

INTEGRATED ANALYSIS AND SIMULATION FOR ENHANCING WALL ASSEMBLY PROCESS EFFICIENCY BY RESOLVING BOTTLENECKS

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ABSTRACT

Unbalanced production rates of activities and abundant resource allocation are the leading reason behind bottlenecks in processes and have been one of the causes that negatively affect projects leading to wasted resources. Many industries suffer from unbalanced resource workloads, where manufacturing takt times at some workstations are out of sync with preceding stations, consequently leading to an abrupt in the workflow between activities. This research aims to assess the current state of the manufacturing process of a wall assembly line from material cutting to installation, identifying bottlenecks, and creating a framework that would contrast both cycles to finally propose a solution through simulation. A case was studied to propose innovative methods to improve the process flow and to eliminate any waste generated by bottlenecks. This will not only reduce the process duration but will also significantly increase cost expenditure since the amount of idle time and resources will be reduced.

1 INTRODUCTION

Wooden panel assembly is a system where automation implemented in modular construction techniques has become a popular method to displace traditional construction due to its benefits of minimizing time and costs. Modular construction refers to factory-built units completely assembled or fabricated in a manufacturing plant away from the job site, then transported and assembled on site (Pasquire 2002; Lu and Koreman 2010). Modular construction is an offsite construction method that has become an alternative construction procedure and shows benefits in the reduction of delays derived from weather conditions, as well as reduction of accidents, lead times, and variability through the implementation of lean principles.

However, traditional prefabricated construction has always faced several problems that directly impact production times and costs, such as unevenness of workload, large resource utilization rates, uncontrolled number of inventories, and idleness of resources that affect workflow and thus generate bottlenecks. To address these problems, construction industry managers applied lean philosophy to standardize processes, eliminate waste and variability, and the benefits of continuous improvement, thus creating value-added products in the eyes of customers. In particular, value-stream mapping and multi-skilling were utilized and their efficiency proven in many studies (Barkokebas et al. 2020). In addition, discrete event simulation has also been successfully applied mostly in prefabricated construction to forecast different scenarios and establish measures for future states (Goh 2019). The use of Discrete Event Simulation (DES) has helped in providing means to test the concepts of lean in construction simulation, and templates have been suggested to quantify the impact of implementing such concepts (Barkokebas et al. 2020).

Despite this, the combination of DES with lean principles, especially with multi-skilling, was less discussed. However, as shown in previous studies, the combination of DES and lean has the opportunity to make improvements through the implementation of well-thought-out and effective solutions that would mitigate or even eliminate these problems. Hence, this paper proposes a method combining lean ideas, especially multi-skilling along with DES to increase prefabricated construction productivity. A wall assembly line project has been selected as the case study. The development of current and future value stream mappings within simulation models is performed to contrast and identify improvements and their relevance in the process. Finally, validation of the simulation models was achieved by performing extreme condition tests, Symphony integrity checks and parameter validity- sensitivity analysis.

2 LITERATURE REVIEW

Researchers have developed various techniques to enhance the productivity of modular construction. These methods include implementing lean principles, such as multiskilling, to eliminate waste, reduce inventory, and optimize production flow (Yu et al. 2013; Afifi et al. 2016; Innella et al. 2019). Peiris et al. (2023) have introduced a digitalization technique for modular construction, using simulations to forecast activity durations and identify underutilized resources, thereby enhancing manufacturing productivity. Zhang et al. (2020), on the other hand, proposed a process-oriented framework that combines value stream mapping with a production line breakdown structure. This framework analyzes the performance of the production line using key performance indicators and suggests measurement metrics for improved performance.

The integration of onsite and offsite construction through aggregated scheduling can help overcome obstacles faced in construction projects. By identifying and addressing factors that limit productivity, overall production can be increased. This section analyzes the different lean and simulation approaches that can be applied to significantly improve production rates in modular construction facilities.

2.1 Productivity Rates in Factories

Prefabricated construction can benefit wall assembly logistics and site operations by reducing site disruptions, excessive subcontracting, and spatial requirements (Arashpour, et al. 2016). The main benefits of offsite manufacturing can be divided into 7 categories as follows: sustainable construction, cost savings, flexibility, quality, safety increase, a decrease in time, and fewer site disruptions (Durdyev and Ismail 2019).

However, it still has some challenges to implementing prefabricated construction. For example, some operations in off-site construction take longer than others, resulting in an imbalance of inventory along the production line. In addition, the different production rates will result in resource imbalance at workstations, leading to two distinct issues: either resources become excessively utilized, causing bottlenecks, or they are underutilized, resulting in non-bottleneck situations (Arashpour et al. 2014). Hence, it is vitally important to carefully schedule the prefabricated construction process and make the production line flow.

2.2 Prefabrication Process Improvement Techniques

2.2.1 Lean Principles and Multi-Skilling

In order to make the prefabricated construction production line flow, one solution is to adopt lean principles. Lean principles are well-known as one of the main contributions for improving productivity in the manufacturing industry. Its principles were adopted in a wide spectrum of industries, one of which is the construction industry. Several studies in the construction industry investigated the application of lean principles and tools for the construction industry and identified factors that could facilitate or impede their implementation (Singh and Kumar 2020). Implementing lean in construction can lead to improved project

outcomes, such as reduced waste, increased productivity, and enhanced stakeholder satisfaction (Al-Aomar et al. 2018; Tezel et al. 2018).

Several tools were considered effective in implementing lean principles, such as value stream mapping, multi-skilling, and the pull system. Amongst them, value stream mapping is a visual technique employed to examine and enhance the flow of materials, information, and activities required to deliver a construction project, and the pulling system is a fundamental principle of lean that concentrates on creating a demand-driven production system (Barkokebas et al. 2020). In addition, Gomar et al. (2002) described multi-skilled labor as laborers who have the ability and skill to participate in two or more different activities on site. This means that instead of only having the skills of a steel fixer, for example, the laborer would also be able to carry out plumbing tasks (Saleh et al. 2021). These tools have been demonstrated to be effective in reducing waste, preventing errors, and managing inventory, as shown in studies by Salvatierra-Garrido et al. (2011), and Wongwai (2011). Off-site prefabricated construction, such as wall framing, provides an ideal environment for the deployment of multi-skilled resources as it is a unique hybrid of manufacturing and construction (Azimi et al. 2011; Ashapour et al. 2014). The fact that off-site construction operations are semi-automated and fairly simple makes process integration and using multi-skilled resources feasible. An agile or flexible cross-trained workforce is able to function dynamically in response to variability in product demand and labor resources (Arashpor et al. 2016).

The correct application of the lean principles to modular construction operations can prove to be very beneficial in terms of reducing idle time caused by bottlenecks, since the idle workers can be assigned to workstations that may require additional labor, and in turn increasing cost expenditure efficiency.

2.2.2 Simulation Models

Simulation models have been used to analyze and optimize the performance of modular construction projects, especially for off-site processes. Several studies were conducted to simulate the off-site and on-site processes of modular construction. Lu (2018) developed a simulation model to study the impact of different modularization levels on the project's duration and total cost. The results showed that the higher the modularization level, the lower the project duration and cost, with the maximum reduction being 28% and 17%, respectively. Alternatively, Goh (2019) simulated the production of modular components in a high-rise building, which showed a 15% reduction in project duration and a 28% increase in construction efficiency after analyzing the simulation model to come up with an optimized layout and transportation plan. The correct simulation of a construction process has proved to be vital in the improvement of modular construction by clearly highlighting the issues faced in a system and overcoming them.

Despite the aforementioned technologies having shown efficiency in improving prefabricated construction productivity, there were few discussions in previous research on the integration of multi-skilled workers as a lean technique with discrete event simulation. Hence, the aim of this research is to suggest ways for the factory to enhance its production processes by examining the effects of introducing lean techniques and employing workers with multiple skills. The authors used simulation modeling to evaluate both the current and future states of the production line and to propose the best optimal solutions based on different constraints such as the number of workers, layout space, takt times, and budget available to expand the factory.

3 METHODOLOGY

Figure 1 shows the research methodology for this study, where an extensive literature review was followed to determine the activities of the offsite process of modular construction projects, as well as their durations and duration distributions. After the data collection, value stream mapping was adopted to gain a comprehensive understanding of the existing state of the workflow. Subsequently, a simulation model was developed using Symphony.Net software. The model was based on the current-state logic between the

manufacturing workstations to determine the overall duration for the fabrication of a two-storey module. The simulation model was used to determine the utilization of each of the resources, which determined the location of the bottlenecks. Improvements to the current system were applied to come up with higher utilization for the resources, and to reduce the total duration required to fabricate the modules. Meanwhile, in the pursuit of improvement, two previously mentioned lean techniques, namely pulling system and multi-skilling, have been utilized.

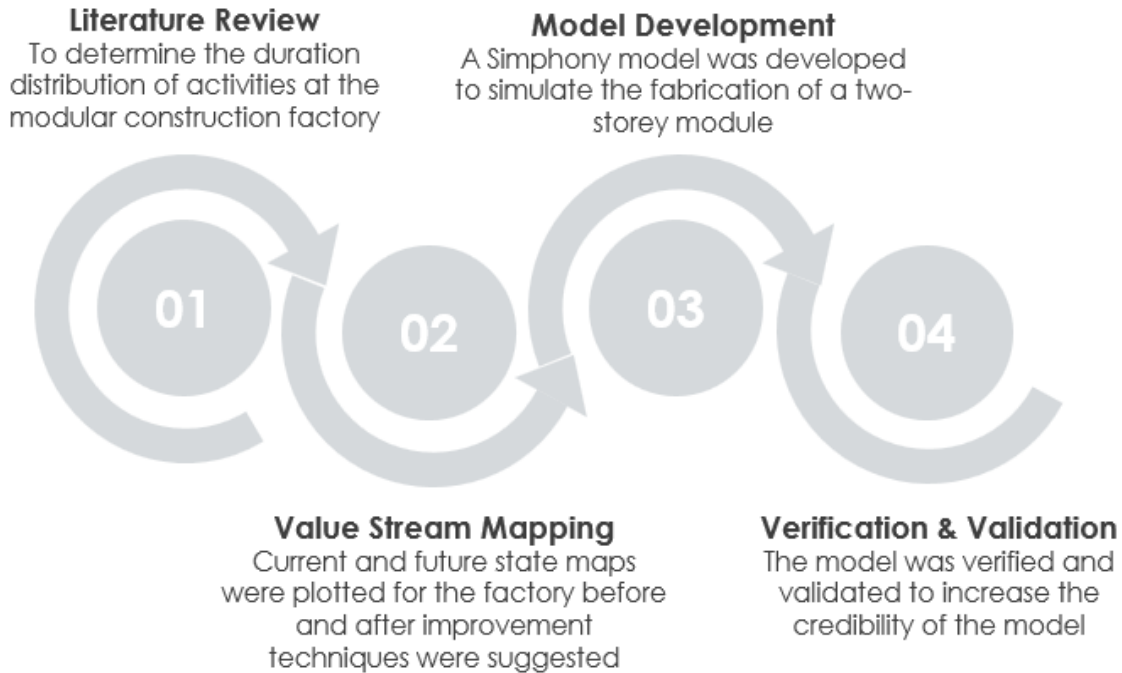


Figure 1: Research methodology.

4 CASE STUDY DESCRIPTION

To better understand the different workstations in a wooden wall assembly line, data from a project by Igloo prebuilt homes was consulted. Details of durations of each station, dimensions of panels and the process itself was obtained from (Mansooreh M. 2014), and then, modified based on different assumptions. This project produces two story modules of 245.2 sq ft each, which account for 14 external walls, 18 internal walls, 2 floors and 1 roof. The following chart depicts the different workstations, where wall framing and floor, mechanical plumbing begin concurrently at the wall set and cubing station. This is followed by roof and ceiling installation, which commences during the rough in and electrical task. Subsequently, painting and window installation join the workflow at the taping and roofing table. Figure 2 shows the workflow of the manufacturing process.

5 MANUFACTURING PROCESS ANALYSIS TO PROPOSE IMPROVEMENT

5.1 Distribution of Durations

The required man-hours for each of the activities was determined based on equation developed by Moghadam (2014). The required man-hours were a function of the effective length and the number of components in each element of the module. The following equation was used to determine the effective length of exterior walls, as an example:

$$EL_{EW} = \alpha C + \beta L \quad (1)$$

Where:

EL=converted length; C=total number of components; L=linear length of wall

α =wall converting coefficient (0.87); β =wall converting coefficient (0.2)

Once the effective length is determined, the required man-hours can be calculated using the following equation (Moghadam, 2014):

$$D_{EW} = \alpha EL - \beta \tag{2}$$

Where:

α =productivity rate of labor=2.7 mnhr/ft; β =statistical constant

A triangular distribution was also developed for each of the module elements. Moghadam (2014) came up with the following factors to determine the triangular distribution parameters for the exterior walls:

$$\text{Minimum: } 0.4D_{EW}; \text{ Maximum: } 3.2D_{EW}; \text{ Most – likely: } 1.0D_{EW}$$

The reader is referred to the study conducted by Moghadam (2014) for the man-hour requirement distributions of the remaining elements.

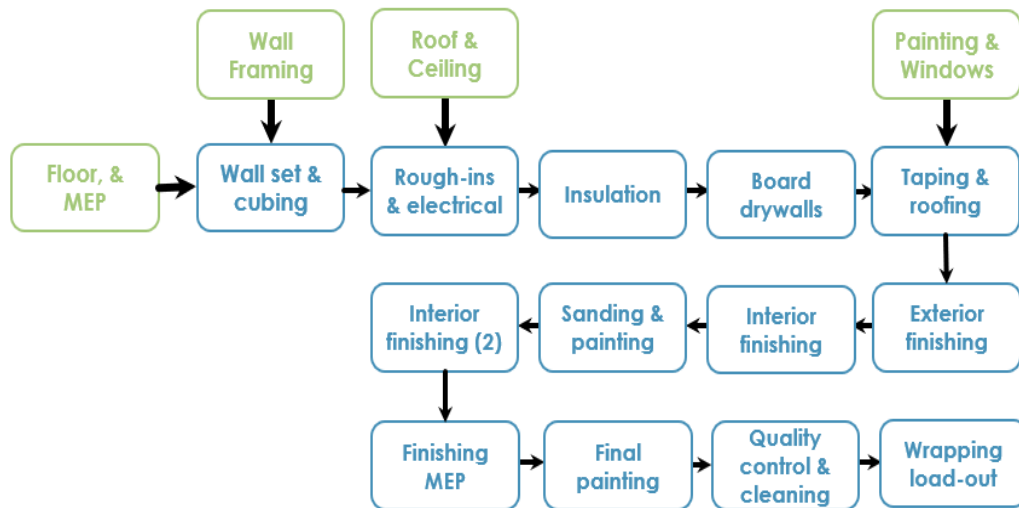


Figure 2: Wood wall production process.

5.2 Model for the Current State Map

The current state mapping, as shown in Figure 3, is drawn based on the case study information. There are 9 stations in total, and the transportation of wooden houses between each station will cost 0.25 hours. In addition, there is an inventory, 14 external walls, and 18 internal walls, between the wall framing station and cubing process station. Assuming that the demand of the customers will be 2 hours per month, and there are 20 trays for one month, the takt time is 20 hours for wall framing and 40 hours for floor plumbing. For other stations, the takt time is 80 hours.

To further provide insight into the manufacturing process and reveal the bottleneck, a simulation model of the current state mapping was created. This paper uses Symphony.Net (version 4.6.0.385) to create the model. The model for the current state mapping is shown in Figure 4. The resource elements for each station and crane have been created based on the current state mapping. However, the workers from different stations are independent of each other. The only resource that will be shared among different stations will be the crane, which is used to lift the roof, wood walls, and floors.

After running the simulation 100 times, the detailed analysis of the simulation result is shown in Figure 5. It appears that the average utilization of wall framing reached almost 99%, whilst more workers have

been assigned to the wall framing station because it is critical for the whole process. Meanwhile, the average utilization of other stations is relatively low compared to the wall framing station. It shows that the workload between each station is not evenly distributed. Furthermore, the cycle time for the wall framing and the cubing process is higher than the required takt time. Unexpectedly, the utilization rate of workers at the cubing process station is low, but the cycle time is high. It is plausible that the workers are waiting for the work and the long cycle time is increased due to idleness and waiting time.

5.3 Model for the Future State Map

In order to optimize the whole manufacturing process, a simulation model for future state mapping was created. Compared with the original model, the inventory between the wall framing and the cubing process was removed. Figure 6 shows the simulation model with the inventory, whereas Figure 6 (A) and (B) shows the simulation model without inventory.

In the current state model, the wall entities will wait at the end of the framing station until the number of walls required for one module is reached. In the future state model, any finished wall entity is allowed to flow into the cubing process when framing is finalized. As a consequence, the average total duration of completing one module has been reduced to 178.6 hours based on the simulation result. However, the utilization rate of the wall framing workers remained at 96.9%. Therefore, it was suggested to double the working space and add more workers (9 for each station) for the wall framing station as it is the bottleneck activity.

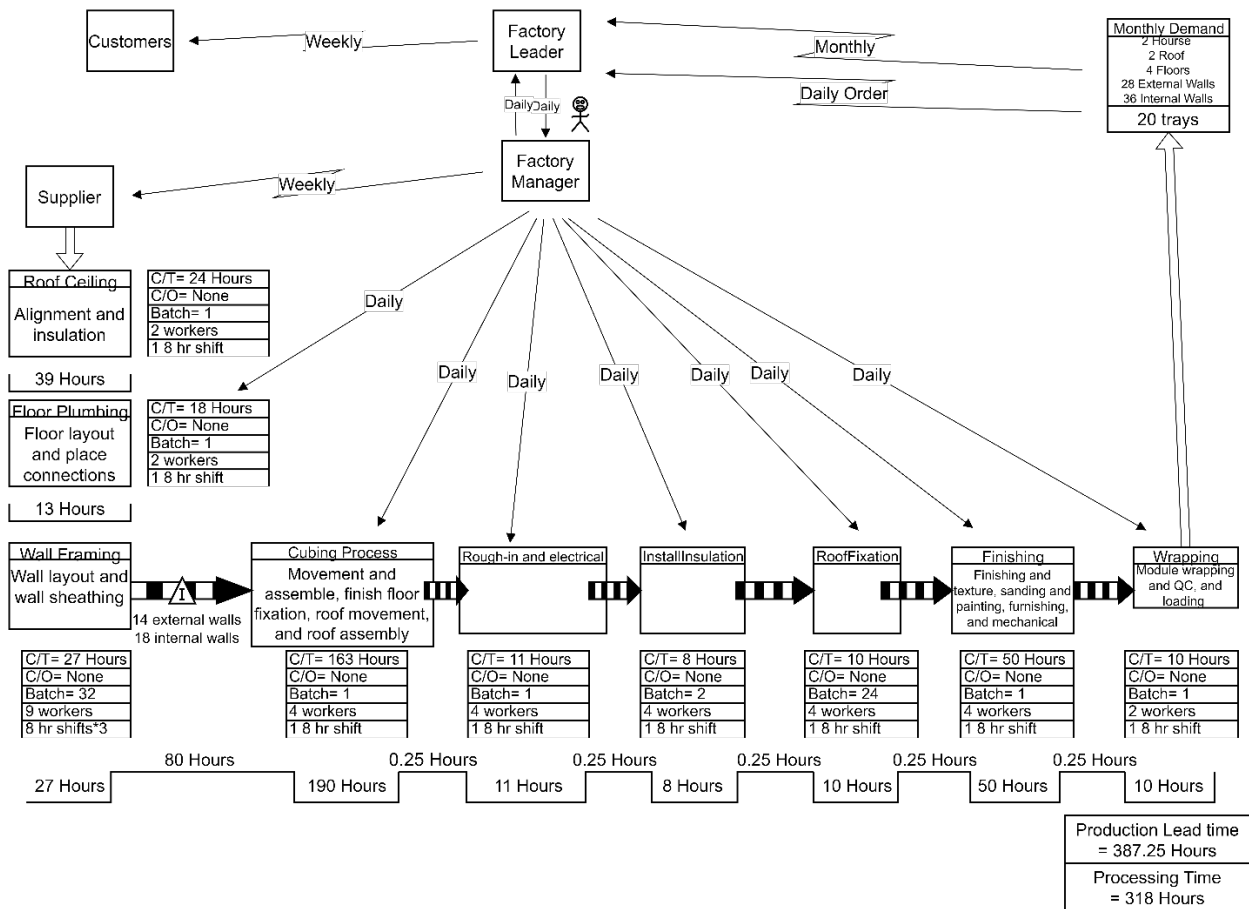


Figure 3: Current state mapping for the manufacturing process.

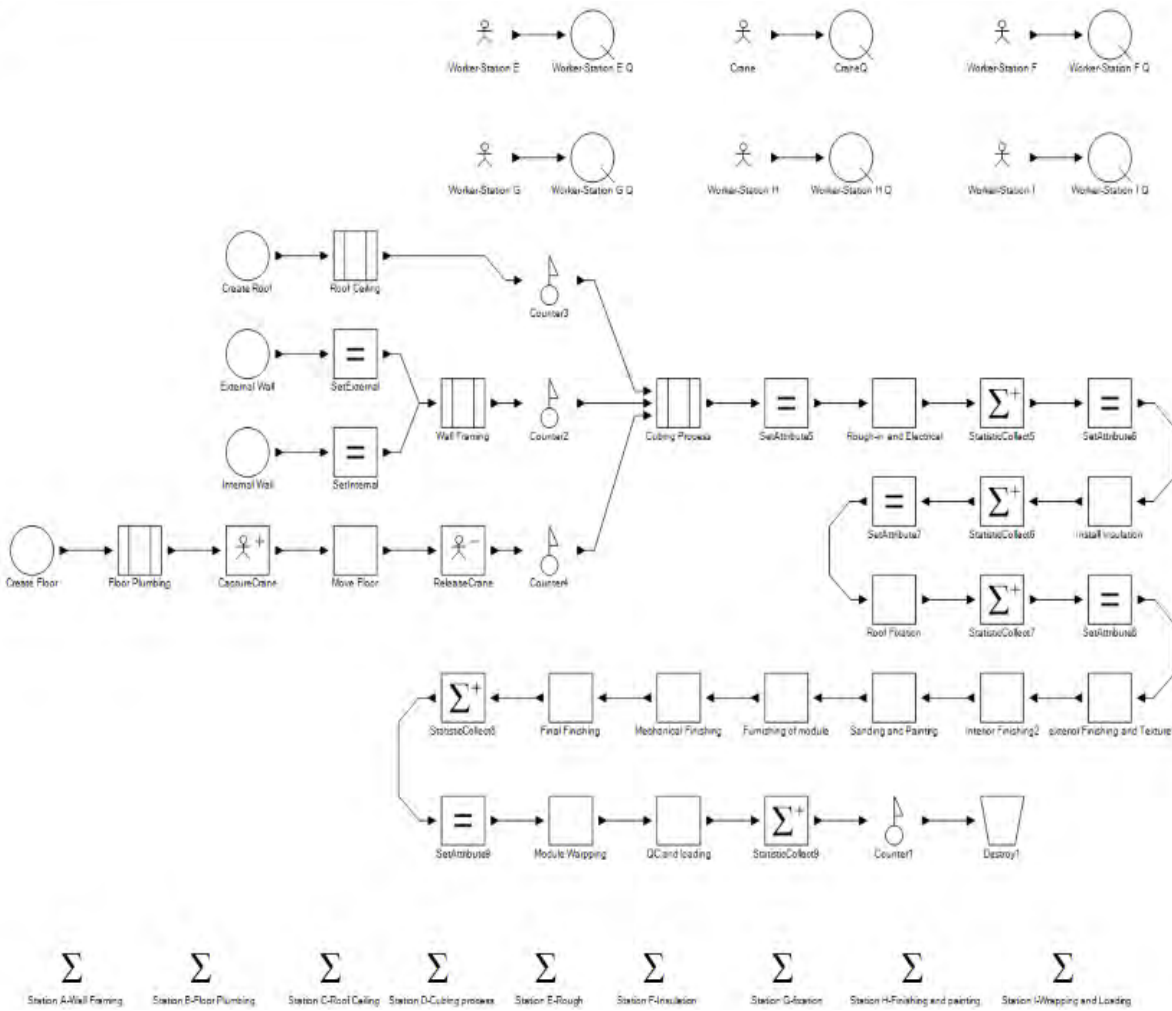


Figure 4: Simulation model.

The results for the updated simulation model are shown in Figure 7 (A) and (B). By increasing the number of wall framing stations to 3 stations, the average total duration for completing one house was reduced to 66.5 hours. Meanwhile, the utilization rate of wall framing decreased to 88%, and the utilization rates for other stations increased. Additionally, the cycle time for each station is now less than the required takt time. However, the utilization rate for stations “rough-in,” “insulation,” “roof fixation,” and “wrapping” are relatively low. In order to reduce this uneven workload, multi-skilling is suggested to the factory, specifically, to incorporate multi-skilled workers on the “wall framing” station as well as the aforementioned stations. As a result, the utilization rate of the wall framing activity, after allocating multi-skilled workers, has been reduced to 80%, meanwhile the utilization rate of other stations also increased as can be seen in Figure 8 (C). The total duration of manufacturing one house will be 53 hours. In addition, the cycle time of the cubing process has further decreased, as shown in Figure 8 (D). It is logical that it decreased due to the higher utilization rate of the workers in the cubing station since there is a lower wait time for the walls.

5.4 Suggested Improvements for Future State Map

Based on the simulation results, the main problems for the factory were the following: (1) wall framing is the bottleneck of the whole process, (2) inventory will hinder the manufacturing process and increase the total manufacturing duration, (3) unevenness of workload between each station. By running the simulation model, the following three suggested improvements are summarized by the authors: (1) removal of the inventory between each station, especially between the wall framing and cubing station, for improved product flow, (2) increase the number of wall framing stations with 9 workers on each station, to decrease the cycle and takt times, (3) train the multi-skilled worker to be allocated to the wall framing stations as well as other stations with low worker utilization rates for a more even workload distribution.

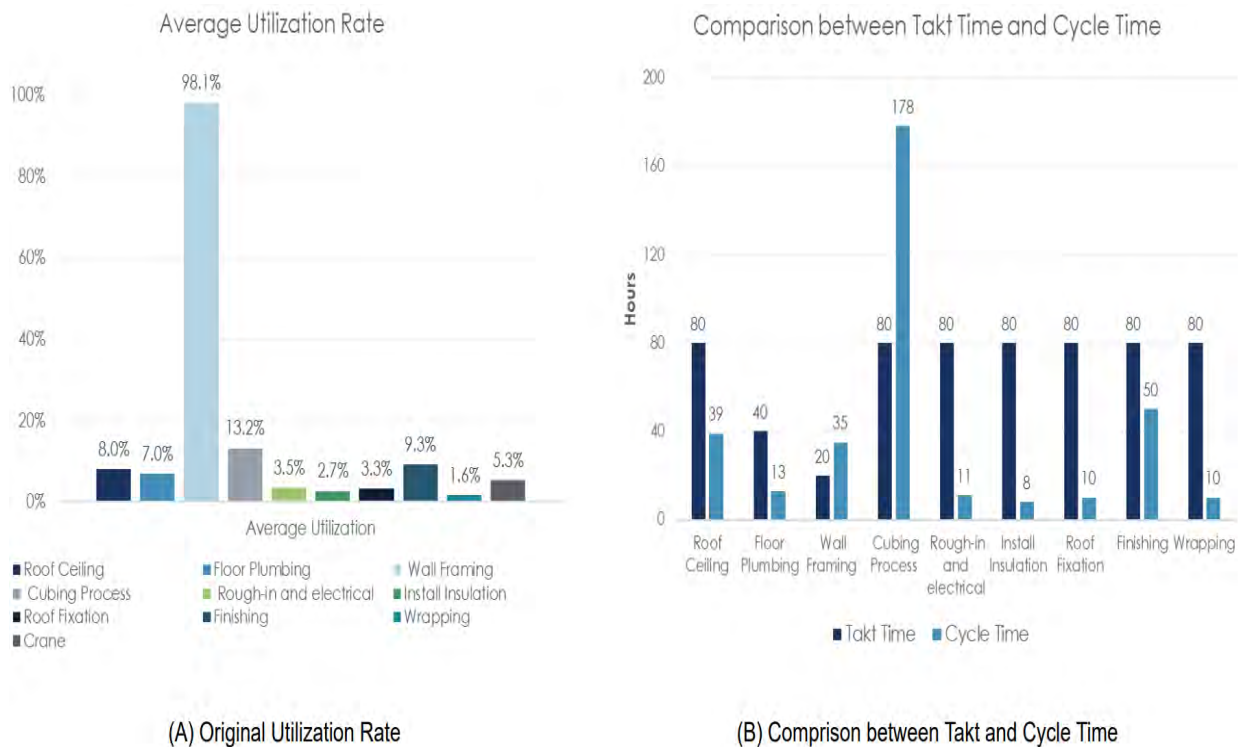


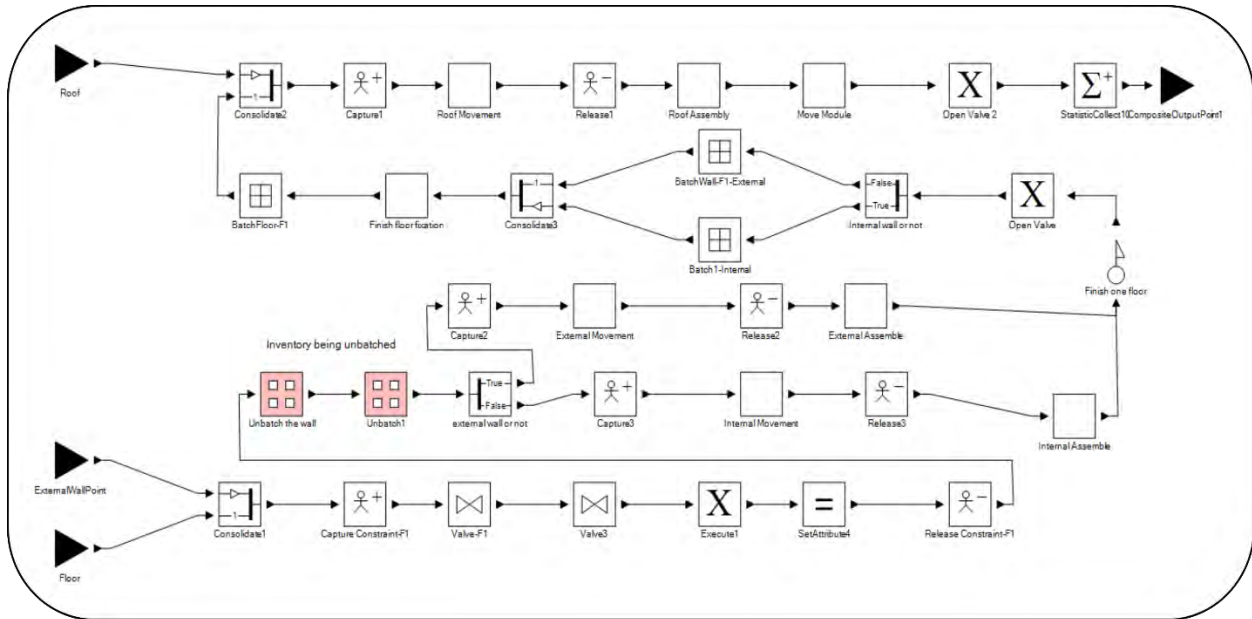
Figure 5: Analysis of the current state simulation model.

6 VALIDATION AND VERIFICATION

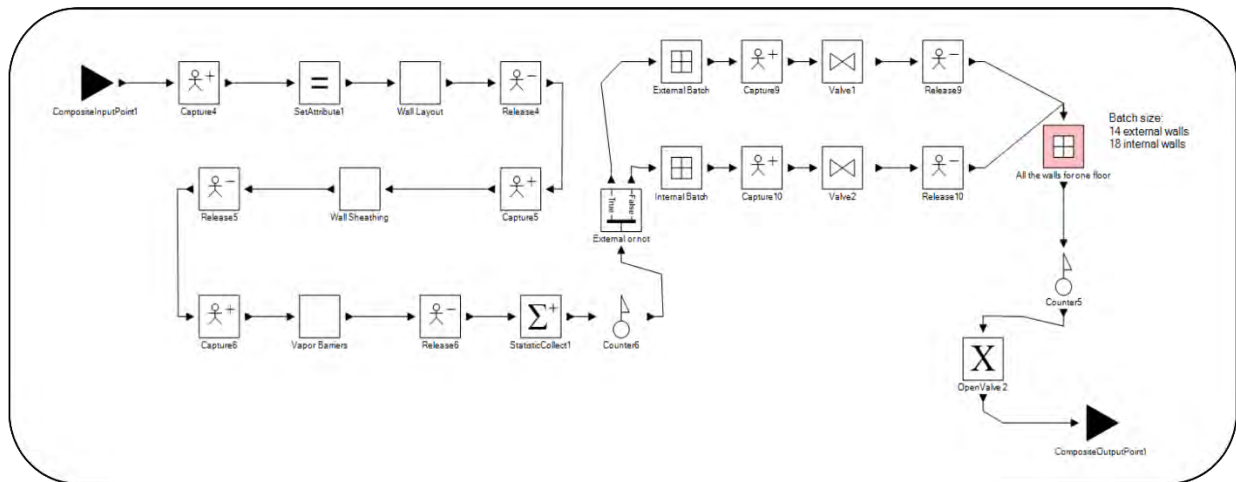
The project was verified and validated through a set of different tests that were suggested by Sargent (2007). For conceptual validation, the technique used was *Event Validity*, where the model results were compared with another model, developed by Moghadam (2014). To attain an accurate comparison, the developed model was set to the same conditions of the model developed by Moghadam (2014), by removing the set inventory. When making the comparison, the results showed that it took 172.47 hours to complete one module versus 178 hours taken by the other model, giving a difference of only 3%.

Regarding verification, Symphony.net verifies that the model is error-free, where the model would not run unless it passes all the integrity checks. Furthermore, two additional tests were used to verify the model, which were the *Parameter Variability* and the *Extreme Conditions* tests. For the parameter variability test, the duration of the bottleneck activity, wall framing, was increased by 25%, which led the total duration for the production of 20 units to increase by 25%. Additionally, the cycle time for the wall framing activity also increased by 26% which indicates that there is a direct relationship between increasing the duration of the bottleneck activity and the total duration of the whole process, which is a logical correlation. For the

Extreme Conditions test, the number of the resources for the wall framing activity was set to zero. This led to the cycle time of the wall framing activity, and the cycle time of the succeeding cubing activity to both become zero, which again follows the rationale of the real system since production of the wall frames would halt if there were no resources to carry out the activity.



(A) Cubing Process with Inventory



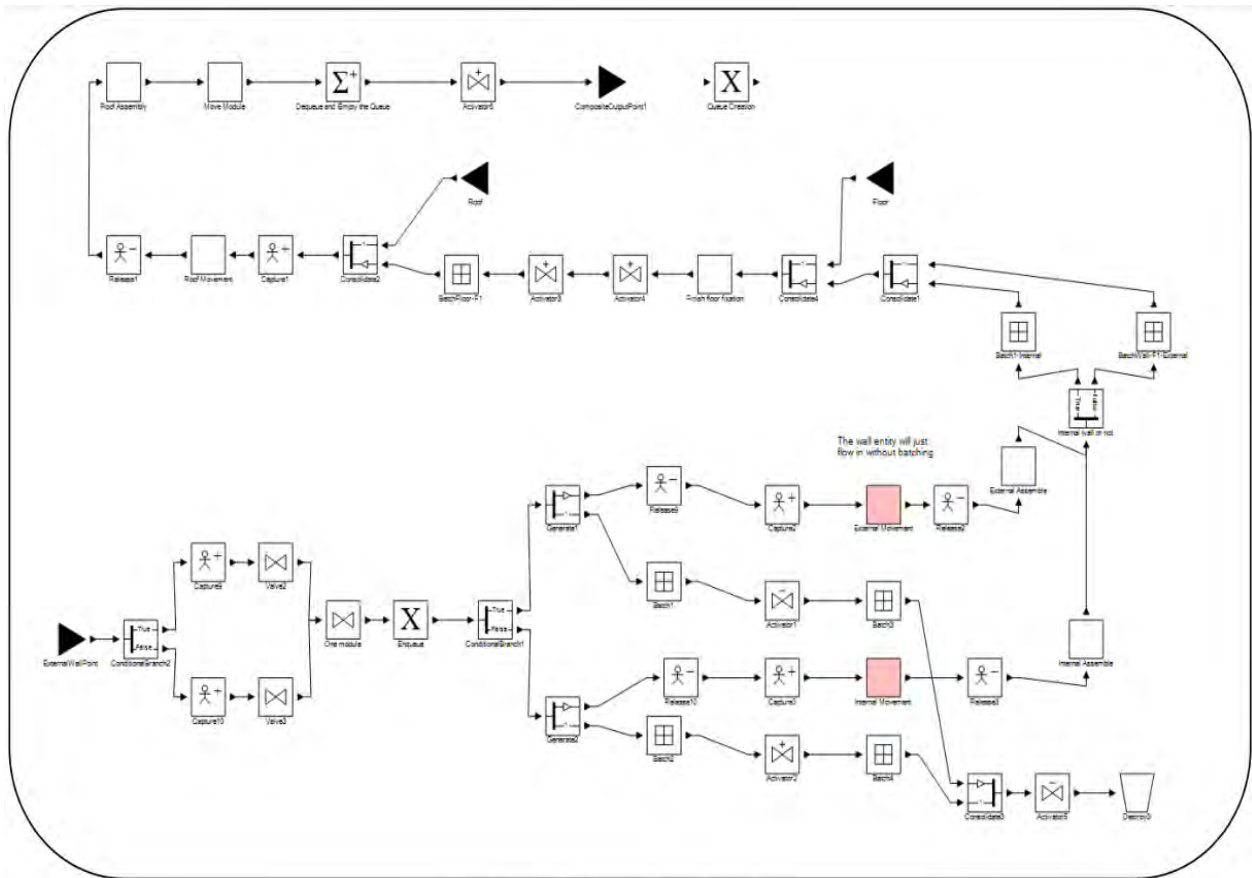
(B) Wall Framing Process with Inventory

Figure 6: Simulation model with inventory.

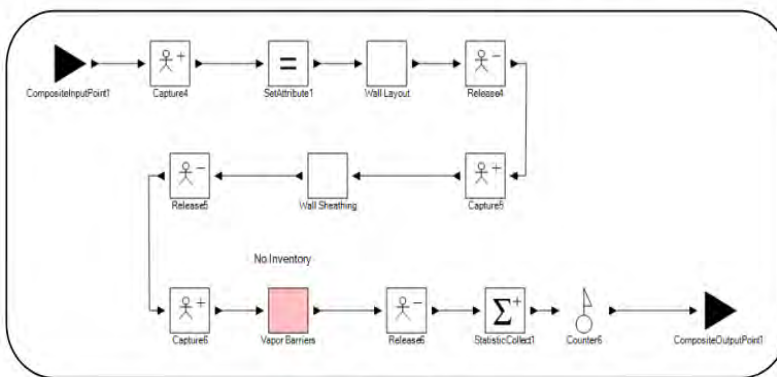
7 CONCLUSION

Previous studies with prefabricated construction mainly focused on using a single method to enhance the process. The combination of DES with Lean principles, especially simulation with multi-skilling, was not tackled extensively in previous research. Hence, this paper explored the significance of the combination of lean, multi-skilling, and DES on prefabricated construction by studying a wooden wall assembly line. Results demonstrated that prefabricated construction would benefit from the three methods by identifying

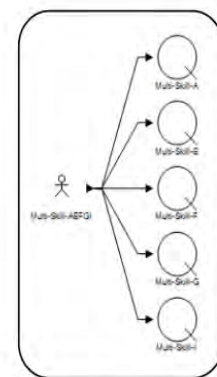
the bottleneck activities, removing uneven workload, and reducing the cycle time to meet customers' requirements.



(A) Cubing Process without Inventory



(B) Wall Framing Process without Inventory

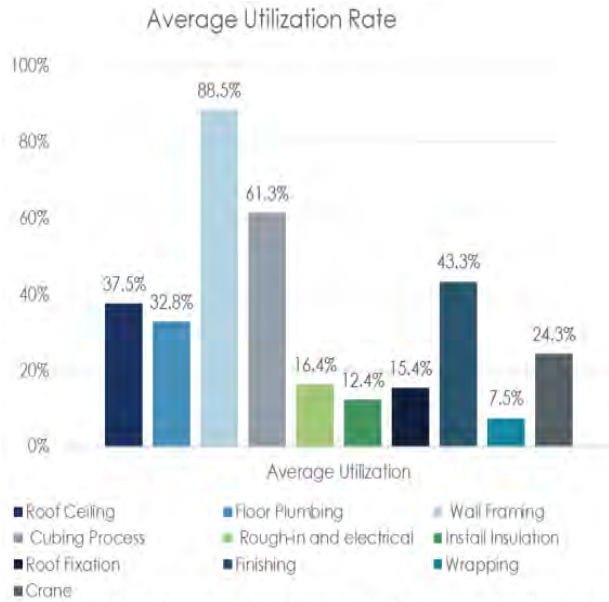


(C) Multi-skilled Workers

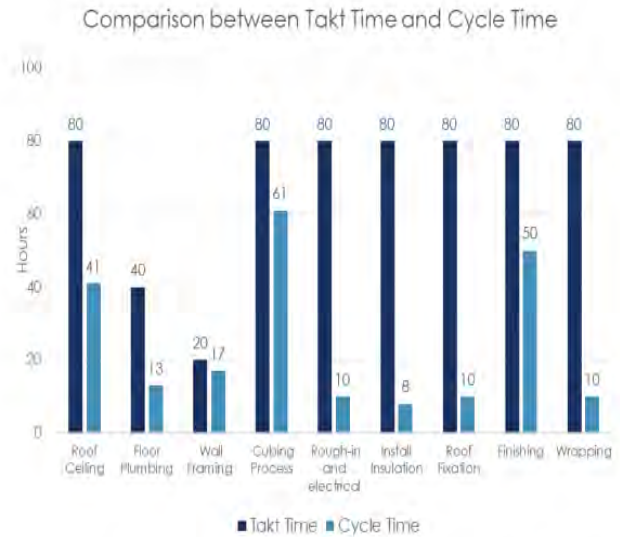
Figure 7: Simulation model with improvements.

However, limitations have been identified by the authors. Firstly, the DES is hard to dynamically represent the productivity change caused by the change of workers. Hence, continuous simulation is

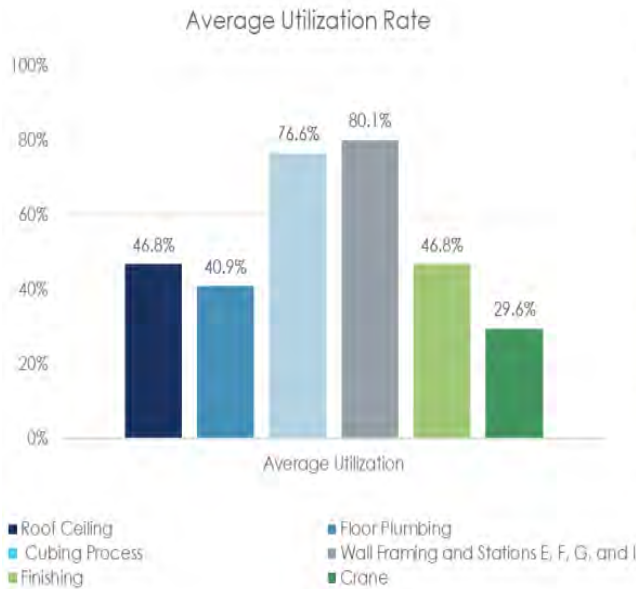
suggested to further combine with DES to further explore multi-skilling on prefabricated construction. Secondly, the cost of adding workers is not considered in the proposed method. It is hard to trade-off between adding more workers and increasing the productivity rate. Hence, further studies are recommended to further this research area by addressing the limitations.



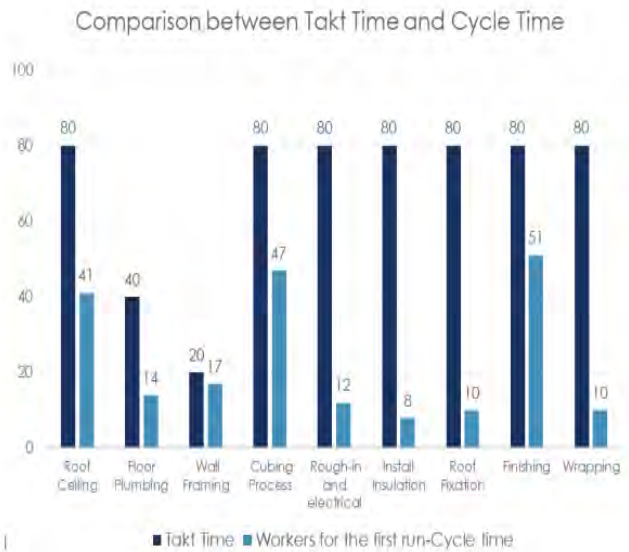
(A) Average Utilization Rate for Future State Map



(B) Takt Time and Cycle Time for Future State Map



(C) Average Utilization Rate for Multi-Skilling



(D) Takt Time and Cycle Time for Multi-Skilling

Figure 8: Simulation results and analysis.

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