AN ENHANCED SCHEDULING TECHNIQUE FOR MODULAR CONSTRUCTION MANUFACTURING

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ABSTRACT

Modular construction manufacturing (MCM) is potentially built through a more efficient and cost-effective method compared to the on-site construction practice. The increased interest in manufacturing of the building construction process demands special methods of design and manufacturing to improve production efficiency. MCM provides opportunities to apply Lean for production efficiency in the plant, including eliminating waste and supporting the delivery of customized products in a shorter time and at a lower cost. Lean is a concept first developed in the manufacturing industry which has been since adapted to the construction industry. Although the focus of Lean in both industries is the same, Lean tools vary between manufacturing and construction since these two industries differ in nature. Lean as the concept is applicable to any industries, taking into consideration that MCM has characteristics of both manufacturing and construction yet is distinct and should be seen in the class of its own. Given the distinct nature of MCM, the technical elements in "Lean production" and "Lean construction" are not sufficient to achieve the Lean goals for MCM industry, necessitating a modified framework by which to exploit the potential benefits of modular building.

This paper provides a deeper understanding of the modular construction manufacturing and the difference between the manufacturing, construction, and MCM industries. The focus of this paper is to adopt an enhanced scheduling technique which can adequately fulfill the production efficiency demands based on particular characteristic of modular construction manufacturing.

KEYWORDS

Modular construction manufacturing, Scheduling, Production, Design, Efficiency.

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. Modular buildings are potentially built through a more efficient and cost-effective engineering method that can deliver market requirements

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for increased construction speed, improved quality, and rapid return on investment, but in current manufacturing-based approach to construction a gap still exists between drafting and the production line (Moghadam and Al-Hussein 2013). Meanwhile, interest in a manufacturing approach to building is increasing, which necessitates improvement in production efficiency to meet growing market demand. Improving the modular industry requires special techniques and tools for design and manufacturing of modular buildings.

Modular manufacturing construction (MCM) provides opportunities to apply Lean for production efficiency in the plant, thereby eliminating waste and supporting the delivery of products in a shorter time and at a lower cost. “Lean production” is a concept first developed for Toyota Production System (TPS) to reduce waste from the production process in order to improve the production process (Singh et al. 2010). Lean production has been widely used in the manufacturing industry as the foundation for efficiency improvement in manufacturing. More recently, potential applications of Lean production for construction process improvement have been identified (Winch 2003), and Lean has since been adapted to the construction industry as a new production philosophy referred to as “Lean construction”. Although the focus of Lean in both industries is the same, to reduce waste, increase value for the customer, and achieve continuous improvement (Howell 1999), Lean tools to reach the aforementioned goals vary between manufacturing and construction since these two industries differ in nature. MCM is capable of Lean application in the plant to improve production efficiency, taking into consideration that MCM has characteristics of both manufacturing and construction yet is distinct from both and should be seen in a class of its own. The technical elements in Lean production or Lean construction, however, are not sufficient to achieve the Lean goals of MCM, thereby necessitating a new framework by which to capitalize more fully on the capabilities brought by modular building. The unique characteristics of the MCM industry require adapted strategies which can adequately fulfil the production efficiency demands of modular building.

LEAN TOOLS FOR MODULAR CONSTRUCTION MANUFACTURING

There are basic similarities between manufacturing and construction. These similarities provide opportunities to share innovations, experience, and findings between the two industries (McCrary et al. 2006). Manufacturing has been a reference point and a vital source for innovation and competitiveness in construction for several decades, having contributed disproportionately to research, development, and productivity growth. The term, Lean production was first coined by Ohno (1988), whose research focused on waste reduction in the Toyota Production System (TPS) and introduced a new form of production which is neither craft-based nor mass production. One of the first studies to adapt the Lean production concept to the construction industry was carried out by Koskela (1992) which challenged the implementation of Lean production philosophy within the construction industry and presented an initial set of principles as implementation guidelines to create flow processes in construction.

Similar to that for Lean production, the focus in Lean construction is on reducing waste and improving the process continuously by considering construction projects as temporary production flow. However, despite the similarities, construction and manufacturing are distinct business processes. Based on that, though Lean production and Lean construction share common basis, some strategies are developed specifically for the application of Lean in either construction or manufacturing. Besides, MCM reflects some of the characteristics of both the manufacturing and construction industries; therefore, it cannot be understood to be exclusively either manufacturing or construction and should be seen in the class of its own industry. The unique characteristics of MCM necessitate improved techniques which can adequately fulfil the production efficiency demands of modular construction. This paper focuses on scheduling requirement and adopted framework for MCM which is discussed below.

In construction, different contractors are responsible for different aspects of the project, and each creates a work plan in their own interest to minimize risk for their organization. As a result, localized scheduling leads to overlapping activities performed by contractors, which disrupts the overall project schedule. As such in construction it is difficult to maintain a fixed schedule which aligns the interests of all stakeholders. The repetitive work process in manufacturing provides a reliable work sequence which helps to ensure completion of all requirements before starting a task so that schedule constraints are satisfied. In Lean production, a task starts after completion of preceding tasks in the production line. The schedule is presented in Value Stream Map (VSM) and controlled by lead time and Takt time (MHRA 2007), which is the production rate at which tasks must be completed in order to meet demand. The developers of Lean construction invented the Last Planner System (LPS), which is a high-level planning technique that addresses project variability in construction. LPS is a reverse-phase schedule which relies upon the completion of tasks and pulls assignments (Bhatla and Leite 2012). A task is started when all prerequisites are at hand, whereas in traditional practice a task starts according to master schedule. In MCM although estimated scheduling is predictable for each product, overall scheduling is required in order to consider the consequences of individual schedules through the entire production line, where gaps or overlapping may occur.

SCHEDULING REQUIREMENTS FOR MCM

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, alternatively, task durations are not fixed and instead duration can be represented by an independent random variable based on probability distributions. The probabilistic duration is defined with individual data distributions for each workstation, such that it defines the most probable duration and man-hour requirements through the production line. The probabilistic duration is useful for cost estimation purposes and overall production evaluation. Generally, management teams focus on target man-hour requirements calculated using historical data or ideal-state estimation; therefore, the use of probabilistic duration results in more precise cost control information. On the other hand, accurate activity duration plays an important role in creating the schedule when it comes to developing production flow for customized manufacturing where the production schedule is not easily predicted. Scheduling is therefore required in order to reflect exact work duration for labor allocation planning and production leveling purposes.

There are various scheduling methods in construction and manufacturing practices. In Lean production practices, scheduling is done through value stream mapping (VSM) and Takt time calculation for working cells in the production line. In Lean construction practice, LPS is a production control technique by which to predict work flow. In traditional construction practices, Critical Path Method (CPM) creates a schedule based on the work breakdown structure of the defined scope. In projects with repetitive tasks, the Linear Scheduling Method (LSM) focuses on continuous resource utilization. According to MCM scheduling requirements, the combination of the four methods brings about a more effective scheduling plan. In MCM the product is fabricated and assembled through the workstations of the production line, which define the Takt time for the production and must be finished on time in order to deliver the product on time. A resource allocation plan fulfills these activities' requirements to guarantee on-time delivery of the product. These activities are thus placed in the critical path of the production. There are also secondary activities taking place simultaneously, including supporting activities such as material handling and off-line activities such as component assembly to feed the line station which are not critical and have float to be completed.

The challenge in modular production is achieving continuous work flow at each station. In this regard, a schedule must be generated for all individual modules to be fabricated through the entire production line considering production constraints such as activity sequence, location (workstation), equipment and material requirements, and labor utilization. Figure 1 shows a schedule of four sample residential modules which vary in size and layout but which are fabricated back-to-back in the production line. In this linear scheduling graph, the horizontal axis plots time, the vertical axis plots workstation progress based on the moving module through the production line, and the sloping lines represent production rate. The technological predecessor is based on the sequence of activities, and the crew must have completed work on a given module before the next module moves to the station. Since products vary in size and layout, the production rates vary for each module at each station.

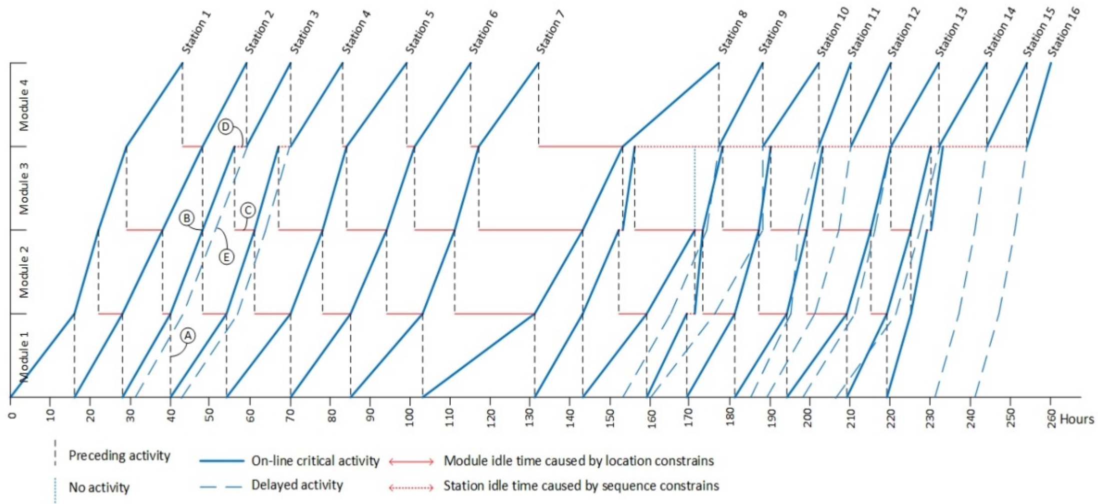


Figure 1: Production line schedule for sample modules

For example, the work on module 1 at station 3 starts at day 38 and ends at day 40; this module then moves to station 4 and module 2 moves to station 3 (A). After work completion on module 2 at station 3 it moves to station 4 and module 3 moves to station 3 immediately (B). The work on module 3 at station 3 is completed at day 56 and it is ready to move to station 4, but the work on module 2 at this station finishes at day 61, so module 3 has to wait 5 days until station 4 becomes available (C). Meanwhile, following work completion on module 3 at station 3 at day 56, the crew cannot start work on the next module, module 4, because this module is still at the previous station, station 2, and work completes at day 59. The crew must wait for 3 days until the next module moves to the station (D). In order to eliminate crew idle time, all activities on previous modules can be delayed so the crew works continuously (E). Although this option temporary solves the problem, in order to find the most effective scheduling technique for MCM a combination of existing techniques is proposed. In this strategy individual tasks are ranked to use the total float in order to optimize resource utilization. The combination of CPM, LPS, LSM, and VSM provides an informative plan by which to define pull intensity, work float, production progress, and percent planned complete calculation.

CPM scheduling provides the flexibility that Lean practice requires in order to meet the demands of project stakeholders and to deliver value to teams with different required delivery targets. Therefore project stakeholders negotiate for duration and work sequence considering overall production plan and downstream trades by the look-ahead schedule in LPS, which shapes the sequence and rate of work. A detailed work plan specifies handoffs between modules at each station and the backlog of ready work. Milestones are defined for non-critical activities such as just-in-time delivery dates. A logical plan is then assembled based on stakeholders' opinions through stream mapping sessions, as well as on calculated start and finish dates based on relationships which detail the crew requirements. After calculating the lead time and Takt time for the critical activities through the production line, total float is calculated in order to level resources where needed, and production constraints are defined for repeated activities in LSM. As presented in Figure 2, the ideal production schedule is obtained when stations have equal Takt time and production rate, such that within a certain period of time each module can be completed regardless of variation in size, layout, or specifications.

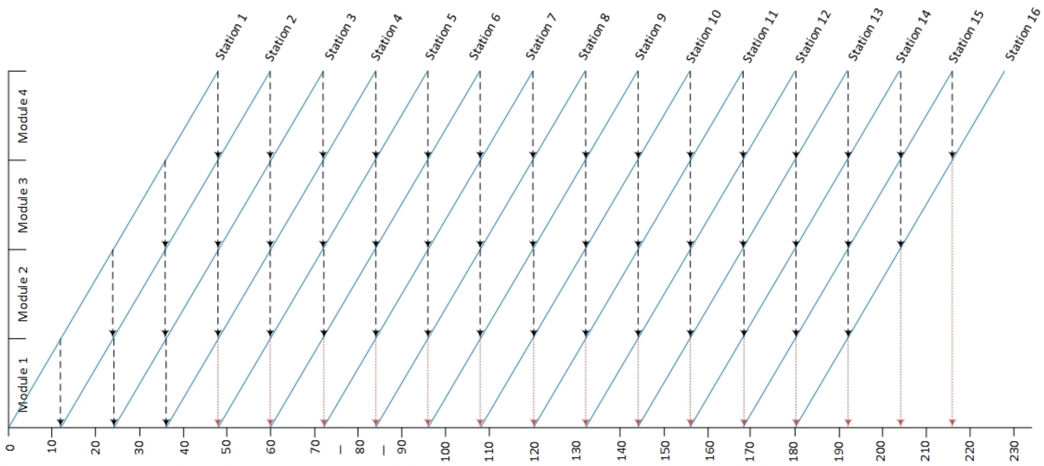


Figure 2: Ideal production line schedule for sample modules

In the real world it is not practical or rational to force activities to take place with equal production rates since this increases labor requirements in addition to creating high variation in labor utilization. Instead, imposing an equal Takt time for all the on-line critical stations is a more effective and practical means by which to create a continuous flow through the production line. In this practice, a group of multi-skilled labor is required to work in any stations where needed. Table 1 presents the number of required labor for each module at each station in order to achieve a uniform Takt time throughout the production line for aforementioned sample modules. To schedule and arrange labor to best suit the increased man-hours at any time while minimizing total number of labor personnel, the objective function for labor balance is defined in Equation 1.

Equation 1: Labor balance objective function

$$Minimize \sum_{i=1}^{W} \sum_{j=1}^{S} X_{ij}$$

where:
W = Number of multi-skilled labor, $i = \{1,\ldots, W\}$;
S = Number of available stations to travel between, $j = \{1,\ldots, S\}$; and
X_{ij} = Number of multi-skilled labor personnel assigned to stations.

Table 1: Resource plan allocation for scheduling

No. Station	On-line Critical Work Station	No. Labor	Module 432 1584 sqft		Module 431A 660 sqft		Module 431B 609 sqft		Module 433 1320 sqft		Takt time	Module 432	Module 431A	Module 431B	Module 433	No. Labor	Module 432	Module 431A	Module 431B	Module 433
			Hr	Mhr	Hr	Mhr	Hr	Mhr	Hr	Mhr	Hour	No. Labor					Labor balance			
1	Wall set-cubing	2	16	32	6	12	7	14	14	28	12	2.7	1	1.2	2.3	2	-0.7	1.0	0.8	-0.3
2	Rough-in	4	12	48	10	40	10	40	11	44	12	4	3.3	3.3	3.7	2	-2.0	-1.3	-1.3	-1.7
3	Insulation	2	12	24	8	16	8	16	11	22	12	2	1.3	1.3	1.8	2		0.7	0.7	0.2
4	Boarding drywalls	4	14	56	7	28	6	24	13	52	12	4.7	2.3	2	4.3	2	-2.7	-0.3		-2.3
5	Taping	4	16	64	8	32	6	24	15	60	12	5.3	2.7	2	5	2	-3.3	-0.7		-3.0
6	Texture & Prime	2	15	30	9	18	7	14	14	28	12	2.5	1.5	1.2	2.3	2	-0.5	0.5	0.8	-0.3
7	Interior finishing 1	2	18	36	8	16	6	12	15	30	12	3	1.3	1	2.5	2	-1.0	0.7	1.0	-0.5
8	Paint 1	2	28	56	12	24	10	20	24	48	12	4.7	2	1.7	4	2	-2.7		0.3	-2.0
9	Cabinet	2	12	24	9	18	3	6	11	22	12	2	1.5	0.5	1.8	2		0.5	1.5	0.2
10	Hardwood	2	16	32	12	24	0	0	14	28	12	2.7	2	0	2.3	2	-0.7		2.0	-0.3
11	Tile & Carpet & Vinyl	4	10	40	2	8	5	20	8	32	12	3.3	0.7	1.7	2.7	3	-0.3	2.3	1.3	0.3
12	Interior finishing 2	2	12	24	6	12	3	6	10	20	12	2	1	0.5	1.7	2		1.0	1.5	0.3
13	Mechanical finishing	2	13	26	5	10	4	8	12	24	12	2.2	0.8	0.7	2	2	-0.2	1.2	1.3	
14	Paint 2	2	15	30	6	12	5	10	12	24	12	2.5	1	0.8	2	2	-0.5	1.0	1.2	
15	Wrapping & cleaning	2	10	20	6	12	5	10	10	20	12	1.7	1	0.8	1.7	2	0.3	1.0	1.2	0.3
16	QC & Load Out	2	6	12	4	8	3	6	6	12	12	1	0.7	0.5	1	2	1.0	1.3	1.5	1.0

In Lean practice, the VSM is a tool by which to control the production rate and product delivery time. VSM becomes complicated after adding sub-assembly stations and supporting milestones. Sub-assemblies are supposed to occur simultaneously and end at the same time in order to be fed to the production line, but in real situations they have different yield times and error rates. In order to combine sub-assemblies to the main stream in VSM, it is required to consider a default production rate for feeding the production line which reduces the work flexibility and leads to inventory in sub-assemblies. The statistical calculations of Lean tools alone are in this regard inadequate for MCM, since it is necessary for judgments and probability rates to be generated in addition to the outputs of these tools. However, in the context of MCM, utilization of VSM is complicated by the high product variation and low volume demands, making the current VSM method impractical in creating continuous flow. Also, the production process consists of hundreds of activities, each with a complex predecessor activities network, which barely fit on one single map. Dividing the entire production process into a number of phases with individual VSM, makes the process a complicated one for the VSM team and other stakeholders to handle, and the fragmented flow makes it difficult to synchronize the Takt time. Furthermore, the current definition of some of the statistical measures used in VSM, such as cycle time, up-time, available time, and inventory are not applicable to MCM.

In MCM, due to the large number of activities during the production process, it is required to assign different types of parallel group activities to one workstation such that multiple crews work on the same module concurrently. In VSM every station therefore needs to be divided into a number of sub-stations to reflect associated attributes, including process time, number of labor personnel, and yield throughput. On the other hand, due to the duration variation of activities in the process for different modules, it is common that some activities extend to subsequent workstations. The production line moves according to Takt time or based on the push system; a module therefore leaves a workstation regardless of activity completion. Otherwise, if an activity is not completed on a module, then neither the module nor any upstream modules move. Further activity completion forces a crew to float over multiple workstations carrying necessary material and equipment with them in order to finish the job; this makes measuring processing times accurately a difficult task.

In this research, in order to increase the level of control over the production flow, the VSM is modified in order to map the production process in such a way as to reflect two types of duration - fixed and variable - in terms of man-hours. Fixed durations remain consistent throughout the production of different modules, while variable durations depend on modules' specifications and change from module to module. In each individual station, various numbers of activities that differ in duration type are performed on a module. Therefore, all production activities must be reviewed once to categorize activities to ensure accurate production planning. For this purpose, one useful technique is process mapping using stick notes. Process mapping displays the sequence of activities which occur within the production process and identifies the responsibilities of work crews. In this approach, every individual worker is involved in process mapping, presenting their tasks on sticky notes with arranged sequences. After this step, the process map is documented for future planning as presented in Figure 3. In this process activities that have fixed durations regardless of modules' specifications are specified as the baseline for labor allocation. Other sets of activities with variable durations are estimated by means of quantification rules based on modules' dimensional properties. The total duration of both sets of activities define a proper resource allocation plan.

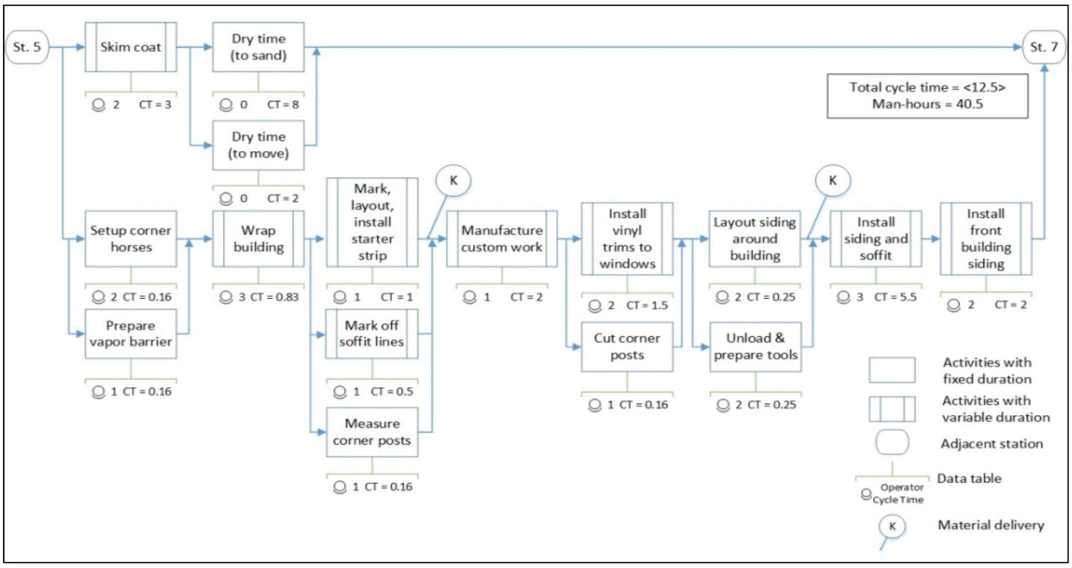


Figure 3: Sample process map for one station

MCM SCHEDULING EVALUATION THROUGH SIMULATION

In this phase, simulation models of the current and future states of the production process are generated in Simphony.NET 4.0 (Hajjar and AbouRizk 2002). The current-state production process is generated based on the current-state VSM and current scheduling technique. Numbers of labor personnel are constant variables and activity durations are defined by data distributions. The future-state simulation model is generated based on proposed scheduling technique. The simulation model depicts the production line layout; individual and overall production schedules through the production line for 10 modules that vary in size and specifications; resource requirements based on each module's dimensional properties; and the optimum Takt time to reach an optimum resource allocation plan. The inputs for this model are frontloaded from information in the BIM-generated 3D model of sample modules. Modules are custom designed and 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. Therefore required man-hours at different work-stations are calculated based on modules dimension and specification, which is beyond the scope of this paper. Then required man-hours are imported into a database which is linked to the simulation model. The simulation model delivers results for different production scenarios and provides the opportunity to choose the optimum scenario based on company's requirements.

CURRENT-STATE MAP

The current-state simulation model of the factory production line is shown in Figure 4. All activities and their sequences in each station are generated and proper data distributions for the processing time of each activity are defined based on current scheduling technique. In this model, the current-state of the production process is simulated based on the factory current-state VSM for 10 sample modules. The numbers of assigned labor personnel are fixed at each station and there is no cross-training through the production line. The results of the simulation model comprise processing time for sample modules to be fabricated at each station, total processing time, idle time, and total man-hour requirements for the current-state production process. Variations in processing time at each station for different modules are plotted in output charts as well as total processing times for all the sample modules as presented in Figure 5(a). The duration variation of processing hours to complete each module at different stations and overall are presented in Figure 5(b).

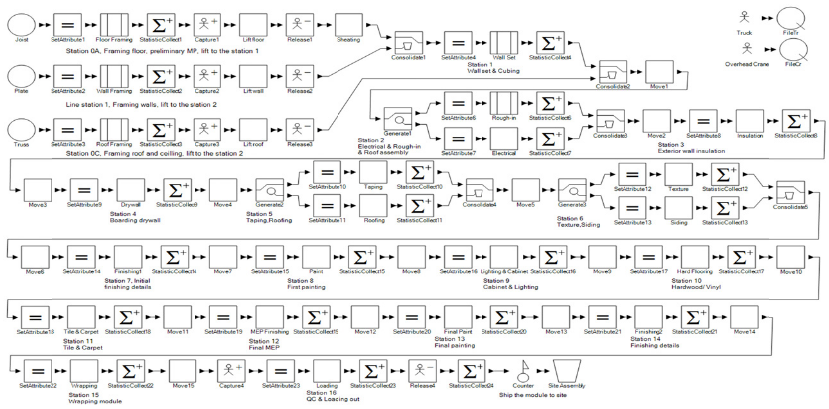
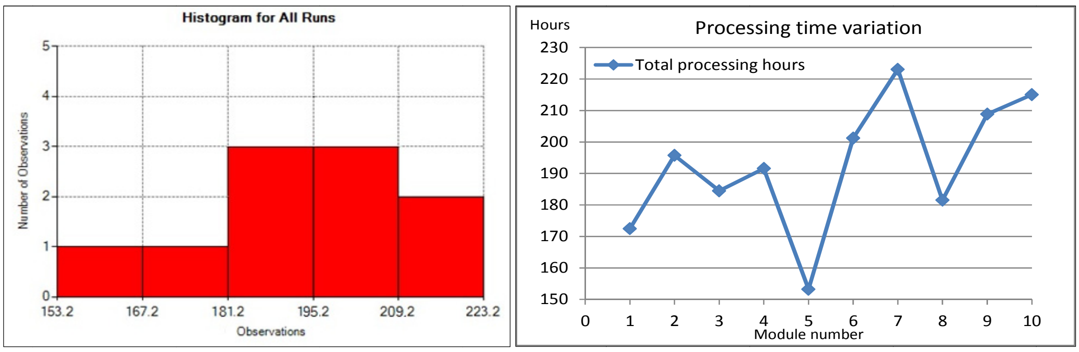


Figure 4: Current-state simulation model



(a) (b)

Figure 5: Current-state (a) Total processing hours, and (b) Processing time variation

The results of the simulation model demonstrate the variation in module completion duration at each station. When a larger module enters the production line, it is returned to the bottleneck of the production line, keeping upstream stations idle. Also, modules in the downstream stations are unable to move since the work on the previous module is not complete. As a result, the production capacity is decreased and the scheduled target based on customer demand cannot be reached.

FUTURE-STATE MAP

The future-state of the production process is generated based on proposed scheduling technique. The number of labor personnel at each workstation is not fixed. Activities duration are defined through both fixed and variable constant in the production process map. Takt time is defined in such a way as to move the line at a steady space and create continuous flow. Different scenarios are therefore run in order to find the near optimum result for the Takt time at which an optimum resource allocation plan is reached with the least fluctuation in labor requirements for different modules. The future-state simulation model, as shown in Figure 6, determines resource allocation plan scenarios of the future-state production process. This model runs the simulation for a series of Takt times and calculates man-hour requirements for a number of sample modules at all the stations through the production line. Then, the best match for number of labor personnel at each station is defined, and, based on this the man-hour fluctuation caused by module variation at individual stations is measured. The model then calculates for each station and for the entire production line (1) total labor idle time due to earlier completion of a module; and (2) additional man-hour requirements due to late completion of a module. The total required time that is covered by idle labours defines the required number of labor personnel in the multi-skill worker crew that is cross-trained through the production line to increase production rate at stations which are behind the scheduled Takt time. The model is run to find the scenario with the minimum man-hours not covered by the multi-skill worker crew. Table 2 presents the required number of labor personnel and labor fluctuations at the floor station for sample modules for different scenarios, with Takt times ranging from 6 to 11 hours.

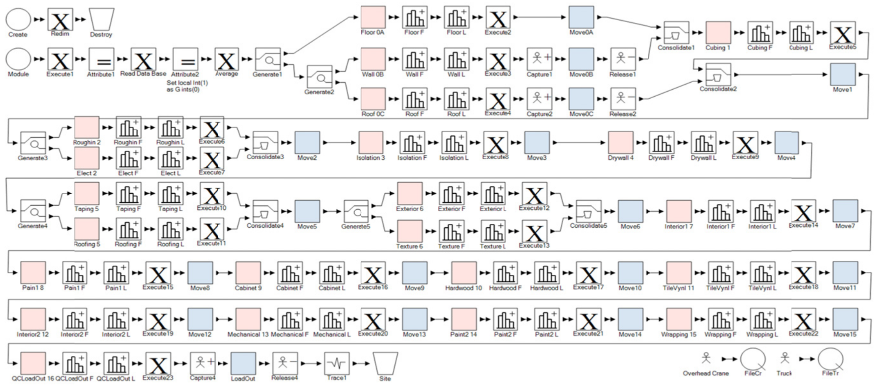
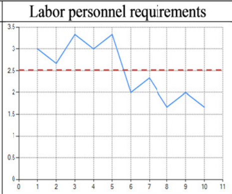
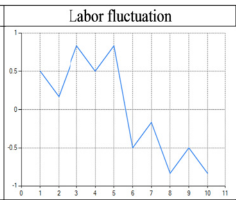
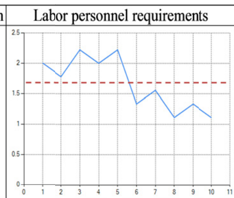
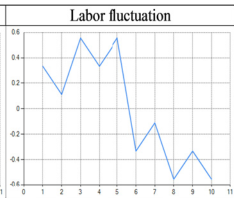
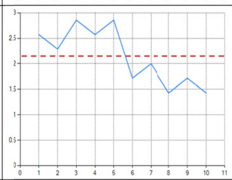
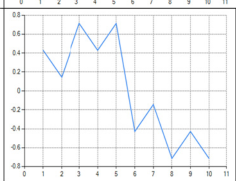
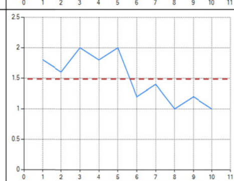
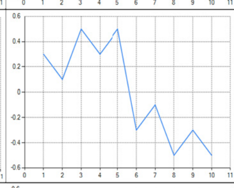
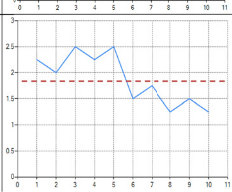
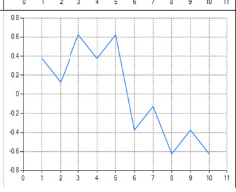
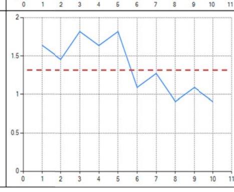
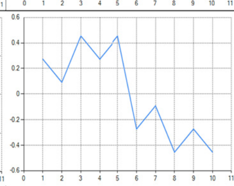


Figure 6: Future-state VSM simulation model

Table 2: Labor requirements and fluctuation at floor station for different scenarios

Run	Labor personnel requirements	Labor fluctuation		Run	Labor personnel requirements	Labor fluctuation	
1			Takt time = 6 hours Unleveled hours = 17	4			Takt time = 9 hours Unleveled hours = 8
2			Takt time = 7 hours Unleveled hours = 28	5			Takt time = 10 hours Unleveled hours = 13
3			Takt time = 8 hours Unleveled hours = 15	6			Takt time= 11 hours Unleveled hours= 5

A number of scenarios offered by the simulation model are presented in Table 3. Based on a selected Takt time, which varies between 6 and 11 hours, the number of fixed labor personnel and multi-skill labours change. The results provide various options from which to select according to company strategies. For example, in scenario 1 with 6-hour Takt time, 71 labor personnel are required in total, including 67 stationary labor personnel and 4 multi-skill labor personnel, whereas in scenario 6 with 11-hour Takt time, 37 labor personnel are required in total, all of which are stationary. Although the total number of labor personnel required in scenario 6 is half of that required in scenario 1, due to the long Takt time the production rate is 21 modules per month, whereas the production rate in scenario 1 is 40 modules per month. A moderate scenario (scenario 3) is presented in which the total number of labor personnel is balanced with production rate. A decision on resource allocation can therefore be made by the management team based on the strategic vision of the company.

Table 3: Scenario analysis for future-state production process

Scenario	Takt time (hour)	Total fixed labor personnel number	Cross-training hours at stations	Requiring hours at all stations	Uncovered hours	Multi-skill labor personell number	Total labor personnel number	Production rate (module/month)
1	6	67	78	105	17	4	71	40
2	7	56	63	91	28	3	59	34
3	8	50	60	75	15	2	52	30
4	9	45	58	66	8	1	46	27
5	10	40	54	67	13	1	41	24
6	11	37	54	59	5	0	37	21

CONCLUSIONS

In the past decade, due to increased interest in manufacturing of modular buildings, there has been recognition within the MCM industry that it is essential to make improvements to the production process in order to meet market demand. In seeking to reach this goal, the benefits of Lean production have been recognized by the MCM industry and Lean principles have been implemented to some degree. The benefit brought by Lean to the MCM industry, however, has been limited due to the inconsistent and incomplete application of Lean principles and tools. Many argue that existing Lean principles are applicable in any industry, including MCM, despite the differences among manufacturing, construction, and MCM. Nevertheless, Lean principles are taken as a whole and the basis remains the same. However, technical elements in Lean production or Lean construction are not sufficient to achieve the Lean goals for MCM, thereby demanding a new framework to exploit the capability brought by modularity. This paper presented scheduling requirements for MCM and proposed modified scheduling technique by which to balance work flow with labor requirements and process mapping to control resource allocation plan in production flow. The proposed technique was evaluated through simulation modeling which proved the effectiveness of modified scheduling technique for modular construction manufacturing.

REFERENCES

Bhatla, A. and Leite, F. (2012). "Integration framework of BIM with the Last Planner System™." Proceedings, Annual Conference of the International Group for Lean Construction, San Diego, CA, USA, Jul. 18-20.

Hajjar, D. and AbouRizk, S. M. (2002) "Unified modeling methodology for construction simulation." Journal of Construction Engineering and Management, 128(2), 174-185.

Howell, G. A. (1999). "What is Lean construction?" Proceedings, Annual Conference of the International Group for Lean Construction, Berkeley, CA, USA, Jul. 26-28, 1-10.

Koskela, L. (1992). "Application of the new production philosophy to construction." TR072, Stanford University, Palo Alto, CA, USA.

Marvel, J. H. and Standridge, C. R. (2009). "A simulation-enhanced Lean design process." Journal of Industrial Engineering and Management, 2(1), 90-113.

McCrary, S. W., Smith, R. R., and Callahan, R. N. (2006). "Comparative analysis between manufacturing and construction enterprises on the use of formalized quality management systems." Journal of Industrial Technology, 22(3), 2-8.

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

Moghadam, M. and Al-Hussein, M. (2013). "Resource optimization for modular construction through value stream map improvement." Proceedings, Annual Conference of the International Group for Lean Construction, Fortaleza, Brazil, Jul. 31-Aug. 2.

Ohno, T. (1988). "Toyota production system: Beyond large-scale production." Productivity Press, Portland, OR, USA.

Singh, B., Garg, S. K., Sharma, S. K., and Grewal, C. (2010). "Lean implementation and its benefits to production industry." International Journal of Lean Six Sigma, 1(2), 157-168.

Winch, G. M. (2003). "Models of manufacturing and the construction process: The genesis of re-engineering construction." Building Research & Information, 31(2), 107-118.