. Customers requesting modular-built facilities have the same demands as those in the market for traditional site-built

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facilities for unique buildings that are individually customized to meet their needs. Configuration of the plant to meet demands for customization will affect production efficiency, since it involves deviating from a standard work flow process (Nahmens and Mullens 2009). In current practice, one of the major problems is the lack of a theoretical foundation which considers production variety in modular products which affects resource allocation within work stations in production line.

INTRODUCTION
Manufacturing provides opportunities to apply Lean thinking strategies for production efficiency in the plant, including eliminating waste and supporting the delivery of a wider variety of products which are more responsive to customer preferences in a shorter time and at a lower cost (Moghadam et al. 2012b). The core tool in Lean applications is value stream mapping (VSM), which is basically a pencil-and-paper technique. The value stream map graphically represents the flow of materials and information through the production line as value is added to the product (MHRA 2007). VSM creates a map to identify the future state of the system, called the future-state map, which provides a picture of the Lean transformation process (Rother and Shook 2003). The required improvements to the current-state and an overall concept of how the factory should ideally operate are identified and presented in a future-state map (Marvel and Standridge 2009). Although VSM is an efficient tool in manufacturing, there are two major shortcomings regarding the application of VSM in modular construction: (1) VSM does not provide information regarding the effect of variety on the work flow, and (2) VSM only proposes improvements, and does not validate the performance of the system. This research focuses on addressing these major issues in order to increase the capability of future-state VSM.

To make improvements to a production line within the context of Lean, the integration of VSM and simulation techniques brings about a more effective approach for process management. The impact of Lean transformation can be analyzed to determine where valuable resources should be utilized before the actual implementation (Shararah et al. 2011). Simulation is a computer-based tool that represents real-world objects and processes in order to effectively evaluate and examine various scenarios prior to implementation and also facilitates the decision-making process (Moghadam et al. 2012a). In this research, Simphony.Net4.0 was used to develop a simulation model for VSM and simulation of the production process. The methodology provides an efficient and effective method of estimating probabilistic productivity rates for framing stations. In order to overcome some of the shortcomings of VSM, this method considers construction production variety along with a numeric model to estimate the probabilistic duration to complete various modules depending on several resource allocations and station reconfiguration scenarios.

PROPOSED METHODOLOGY
This research proposes a model to optimize resource usage, including time and labour, through VSM improvement techniques. The project components’ schedules and quantity take-off lists are extracted from the design drawings and used to estimate the probabilistic duration along with the resource usage for different tasks. The factory production line consists of a series of workstations where specific tasks with defined
resources are carried out on parts of a module as it passes through each station. The entire production process is divided into small work packages which are assigned to stations along the line as it presented in Figure 1. The challenge in creating work flow and balancing the production line lies in the assignment of these work packages to stations and to quantify statistically the productivity rate and probabilistic duration for each task.

Figure 1: Production tasks layout of a modular building

In traditional scheduling methods, a fixed duration is assumed for each activity and as a result, there would be a fixed duration for total work. In the real world, task durations are not fixed and instead duration can be represented by an independent random variable based on a probability distribution. In order to achieve this objective, a comprehensive time study is conducted to estimate the operation time for individual tasks at each station. The construction of 11 modules is monitored in a time study to determine the duration and labour requirements for each activity completed within the entire stations. In this paper, detail analysis of wall framing station is presented. A value stream map is generated sequentially in order to depict the production line layout and schedule, based on the information from the probabilistic productivity model and the predefined Lean criteria. Current- and future-state maps of the factory production line are compared to validate the effectiveness of the proposed methodology. Finally, all of the data is combined within a simulation model using Simphony.NET4.0 to estimate the total duration and human resource requirements for each module. Figure 2 below represents the research methodology.

Figure 2: Proposed methodology
CASE STUDY

This research considers a case study of the current processes and practices of Igloo Prebuilt Homes, a modular manufacturing company located in Edmonton, Alberta, Canada. Modules are prefabricated in the factory and are transported to the site to be assembled. Similar with on-site construction, customers can choose from among existing floor plans or provide their own customized floor plan which fits their needs and lot size. As a result, the factory production line cannot be run at a steady pace since the activities taking place at each station are contingent upon individual design. In order to measure the effect of product variety on the production line pace, a time study was conducted. In the time study, duration and resource usage of 11 modules, including bungalow and two-storey, were collected as they progressed through 16 work stations in the plant. The goal was to select modules that vary in terms of design layout, dimensions, floor number, and material specifications in order to record the required time and resources for a variety of products. The time study assisted in identifying the key elements that affect duration based on the predefined tasks taking place at a particular station.

IMPLEMENTATION OF PROPOSED METHODOLOGY

In this paper, detail estimation process to calculate probabilistic duration and productivity of wall framing station is presented. Wall framing is part of module framing activities where exterior and interior walls are fabricated. To frame a wall, studs take place between top and bottom plates along with pre-built components including doors and windows. Wall framing duration takes considerable amount of variability based on the key element including number of studs, doors, windows, and joint walls. Therefore, the length of the wall is converted to an effective length considering the effect of key elements. The converted length of the exterior wall is calculated satisfying Equation 1. To determine the effective length, the correction coefficients $\alpha$, $\beta$, $\gamma$, and $\delta$ are determined using a linear optimization model. The goal is to adjust the coefficients to optimize a curve of best fit through the data point while achieving as close to a steady production as possible. Since there is no window in interior walls, the related coefficient would be zero for interior walls.

$$CL = \alpha*S + \beta*D + \gamma*W + \delta*J$$

where:

- $CL$ = Wall Converted Length [ft.];
- $S$ = Number of Studs;
- $D$ = Number of Doors;
- $W$ = Number of Windows;
- $J$ = Number of Joint walls; and
- $\alpha$, $\beta$, $\gamma$, $\delta$ = Wall converting coefficients.

Wall framing duration is effectively changing with a significant variance due to the wall converted length. Therefore, a probabilistic distribution will be used to represent the total time to complete the activity. Table 1 presents a sample of wall properties extracted from the design drawings originally for 11 modules including 34 exterior walls and 65 interior walls. The coefficient values and objective function value are presented in Table 2.
The graph related to converted length and corresponding time to frame a wall is presented in Figure 3. To estimate the probabilistic duration of framing a wall, various trend has been tried to find the best fit. According to the presented graph, a linear trend with R-square value of 0.92 fits the exterior walls framing data distribution, and an exponential trend with R-square value of 0.87 fits the interior walls framing data distribution. Since the length and corresponding framing duration of the wall is effectively changing, the productivity will change proportionately, and is calculated satisfying Equation 2.
Figure 3: Exterior and Interior probabilistic duration

\[ y = 1.05x - 42 \quad R^2 = 0.92 \]

Equation 2: Productivity rate

\[
\text{Productivity rate } (P) = \frac{\text{Productive output}}{\text{Productive hours}} = \frac{\text{CL}}{\text{Tmhr}}
\]

where:
\( \text{CL} \) = Wall Converted Length [ft.]; and
\( \text{Tmhr} \) = Total man-hours [min].

The productivity of the entire walls were calculated and used to create the probability density function and cumulative density function of effective productivity. Selected data distributions including Beta, Gamma, LongNormal, Exponential, and Normal distribution were fitted to the wall framing productivity rate data set and Probability Density Function (PDF) of data distribution is shown in Figure 4. Chi-Squared and Kolmogorov Smirnov test were used to find the most fitted distribution as presented in Table 3. According to the presented ranking, Gamma distribution is a better fit to estimate the exterior wall framing productivity rate and is calculated satisfying Equation 3.

Figure 4: Probability Density Function of exterior wall productivity rate
Table 3: Goodness of fit for data distribution

<table>
<thead>
<tr>
<th>Distribution</th>
<th>Kolmogorov Smirnov Statistic</th>
<th>Rank</th>
<th>Chi-Squared Statistic</th>
<th>Rank</th>
</tr>
</thead>
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<td>1.4046</td>
<td>4</td>
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<tr>
<td>Exponential</td>
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<tr>
<td>Uniform</td>
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<td>4</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>

\[ P = f(x) = \begin{cases} \frac{\beta^a x^{a-1} e^{-\frac{x}{\beta}}}{\Gamma(a)}, & x > 0 \\ 0, & \text{otherwise} \end{cases} \]

Equation 3: Exterior wall Productivity

where:
\( a = 22.039 \) and \( \beta = 0.06851 \)

The probabilistic duration and productivity rate for all the activities of each work station were calculated using the same methodology and were used in the simulation model.

SIMULATION MODELING

The current- and future-state value stream maps simulation models are presented in this paper. The current-state model represents current situation of the production line considering the target time defined for each station. The future-state simulation model represents some of the changes proposed in the module framing stations layout based on Lean manufacturing concepts. The proposed probabilistic duration and productivity rate were used in this simulation model to optimize the crew size and estimate the processing time, as well as to evaluate potential scenarios for production line resource allocation.

CURRENT-STATE SIMULATION

The current-state simulation model of the factory production line is shown in Figure 5. All activities and their sequences in each station were clarified and triangular or beta distributions for the process time of each activity were defined. In this paper the simulation model for a two-storey, modules 420A and 420B, is presented. The optimum run for the current-state of resource allocation is presented in Figure 6. Total processing hours to complete both modules with 90% level of confidence is 642 man-hours and the total duration is 288.6 hours (36 days).
The simulation model assists in estimating the percentage of on-time module completions and determining the Takt time for the entire production, as well as the completion probability for a given Takt time. For the case study, in order to balance the flow of the production line, Takt time is projected to be 12 hours, which means it is required to move the module to the next working station every 12 hours in order to complete the module within the estimated duration. In this case, the probability of on-time completion is 97%.

**FUTURE-STATE SIMULATION**

Considering Lean techniques to eliminate waste from the work flow, a number of changes were proposed including: (1) changing the layout of the module framing stations, which consists of floor set-up, roof set-up, wall framing, and cubing stations; (the proposed layout eliminates five non-value adding activities and three waste activities); (2) using jigs for wall framing table to eliminate workers’ attempts to square the walls; (3) using a radial arm saw with measuring ability to cut several pieces to size at once; and (4) providing an adjustable work platform to set up the roof for various layouts.
Resource optimization for modular construction through value stream map improvement

The future-state VSM simulation model as shown in Figure 7, determines the optimum resource allocation considering proposed changes to the activities and production line layout. Also the duration for each station is calculated based on the proposed methodology and according to the design drawings properties. The optimum run for the future-state of resource allocation is presented in Figure 8. Total processing hours to complete both modules with 90% level of confidence is 585 man-hours and the total duration is 245.3 hours (30 days). For the future-state, in order to balance the flow of the production line, Takt time is projected to be 10 hours, which means it is required to move the module to the next working station every 10 hours (1.25 day) in order to complete the module within the estimated duration. In this case, the probability of on-time completion is 98.5%.

According to the simulation results, total processing hours saved from the future-state simulation is 57 man-hours and total 5% reduction in labour. Also total duration to complete both modules is reduced by 43 hours (6 days). The production efficiencies obtained in the future-state is due to the resource reallocation and the proposed changes in framing stations which increased the productivity due to Lean implementation.

CONCLUSION

Uncontrolled conditions and work site limitations have negative effects on cost, schedule, and project quality. Modular manufacturing offers a solution to these challenges, but current manufacturing-based approach does not meet the potential
productivity offers by modular building. In this research, an integrated model which implements and unifies Lean, product variety, and simulation has been proposed to improve the efficiency, productivity, and cost-effectiveness of a modular manufacturing production. The module components’ properties and quantity take-off list extracted from design drawings. VSM is carried out sequentially in order to depict the production line layout and schedule based on the drawings, defined Lean criteria, and developed quantification model for components’ probabilistic duration and productivity rate. A simulation model was generated to evaluate the current- and. The result of the future-state VSM simulation model was compared with a current-state result and proved the effectiveness of the proposed methodology. In this research, advanced methods and techniques in productivity efficiency have been integrated in the creation of a new methodology for manufacturing construction which reduces waste, time, and resource usage.

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REFERENCES