RESOURCE OPTIMIZATION FOR MODULAR CONSTRUCTION THROUGH VALUE STREAM MAP IMPROVEMENT

Mana Moghadam[1] and Mohamed Al-Hussein[2]

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

---

[1] Ph.D. Candidate, Construction Engineering and Management, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, AB, T6G 2W2, Canada, Phone +1 (780) 492-6293, mansoore@ualberta.ca

[2] Professor, NSERC Industrial Research Chair in the Industrialization of Building Construction, Construction Engineering and Management, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, AB, T6G 2W2, Canada, Phone +1 (780) 492-0599, malhussein@ualberta.ca

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.

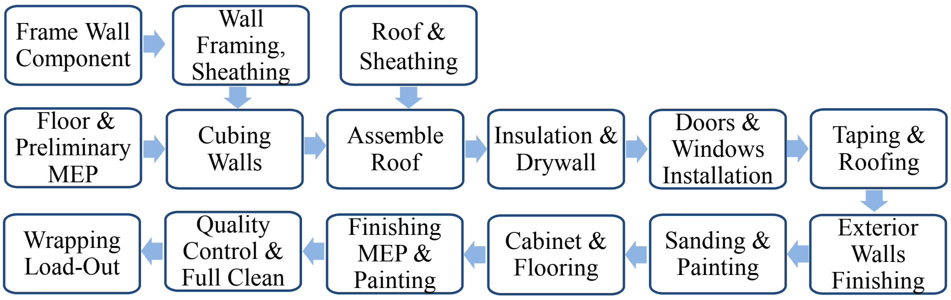

Figure 1: Production tasks layout of a modular building

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.

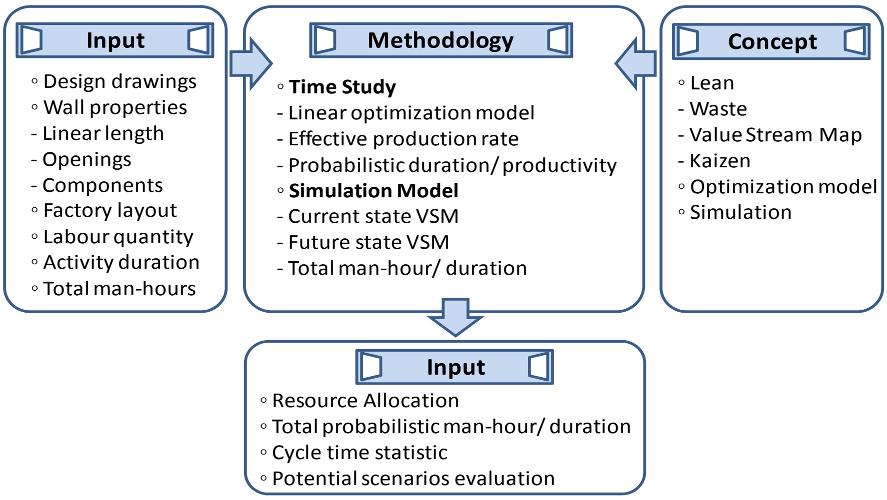

Figure 2: Proposed methodology

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 α, β, γ, and δ 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.

$$CL = \alpha * S + \beta * D + \gamma * W + \delta * J \qquad \text{Equation 1: Wall converted length}$$

where:
CL = Wall Converted Length [*ft.*];
S = Number of Studs;
D = Number of Doors;
W = Number of Windows;
J = Number of Joint walls; and
α, β, γ, δ = 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.

Table 1: Exterior and interior walls converted length

Exterior Wall Framing											Interior Wall Framing										
Module	Panel No.	Duration (min)	men	manhours (min)	Length (ft)	No. Studs	No. Doors	No. Windows	No. Joint walls	Converted Length (ft)	Module	Panel No.	Duration (min)	men	manhours (min)	Length (ft)	No. Studs	No. Doors	No. Joint walls	Converted Length (ft)
Module 420A	M1-2-7-11E	30	1	30	17	18	3	0	0	51.75	**Module 432**	M22I	4	1	4	5.5	2	1	0	4.75
	M4-5E	80	1	80	37	39	0	0	3	106.5		M10I	5	1	5	8	7	0	0	8.75
	M9-10E	70	1	70	35	36	0	1	1	93		M6I	5	1	5	5.6	6	1	0	9.75
	M3-6-8E	75	1	75	32	30	0	2	4	104		M21I	5	1	5	7	6	1	0	9.75
Module 420B	S4-5E	55	1	55	34	38	0	0	0	85.5		M38I	6	1	6	4.6	7	1	0	11
	S1-2-3-6E	85	1	85	30	38	0	3	1	109		M27I	6	1	6	7.2	8	0	1	11.3
	S7-8E	80	1	80	36	38	0	1	3	110		M3I	7	1	7	9	9	0	1	12.5
Module 432	M2-3-10E	48	2	96	56	50	0	0	4	137.5		M15I	8	1	8	8	10	1	0	14.8
	M5-7-9-8-6E	85	2	170	59.5	62	1	3	4	185.5		M31I	8	1	8	7.2	8	1	1	13.5
	M1-4E	100	2	200	57	65	2	4	7	220.5		M25I	8	1	8	9.8	11	0	1	15
Module 431A	M1E	60	1	60	33	35	0	0	3	97.5		M30I	11	1	11	9	10	1	1	16
	M4E	60	1	60	33	34	0	0	4	101.5		M13I	10	2	20	12.5	12	0	1	16.3
	M2-3-5E	90	1	90	40	48	2	2	2	139.5		M2I	11	2	22	10.5	11	1	1	17.3
Module 431B	S1E	50	1	50	33	35	0	0	3	97.5		M33I	10	2	20	9	11	1	1	17.3
	S4E	50	1	50	33	34	0	0	3	95.25		M5I	13	2	26	15	13	0	1	17.5
	S2-3-5E	80	1	80	40	48	0	4	2	143.5		M19I	15	2	30	12	14	0	1	18.8
Module 443A	M6-7E	30	2	60	30	31	0	1	4	100.5		M26I	17	2	34	8	10	1	4	19.8
	M1-2E	20	2	40	35	30	0	1	0	73.25		M1I	16	2	32	12	13	1	0	18.5
	M3-4-5-8E	45	2	90	45	43	2	2	3	134.5	**Module 443A**	M4I	20	1	20	8.5	12	1	2	19.8
Module 443B	S6-7E	30	2	60	30	35	0	1	3	103.25		M9I	10	1	10	7.8	11	0	1	15
	S1-2E	20	2	40	35	34	0	1	3	101		M1I	4	1	4	5	5	1	0	8.5
	S3-4-5-8E	50	2	100	45	43	0	2	2	120.75		M13I	10	1	10	5.5	6	1	0	9.75
Module 433	M4-5-10E	50	2	100	54	50	0	0	4	137.5		M6I	4	1	4	5.1	8	0	1	11.3
	M1-2-3-8-9E	80	2	160	58	62	1	3	4	185.5		M12I	15	1	15	5.9	9	1	1	14.8
	M6-7E	95	2	190	55	60	2	4	7	209.25	**le 443B**	S2I	20	1	20	9.1	11	1	0	16
Module 434	M2-3-10E	43	2	86	56	50	0	0	4	137.5		S10I	4	1	4	5.9	8	0	0	10
	M5-7-9-8-6E	75	2	150	59.5	62	1	3	4	185.5		S11I	4	1	4	3	4	1	0	7.25
	M1-4E	90	2	180	57	65	2	4	7	220.5		S8I	35	1	35	7.5	12	1	1	18.5

Table 2: Wall Converted Length Coefficients

Exterior Walls			Interior Walls		
Studs coefficient	α	2.25	Studs coefficient	α	1.25
Doors coefficient	β	3.75	Doors coefficient	β	2.25
Windows coefficient	γ	5.75	Joint walls coefficient	γ	1.25
Joint walls coefficient	δ	6.25			
Objective function					
Exterior CL = 2.25*S + 3.75*D + 5.75*W + 6.25*J					
Interior CL = 1.25*S + 2.25*D + 1.25*J					

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.

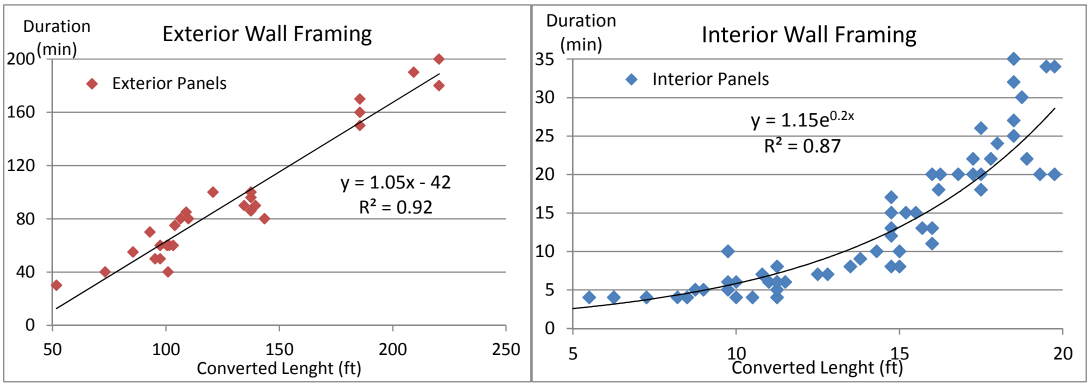

Figure 3: Exterior and Interior probabilistic duration

$$Productivity\ rate\ (P) = \frac{Productive\ output}{Productive\ hours} = \frac{CL}{Tmhr}$$ Equation 2: Productivity rate

where:
CL = Wall Converted Length [*ft.*]; and
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.

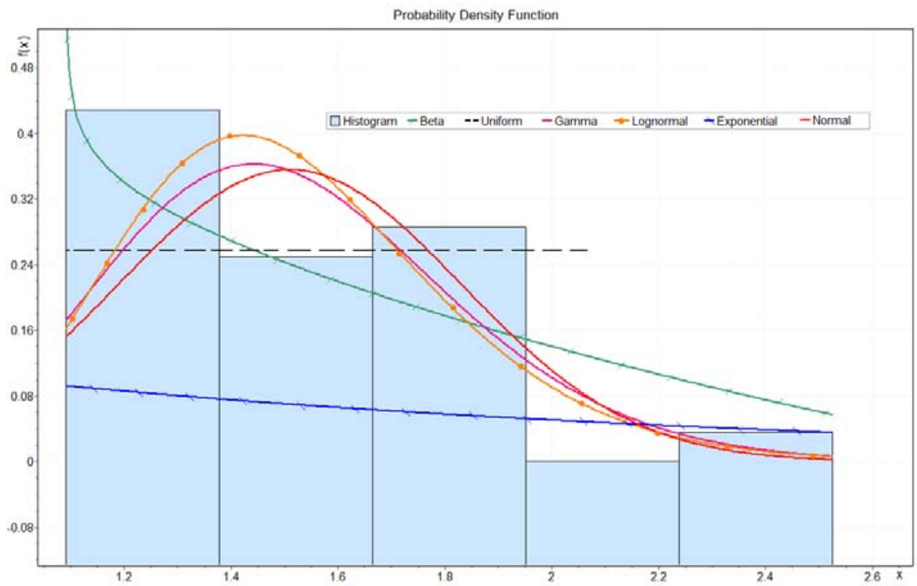

Figure 4: Probability Density Function of exterior wall productivity rate

Table 3: Goodness of for data distribution

Summary of Goodness of Fit				
Distribution	Kolmogorov Smirnov		Chi-Squared	
	Statistic	Rank	Statistic	Rank
Beta	0.21271	5	1.4046	4
Exponential	0.51457	6	46.688	5
Gamma	0.09075	1	0.34428	2
Lognormal	0.09238	2	0.48738	3
Normal	0.1134	3	0.27709	1
Uniform	0.12828	4	N/A	

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

Equation 3: Exterior wall Productivity

where:
$\alpha = 22.039$, 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).

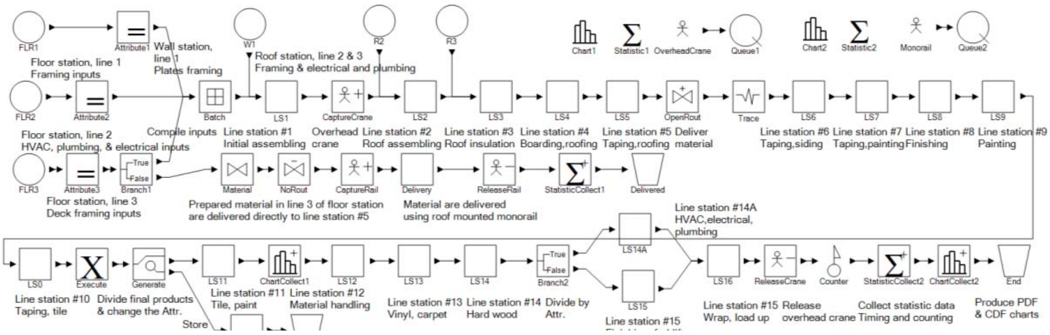

Figure 5: Current-state VSM simulation model

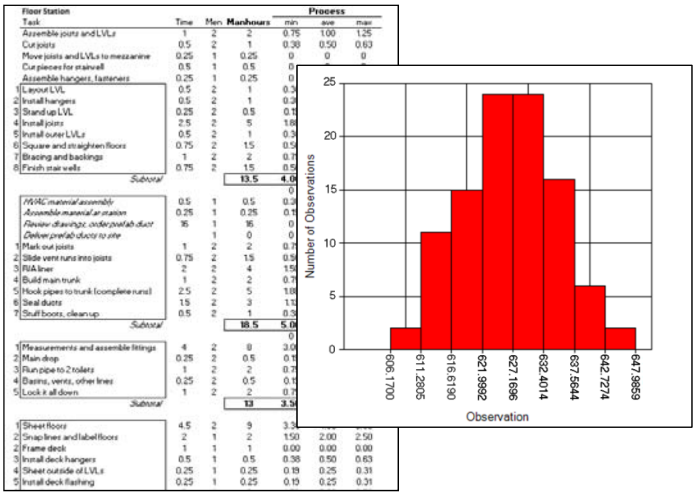

Figure 6: Current-state simulation result of module 420

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.

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%.

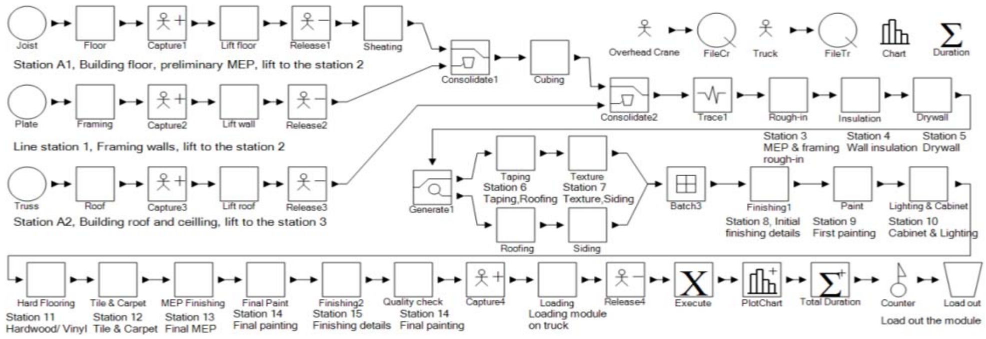

Figure 7: Future-state VSM simulation model

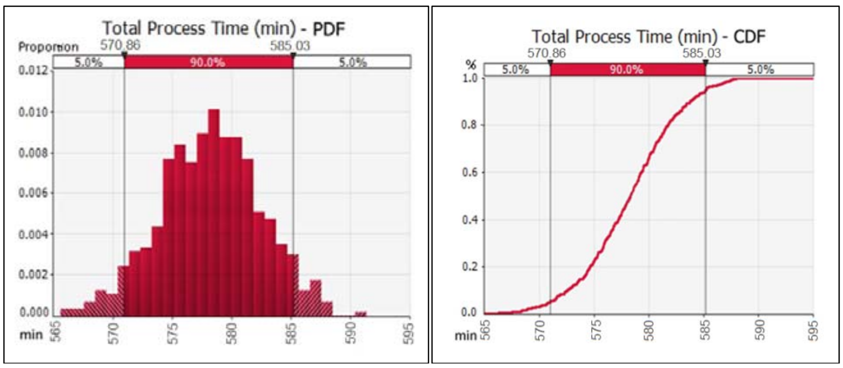

Figure 8: Future-state simulation result of module 420

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.

ACKNOWLWDGMENTS

The authors are sincerely grateful to IGLOO Prebuilt Homes for providing the required data for this research. Any opinions, findings, and conclusions expressed in this paper are those of the authors and do not necessarily reflect the views of teams involved in this research from IGLOO Prebuilt Homes.

REFERENCES

Manufactured Housing Research Alliance (MHRA) (2007). "Pilot Study: Applying Lean Principles to Factory Home Building." *Technical Report*, U.S. Department of Housing and Urban Development.

Marvel, J.H. and Standridge, C.R. (2009). "A Simulation-Enhanced Lean Design Process." *Journal of Industrial Engineering and Management*, 2-(1), 90-113.

Moghadam, M., Al-Hussein, M., Al-Jibouri, S., and Telyas, A. (2012a). "Post Simulation Visualization for Effective Scheduling of Modular Building Construction". *Canadian Journal of Civil Engineering*, 39-(9), 1053-1061.

Moghadam, M., Alwisy, A., and Al-Hussein, M. (2012b). "Integrated BIM/Lean Base Production Line Schedule Model for Modular Construction Manufacturing." *Proceedings, Construction Research Congress*, IN, May 21-23, 1271-1280.

Nahmens, I. and Mullens, M. (2009). "The Impact of Product Choice on Lean Homebuilding." *Construction Innovation*, 9-(1), 84-100.

Rother, M. and Shook, J. (2003). *Learning to See: Value Stream Mapping to Add Value and Eliminate Muda*. Lean Enterprise Institute Inc., Brookline, MA.

Shararah, M.A., El-Kilany, K.S., and El-Sayed, A.E. (2011). "Value Stream Map Simulator Using ExtendSim." *Proceedings, World Congress on Engineering*, *Vol. I*, London, UK, Jul. 6-8, 755-758.

Venugopal, M., Eastman, C.M., Sacks, R., and Teizer, J. (2012). "Semantics of Model Views for Information Exchanges Using the Industry Foundation Class Schema." *Advanced Engineering Informatics*, 26-(2), 411-428.