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Lean production theory-based simulation of modular construction processes

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ABSTRACT

One way to encourage adoption of prefabrication and off-site manufacturing (OSM) techniques, such as modular construction, is to improve the efficiency of site operations, which makes the technology more attractive to non-adopters. Lean principles have been widely applied to improve the productivity and efficiency of construction operations, while simulation augments Lean theory by allowing its benefits and issues to be analyzed quantitatively before actual implementation. Thus, this study aims to conduct a detailed simulation study of modular construction operations, otherwise known as Prefabricated Prefinished Volumetric Construction (PPVC) in Singapore. In contrast with existing research, which are frequently focused on the barriers and drivers to the adoption of prefabrication, this study will provide and evaluate recommendations to improve modular construction efficiency through application of Lean concepts. A detailed baseline (As-Is) simulation model of an ongoing PPVC project case study was first developed. Lean Construction principles were then applied to the baseline simulation model. Key Lean Construction principles and concepts implemented includes Total Quality Management, E-Kanban based Just-In-Time deliveries, cross training and the use of construction robotics. Lean (To-Be) simulation models were developed based on the Lean Construction principles. The outputs from the baseline and Lean models were compared to assess the impact of the proposed improvements. The findings demonstrated that through the application of Lean concepts, reductions in cycle time and process time, and increases in process efficiency and labor productivity can be achieved. The case study also provides a detailed description of the simulation approach, which is a useful reference for future application of simulation in offsite construction research.

1. Introduction

With its ability to harness the efficiency of manufacturing processes, offsite construction, offsite manufacturing (OSM) or prefabrication, has long been seen as the way forward in enhancing productivity of the construction sector [1–3]. It offers significant benefits, such as reduced project duration and defects, and improved health and safety [2,4]. Modular construction is a subset of OSM, where each prefabricated module is a volumetric component that can be a complete or partial room or unit (e.g. bathroom or lift) [5,6]. In contrast, non-volumetric offsite construction includes two-dimensional elements like walls and columns.

Interest in OSM persisted across the years. In the United Kingdom, for example, the OSM sector has seen tremendous growth since the Egan Report (Egan 1999) [7], which recommended OSM as a solution to boost productivity and overcome labor shortages. OSM continues to be highlighted in the “Construction 2025” document [8]. Similarly, the US National Research Council has identified offsite construction as the key to improving the competitiveness of its construction industry [9].

Offsite construction has been used in Singapore since the 1980s. Efforts to increase the use of prefabrication have largely been spearheaded by the Building and Construction Authority (BCA). In 2014, BCA unveiled its Second Productivity Roadmap [10] which aimed to increase the prevalence of Design for Manufacturing and Assembly (DfMA), including the prefabrication of components that can be assembled on site. One of the key technologies promoted in Singapore is Prefabricated Prefinished Volumetric Construction (PPVC), in which building modules complete with internal finishes and fittings are manufactured off-site and assembled on-site in a Lego-like manner. PPVC is essentially modular construction using complete and pre-finished room units.

Nonetheless, barriers to prefabrication such as perceived higher capital costs have impeded its adoption [11]. For instance, OSM only contributed to 2.1% of total construction value in the UK in 2007 [12].

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Likewise in Singapore, even with incentives through Government Land Sales (GLS) and the Productivity Improvement Programmed (PIP), PPVC adoption has been low and limited to established contractors [13]. Existing literature on prefabrication, OSM and modular construction largely focus on providing information on the existing approaches and the drivers and barriers to their adoption. According to Blismas and Wakefield [1], these only serve to generate awareness among non-adopters and does little to spur adoption. In contrast, several studies have recommended applying manufacturing principles to improve the efficiency of OSM operations [1,14,15], which mitigate the barriers such as higher capital costs, and are more impactful in promoting the use of offsite construction.

Lean Construction and simulation have been used to improve construction processes such as housebuilding [16], bridge deck construction [17] and block and bricklaying operations [18,42]. Lean Construction aims to improve construction operations through minimizing waste and maximizing value [19]. Applying Lean Construction principles to PPVC can potentially increase its efficiency and promote its adoption. Simulation augments lean construction by allowing its benefits and issues to be evaluated and understood quantitatively before implementation, thereby aiding decision making capabilities from the managerial perspective. Therefore, a detailed simulation case study of an actual PPVC construction site in Singapore was developed and evaluated. Lean Construction principles were then implemented in the simulation model to assess the potential impact of the proposed improvements. The case study provides insights into the onsite challenges of implementing PPVC and demonstrates the applicability of Lean Construction and simulation in improving efficiency of PPVC and modular construction. By proposing ways to optimize on-site modular construction operations, the study aims to mitigate barriers to adoption such as higher capital costs and unfamiliarity with the technology, thereby spurring greater uptake. The case study also describes the simulation methodology in detail, which will be a useful reference for future application of simulation in offsite construction research. The scope of this case study is limited to the on-site installation of PPVC modules.

2. Literature review

The benefits of prefabrication and OSM are well-documented. For instance, the UK construction industry has experienced reductions in defects, health and safety risks, project durations and improvements in sustainability, productivity and life cycle performance arising from offsite construction adoption [2]. On the modular construction front, Ogden and Lawson [20] found that speedier construction times bring about financial benefits in reduced interest charges of 2–3% in the construction phase and an earlier commencement of business and rental incomes. The findings of the 2011 Smart Market report indicated that modular construction proved to be beneficial among industry players and is perceived in a positive light by non-users (Cassino et al., [21]).

However, adoption of prefabrication has been impeded by several barriers. Pan and Sidwell [15] found that construction companies associate OSM with large capital outlays and difficulty to attain economies of scale. Many industry professionals also lack knowledge on fabrication, approval, transportation and on-site assembly procedures, especially with regard to modular construction [1,22]. Blismas and Wakefield [1] recommended that research should be conducted to understand how manufacturing principles can be applied to optimize OSM processes. Improving process efficiency leads to increased cost savings which can potentially circumvent barrier of perceived higher capital costs [15], thereby making OSM more attractive to non-adopters.

The construction industry had been trying to improve its performance by applying lessons from the manufacturing industry [14,23,24]. Lean Production, which has its roots in the manufacturing industry, have been found to be applicable in construction due to the similar nature of goals [25]. The aim of Lean Construction is to seek opportunities to reduce waste and maximize value in construction projects continuously [19]. There were many case studies of successful implementation of Lean Construction. For example Telyas [26] used Value Stream Mapping to identify waste in a modular construction factory. Lean principles were applied in the form of the 5S - sort, straighten, shine, standardize and sustain to improve the identified areas of waste. Findings indicate that dramatic improvements in productivity, throughput and labor costs were observed in half a year.

Marvel and Standridge [27], however, argue that although Lean theory is a powerful method for process improvement, it is deterministic in nature and therefore unable to address variability in a system nor able to analyze the performance of a future state system. Lu et al. [28] therefore proposed an integrated Lean and simulation approach where simulation augments Lean Construction by modelling system variability, analyzing system performance quantitatively and identifying issues with the proposed system before actual implementation. This results in a robust methodology for process improvement in construction as simulation is able to provide insights and predict outcomes for multiple what-if scenarios Abbasian-Hosseini et al. [18] for instance, modelled a brick laying process and used Discrete Event Simulation (DES) to assess the impact of applying Lean Construction principles. However, despite the benefits of a Lean – Simulation approach, Mostafa et al. [14] found a lack of its use prefabrication and modular construction context, with just 13% and 7% of research on prefabrication covering Lean principles and integrating Lean with simulation, respectively. Furthermore, it is noted that none of the current studies were focused on on-site assembly phase of modular construction.

3. Approach

A case study approach was used in this research as it allows systematic and in-depth inquiry of the system of interest and its individual components, of which the research has no control or influence over [29]. This allows for an intimate understanding of the system to be developed through the triangulation of multiple sources of data such as interviews, historical records and observations, which is essential in simulation model development. The case study is focused on the on-site PPVC processes in an executive condominium project in Singapore. Although OSM processes may differ across the world, the phases involved are by and large the same. OSM projects almost always consist of the following phases: Design, Develop, Detail, Order, Fabricate, Transport and Assembly (National Institute of Building Science, [30]; [22]). In the assembly phase, cranes are used to lift modules or panels from designated pick points and settled into place. Similarly, the PPVC case study reported herein involves the fundamental OSM processes and phases, thereby allowing this study to present useful insights to any OSM projects internationally.

The simulation study is divided into four phases – product abstraction, process abstraction and modelling, experimentation, and decision making [31] (see Fig. 1).

3.1. Abstraction and modelling

A conceptual process map of the operation was first created, refined and validated. Five System Experts (SEs) were interviewed on multiple occasions during the site visits. Each of the SEs are intimately familiar with the lifting and installation process and have at least five years of experience in the construction industry. A period of > 20 days, stretched over two months, was spent on the site for data collection.

Following that, the conceptual model was translated into a computer Discrete Event Simulation (DES) model (an As-Is model reflecting the existing PPVC operations). For this study, the Arena simulation package [32] was used. The fundamental elements of modelling in Arena are known as *Modules*, which can be categorized into *Flowchart and Data Modules*. *Flowchart modules*, e.g. *Create*, *Dispose*, and *Process*, are used to model the dynamic processes of the system, including the

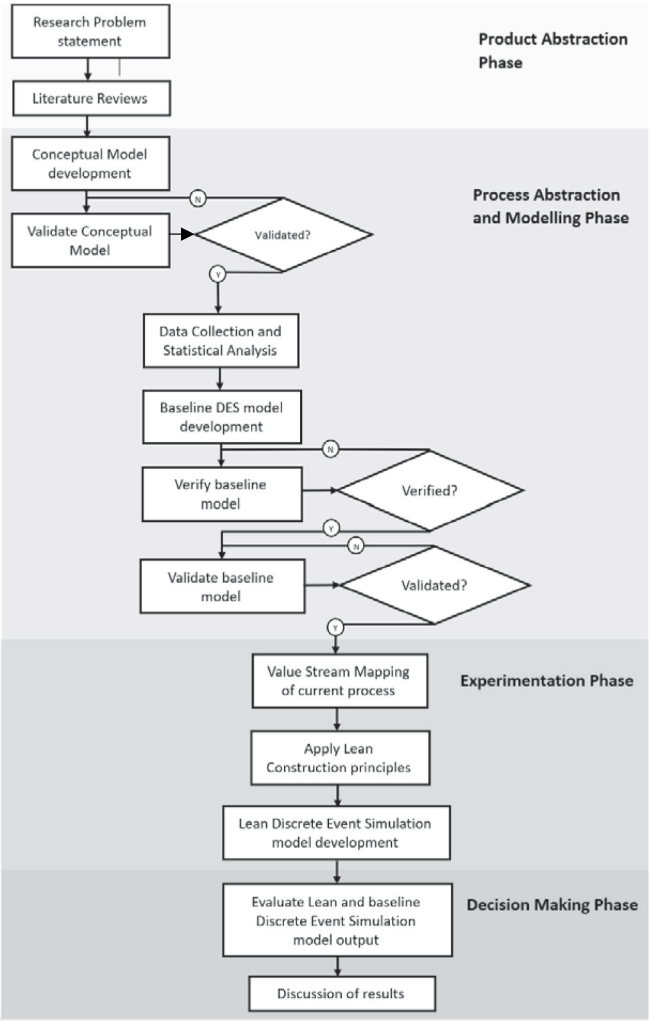


Fig. 1. Research methodology.

arrival, flow and disposal of materials. Conversely, *Data Modules* define the various characteristics of the system's components such as resources, variables and expressions [33].

Each process in the lifting and installation operation was modelled with the *Process flowchart module*, whereby duration Probability Density Functions (PDFs) and required resources were specified. Resource characteristics such as worker availability were modelled using the *Schedule Data module*, while entity (4 and 6 Hook modules) arrivals were modelled using *Create and Assign* modules to specify the distributions for arrival batch sizes and entity attributes, respectively. Empirical data on module arrivals, resource availability and process durations was collected based on historical records, interviews with SEs and observations with a stopwatch for two gantry cranes in operation. Distinctions were made between 4 hook and 6 hook modules and if rework was required. All observations were taken under similar working conditions and in good weather.

Kelton [33] proposed using theoretical distributions over empirical data as a basis of simulation. This is because values which have not been observed can be generated, leading to a more accurate representation of the actual population. As such, collected data sets were subject to statistical analysis to specify required input PDFs. This was done using the Arena Input Analyzer [33], which applied Goodness of Fit (GOF) tests or the lowest square error to select the most suitable distributions (based on *p*-value and square error) for each process data set. Additionally, estimates had to be obtained for data that could not be feasibly collected. For instance, as the "Attach/Detach Spreader Beam" process only occurs once or twice a day, it was more feasible to obtain a duration estimate from the SEs compared to physical measurement. The triangular distribution is commonly used for obtaining such parameter estimates [34]. SEs were therefore asked to provide the minimum, maximum and most likely duration estimates for the process. Data for module arrivals, work schedules and resource characteristics such as maintenance frequency were obtained via interviews with SEs and historical records. These were used to specify the entity arrival rates, resource availability and resource attributes.

3.2. *Verification and validation*

Subsequently, verification and validation were conducted. Verification involves ensuring that the conceptual model is correctly reflected in the simulation model, while validation is about ensuring that the simulation model is an accurate representation of the system [34]. Law [35] presented several techniques for the verification of simulation models. To ensure that the DES model is properly constructed, its outputs can be examined for reasonableness under a variety of input parameters and its state variables and counters can be traced. Sargent [36] proposed a quantitative parameter variability-sensitivity analysis, where both the direction and magnitude of changes in output in relation to inputs are specified to increase reliability. Exogenous variables entity arrival rate and resource schedules were changed and the corresponding direction and expected changes were hypothesized. Subsequently, the actual changes in output were compared to the expected changes and evaluated for reasonableness. As Yeh and Schmeiser [37] provided that model output accuracy can be achieved by using 10 to 30 replications, the baseline model was run for 30 replications, each at a length of 25 simulation days. Shi [38] proposed examining the simulation activities in a chronological order to verify if they are initiated and advanced in the correct sequence. If the report of the first cycle is correct, it is highly likely that subsequent cycles will operate correctly. A chronological simulation report was generated with Arena's *Trace* function and contrasted with the actual data collected during lifting and installation operations. The entity used for the *Trace* was a single 4 hook module.

Next, the three-step model validation approach proposed by Naylor and Finger [39] was used, which includes: (1) build a model that has high face validity, (2) validate model assumptions, and (3) compare model input-output transformations with corresponding input-output transformations for the real system. As described earlier, face validity test was executed by interviewing various SEs. Each SE was provided with a print-out and explanation of the DES model and was asked to rate the model's correctness in comparison to the actual lifting process from a scale of one to five, five being very accurate and one being not accurate at all. The face validity tests took 20 min on average.

Model assumptions can be categorized into structural and data assumptions. Structural assumptions involve queries on how the system operates. These should be validated through close observation of the system and confirming operational scenarios with SEs to ensure that the mechanics of the system are properly represented [34]. In this study, structural assumptions such as the mechanics of spreader beam usage have been verified with SEs in the conceptual model validation stage. Conversely, data assumptions are based on the collection of reliable data and fitting the appropriate distributions, which was carried out earlier in the DES model development with the Arena Input Analyzers.

To compare input-output transformations between the model and actual process, the confidence interval approach was used. Law [35] argued for confidence intervals in validation instead of hypothesis testing as the simulation model is only an approximation of the actual system. If the mean of the actual observations falls within the confidence interval constructed from a sample of replicated means, it can be deduced that the actual and simulated population distributions are close enough and there would be no reason to not consider the model valid [40].

Table 1
List of VSM elements.

Elements	Definition	Formula
Lead time	Time between the arrivals of an entity to the start of a process. Lead times serve as downstream buffers for upstream variability.	Start time of current process − Time of arrival
Process time	Duration required for a single process to be completed.	End time of current process − Start time of current process
Changeover time	Time taken for a resource/resources to switch from working on one module to another.	N.A
Cycle time	Total time taken from the arrival of an entity to completion of all processes. Cycle time is the sum of lead times and process times.	Σ (Process time + Lead time)
Yield	Percentage of entities that finish a process without the need for rework.	Number of entities not requiring rework / Total entities
Scheduled utilization	The percentage of a resource's available time spent on a process/processes. Utilization rates > 1 indicate that the resource is being seized during unavailable times (i.e. during breaks) while < 1 indicate that the resource has idle time.	Duration utilized / Schedule availability

3.3. Experimentation and decision making

With the development of a credible baseline model, the study can proceed to the experimentation phase. Value stream mapping (VSM) is a tool to depict various characteristics of the system of interest such as information and material flows. It serves to identify waste such as non-value adding activities and other weaknesses in a system [41]. Using baseline model (As-Is) output, a VSM of the current process was created with the aim of uncovering areas of waste in the current process. Table 1 provides explanations for the key elements used in the VSM.

The root causes for each area were identified and addressed by proposing recommendations derived from lean construction principles. These were then incorporated into the DES model as a representation of the proposed lean process. Finally, in the decision making phase, lean and baseline model outputs were compared and discussed to evaluate the potential benefits of lean construction with respect to PPVC operations.

4. Overview of case study

The case study is based on a PPVC executive condominium project in Singapore. The proposed executive condominium will house a total of 638 units, producing a gross floor area (GFA) of 67,000 square metres and constructed with about 4500 PPVC modules. The site comprises eight blocks of 12-storey residential flats and a five storey multistorey carpark with a roof garden and communal facilities. Two Gantry Cranes are employed for the four middle blocks (3–6). Each Gantry Crane serves two blocks each while the rest of the blocks (1, 2, 7, 8, and) were served by mobile cranes. Fig. 2 provides a simplified layout of the site and illustrates the positioning of cranes.

This study will focus on the operation of the Gantry Cranes. A total of 66 distinct modules are used, which can be broadly categorized into two groups - smaller modules with four attached lifting brackets (4 hook modules) such as bedroom units and larger modules with six attached lifting brackets (6 hook modules). For load distribution purposes, 6 hook modules require a spreader beam to be attached to the lifting block of the crane before they are lifted. On the other hand, the spreader beam must be detached when 4 hook modules are lifted.

5. Conceptual process mapping

According to Al-Sudairi [42], process mapping is a preliminary method of establishing the interactions between resources, activities, linkages and the flow of material or information in a specific construction process. It allows the conceptual abstraction of the system to be represented in a logical manner and is effective in conceptual model development. The objectives of the process map are to:

1. Clearly establish the sequence and logic of the lifting and installation process
2. Define the exact quantity and type of resources required in each step
3. Provide an accurate and intuitive representation of the lifting and installation process as a basis for simulation model development

The resources required in each lifting and installation operation are: one lifting supervisor, two workers and one gantry crane operator. Each

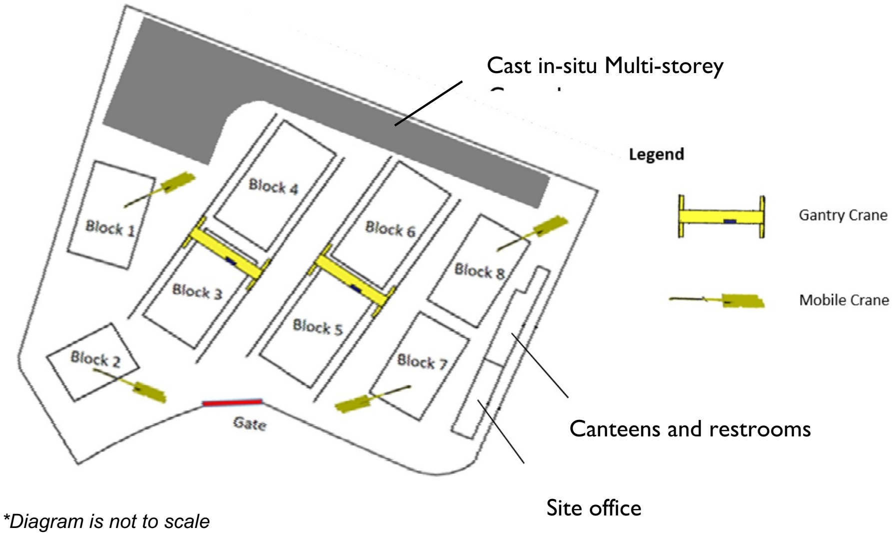


Fig. 2. Site layout.

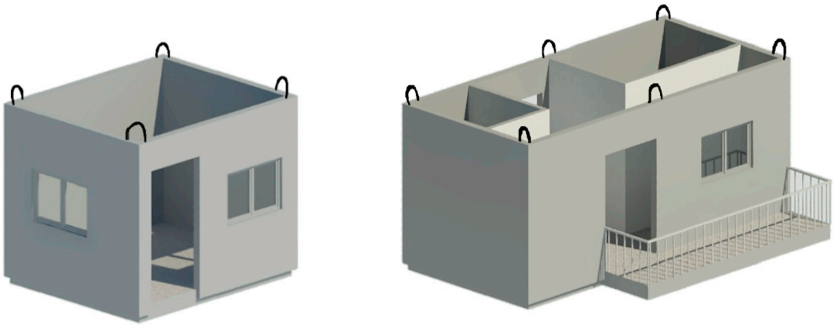


Fig. 3. Illustration of 4 hook modules (left) and 6 hook modules (right).

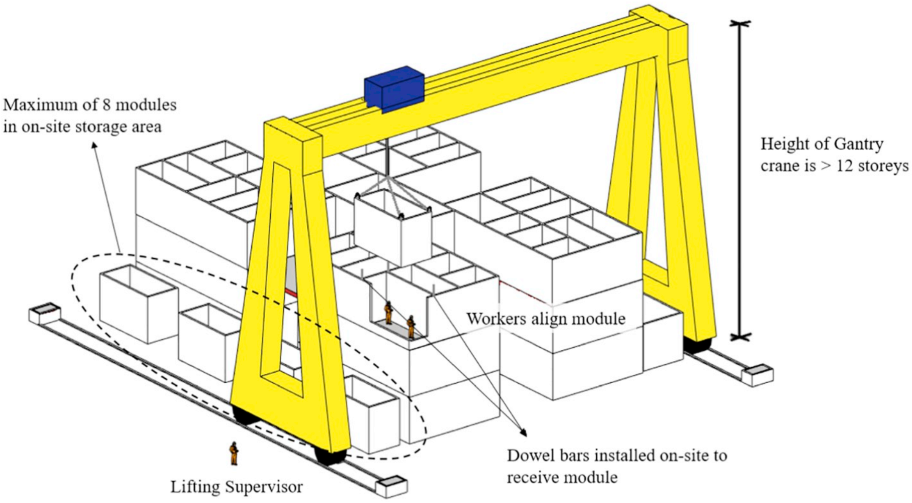


Fig. 4. Illustration of lifting and installation process.

module belongs to one of two categories, smaller modules with four lifting hooks (4 hook modules) and larger modules with 6 lifting hooks (6 hook modules) shown in Fig. 3.

Fig. 4 provides an illustration of the lifting and installation process. The operation consists of five processes:

(1) The lifting supervisor either attaches or detaches the spreader beam, depending on the type of module to be lifted. 6 hook modules require a spreader beam to be attached while 4 hook modules require it to be detached. However, if the current module is similar to the previous, this step can be skipped.
(2) Lifting hooks are attached by the lifting supervisor and the module is lifted into position by the gantry crane.
(3) Workers stationed to receive modules set up the necessary dowel bars and aligns each module to allowable tolerances.
(4) If the module cannot be properly aligned, rework measures are carried out by workers such as hacking and levelling.
(5) Workers then apply screed to the underside of the module before it is lowered into position by the gantry crane and lifting hooks are detached.

A preliminary process map (Fig. 5) depicting the processes was developed and validated through an iterative process of observations and interviews with SEs.

6. Simulation model

The baseline (As-Is) model is shown in the Appendix A. The distributions used in the model are shown in Table 2.

Table 3 provides a summary of the changes to input, expected actual changes to output, and the corresponding magnitudes of change in the parameter variability sensitivity analysis of model outputs. The actual changes to outputs were found to be in accordance with hypothesized changes and were of a reasonable magnitude.

Table 4 provides a summary of the chronological simulation report with respect to simulation time (Tnow). As the entities arrive, they are placed in the queue until resources become available. As the entity used was a 4 hook module, it was correctly directed to the “Attach hooks and lift to destination” process as it did not require the spreader beam to be attached. The process durations and resources seized in each process are also verified to be correct. In addition, during the face validity test, the five SEs interviewed gave an average rating of 4.25 on a scale of one to five, one being completely inaccurate while five being completely accurate, which signifies that the model has achieved face validity.

Output variables selected for confidence interval testing are: Number of 4 hook modules installed per day, Number of 6 hook modules installed per day, and total number of modules installed per day. A total of 30 replications were simulated, each at a length of 25 simulated days, and the mean number of modules lifted per day were recorded. Fig. 6 illustrates how simulated means compare with the actual mean. The upper and lower bounds of the constructed confidence intervals are also shown.

It can be observed that several simulated means fall outside the confidence interval. This is however, inevitable due to the many different input distributions used, and does not discount the validity of the simulation model. With reference to Table 5, the actual mean of each output variable are found to be within the constructed confidence intervals.

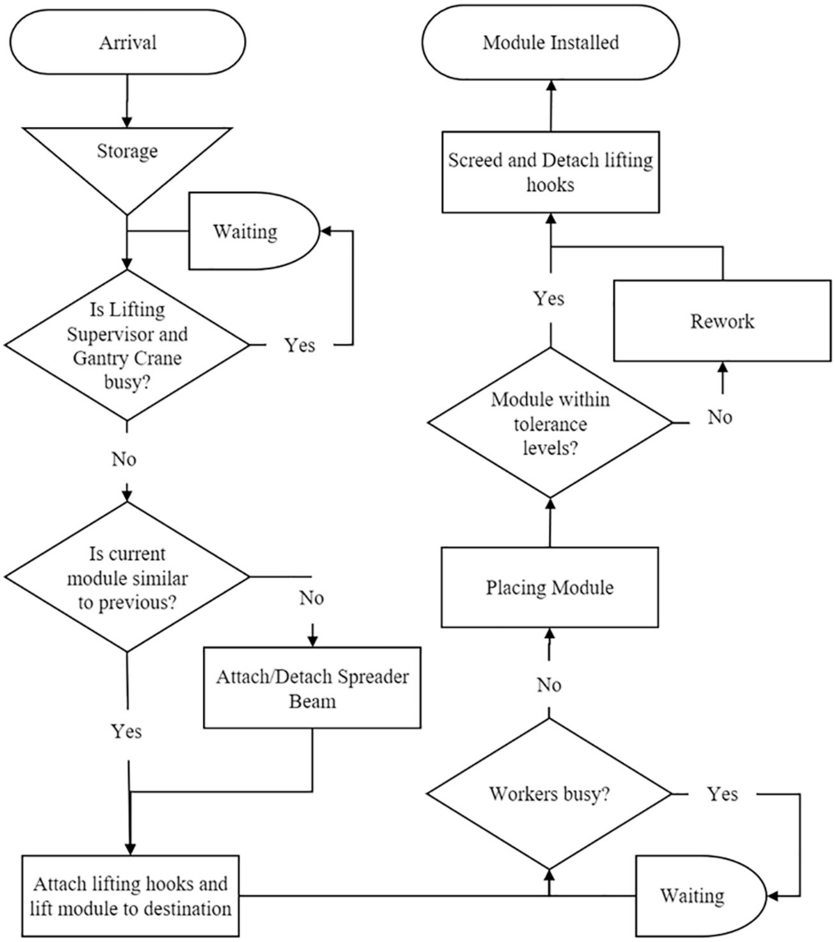


Fig. 5. Preliminary process map of lifting and installation operation.

The results of the verification and validation show that the baseline model is sufficiently accurate.

7. Application of lean construction principles

Fig. 7 maps out the Value Stream from delivery to installation of modules. The PPVC Manager is the conduit for information flows. He is tasked with disseminating the daily lifting plan to each group of workers across various work activities in the lifting and installation process. He also makes decisions on the frequency and quantity of each order by observing work progress and the buffer stock of modules on site. He relays the information to the factory with a lead time of three days for them to prepare the next shipment of modules. These are characterized by manual information flows as they are not facilitated by

Table 2
Probability Density Functions used for baseline model.

Process	Module type	Distribution type	Expression	Remarks
Attach Spreader beam	4 hook	Triangular	TRIA(16.67, 21.67, 26.67)	Expert estimation
Detach Spreader beam	6 hook			Expert estimation
Attach hooks and lifting	4 hook	Weibull	15.5 + WEIB(7.01, 1.83)	*p*-Value = 0.362; Sq. error = 0.0066
	6 hook	Lognormal	31.5 + LOGN(4.06, 3.82)	*p*-Value = 0.362; Sq. error = 0.0066
Placing of module	4 hook	Weibull	20.5 + WEIB(6.14, 2.43)	Sq. error = 0.0066
	6 hook		140 + WEIB(3.73, 1.9)	Sq. error = 0.0066
Placing of module with Rework	4 hook	Gamma	51.5 + GAMM(1.3, 2.64)	Sq. error = 0.0066
	6 hook	Lognormal	198 + LOGN(4.73, 6.86)	Sq. error = 0.0066
Screed and Detach hooks	4 hook	Weibull	4.5 + WEIB(3.3, 1.85)	*p*-Value = 0.362; Sq. error = 0.0066
	6 hook		13.5 + WEIB(2.7, 1.69)	*p*-Value = 0.362; Sq. error = 0.0066
Entity arrivals	4 hook	Poisson	POIS(3.31)	Sq. error = 0.0066
	6 hook		POIS(1.19)	Sq. error = 0.0066
Misc. tasks		Triangular	TRIA (90,120,180)	Expert estimation
Rate of rework			Decide Probability = 50%	Expert estimation

Table 3
Parameter variability sensitivity analysis results.

Change to input	Change to output		Magnitude of change	
	Expected	Actual	To output	To input
Increase entity arrivals to POIS(3.5) and POIS(1.6)	Increase in storage queue durations	Increase in average queue durations from 1.53 days to 2.35 days	+86%	+20%
Increase resource availability by 2 h	Increase in number of entities processed per replication	Increase in average number of 4 hook and 6 hook module entities processed per replication from 76.2 and 29.7 to 77.55 and 33.35	+5%	+21%

*An average of percentage changes to increase in arrival rates of each module type are taken.

electronic means. Once ready, the modules are delivered in large flatbed trucks each of which can carry a maximum of three 4 hook modules OR one 4 hook module and one 6 hook module. As the trucks arrive on site, the modules are unloaded to the storage area, which add to the current buffer stock. The inventory is then consumed by the various module installation work activities.

In this case, Value Adding (VA) activities are work processes which directly create value for the finished product, which is the completed building. Non Value Adding (NVA) activities are processes which do not add value to the completion of the building and should be minimized or eliminated. The first and second work activities are ‘Attach Spreader Bar’ and ‘Attach hooks and lifting’, both requiring one Lifting Supervisor and one Gantry Crane. Both processes have a yield of 100% as there are no observed instances of re-attaching and rework. The average process time required is 4.19 and 21.60 min respectively. They are classified as NVA activities as they do not create tangible value in the form of the actual finished building. The next two activities are ‘Placing Module’ and ‘Apply Screed’, both of which are Value Adding (VA) activities as they contribute directly to the actual building for its future inhabitants. The Placing Module has a Yield of 50% which corresponds to the observed probability of a module requiring rework. Without rework, the ‘Placing Module’ process has a process time of 40.48. However, incorporating the NVA time spent on rework, the process time increases to 60.75. Finally, ‘Apply Screed’ process requires a separate group of 2 workers, the gantry crane (of which the module is still attached to) and the lifting supervisor. After the ‘Apply Screed’ process is done, there is a changeover time of 20 min, whereby the lifting hooks are detached, the gantry crane travels back to the module storage area and the lifting supervisor relays the information on the lifting progress to the PPVC manager and prepares another module to be installed. Each process is characterized by a push arrow as module installation is driven by the PPVC manager's forecasts and not actual demand in each segment of the installation chain (which is characterized as a pull process).

Process and lead times, queue and utilization rate values in the VSM were derived by averaging 30 replications, each for a length of 25 simulation days using the baseline DES model. It should be noted the VSM only depicts 4 hook modules for ease of illustration. Inclusive of the time spent in storage, the average cycle time required for a single 4 hook module to go from arrival at the site to completion is 1.6 days.

Based on the categories of construction waste identified by Formoso et al. [65], several areas of waste can be observed in the VSM:

1. Low yield rate for *Placing Module* process – 50% of modules installed require some form of rework, indicating the prevalence of defects upstream.
2. High ratio of cycle to process time – Lead time accounted for 1.5 days out of the cycle time of 1.6 days, indicating disproportionately long storage times resulting in high inventory costs.
3. Low worker utilization rate of 0.67 – Compared to the lifting supervisor and gantry crane, workers are idling for an excessive amount of time.

A root cause analysis was carried out to identify the root causes of each identified area of waste. Several recommendations were proposed to mitigate or eliminate these root causes. The recommendations include use of Total Quality Management (TQM), use of Construction robotics, implementing E-Kanban Just in Time (JIT) delivery system

Table 4
Chronological simulation report by Arena Trace function.

Trace ID	Tnow	Simulation activities	Equivalent behavior in actual system	Correct?
1	0	Create batch of 4 hook modules	Module delivered at night and placed in storage area due to unavailability of resources	✓
2		Assign attributes		✓
3		Change “Availability” variable from 1.0 to 0.0		✓
4		Check status of spreader beam		✓
5		Placed in queue for “Attach hooks and lift to destination” process		
6	480.00	Lifting Supervisor and Gantry Crane capacity changed from 0.0 to 1.0	Resources commence daily schedule	
7		Lifting Supervisor seized		✓
8		Delay 4 hook module by 23.42 min in the “Attach hooks and lift to destination” process	Lifting Supervisor and Gantry crane carries out “Attach hooks and lift to destination”	✓
9	503.42	Decide module routes 4 hook module to Placing Module process	No rework is required	✓
10		Delay 4 hook module by 36.56 min in the “Placing Module” process	Workers carry out “Placing Module”	✓
11	539.99	Delay 4 hook module by 5.22 min in the “Screed and Detach hooks” process	Workers carry out “Screed and Detach hooks”	✓
12	545.22	Release Lifting Supervisor and Workers	Lifting and installation of 4 hook module is complete	✓
13		Counter incremented by 1		✓
14		4 hook module disposed		✓
15		Duplicate entity “Misc Task” created		✓
16		Seize Gantry Crane resource	Gantry crane carries out miscellaneous tasks	✓
17		Delay Misc. Task entity by 17.96 min in the “Misc Tasks” process		✓
18	563.18	Release Gantry Crane	Gantry crane completes miscellaneous tasks	✓
19		Change “Availability” variable from 0.0 to 1.0		✓
20		Misc. Task entity disposed		✓

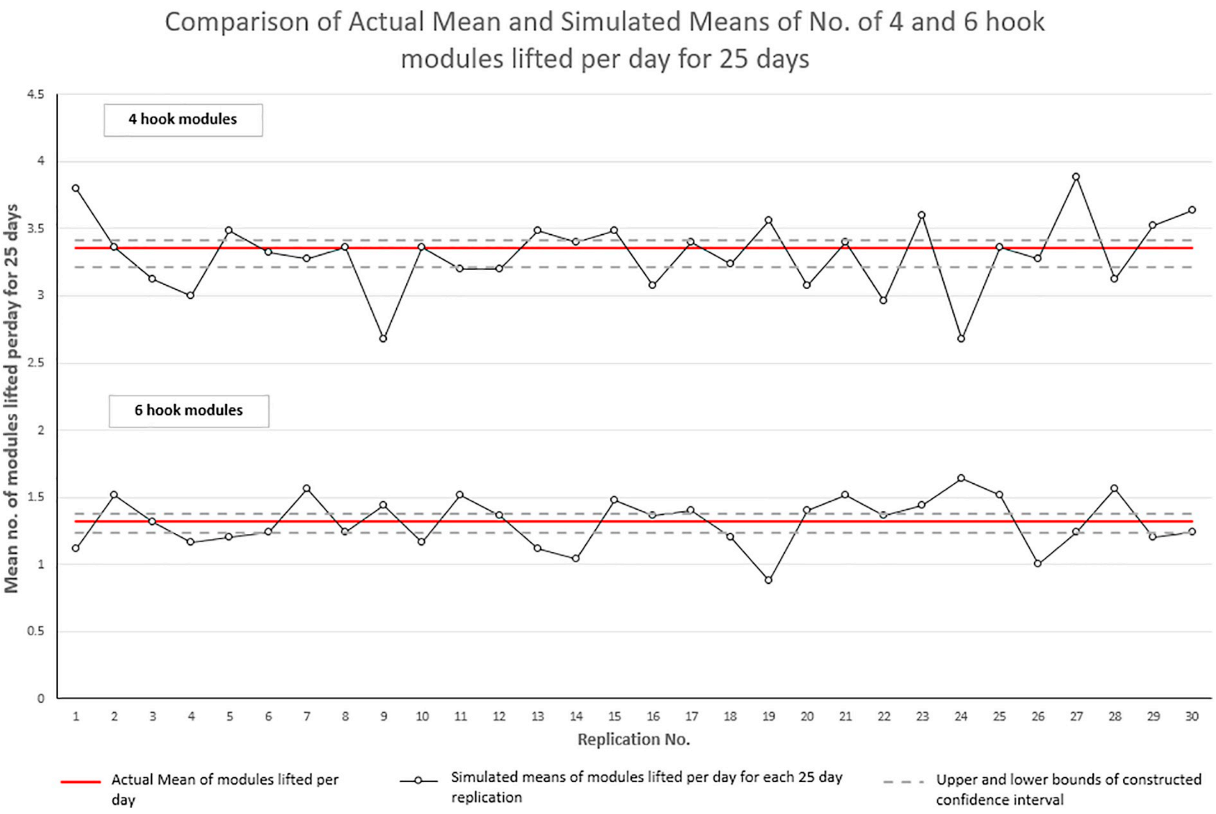


Fig. 6. Comparison of actual and simulated no. of 4 hook modules lifted per day.

Table 5
Results of confidence interval testing.

Output variable	Sample mean, x̄	Sample std. dev, s	95% confidence interval	Actual mean
4 hook	3.31	0.276	(3.21,3.41)	3.36
6 hook	1.31	0.188	(1.24,1.38)	1.32
Total	4.62	0.247	(4.53,4.71)	4.68

and cross training to increase labor flexibility. Table 6 presents the results of the root cause analysis and the corresponding Lean recommendations proposed.

7.1. Total quality management

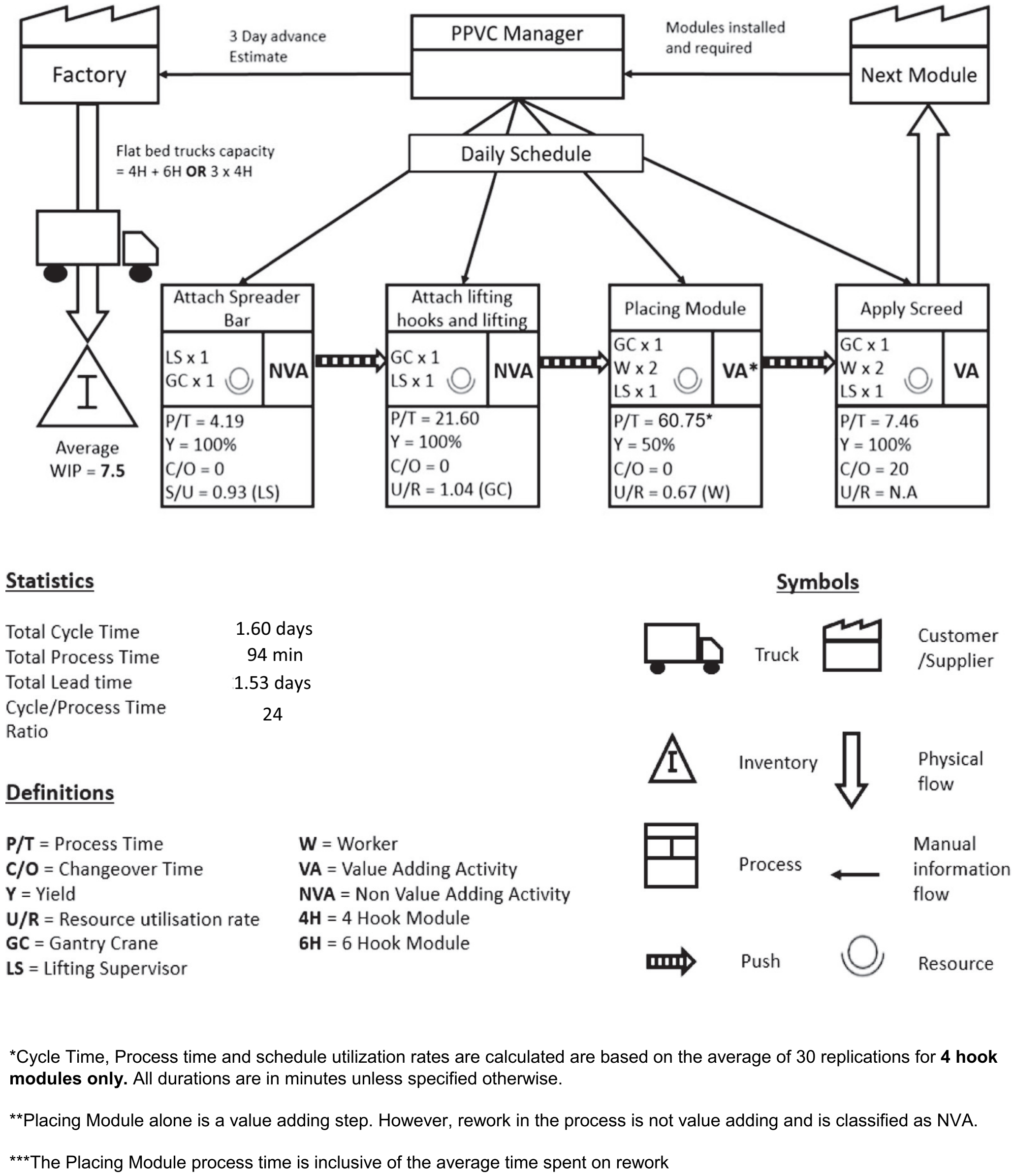
The primary cause of low yield rate of the *Placing Module* process was an accumulation of deviations due to defectively placed modules on the lower floors by workers. Another reason identified was inadequate connection tolerance of the PPVC modules. These can be traced back to a poor organizational culture of quality. Total quality management (TQM) is a framework of management based on the principle of doing things right the first time. It is widely seen as an approach to improving the quality of an organization's goods and services through the involvement of all its members at every level [44]. In the context of the construction industry, TQM has been shown to reduce the occurrence of defective work. Low and Teo [45] examined a Japanese contracting firm involved in projects in Singapore and the benefits it derived from having a TQM oriented culture which includes lower quality related costs and higher employee job satisfaction.

Although there is no one-size-fits-all recipe for a TQM implementation, it is largely agreed among many researchers that the most important and crucial elements are to gain top management commitment, employee involvement, continuous improvement, training and customer focus [46]. Low and Peh [47] provided a series of basic steps in which the parties in construction project can adopt to inculcate a quality oriented organizational culture. Fig. 8 provides a framework adapted from these steps to implement TQM in the context of PPVC. The parties involved are the design consultants, factory and construction managers.

7.2. E-Kanban JIT system

The primary cause of long cycle times were found to be attributable to the push driven system in which the PPVC Manager places a three days advance order based on estimation. Module arrivals often outpace the speed of lifting and installation, causing modules to be stockpiled on site. Contrastingly, a Pull-driven system releases the same entity based on the system's current state and is ideal in preventing high lead time to cycle time ratios [48]. The Just-in-Time (JIT) concept is an example of a Pull system. The focus of JIT involves providing precise amounts of materials just in time for production, minimizing inventory and waste in the process. The JIT concept has been applied to the off-site construction industry with positive results. Low and Chuan [50] for instance, found that benefits of JIT when applied to the installation of precast concrete components included reduced site storage levels and shorter storage durations. However, it was concluded that implementing an absolute JIT system may not be possible due to the large degree of uncertainty in the construction industry. Bates et al. [51] recommended a partial JIT approach in which JIT is practiced only to the extent where it is feasible. Unlike ideal JIT, partial JIT requires an inventory buffer and a pool of Kanban to cater for uncertainty and batch deliveries.

Determining the appropriate Kanban size and buffer level requires substantial planning as specifying wrong values for Kanban size and buffer level could result in over or under delivery of materials. Under delivery of materials negatively impacts labor force morale (Horman et al. [66]). At the same time over-delivery leads to unnecessarily large



Statistics

Total Cycle Time	1.60 days
Total Process Time	94 min
Total Lead time	1.53 days
Cycle/Process Time Ratio	24

Definitions

P/T = Process Time
C/O = Changeover Time
Y = Yield
U/R = Resource utilisation rate
GC = Gantry Crane
LS = Lifting Supervisor
W = Worker
VA = Value Adding Activity
NVA = Non Value Adding Activity
4H = 4 Hook Module
6H = 6 Hook Module

*Cycle Time, Process time and schedule utilization rates are calculated are based on the average of 30 replications for **4 hook modules only.** All durations are in minutes unless specified otherwise.

**Placing Module alone is a value adding step. However, rework in the process is not value adding and is classified as NVA.

***The Placing Module process time is inclusive of the average time spent on rework

Fig. 7. Value Stream Map of current lifting and installation operations.
*Cycle Time, Process time and schedule utilization rates are calculated are based on the average of 30 replications for **4 hook modules only**. All durations are in minutes unless specified otherwise.
**Placing Module alone is a value adding step. However, rework in the process is not value adding and is classified as NVA.
***The Placing Module process time is inclusive of the average time spent on rework.

inventories. It is therefore imperative that appropriate buffer levels and Kanban sizes are calculated.

A mathematical optimization method was used with Arena OptQuest, an add-on program which runs the DES model in parallel while searching for an optimal arrangement of input controls to achieve the objective [33]. Based on Little's Law which states:

$$Cycle\ Time = WIP/Average\ completion\ Rate\ (ACR) \quad (1)$$

Minimizing the Kanban size would reduce WIP levels, which would lead to a reduction in overall cycle time based on Little's Law (Liu et al. [53]). An experimental simulation model was first created. 4 Hook and 6 Hook Kanban *entities* are used to represent the pool of available Kanban while *Process modules* seize and release Kanban whenever PPVC

Table 6
Root cause analysis and proposed Lean recommendations.

Area of waste	Root cause	Lean recommendations
Low yield rate	Lack of overall quality culture at managerial and organizational level among design consultants, contractor and factory staff [43].	Total quality management Construction robotics
High CYCLE time	Push driven deliveries based on PPVC manager 3 day advance orders.	Internet based E-Kanban Just-In-Time delivery system
Low utilization rate	Inadequate labor flexibility on-site	Increase functional flexibility by cross training

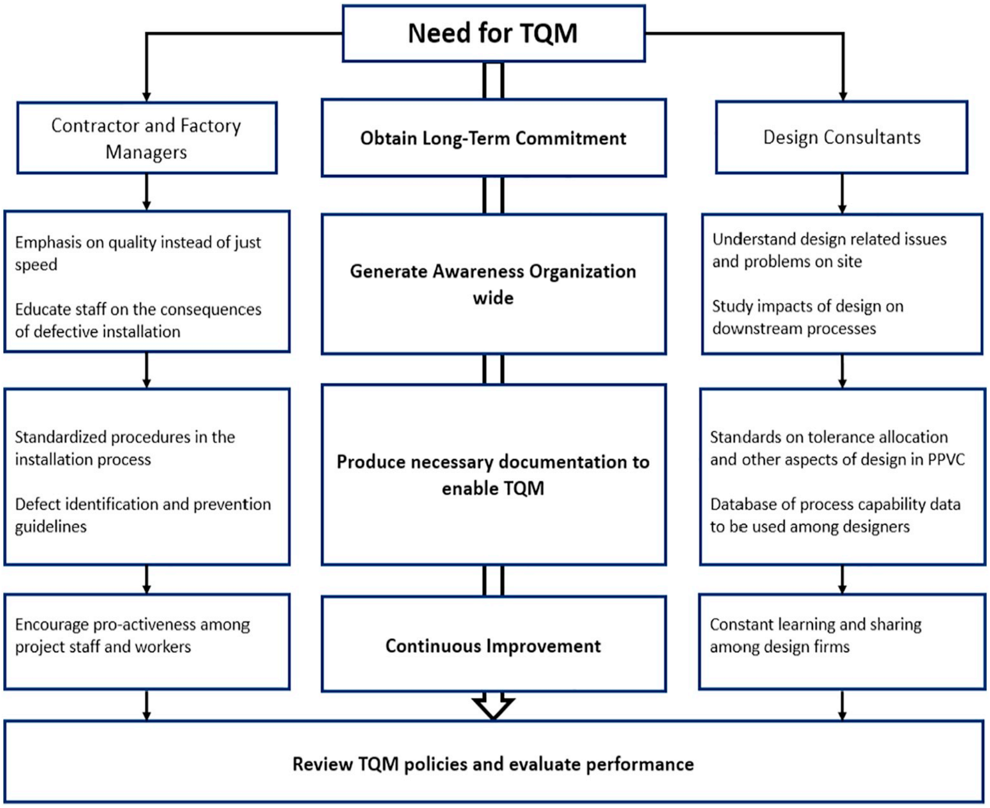


Fig. 8. TQM implementation framework adapted from Low and Peh [47].

Table 7
Optimal values for JIT system variables.

Variable	Optimal values
Buffer level	5
4 Hook Kanban	7
6 Hook Kanban	4

modules are delivered and lifted respectively. *Hold and Assign modules* are used in conjunction with a "*BufferStock*" *variable* to permit or stall deliveries whenever actual WIP levels fall short of or exceed the permitted buffer level. The following objective and constraints were specified on OptQuest:

$$Objective: Min \sum K_1 + K_2$$
$$Constra\,int\,s: 8 \geq S \geq 1 \qquad (2)$$

where,

K_1 = 4H Kanban
K_2 = 6H Kanban
S = WIP Levels

The range of WIP levels specified ensured that there will be no over or under delivery of modules. OptQuest was allowed to run until the optimal values of each variable had been found. The optimal values of each variable were found within 80 replications of the model. The results of optimization are shown in Table 7.

These values mean that at any one time, only a maximum of four 6 hook modules and seven 4 hook modules are either on-site or scheduled for delivery. Once the WIP level on site exceeds five, no delivery will be permitted until the next day, when WIP levels fall below the allowable limit of five. Powell [54] concludes that conventional paper based Kanban systems lack the visibility of the value stream required for systems spanning over vast distances. As such, an Internet based E-Kanban system is proposed. E-Kanban systems make use of electronic signals which replace physical Kanban via barcode scans and enable information to be sent in real time to the upstream supplier, thereby increasing visibility across the system [55].

7.3. Increase labor flexibility through cross-training

Low utilization rates were caused by workers idling in between lifting operations as they were not trained to carry out other tasks. This was attributable to low labor flexibility on site. This can be dealt with two strategies, namely using WIP buffers to avoid work starvations and/or use multi-skilled resources such that capacity from under-utilized resources is directed to bottleneck activities. WIP buffers however, hinder work performance, impede workflow and are wasteful (Horman and Thomas [52]). This is contrary to the goals of Lean Construction, which is to eliminate waste. Having multi-skilled resources, on the other hand, increases labor flexibility, enabling resources to address variability in resource demand and improve production throughput [56–58]. Multi-skilled resources are capable of handling other tasks during their idling time [56].

Arashpour et al. [59] presents several cross training and process integration strategies. As cross training all workers on site is not feasible, the optimal cross training strategy or combination of strategies should be chosen with regard to the nature of the bottleneck and production process. The proposed Lean process involves maintain low WIP while simultaneously improving cycle times. The optimal strategy for

Fig. 9. Partial Skill Chaining [59].

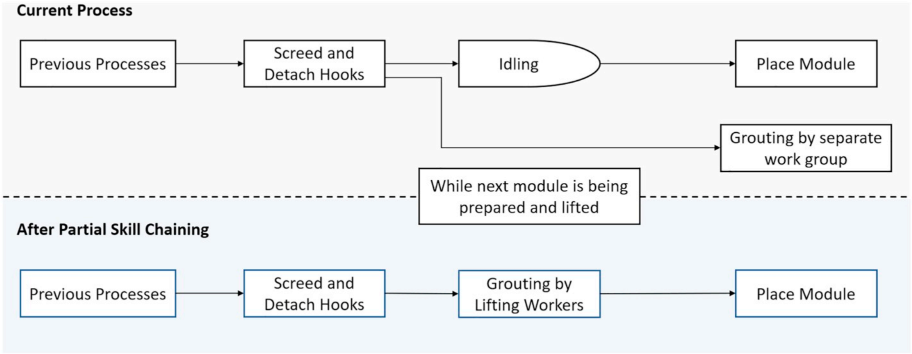


Fig. 10. Comparison of current and post-PSC process.

construction production networks with variable processing times and low WIP is Partial Skill Chaining (PSC) in which resources are trained to handle operations of immediate successors and cover adjacent work stations [59,60]. Fig. 9 illustrates a hypothetical situation where each resources (1–8) are cross-trained to cover two consecutive stations.

In the current process, the adjacent activity to the "Screed and Detach Hooks" process is to fill the structural connections between the newly settled module and its neighboring modules. Through interviews with SEs, it was understood that another group of workers would arrive at a later point in time to carry out the grouting task as workers involved in lifting and setting operations were not trained to perform grouting. This results in them idling while waiting to receive the next module after the completing the "Screed and Detach Hooks" process. To reduce idling time, the lifting workers can be cross-trained to cover the adjacent grouting task, which will not only reduce idling time and improve utilization rate, but also free up the grouting workers. These otherwise lost labor capacity could be beneficially used for productive tasks in other areas of the site such as problem solving, training and improving construction operations. (Fig. 10). (See Fig. 11.)

The SEs were supportive of the proposed cross-training strategy and were keen to adopt it in future projects. They also added that they had previously underestimated the waiting time in between operations and therefore did not assign grouting tasks to the lifting workers.

7.4. Use of construction robotics

A more advanced way of reducing the prevalence of defective work is to use construction robots. Robots can greatly reduce human error and improves the efficiency of performing construction tasks [61]. Some examples of robotics enabled construction include the Future Home project [62] where prefabricated modules were manipulated and assembled with an automated small gantry crane and the Shimizu Manufacturing system by Advanced Robotics Technology (SMART). SMART comprises a roof fitted to four jacking towers with computer controlled gantry cranes which lifts and places prefabricated components from the ground level to each floor. In the context of PPVC, automated gantry cranes can be used to pick and place modules without the need for lifting supervisors or workers. A study by Son et al. [61] revealed notable progress in the domain of automated machines for pick and place operations fueled by developments in Laser Radar (LADAR) and Radio-Frequency Identification (RFID) technology which affirms the potential of automation in modular construction.

7.5. Development of Lean (To-Be) models

Each recommendation was implemented into the Lean (To-Be) model by making changes to the baseline DES model. Where applicable,

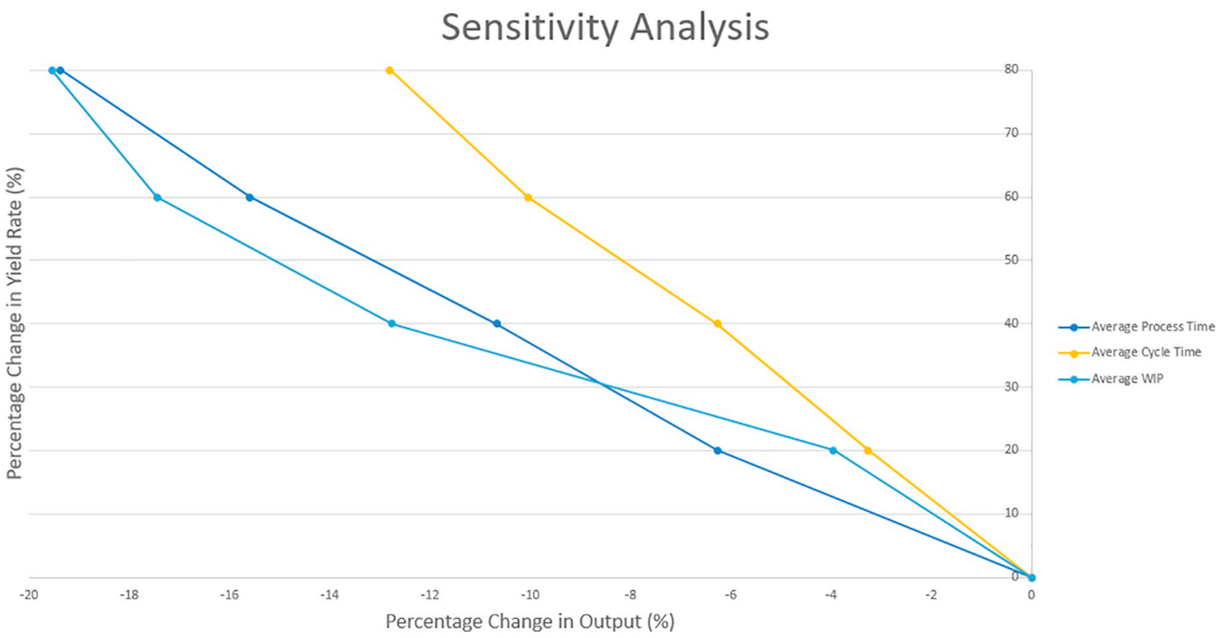


Fig. 11. Sensitivity analysis.

Table 8
Summary of changes made to baseline (As-Is) model.

Lean model	Recommendation	Changes to baseline (As-Is) model	Remarks
1	Total quality management	Increased Decide module probability from 50% to 90% to reflect increased Yield Rate.	Interview with PPVC Manager who was asked to estimate the Yield Rate improvement
	E-Kanban JIT system	Experimental JIT modules are added to baseline model. BufferStock variable is set to 5 while 4 Hook and 6 Hook Kanban entities are set to 7 and 4 respectively.	Mathematical optimization using OptQuest
	Increasing functional flexibility through cross training	Duplicate and Assign modules used to create new Grout Task entity. A new Grout process module is created with a distribution of TRIA (15, 30, 40).	Interview with Lifting supervisor and Site Engineer to estimate duration of Grout task
2	Use of construction robotics (as an extension of Lean Model 1)	Process modules “Attach Spreader beam” to Screed and “Detach Hooks” are replaced with a single “Pick and Place” Process module. Distribution used is similar to existing “Attach lifting hooks and lift to destination”	Conservative estimate based on gantry and cross travel speeds of Automated Stacking Cranes used in port operations at 240 and 60 m/min respectively

estimates from SEs were obtained to serve as the basis for new parameters.

Due to significant differences between the proposed robotics enabled and conventional PPVC process, two separate Lean models (Appendix A) were constructed. Lean Model 1 presents the proposed system after implementing TQM, JIT and Cross Training. Lean Model 2 presents the proposed system in which automated gantry cranes are used. These automated gantry cranes are modelled after port automated port gantry cranes, which usually have a telescopic spreader that can cater to modules of different sizes. This replaces the need for having to manually attach and detach the spreader bar. In addition, with the use of laser-guided systems, the precision of the lift will be improved thus minimizing possible defects and tolerance issues. Thus, Lean Model 2 contains the relevant improvements in Lean Model 1, namely the use of an E-Kanban JIT system and Cross-Training, in addition to replacing process modules from “Attach Spreader beam” to “Screed and Detach Hooks” with a single “Pick and Place” module.. Cross-Training initiatives serve to equip the replaced labor with skills necessary for redeployment to other more productive aspects in the site. It should also be noted that the “Grout” task still requires labor and is thus not replaced. A similar approach has been employed by Yu et al. [16] to forecast the effects of 5S initiatives and work standardization on modular housebuilding operations. Table 8 explains how each proposed recommendation is reflected in each Lean Model.

The increase in Yield Rates from 50% to 90% are obtained from expert's judgement, and may not be as accurate as empirical data. As such, a sensitivity analysis was carried out to determine the sensitivity of model outputs with the expected improvements to Yield Rate. Fig. 7 shows the sensitivity analysis. The ratio of percentage changes in model output, namely Process Times, Cycle Times and WIP, to changes in Yield Rate is less than one. It can therefore be concluded that model output is not sensitive in the increase in Yield Rate, hence, the impact of the potential error introduced by expert judgement will be minimal.

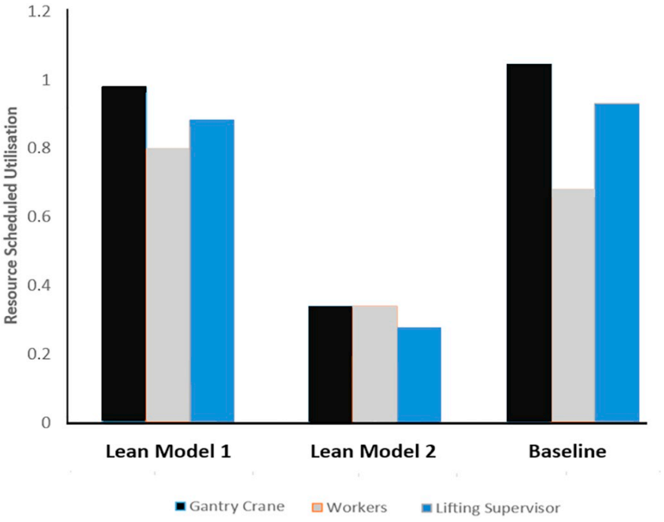


Fig. 12. Comparison of resource utilization rates.

7.6. Analysis of results and discussion

With reference to Table 9, the key outputs of the lean and baseline models were compared and evaluated.

With JIT significantly limiting the number of modules on-site and TQM reducing labor hours spent on rework in Lean model 1, it is not surprising that Table 9 shows improvements of 13.5% and 39.5% for process and cycle times, which translates to shorter project durations and cost savings. The effects in Lean model 2 are significantly more pronounced as process and cycle times decreased by 77.3% and 81.3%

Table 9
Comparison of baseline (As-Is) and Lean (To-Be) model outputs.

Output variable	Results of baseline model		Results of lean model 1		Results of lean model 2		Improvement (%)	
	4H	6H	4H	6H	4H	6H	Model 1	Model 2
Total process time	71.4	236.7	60.7	206.3	21.6	35.4	13.5	77.3
Average cycle time	2323.1		1427.3		434.5		39.5	81.3
Worker utilization	0.7		0.8		0.3		17.9	− 49.3
Average WIP	7.5		4.1		1.9		44.6	74.3

*Improvement percentages for process and cycle times are the average of 4 hook and 6 hook improvements.
**All values are obtained from the average of 30 replications at a length of 25 days.

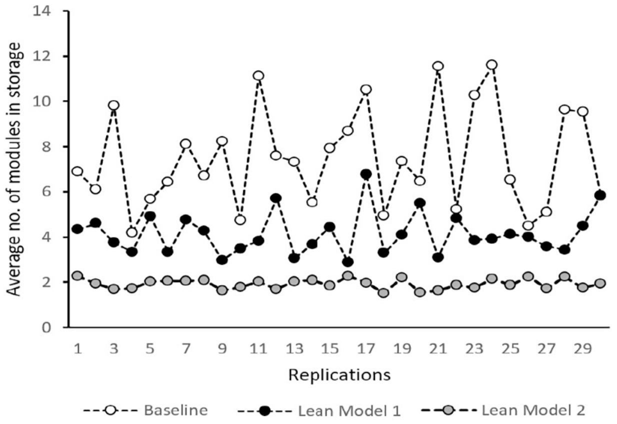


Fig. 13. Comparison of WIP levels.

Table 10
Lean and baseline model outputs descriptive statistics.

Group	Pair		*t*-Statistic	p-Value	dof	Conclusion
1	1	4H	29.54	0.00	29	Statistically significant
		6H	23.28	0.00		
	2	4H	133.08	0.00		
		6H	197.30	0.00		
2	1		6.50	0.00		
	2		13.97	0.00		
3	1		7.61	0.00		
	2		13.81	0.00		
4	1		−11.57	0.00		
	2		40.23	0.00		

*Pair 1 = Baseline and Lean Model 1 while Pair 2 = Baseline and Lean Model 2.
**The sample size for each test is set at $N = 30$. A confidence level of 95% was selected, resulting in critical values of ± 2.048 and $\alpha = 0.05$.

Table 12
Comparison of process efficiency.

Model	Average total labor time spent per module (min)	Average labor time spent on VA work per module (min)	Process efficiency (%)
Baseline	548.39	368.61	67.21
Lean model 1	524.79	458.72	87.40
Lean model 2	110.22	95.27	86.42
Improvement (%)		Lean Model 1	30.06
		Lean Model 2	28.50

with the use of automated gantry cranes. It should be noted that these improvements did not take into account potential challenges such as the time taken for the new system to stabilize and the investment required. Nevertheless, the simulation model provides justification for the initial investment.

Fig. 12 illustrates the differences in resource utilization across the baseline and lean models. Worker utilization improved by 17.9% in Lean model 1 because workers carried out grout tasks, instead of idling between lifting operations. On top of that, it can be seen that overall resource utilization rates are notably more level, indicating a balance in resource supply and demand and resulting in a more productive and satisfied labor force. Worker utilization rates in Lean model 2, however, decreased by 49.3%. This is because current module arrival rates was unable to keep up with the more efficient installation process resulting in under-delivery and consequently reduced utilization rates. These can, however, be improved by increasing delivery frequency to match the rate of lifting on-site.

Fig. 13 illustrates the differences in WIP levels between the current and Lean processes on a per replication basis. On average, WIP decreased by 44.6% and 74.3% in Lean model 1 and 2, respectively. It is noteworthy that in addition to a reduced number of modules on site, both Lean models also experienced fewer fluctuations, indicating relatively stable deliveries and added benefits of reduced storage costs and space requirements.

A paired t-test was carried out to ensure that differences between Lean and baseline model outputs are due to differences in model design and not inherent randomness of the simulation models [35]. Tables 10 and 11 present the descriptive statistics of Lean and baseline model outputs and the results of the paired *t*-test. Table 10 shows that each Lean and baseline model output group produced p-values of < 0.01, indicating that the differences between the baseline and lean model are statistically significant and can be attributed to the Lean recommendations Table 10: Lean and baseline model outputs descriptive statistic.

7.7. Process efficiency and labor productivity

Process efficiency is an indicator of how efficiently labor hours are used. It can be calculated by dividing the amount of time spent on value-adding activities by the total labor time taken for the process [42]. The proportion of time spent on NVA activities can be reduced if the time spent on VA activities are increased, thereby increasing process efficiency.

$$Process\ Efficiency = \frac{Labour\ Time\ consumed\ by\ Value - Adding\ Work}{Total\ Labour\ Time\ spent} \tag{3}$$

Table 11
Paired *t*-test results.

Group	Output variables		Mean		Standard deviation	
			4 hook	6 hook	4 hook	6 hook
1	Process time	Baseline	71.35	236.68	2.09	5.51
		Lean model 1	60.74	206.34	1.13	3.70
		Lean model 2	21.63	35.42	0.38	0.59
2	Cycle TIME	Baseline	2169.10		710.90	
		Lean model 1	1293.93		212.02	
		Lean model 2	434.65		32.84	
3	Average WIP	Baseline	7.47		2.20	
		Lean model 1	4.14		0.93	
		Lean model 2	1.92		0.23	
4	Worker utilization	Baseline	0.67		0.05	
		Lean model 1	0.79		0.04	
		Lean model 2	0.34		0.03	

Table 13
Comparison of labor productivity.

	Average man-hours consumed per module	Labor productivity (modules/man-hour)	Improvement (%)
Baseline	9.14	0.109	–
Lean model 1	8.74	0.114	4.58
Lean model 2	1.84	0.543	398

By implementing TQM and cross training in Lean model 1, less time will be spent on NVA activities such as rework and idling. Likewise, automating the process in Lean model 2 greatly reduces the total labor hours spent and increasing the proportion of value added hours spent in each operation. Table 12 shows that a significantly larger amount of time is spent on Value Adding work after the Lean process improvements have been instituted due to the reduction of defects and resource idling. In Lean Model 2, the robotics enabled process greatly reduces the need for labor, resulting in improved process efficiency.

Productivity is a measure of output per unit input of a process [64]. A productive organization is likely to be more profitable as it can produce more with the same amount of input. The labor productivity equation used is as follows:

$$\textit{Labour Productivity} = \frac{\textit{Number of Modules Installed}}{\textit{Total number of manhours}} \tag{4}$$

As can be seen from Table 13, Lean model 1 achieved an improvement of 4.6% in labor productivity over the current process. Lean model 2 attained a considerably larger margin of improvement at 398%. This is because the recommendations in Lean model 1 led to substantial reductions in waste, the quantity of labor and consequent man-hours required per operation remain largely unchanged. On the other hand, mechanization of the operation in Lean model 2 translates to less man-hours consumed per module installed, resulting in a significantly larger productivity gain. However, there are many barriers to mechanization in construction which include high capital costs, substantial commitment required to maintain technology and incompatibility with existing processes, which hinder its implementation.

8. Conclusions

Modular construction and prefabrication offer significant benefits over traditional construction methods and are seen as the way forward in increasing the competitiveness of the industry. This study responds to Blismas and Wakefield [1] and Mostafa et al.'s [14] call for research into applying Lean simulation into off-site construction so as to encourage its adoption. It contributes to existing OSM literature by providing an in-depth simulation study into the on-site portion of OSM construction methods, which to the author's best knowledge, is currently lacking. The study was done in the context of a Prefabricated Prefinished Volumetric Construction (PPVC) (a form of modular construction) site in Singapore. Discrete Event Simulation and VSM were used to represent the PPVC operation in a simulation model and identify areas for improvement. Lean recommendations include implementing Total Quality Management (TQM) to reduce presence of defects, an Internet based E-Kanban system to optimize deliveries, minimize cycle times, cross training to reduce idle time of resources and using Construction Robotics to replace the need for manual labor. The findings show that significant improvements can potentially be attained by implementing the proposed recommendations. In comparison with the baseline simulation model, cycle and process times decreased by up to 81.27%, resource utilization rates increased by 17.91%, work-in-progress (WIP) levels decreased by up to 74.30% and process efficiency and labor productivity improved by 4.58% and 398% in Lean Models 1 and 2 respectively, albeit the improvement in Lean Model 2 was due to eliminating labor in the construction process. However, as demonstrated in the paper, reducing the need for labor would mean that labor capacity can be re-deployed to other even more productive functions in the company, which is beneficial. The simulation results can be used to encourage adoption of modular construction. From a methodological perspective, the study provided a detailed case study demonstrating how simulation can be used the context of modular construction.

9. Limitations and future research

This study contains several limitations. First, the Lean recommendations proposed have only been tested on the ARENA simulation platform and not on the actual case study project. Simulation is however, the most ideal way to quantitatively assess the effects of the proposed recommendations, which would otherwise be impossible to implement in the ongoing project case study. Repeated verification and validation of the model with system experts ensured that the As-Is and To-Be models are as realistic as possible, thereby reinforcing the credibility of the simulated results. Secondly, several parameters of the DES model were derived from estimates by SEs due to the unavailability of data. Even though these were not as accurate as compared to empirical data, the SEs interviewed were the most familiar with site-operations, which ensured that the estimated parameters were as accurate as possible. Thirdly, the As-Is and To-Be models are linear in nature, which is a limitation as production models in OSM are non-linear due to the presence of variability in OSM environments [59]. However, the objective of this study is not to create an absolute representation of the assembly process. This would require an excessive amount of resources and yet derive a less than proportional amount of value as construction projects vary widely from site to site. Instead, the study aimed to develop a reasonably accurate model which was capable of evaluating the impact of process improvements. This objective has been achieved by verifying and validating the model with several SEs. Fourth, as the case study is based in Singapore, there may be regional limitation to the findings. There are no two identical modular construction projects. Each project differs in various areas such as the crane typologies used the project, positioning of pick points and module placement methods and sequence. However, as emphasized in the earlier section, projects are similar in that they involve the same fundamental processes and phases. This case study captures these modular construction processes such as the transportation of the modules to site and lifting each module with cranes. These similarities are sufficient to apply the findings to other regional and global projects, albeit with consideration to the specific differences stated above. Fifth, the paper had recommended substituting labor with automated gantry cranes. This elimination of labor might not be an acceptable solution where employment is a social concern and it could possibly lead to a higher level of structural employment in countries where the workforce lacks access to quality retraining and upgrading programmes. Last, it must be noted that labor utilization is only one factor influencing productivity. Future studies can therefore include a more comprehensive study on other factors of productivity such as mechanization, design constructability, work methods and skills.

Acknowledgement

The authors would like to thank the contractor for permitting access to their site and their patience and co-operation in supplying the required data.

Appendix A

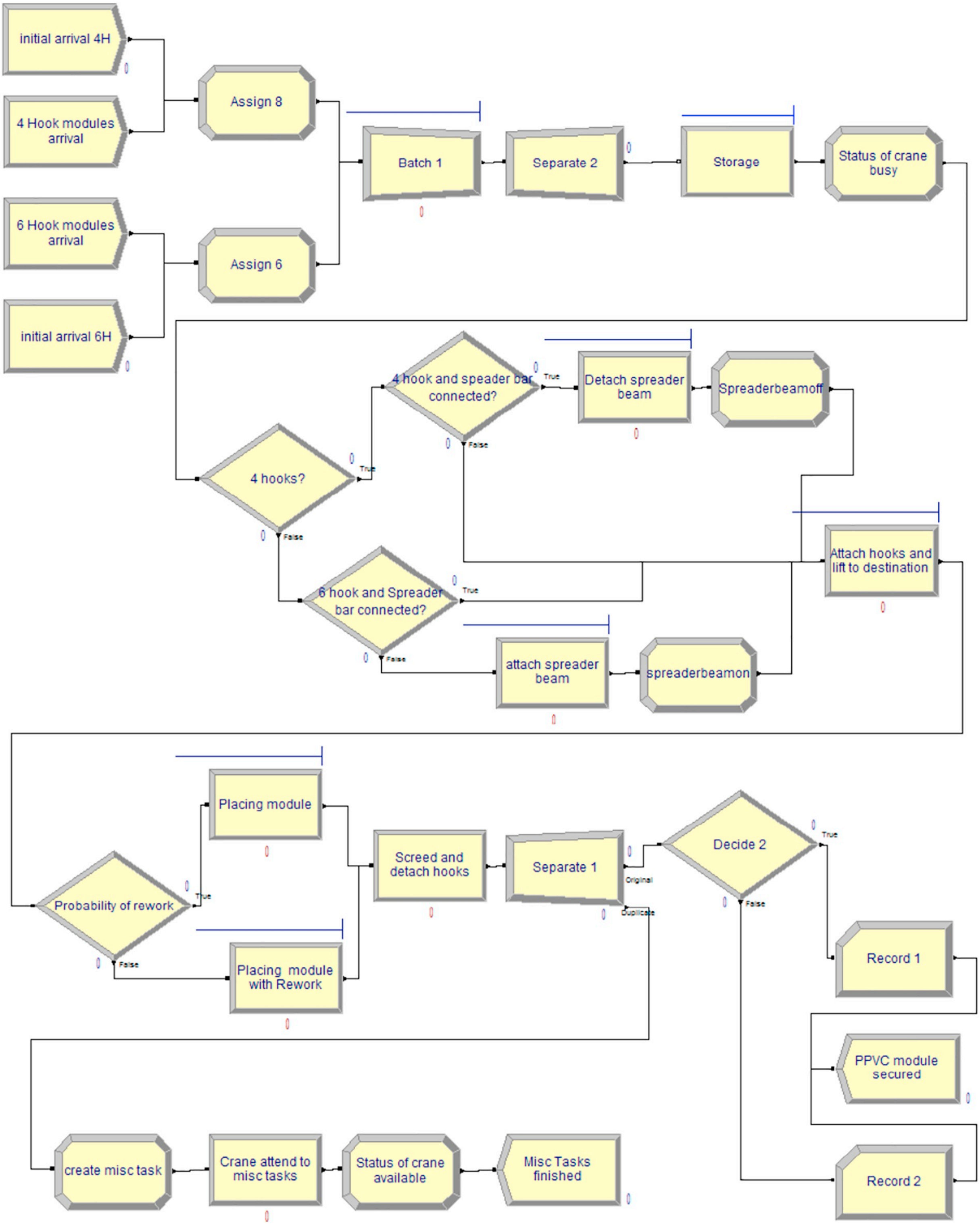


Fig. 14. Baseline (As-Is) DES model.

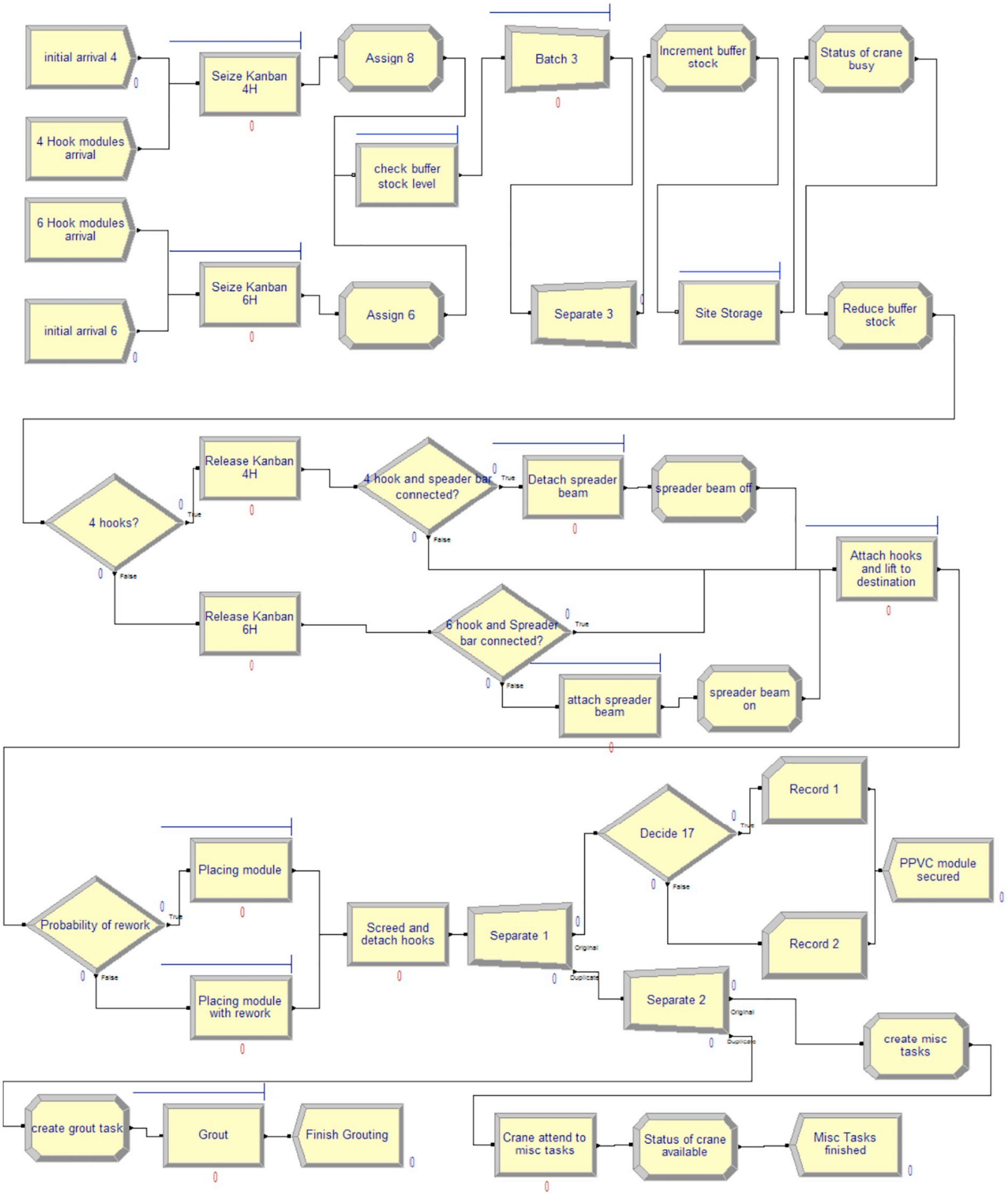


Fig. 15. Lean (To-Be) model 1.

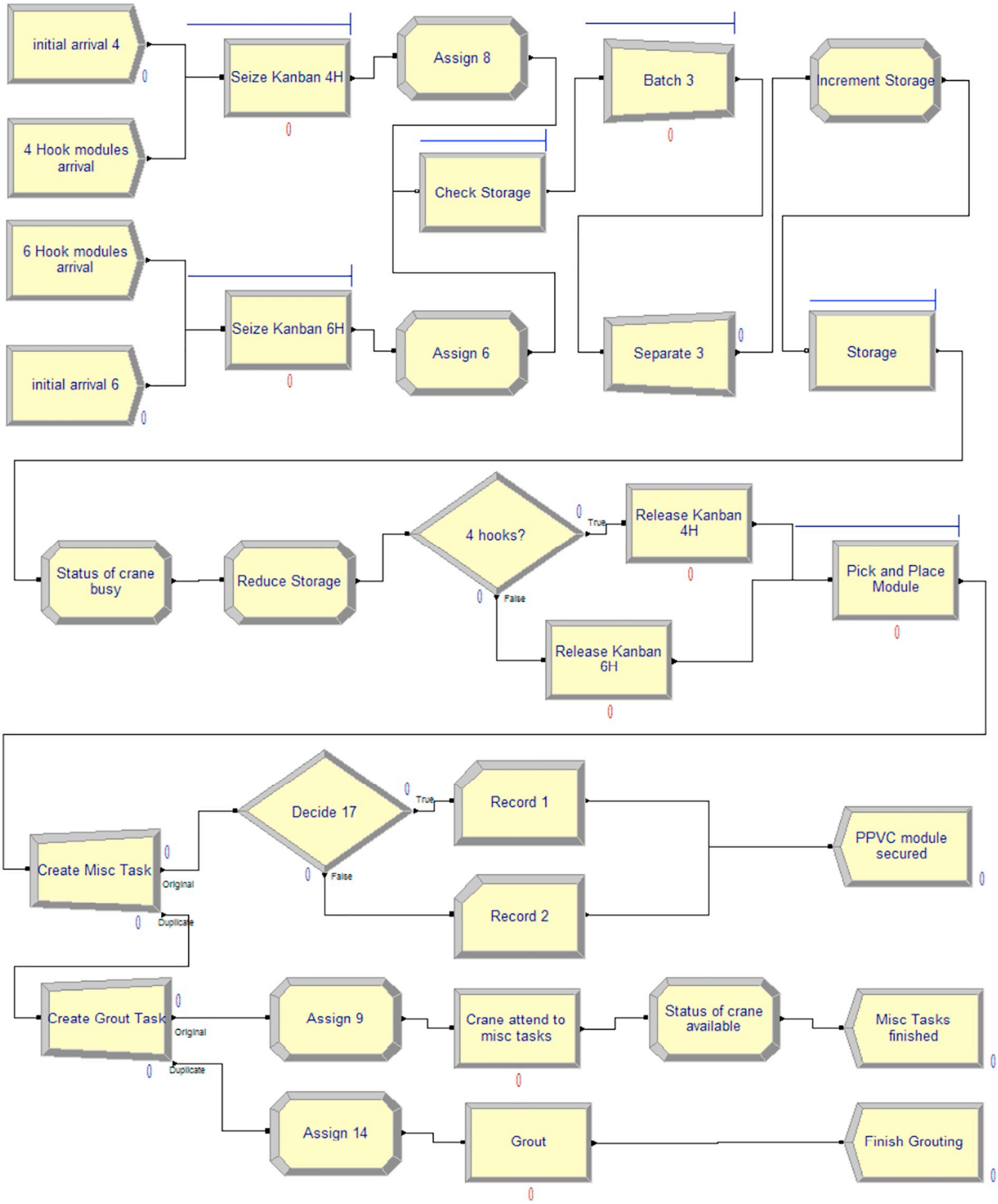


Fig. 16. Lean (To-Be) model 2.

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