Production Improvements in Offsite Construction Facilities Using Simulation and Lean Principles

by

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ABSTRACT

To capitalize on the efficiency observed in the manufacturing sector, the industrialization of construction has been used to update traditional construction methods. By applying manufacturing principles to the construction process in offsite construction facilities it is possible to transform traditional construction methods for buildings and building components into a more efficient, cost effective and continually improving process. In this research, three different offsite construction facilities are investigated. The first is a panelized home manufacturer that produces two-dimensional building sections, which are then assembled on-site. Second is a modular home manufacturer; this facility assembles buildings into a volumetric unit before shipping the module to site. The last is a cabinet manufacturing facility that produces custom cabinets for numerous types of buildings. Each of these production types can be made more efficient by industrializing the construction process and applying manufacturing principles. The first three papers in this thesis develop methods to increase production efficiency using various production improvements in offsite construction facilities. The final paper develops a method in which production efficiency and performance can be measured in an offsite construction facility. In each paper, a case study is presented in which current practices of the facility are modelled in a simulated environment and inefficiencies in current production are identified. Based on these inefficiencies, possible solutions to improve production are developed. These proposed solutions include lean process improvements, multi-skilled labour implementation and the use of an innovative roof design. Lastly, the proposed solutions are tested and analyzed through future state simulation to determine the production benefits for the offsite construction facility. The advantages gained from the industrialization of construction are presented through these real-world case studies to validate the feasibility and benefits of construction manufacturing.

PREFACE

This thesis is the original work by Ryan Brown. One journal paper and three conference papers related to this thesis have been submitted or published and are listed as below. As such the thesis is organized in paper format by following the paper-based thesis guideline.

1. **Brown, R.**, Ritter, C., and Al-Hussein, M. 2019. Simulation Based Approach for the Industrialization of a Cabinet Manufacturing Facility. Proceedings of the 2019 Modular and Offsite Construction (MOC) Summit, Banff, Alberta, Canada, May 21–24, 2019, pp. 301–308.
2. Barkokebas, B., **Brown, R.,** Al-Hussein, M. 2019. Evaluation of Multi-Skilled Labour in an Off-Site Construction Facility Using Computer Simulation. International Conference on Computer in Civil and Building Engineering (ICCCBE), Sao Paulo, Brazil, June 2-4, 2020. (Submitted)
3. **Brown, R.** and Al-Hussein, M. 2019. Manufacturing of Gable-to-Gable Roofs in an Offsite Construction Facility. Journal of Construction Innovation: Information, Process, Management. (Submitted)
4. **Brown, R.,** Barkokebas, B., Ritter, C. and Al-Hussein, M. 2019. Predicting Performance Indicators Using BIM and Simulation for a Wall Assembly Line. Proceedings of the 2019 International Group for Lean Construction (IGLC) Conference, Dublin, Ireland, July 1-7, 2019, pp. 853-862.

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Chapter 1: Introduction

1.1 Background and motivation

Traditional on-site construction suffers from low efficiency, high wastes and poor productivity. The same methods have been used for decades for on-site construction with little technological innovation. Offsite construction has been used to update traditional construction methods due to its increased productivity, quality and safety while reducing wastes in its many forms. The industrialization of construction through the use of offsite construction facilities is a possible solution to the long-outdated methods of traditional on-site construction. In an offsite construction facility, buildings and building components are manufactured on production lines in a controlled environment that are then shipped on-site for final assembly. This method of construction consists of buildings that are assembled with prefabricated components that were manufactured offsite. The extent of prefabrication ranges broadly and depends on the level of manufacturing and the degree of offsite assembly. Panelized residential home construction is a popular type of offsite construction in which walls, floors and roofs are built on assembly lines in two dimensions, these components are then shipped to site to be assembly into a three dimensional unit. Volumetric construction is another common type of offsite construction in which homes are made into three dimensional units before shipping, this typically involves less assembly time on site but increased shipping requirements. Additionally, many building components are built offsite in specialized facilities, this include cabinets and windows which cannot be effectively built onsite due to their complexity. In each of these processes varying levels of automation are utilized and production techniques change between each facility. For these reasons offsite construction facilities must be evaluated and improved based on the current state of that facility, rather than a standard model of production.

Offsite construction manufacturing allows construction manufacturers to use proven concepts adapted from the manufacturing sector to continually improve the offsite construction process. Koskela (1992) first described how manufacturing principles can be used in the construction process, which laid the foundation for lean construction. Lean concepts can be applied to all levels of production in order to reduce wastes, lead times, and costs. This has allowed offsite facilities to remain competitive and undertake increased production volumes without significantly increasing their resources. Lean has been used to optimize offsite construction facilities in numerous cases (Moghadam et al., 2012; Yu et al., 2013; Zhang et al., 2016). Lean production principles and techniques such as value stream mapping, 5S and Kaizen can be used in offsite construction facilities to reduce waste in its seven forms. Value stream mapping is a tool that is used to breakdown production by showing the interaction between production steps, the visualization of takt times of each station, and the depiction of material flow. This can aid in bottleneck identification and can be used to show personnel the root cause of the production inefficiencies. 5S is set of basic principles that uses cleanliness and organization to gain efficiency, and when implemented in an offsite construction facility, 5S often produces the most immediate and low-cost results. Kaizen is a lean concept that shifts company culture into one of continuous improvement by allowing improvement suggestions from every level within the organization. This is vital to the success of an offsite construction facility because it is the personnel on the production lines, not management, that are the most knowledgeable about the inefficiencies within the production line. While lean principles can be used to improve a facility, it is vital to test and understand the impact of such changes before implementation. Computer simulation can be used as a virtual environment in which changes to production can be tested and evaluated before they are implemented in the facility. Discrete event simulation (DES) can be used to determine production schedules and labour requirements, and to breakdown production into manageable portions. Computer simulation has been used in the case studies investigated in this thesis to provide a low-cost environment to test future state improvements before they are implemented in the case study facilities.

1.2 Research questions

This research seeks to improve the production efficiency of offsite construction facilities by addressing the following four research questions:

1. *How can the facility layout and production sequence be optimized?*

2. *What are the effects of introducing multi-skilled labour?*

3. *What effects will introducing new and innovative designs have on production?*

4. *How can performance indicators be predicted on a per project basis and over a production period?*

Each of the above questions will be answered in chapters 4, 5, 6, and 7 respectively. Furthermore, this research explores the how manufacturing techniques can be used to improve the production efficiency of offsite construction facilities. Specifically, this study focuses on the identification of facility bottlenecks and inefficiencies, developing solutions and testing proposed solutions in a simulated environment before implementation in the offsite manufacturing facility. The proposed solutions consist of optimizing the facility layout, changing production sequences, implementing new building designs, and using multi-skilled labour in the production line. These solutions are then evaluated based on performance indicators relevant to the case study facility. To develop an understanding of this goal, the following objectives are pursued:

1. defining current practices through process mapping and computer simulation.

2. identification of bottlenecks and inefficiencies in current production and development of possible solutions that can be used to optimize production.

3. testing and analysis of proposed solutions through future state simulation to determine the implications and feasibility of applying these solutions to the offsite construction facility.

1.3 Thesis Organization

This thesis consists of eight chapters. Chapter 1 (Introduction) describes the background and motivation for this research, describes the research objectives, and provides an overview of the case studies and the topics to be covered. Chapter 2 (Literature Review) provides a summary of the previous research on the covered topics. Chapter 3 (Methodology) describes the overall methodology and how it pertains to each of the following chapters. In Chapter 4 (Simulation Based Approach for the Industrialization of a Cabinet Manufacturing Facility), the research describes how simulation can be used as an effective tool in identifying and testing process improvements in an offsite construction facility. Chapter 5 (Evaluation of Multi-Skilled Labour in an Off-Site Construction Facility Using Computer Simulation) utilizes simulation to describe how multi-skilled labor can be used in the production line. Chapter 6 (Manufacturing of Gable-to-Gable Roofs in an Offsite Construction Facility) investigates the production of an innovative gable-to-gable roof design and quantifies the benefits of manufacturing this new design. Chapter 7 (Predicting Performance Indicators Using BIM and Simulation for a Wall Assembly Line) describes how simulation can be used in conjunction with performance indicators to evaluate production to determine the expected manufacturing outcomes of production and analyze facility performance. Chapter 8 (Conclusions) summarizes the research contributions, limitations, and direction of future work.

Chapter 2: Literature Review

2.1 Lean and construction

The industrialization of construction first gained momentum with Koskela's (1992) first adaptation of lean production techniques used in the manufacturing industry, applied to the construction of buildings. Koskela (1997) then summarized 11 principles for lean construction: reduce the share of non-value adding activities; increase output value through systematic consideration of customer requirements; reduce variability; reduce cycle times; simplify by minimizing the number of steps, parts and linkages; increase output flexibility; increase process transparency; focus control on the complete process; build continuous improvement into the process; balance flow improvement with conversion improvement; and benchmark. Soon after, Koskela (2000) outlined three fundamental principles for the implementation of lean construction which focused on transformation, process and value to create flow in the construction process. However, utilizing lean manufacturing principles to efficiently construction buildings has been difficult to due to several barriers. Manufacturing produces standardized products, while construction involves unique and complex projects being completed in environments with unknown constraints, tight budgets, and schedules fundamentally different from those for manufacturing products (Howell, 1999). To overcomes these challenges a new system of modular construction was developed. This system produces modules that are individually designed, fabricated in a plant, and assembled on site with the vision of achieving efficiency through industrialization (Bertelsen, 2005). Once modular construction was established as a viable method, other techniques emerged such as preassembly, hybrid systems and panelized systems built in offsite construction facilities. This appears to be one of the most effective approaches in overcoming the challenges to traditional on-site construction (Lu and Ed, 2009). By producing buildings in a factory setting, lean construction practices can be effectively implemented. These practises include pull planning systems, visual management, continuous improvement, the Last Planner System®, 5S processes, reduction of batch sizes, standardization of work structurers and error proofing (Abdelhamid et al., 2008; Sacks et al., 2010). The effect of these lean practises reduces the wastes found in the construction process. These lean wastes are categorized in Figure 2.1.

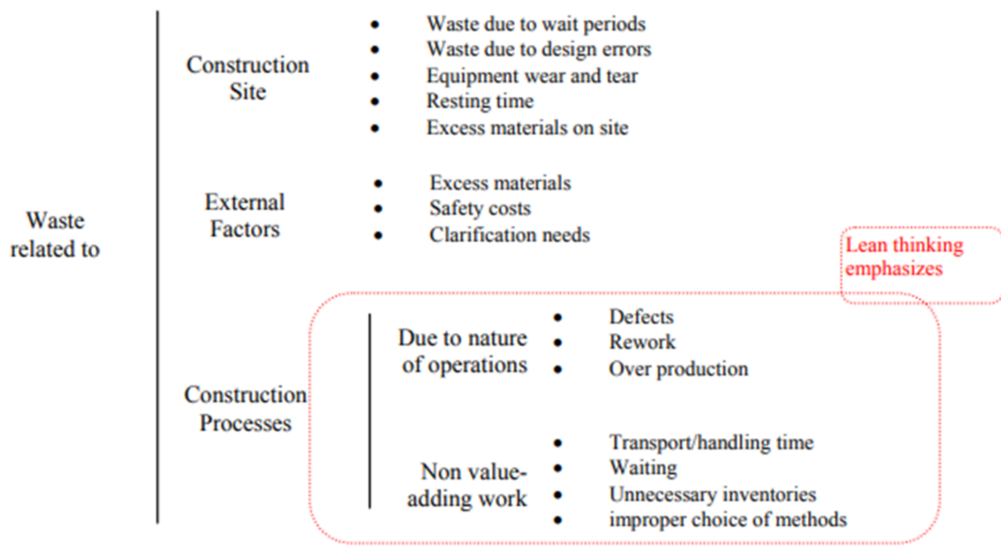


Figure 2.1 Waste categorization considering lean thinking approach (Hosseini et al., 2012)

2.2 Offsite construction manufacturing

Offsite construction manufacturing refers to the prefabrication of buildings in a factory setting. Offsite construction techniques are typically modular (volumetric), panelized (two-dimensional) or a combination. This type of production can be used to produce residential homes, commercial buildings and building components that are too complex to build onsite. Buildings are prefabrication as much as possible, then are shipped to site for final assembly. Delays encountered onsite are significantly reduced by prefabricating components because the share of onsite tasks are minimized. Offsite construction manufacturing has proven benefits for effective and efficient use of resources; reduced defects, rework, accidents and wastes; the ability to accommodate variability in projects; increased quality and value of projects manufactured; and a more sustainable end-product. (Yu 2010; Xu, H. and Wang, X. 2014). Several studies have confirmed the benefits of using offsite construction (Tam et al., 2007; Arif, 2009; Boyd et al., 2013). Typically, manufacturing buildings through the use of offsite construction facilities will result in a end product that is less expensive, shorter in construction time, and is able to be produced through a more environmentally friendly construction process, when compared to the traditional stick-built method (Moghadam, 2014).

2.3 Simulation and offsite construction

Computer simulation provides an effective tool to understanding the outcomes of implementing lean changes to an offsite construction facility prior to implementation. Through simulation precedent relationships between tasks, resource allocation, project requirements and costs can be modelled. Simulation mimics the behavior of the real offsite system and predicts the results regarding cost or completion time before implementation (Mostafa et al., 2016). Due to the complexities of construction projects, simulation is frequently the best and sometimes the only possible tool to address issues in construction operations (Alvanchi, 2012; Martinez 2010; Abudayyeh et al. 2004). Discrete event simulation (DES) is the most commonly used simulation technique employed to model production in offsite construction facilities. Through DES, the simulator can produce entities that change according to discrete points in time, known as events (Brito et al., 2011). Additionally, the user can track and allocate resources, define different resources, link the model's activities with one another, provide a hierarchy of tasks and enter user written code. This flexibility makes DES an effective tool for determining production solutions that can be tailored to that offsite construction facility (AbouRizk, 2010). Hybrid simulation has also emerged as an effective way to the model offsite construction activities. A hybrid simulation model combines the use of DES with continuous simulation. Through continuous simulation the simulator can improve the comprehension of complex production systems by modelling loops of feedback and flow, and the interaction and lag mechanism between the components of the system (Brito et al., 2011). Both DES and hybrid simulation techniques have been used successfully to model complex construction processes. Sacks et al. (2007) used simulation to show that lean principles such as lean process pull flow, reduced batch size, and multiskilling can be used to improve the traditional construction process. Arashpour et al. (2014) examined process integration strategies for the utilization of multi-skilled labourers. Poshdar et al, (2016) developed a simulation that enables modeling of the selective control utilized by the pull systems based on real-time information from project processes. This study improved modelling accuracy for processes that do not follow a fixed queuing arrangement. RazaviAlavi and AbouRizk (2015) used hybrid simulation to accurately estimate production rates and dynamically modelled the mutual impacts of facility size and the production rate. In each of these studies, simulation provides an effective tool for precisely modelling and tracking complex construction operations.

Chapter 3: Methodology

The overall methodology used in each case study is shown in Figure 3.1. This methodology seeks to answer the previous four questions discussed by utilizing a common process for all case studies. The inputs, criteria, main process and outputs are common to all case studies. Each case study follows the main process depicted, while the sub-processes listed will be highlighted as they pertain to certain case studies.

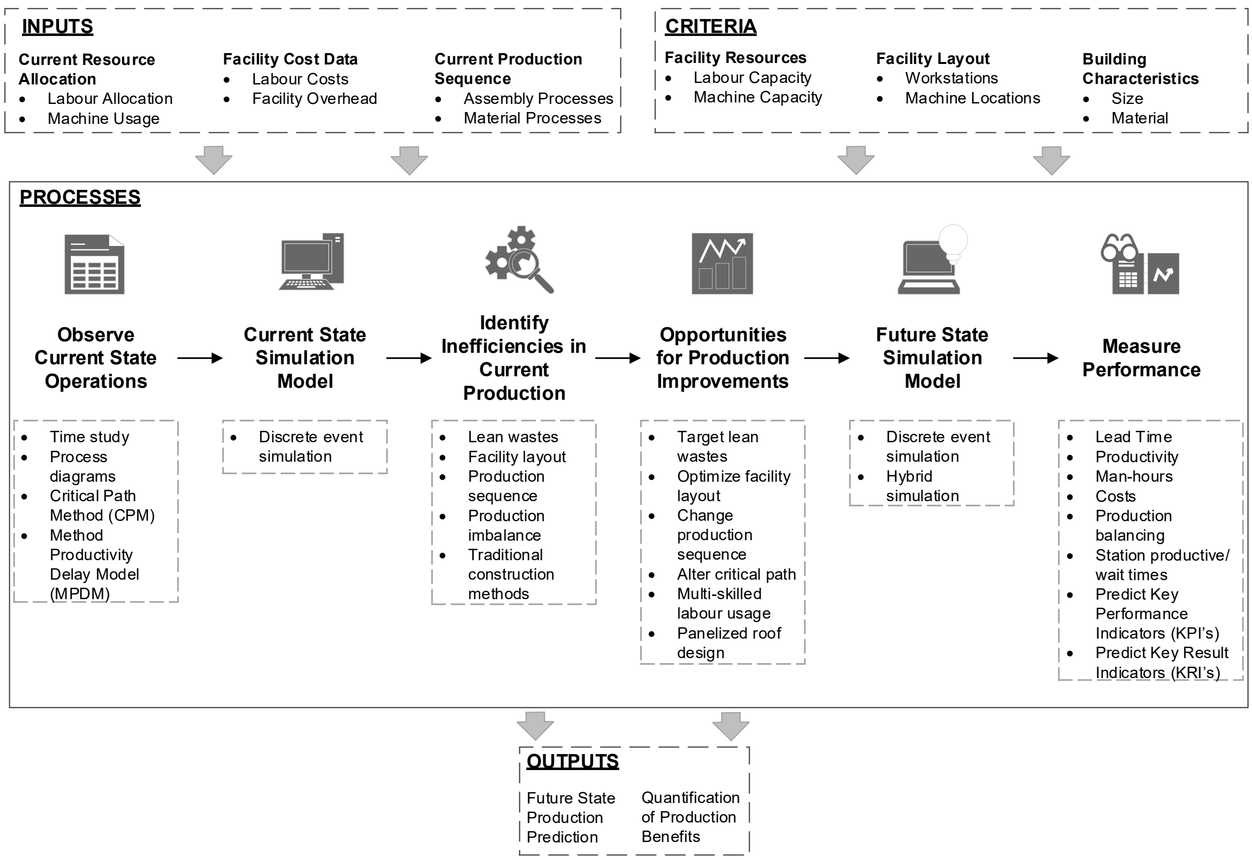


Figure 3.1 Overall methodology

To observe and define current state operations numerous methods are employed. The first step is to conduct a time study to define cycle times for activities in the production process. Next, a process diagram is needed to describe the relationships between each activity. Depending on the required level of depth needed in the study, this may be sufficient for defining the current state operations and a current state simulation model can be developed. If the study requires a more in-depth analysis of the current state operations, the Critical Path Method (CPM) and Method Productivity Delay Model (MPDM) can be employed. The CPM is used to identify the sequence of activities that result in the longest path or minimum production time. Identifying the critical path early on will aid in improving the production process in the following steps. The MPDM can be used to measure the productivities of activities when numerous delays are being incurred. By keeping track of the duration and type of delays occurring during activities, a productivity that captures the plant delays can be defined and used to the model the current state. A current state simulation model is then developed using discrete event simulation (DES). DES is an effective tool for modeling the complexities and operational details involved in construction, including constraints arising from both the facility resources and labour (Alvanchi et al, 2012). To identify inefficiencies in current production lean wastes and their root causes must be determined. Lean wastes are comprised of transport, inventory (work in progress), motion, waiting, overproduction, over processing and defects. Information gathered when observing the current state operations is vital in determining when and where these lean wastes are occurring. Additionally, analysis of the current state simulation model aids in determining where the highest wait times and work in progress are occurring. Root causes for these lean wastes are the facility layout, production sequence, production imbalance and traditional construction methods. A suboptimal facility layout causes unnecessary transport within the facility and excess motion for production activities. An inefficient production sequence and production imbalance are the root causes of waiting, overproduction and defects. When an activity is not being performed at the appropriate time or activities are waiting to be performed due to their precedent activities, these wastes start to accumulate. Defects can be a result of the production sequence not including a quality control measure to mitigate possible production errors. Over processing arises from employing labour intensive traditional construction methods in the offsite construction facility. In order to enhance production and reduce or eliminate lean wastes numerous opportunities for production improvements are proposed. These include optimizing the facility layout, changing the production sequence to alter the critical path, implementation of multi-skilled labour and introducing new and innovative product designs to the offsite construction facility. The implementation of these production improvements is done through future state DES or continuous event simulation. Continuous event simulation is used over DES when operations dynamically change as a result of the feedback from the model (Lee et al., 2009). Continuous simulation is especially useful when production requirements are continually changing as work processes. From the future state simulation, the performance of the offsite construction facility can be measured in terms of project lead time, productivity of labours, man-hours required, production balancing and station productive and wait times. If a more in-depth analysis of the facility performance is needed, Key Performance Indicators (KPI's) and Key Result Indicators (KRI's) can be calculated. KPI's are used to determining time and budget implications on a per project basis, while the KRI's can be used to evaluate performance over a production period. Many different performance metrics are available, and the appropriate ones must be selected based on the types of improvements implemented and the type of production in the offsite construction facility. This effectiveness of this methodology is best shown through the use of case studies. **Error! Reference source not found.**, Figure 3.3, Figure 3.4 and Figure 3.5 each show how the overall methodology is applied to each chapter by highlighting the subprocess as they pertain to that case study.

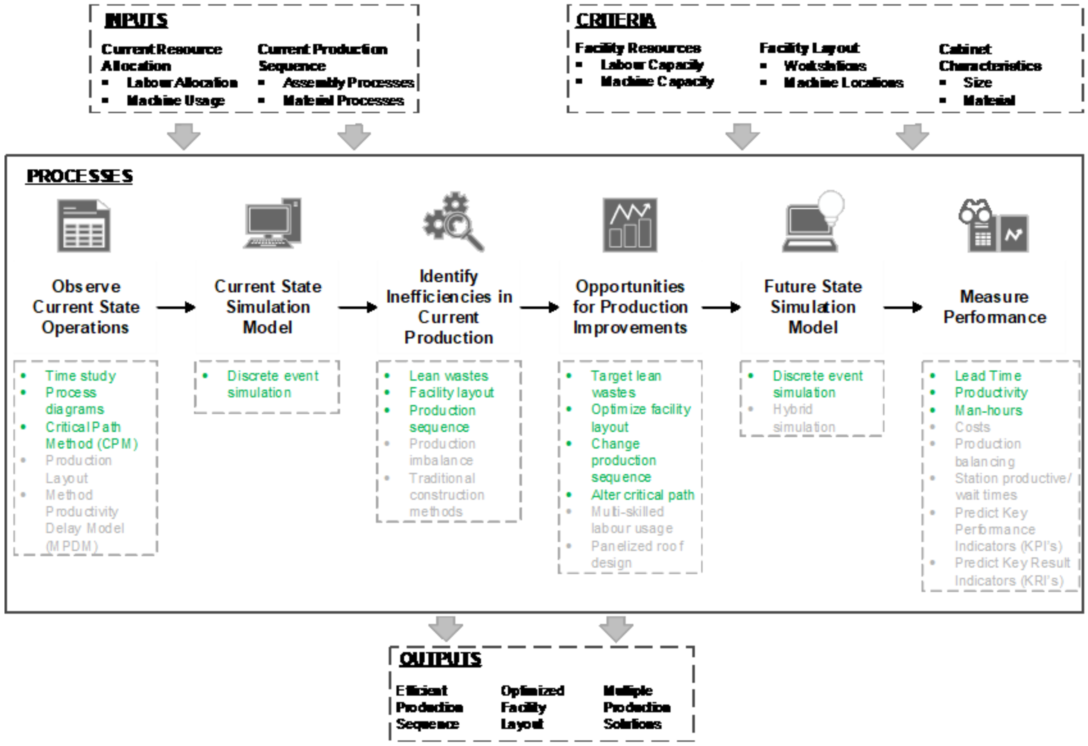


Figure 3.2 Overall methodology for chapter 4

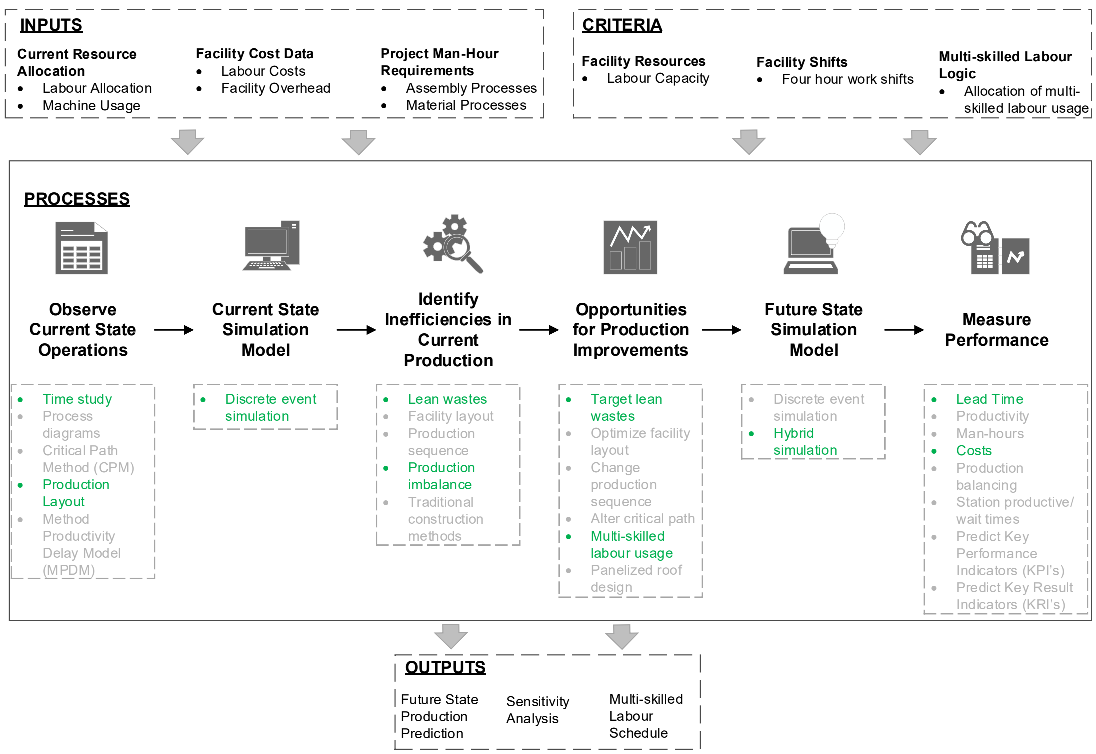


Figure 3.3 Overall methodology for chapter 5

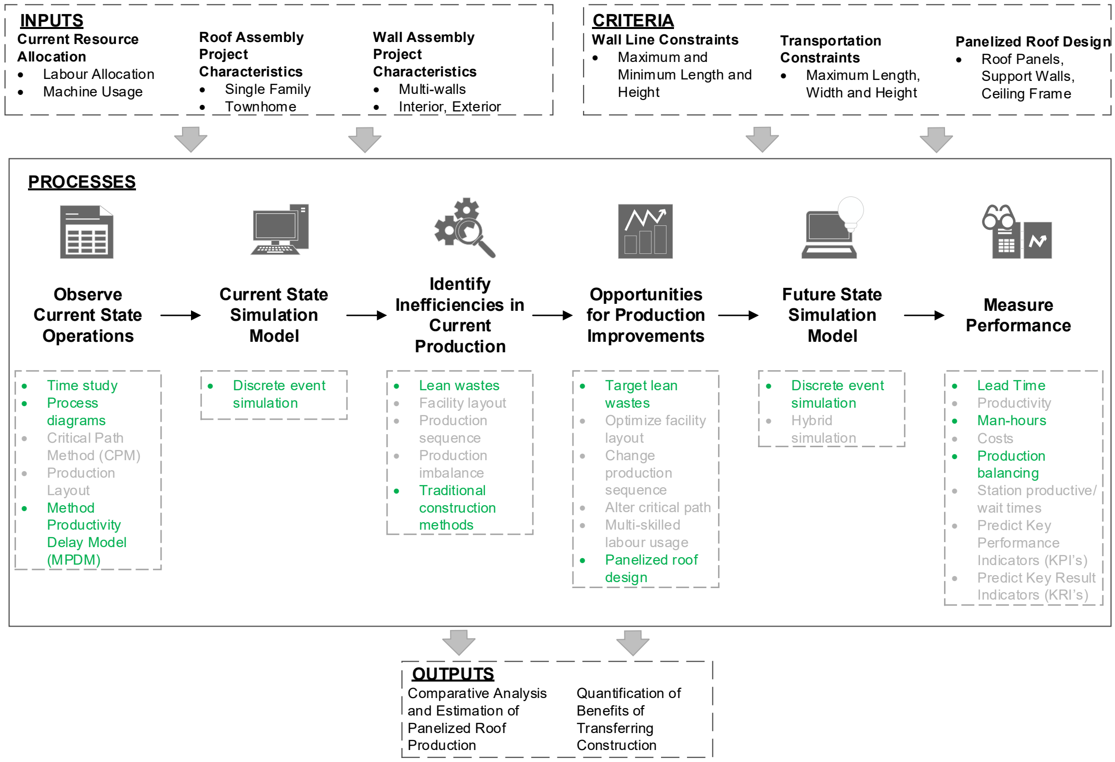


Figure 3.4 Overall methodology for chapter 6

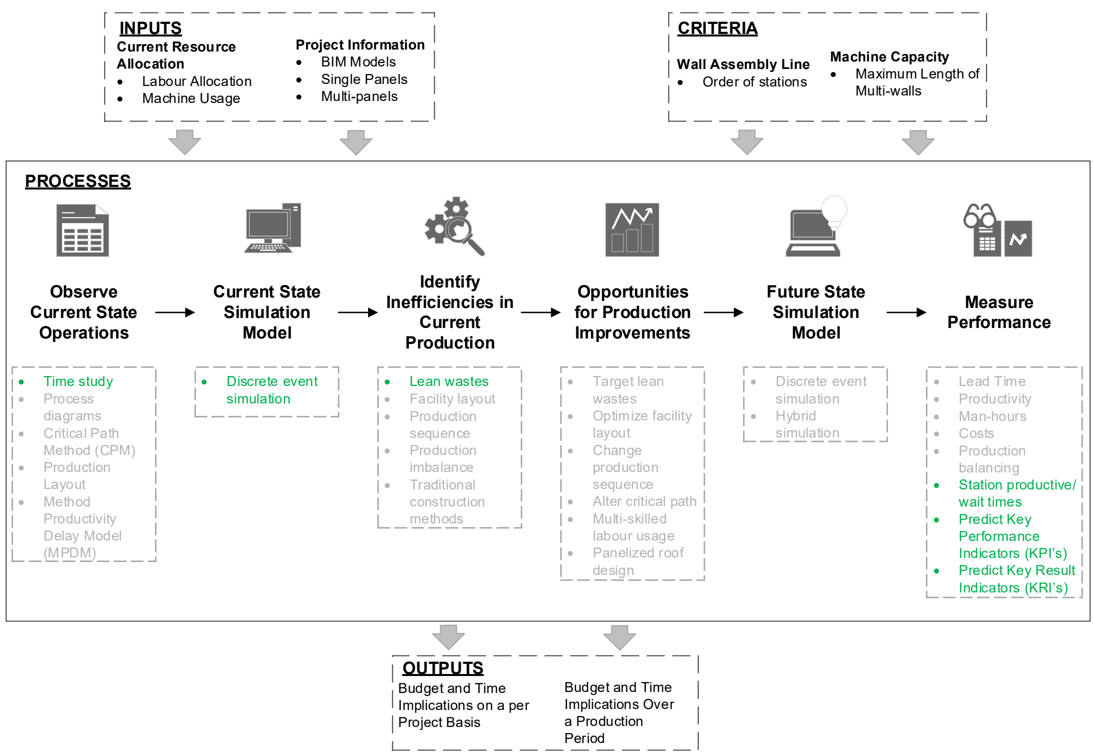


Figure 3.5 Overall methodology for chapter 7

Chapter 4: Simulation Based Approach for the Industrialization of a Cabinet Manufacturing Facility

4.1 Introduction

High-end cabinet making is traditionally an artisan process that utilizes few manufacturing principles. Manufacturing lead time, labour hours required, and productivity can be improved by industrializing the process. This paper focuses on a case study of a high-end cabinet manufacturer in Edmonton AB, Canada and the proposed process and facility improvements. First, computer simulation using Simphony.NET and movement analysis of people/materials of the cabinet manufacturer's current state of operations is conducted to establish a baseline. Next, suggested process and facility layout improvements and their anticipated results are quantified through future state simulation in order to aid management in making decisions for plant changes and to prove their effectiveness. These improvements include: application of lean principles, modification of their current production methods to reduce bottlenecks, and future state facility layout based on an optimized flow of people and materials.

4.2 Literature review

Industrialization of cabinet production by shifting operations from traditional methods into a manufacturing format can achieve productivity and lead time benefits while reducing labour hour requirements. A major tool used to industrialize a process is the use of lean methodologies. Lean production is an approach used to improve manufacturing efficiency by continuously eliminating wastes in its many forms. In this case study, waiting, transportation, and motion wastes are focused on since they are the most prominent in the facility. Lean emphasizes the consideration of flow and value generation in designing construction processes in order to achieve a lean process (Abbasian-Hosseini et al. 2014). By identifying which processes add value to the customer, lean seeks to optimize, continuously improve, and eliminate waste in this value stream. The successful implementation of lean principles increases efficiency, productivity, and quality in the workplace (Kobayashi and Fisher, 2008). Typical benefits of converting from traditional production to fully lean manufacturing can be dramatic and have been documented in a variety of industries (Manufactured Housing Research Alliance, 2007). Examples include the lean transformation of a modular building company that resulted in reduced labour costs and improved labour efficiency (Yu et al., 2013). Another is the improvement of cycle time, productivity, and process efficiency by applying the same principles to a bricklaying process (Abbasian-Hosseini et al. 2014). The implementation of lean principles gives rise to a facility layout problem (FLP). FLP is defined as the placement of workstations within the facility, with the aim of determining the most effective arrangement in accordance with some criteria or objectives under certain constraints (Hosseini-Nasab et al., 2017). In order to eliminate transportation and motion wastes, the workstations must be setup logically to provide the best flow from station to station. To eliminate waiting, each station must be standardized to be task specific to prevent a backlog of different tasks needing to be performed at the same workstation. To eliminate these wastes a process-orientated future state facility layout with standardized workstations is required to solve the FLP and achieve lean production. While lean principles are used to identify potential process improvements within the manufacturing facility, these improvements should be tested and validated in an environment before being implemented on the manufacturing floor. Simphony.NET is an integrated environment for simulating construction activities that was developed by AbouRizk and Mohamed (2000). Simulation models are used to replicate complex operations and to test potential production line improvements. Discrete event simulation (DES) is a cost-effective method to test these changes before they impact the factory floor and is an effective decision support tool that allows people to precisely examine different approaches in order to complete a project in the most efficient manner (Altaf et al. 2015). By simulating proposed process improvements, management can easily judge which changes to implement and the effect that these proposed process improvements will have on reaching company goals.

4.3 Motivation

Selenium Creative Limited is a high-end cabinet manufacturer located in Edmonton, Alberta, Canada. Selenium has grown significantly over the last few years and has recently moved into their current facility, with another planned move in approximately four years. To manage the increased production volume, Selenium seeks to adapt its manufacturing process in order to maintain their strong focus on delivering high quality cabinets Selenium aims to accomplish three specific goals: (1) to decrease their manufacturing lead time by 30%; (2) to decrease the number of labour-hours required for production by 15%; and (3) to increase their productivity by 24%. This paper outlines the process and facility layout improvements proposed to transform current production operations into a more efficient overall manufacturing process that meets the three specified goals. These goals are necessary for Selenium to continue growing into their current facility and to provide a road map of how their future facility should be set up. By achieving these goals, Selenium will be able to maintain their focus on delivering high quality cabinets and continue to prosper.

4.4 Current state manufacturing process

The first step in meeting the manufacturing lead time, labour-hour, and productivity goals is to quantify their current operations and establish a baseline. This is done by studying current operations to identify the flow of material and people throughout the plant. Next, a time study is completed, and a detailed breakdown of fabrication is developed. Then using this information, a current state simulation model is built and validated.

The current production process is shown in Figure 4.1. This flow chart illustrates the main stations used to produce a melamine cabinet box with either wood or polylaminate (P-Lam) faces. The production process for melamine cabinet boxes is as follows: (1) a CNC machine cuts the sheets to the desired size; (2) an edgebanding machine is used to put edges on to cut pieces; (3) the pieces are assembled to form the cabinet box. The process for drawer boxes is the same, except for drawer hardware installation between steps (2) and (3). For polylaminate cabinet faces the operations are as follows: (1) polylaminate sheets are glued onto both sides of particle board to create the sheet material; (2) a CNC machine cuts the sheets to the desired size; (3) an edgebanding machine is used to put edges on to cut pieces; (4) door hardware is installed; (5) the faces are hung onto the cabinet box. For wood faces, the process is as follows: (1) a beam saw cuts sheets to the desired size; (2) unfinished faces are hung on cabinet boxes to check size and alignment; (3) sanding is done three times—before the 1st coat of paint, and after the 1st and 2nd coat; (4) painting is done after each sanding; (5) door hardware is installed; (6) the faces are hung onto the cabinet box.

This production flow and data from the time study is used to build a detailed fabrication breakdown (Figure *4.2*). The detailed fabrication breakdown and labour requirements are then used to construct the current state simulation model (Figure *4.3*). The simulation model was developed through discrete event simulation in Simphony.NET, a program developed by AbouRizk and Mohamed (2000). The current state simulation model was constructed by representing each workstation as an entity. These entities are further broken down into sub-entities to model the individual tasks being performed at each workstation. For each of the tasks, a distribution or average timing was used since the timings varied for each project and person. If enough observations were recorded (approximately ≥10), Simphony.NET was used to find the best fitting distribution, an average time was used for the tasks without enough observations to fit a distribution to. Constant values were used for the glue up, wrapping, and project quality control task timings only, since they were assumed to be relatively fixed. It is important to note that the simulation model focuses on task times involved with productive activities only and not the time taken in between stations.

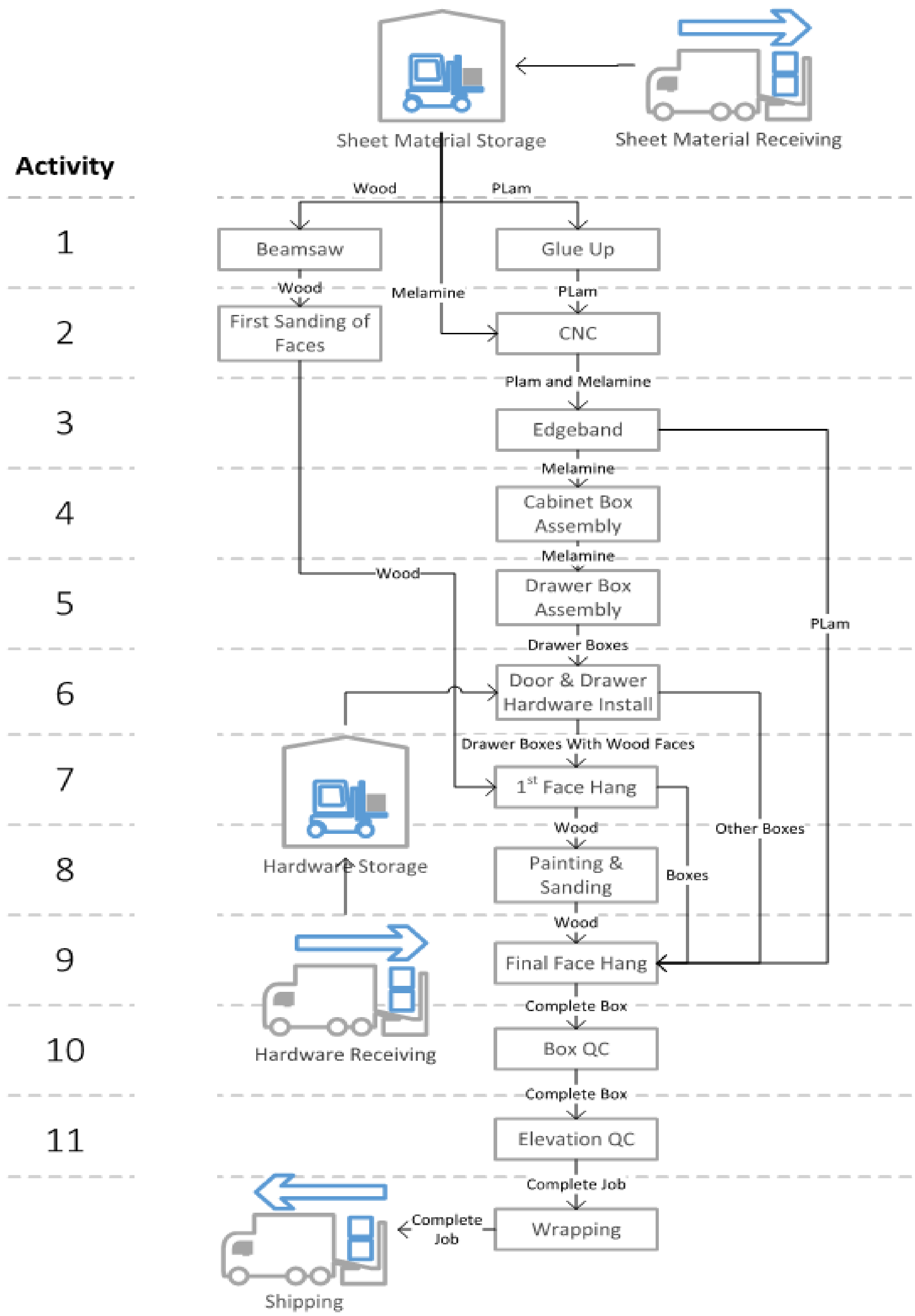


Figure 4.1 Current state production process

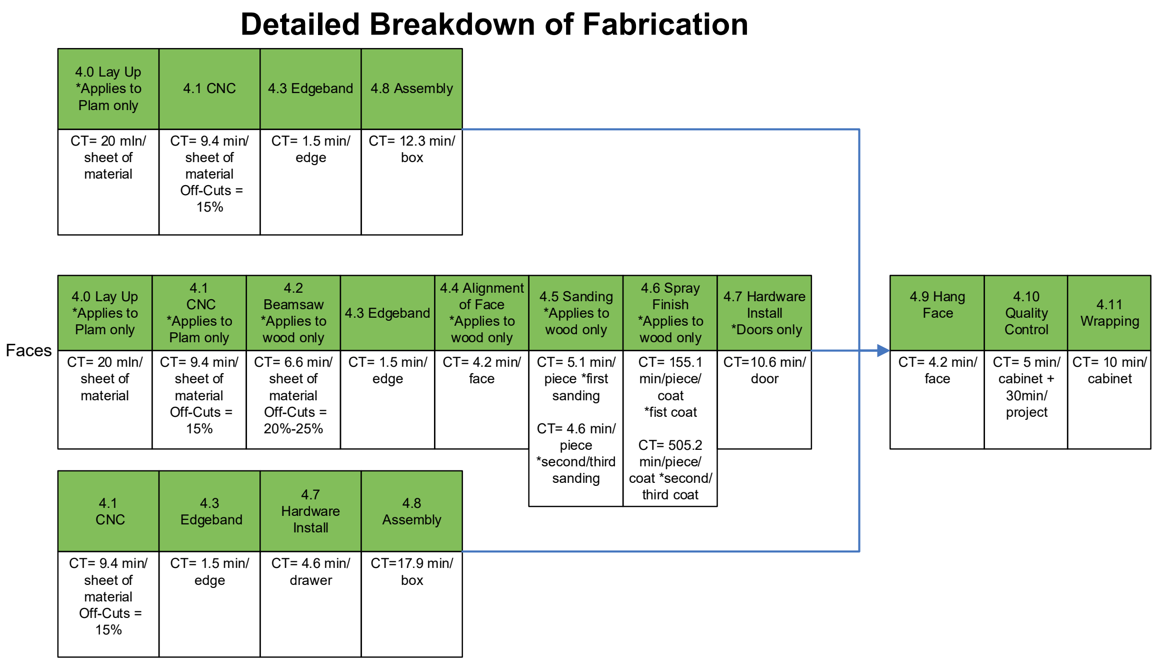


Figure 4.2 Detailed fabrication breakdown

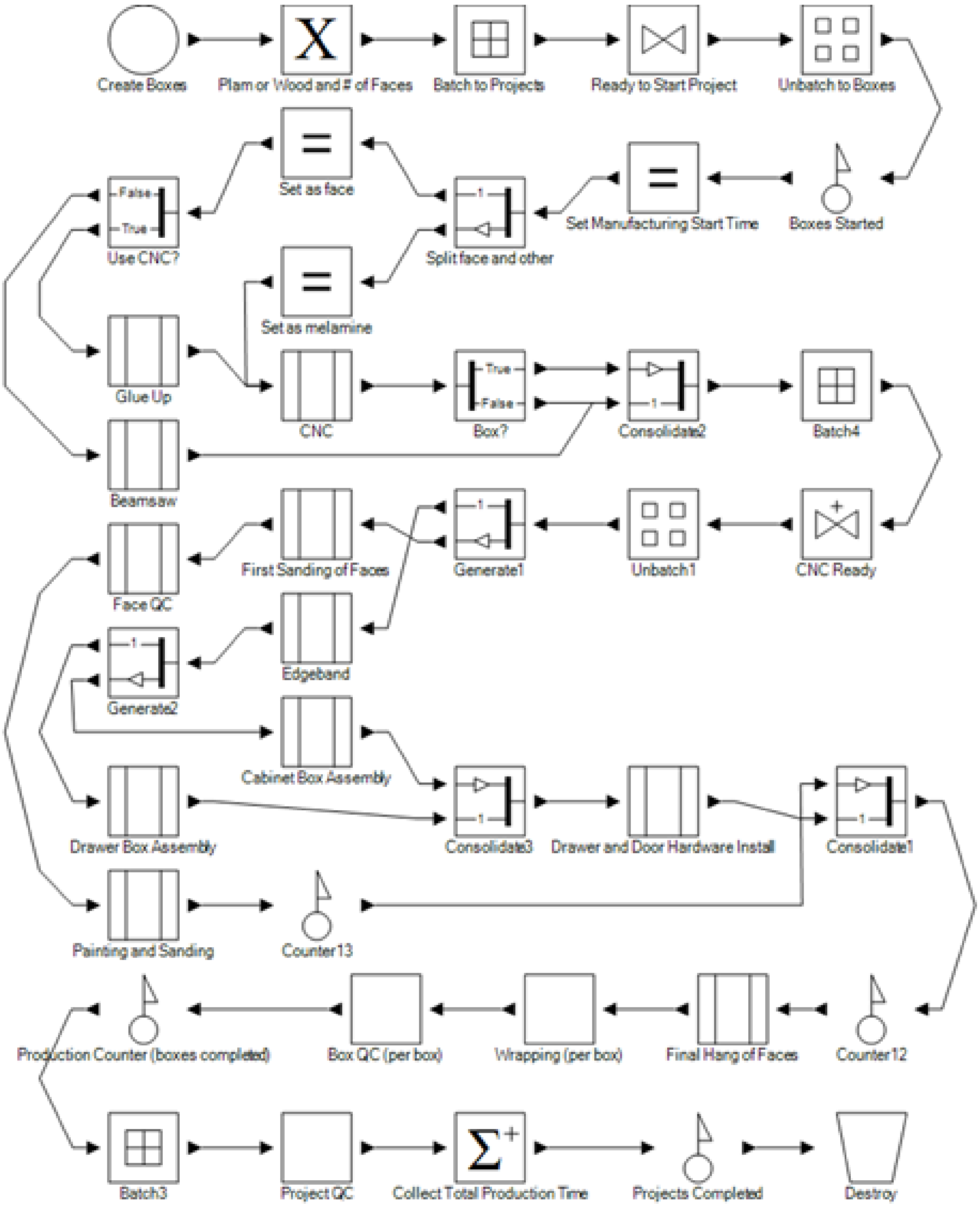


Figure 4.3 Current state simulation model

Validation and Verification of the Current State Simulation Model. The simulation model was validated based on time estimates, project totals, and material usage estimates provided by Selenium from previous studies of their own. The validation of the sheet material usage can be seen in Table 4.1. A 5% error on the number of boxes simulated in the test run year (608 boxes were created in the simulated year and 640 in the sample year provided by Selenium) was also calculated but is considered acceptable as only one year is being used and is available as a reference. Five workers were used in the simulation, each with 5.5 hours of time available each day (due to coffee breaks, meetings, cleaning, and other tasks), and 227 working days per year. A new project was made available to the plant floor every 20 to 25 days, approximately.

Table 4.1 Current state simulation model material usage validation

	Melamine (ft^2)	**Wood (ft^2)**	**P-Lam (ft^2)**
Estimate based on data from Selenium	34,857	2,646	2,484
Simulation Result	32,589	2,710	2,506
Percent Error	7%	2%	1%

4.5 Process improvements identification

Numerous process improvements have been proposed to meet the three goals by targeting areas of inefficiency and bottlenecks. The methods used alter current processes to reduce task durations based on lean principles and change the sequence of production to allow for better flow during manufacturing. The corresponding estimated cost level of implementation is listed in Table 4.2 and the changes are described in detail below. Figure 4.4 shows the split of the main tasks times for a cabinet box, this shows the emphasis needed on painting, drying and sanding task time reduction.

Table 4.2 Estimated cost of implementation

Process Improvement	**Cost**
Kits Made for Cabinet and Drawer Boxes	Low
Reduce Box Quality Control Time	Low
Reduce Edgeband Setup Time	Low
Reduce Sanding Preparation Time	Low
Quality Control Step to Replace First Face Hang	Low
Cabinet and Drawer Boxes Assemblies in Parallel	Low
Hardware Ready	Low
Improve Wrapping	Low - Medium
Reduce Painting Setup Time	Low - Medium
Reduce Walking Time	Low - Medium
Premade Cut Plans	Medium
Reduce Drying Time	High

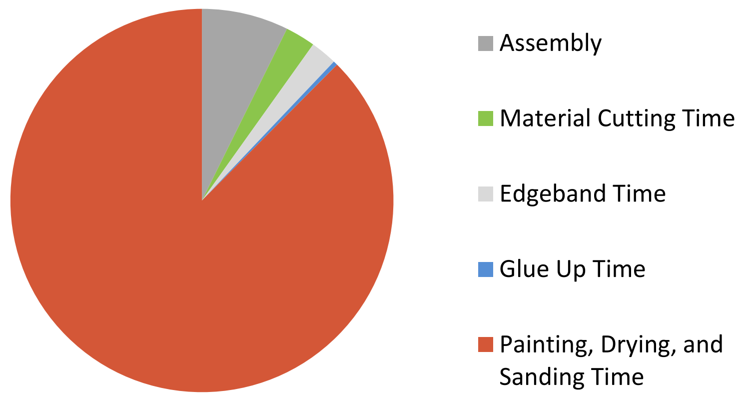


Figure 4.4 Split of task times

Multiple opportunities for improving task times were found throughout the production process; these changes range from minor organizational fixes to major additions to the plant, each of these changes supports the reduction of task times. First, the edgeband setup time can be reduced through better organization of the pieces coming from the cutting area. This will allow more pieces to be completed without adjustment of the machine. The setup time will reduce from an average of 2 minutes per box to an average of 30 seconds per box. A reduction of the time required for sanding preparation can be accomplished by the addition of a dedicated sanding table and drying area. A dedicated drying area will allow for better flow from the paint booth into the drying area and then to the sanding table. A sanding table will also make the required tools readily available for the dried pieces. This should cut the sanding preparation time in half to be 1 min per box per coat. By improving the organization of the paint booth and reducing the batch size of pieces into the paint booth, the painting setup time can be reduced. Having carts that are less full and having more space to move pieces along, along with having the drying area organized, will make it much easier to get set up for painting. It is estimated that the painting setup time can be reduced by about 45 seconds per box. The quality control time is reduced by labelling the boxes and placing them in a designated staging area. It is likely that this improvement will cut time from 5 to 2.5 minutes per box since all components to be inspected will be easily locatable and identifiable. Reduction of the drying time is achieved through the addition of a full drying chamber. This change would have a major effect on production since drying time would be reduced to 0.5 hours from 2 to 3 hours per coat. However, this is a high cost item and a large change to the plant. By producing "kits" for cabinet and drawer boxes, the pieces need for cabinet and drawer box assemblies can be better organized. Instead of pieces being places on a cart after the CNC based on their size, they will be placed according to which cabinet or drawer box they belong to. These kits will be coordinated with hardware packages before being delivered to the cabinet and drawer box assembly lines. Having hardware ready for door and drawer assembly will improve assembly time since all components will be delivered to the correct workstations, rather the person constructing the box needing to go to collect it. Premade cut plans for the CNC and beamsaw will save time by freeing the operator from manually programming the saws. This change reduced the time from 4 minutes per sheet to design the cuts for the CNC and 3 minutes per sheet to enter the cut info on the beamsaw to 1 minute per sheet for each task. Finally, a lazy-susan style wrapping turn table or an automated turn table with a height-adjustable stretch wrap holder should be purchased to improve the wrapping of finished cabinets. This will reduce the hand wrapping time of 10 minutes per box to 1 minute per box.

The changing of the production sequence has the potential to provide impactful change to plant operations. An analysis of the current state process detailed in the process flow diagrams in shows that the critical path for an average cabinet box to be completed would be about 606.5 minutes.

Most of the precedence relationships cannot be changed, but one that can, is the quality control (QC) for the wood cabinet faces. The introduction of a 10-minute QC measure instead of the first face hang would allow a change of the precedence relationships that would make the critical path for the average cabinet 552.7 minutes. The manufacturing lead time can be further shortened by using the parallel production lines to assemble the cabinet and drawer boxes at the same time as opposed to one after another. No task times are changed in this estimate, but flow through these stations will be improved.

4.6 Current state facility layout

The current facility layout has a general flow of materials based on the location of the larger machines and the shipping and receiving doors. In this current layout, workstations are based on the individual working there rather than standardizing for the task being performed. This person-specific workstation approach creates an unpredictable flow, increases wasted transportation, and is a root cause of disorganization in the plant. These three problems can be solved by designing a future state facility layout that focuses on plant flow, minimum walking distances, and the use of standardized workstations.

A movement analysis for people was done through "spaghetti diagrams" (Figure 4.5) to determine the percent time spent walking during a specific task, the colored lines represent walking paths of people completing the jobs listed in Table 4.3. Workers were observed and timed as they performed productive tasks and their walking paths were traced. The total time was recording once the task was finished and is used to calculate average rate of travel by dividing distance travelled by total time, then converting to meters per hour. From here the distance travelled divided by an average walking speed of 1.4 meters per second was used to find the time spent walking. This is finally divided by the total task time to find the percentage of time spent walking. This percent of time spent walking can be considered wasted movement since this should be nearly zero during productive tasks because the person should be stationary if all the correct materials and tools are present. This is how wasted movement was quantified to be 9.8 percent on average. Under the revised plant layout, this time wasted walking can be instead shifted to productive time to determine the possible productivity gain from reducing wasted movement. Additional a “spaghetti diagram” was also developed for the material flow throughout the plan (Figure 4.6). This diagram helps to determine how the future state layout should be setup in order to smooth the transportation routes of the incoming materials, processing of materials and finally the shipment of the finish product.

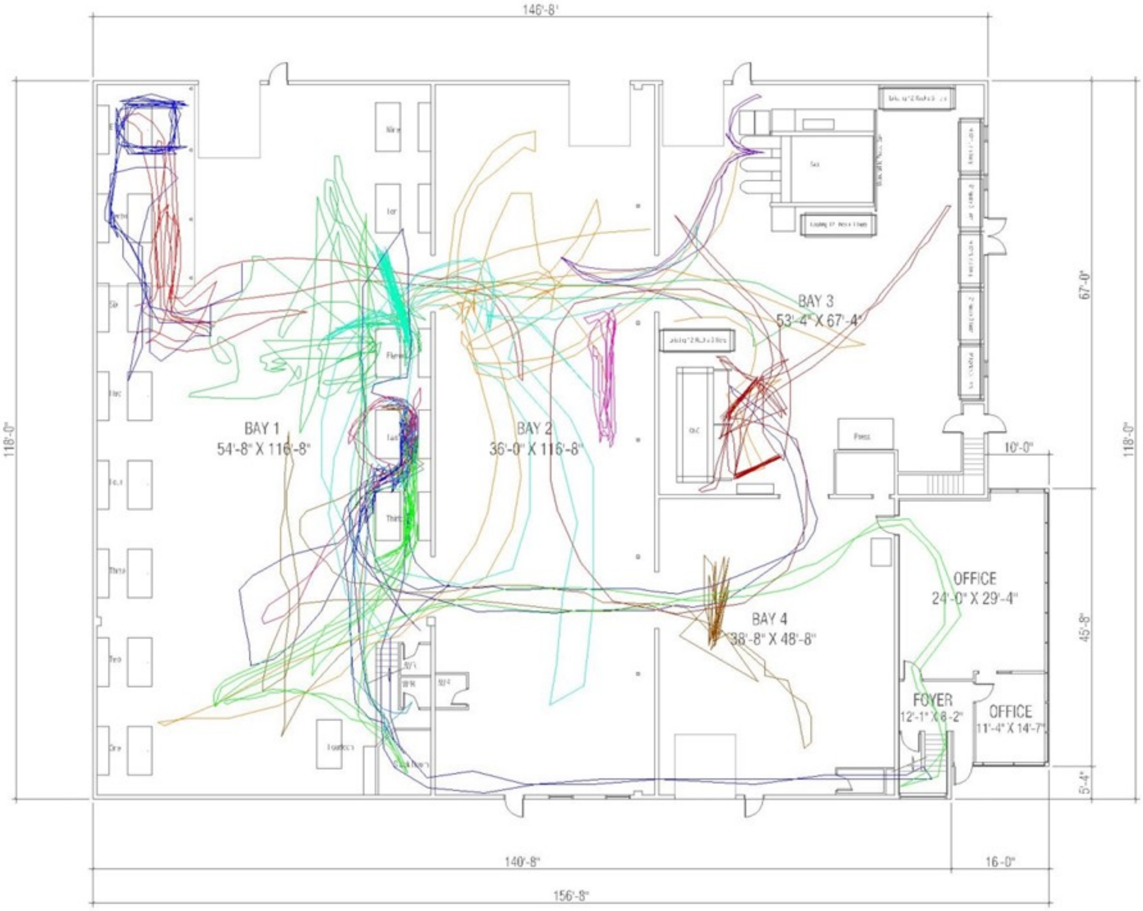


Figure 4.5 Spaghetti diagram for movement of floor staff

Table 4.3 Quantification of wasted movement during productive tasks

Job Description	**Distance Travelled**	**Time (min)**	**Percentage of Time spent Walking***
Edging	64 m	10	7.6%
Assembling Door Jambs	252 m	30	10.0%
Assembling Door Jambs	412 m	75	6.5%
Cutting Door Jambs on Table Saw	268 m	30	10.6%
Painting Doors	166 m	30	6.6%
Assembling Drawer and Door Box	235 m	20	13.9%
Assembling Drawer and Door Box	78 m	10	9.3%
Adding Door Hinges	318 m	40	9.5%
Assembling 2 Door Box	330 m	30	13.1%
Sanding Open Box	74 m	20	4.4%
Painting Cabinet Piece	169 m	10	20.1%
Beam Saw	62 m	4	18.5%
CNC	243 m	20	14.5%
Average	206 m	25	**9.8%**

Figure 4.6 Spaghetti diagram for movement of materials

The current cabinet production process is centered around individual work stations, where each person performs their duties. This type of production creates an uneven use of space and an uncertain flow of materials and people through the plant. This setup also increases the number of tools required at each station, as there is a larger variety of possible jobs that could be done at each workstation. Efficiency can be gained by having set workstations based on the activity being done. These activities include drawer assembly, cabinet assembly, final assembly, sanding, drying, staging, and special projects.

4.7 Future state facility layout

The future state facility layout (Figure 4.7) is based on the current state production flow of people and materials but incorporates walkways, staging and drying areas, improved material transport, rearranging of stations, and specialized workstations. The addition of a painted walkway will ensure indicated areas are kept clear of material to allow for people and products to flow unobstructed through the plant and from station to station. Moving of the special projects' benches and glue up stations will place these stations in a more logical position to increase plant flow and reduce wasted movement. A designated drying and sanding area allows for a cyclical flow of carts from the paint booth to the sanding table, then back to the paint booth if additional coats are needed, thus increasing plant flow and keeping the plant floor unobstructed. A designated staging area will provide an area for all projects to be set up for QC. This will help to keep the pathways clear, as currently staging of projects often blocks passages in the current plant setup. The most major change is the task centered workstations: this change is vital to the success of the future state layout. These numerous changes help to create a natural and predictable flow of people and materials through the plant. Improved organization, a reduction of wasted movement and transportation, and increased standardization and safety are also gained.

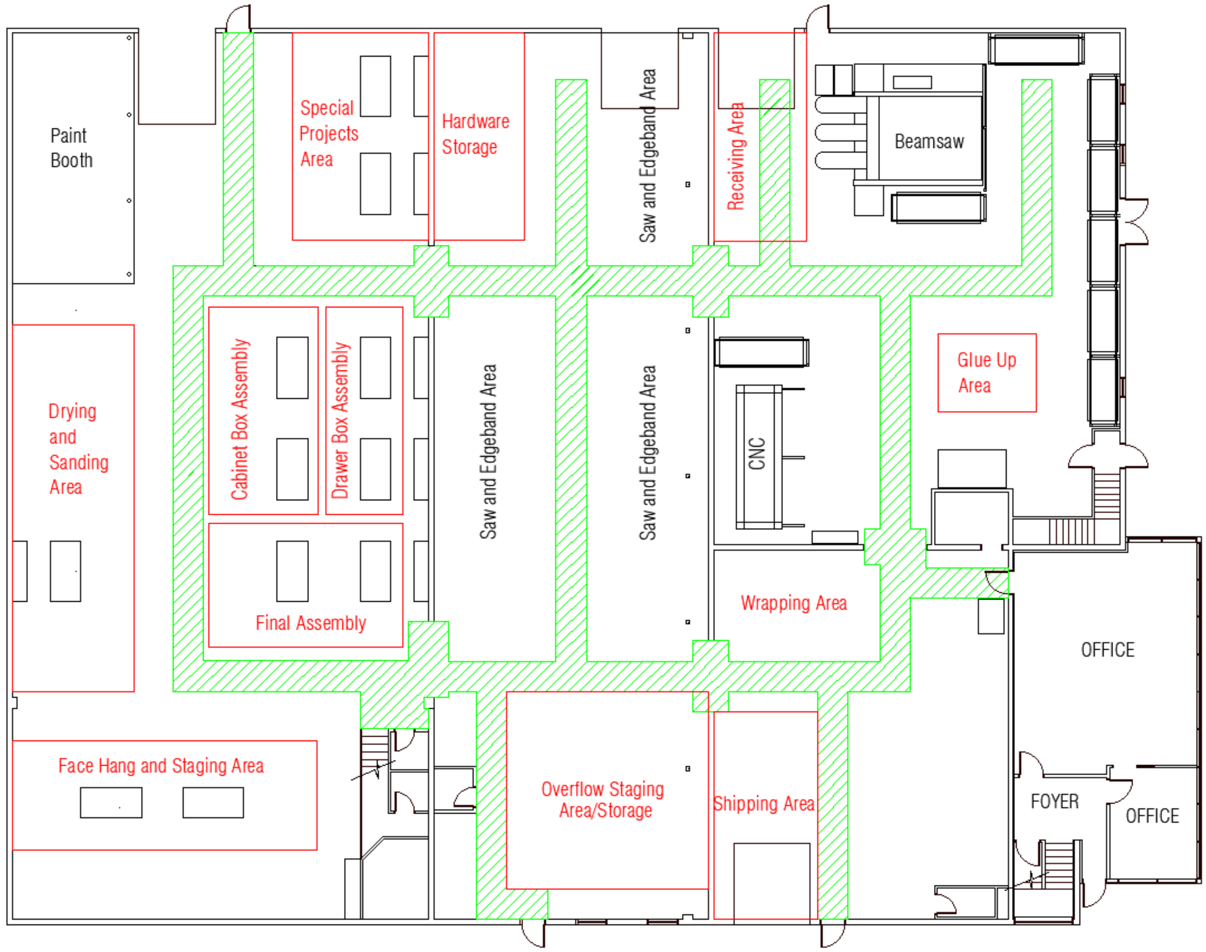


Figure 4.7 Future state facility layout

4.8 Future state simulation

Several process improvements and an improved facility layout have been proposed in order to improve the manufacturing lead time, labour hours required, and productivity. These improvements and their corresponding effect on reaching the three goals are specified in (Table 4.4). These results were found by applying each process improvement individually to the base case. The total effect of all improvements is then modelled to find the cumulative effect of these changes. It is important to note that the sum of the individual changes is not the same result as applying all the changes at once. This is due to resource constraints in the simulation model for the number of workers, machines, and workstations.

Many of the process improvements are low cost and represent slight changes to production. These should be implemented first because they can be done with little disruption while still having a significant impact on lead time, productivity, and labour hours required. The higher cost and more major plant changes, such as purchasing of equipment or significantly altering the production steps, can be implemented once resources are available and management and employees have discussed when and how they will apply these changes. However, all the process improvements discussed are necessary to achieve the desired three goals. All the suggested process improvements were presented to Selenium's management team to ensure that the changes are realistic and feasible for their plant. The feedback received was positive and the facility aims to implement these changes over time as people and resources become available. The priority of the changes will be based on lowest cost and least disruption to the plants operation. Most of suggested changes will be implemented in their current plant, while the purchasing of a full drying chamber is likely to be done once they move into their new facility.

Table 4.4 Future state simulation results

	Lead-Time (hours)		Productivity (box per day per person)		Labour-hours (Labour-hours)	
Process Improvement	**Value**	**% Change**	**Value**	**% Change**	**Value**	**% Change**
Current State (Baseline)	42.02	-	1.50	-	2,382	-
Kits Made	41.99	-0.08%	1.50	0.20%	2,377	-0.19%
Reduce Box QC Time	41.66	-0.86%	1.51	0.89%	2,361	-0.88%
Reduce Edgeband Setup Time	40.18	-4.38%	1.57	4.85%	2,272	-4.62%
Reduce Sanding Preparation Time	41.81	-0.50%	1.52	1.53%	2,346	-1.51%
Replace First Face Hang	40.33	-4.01%	1.52	1.39%	2,349	-1.37%
Cabinet and Drawer Assembly in Parallel	40.87	-2.75%	1.50	-0.08%	2,383	0.08%
Hardware Ready	41.45	-1.36%	1.52	1.59%	2,344	-1.56%
Improve Wrapping	39.36	-6.33%	1.56	3.94%	2,291	-3.79%
Reduce Painting Setup	41.92	-0.24%	1.50	0.50%	2,370	-0.49%
Reduce Walking Time	39.92	-4.99%	1.56	4.34%	2,283	-4.16%
Premade Cut Plans	35.59	-15.29%	1.71	14.59%	2,078	-12.73%
Reduce Drying Time	40.99	-2.45%	1.49	-0.45%	2,392	0.45%
All Changes at Once	27.61	-34.29%	2.23	49.25%	1,596	-33.00%
Goal	29.42	-30.00%	1.86	24.00%	2,024	-15.00%

4.9 Conclusions

By implementing the numerous changes outlined in this report, it is possible for the cabinet manufacturer to reduce lead time and labour hours required by 34% and 33%, respectively, and to increase productivity by 49%. Many changes are found to be low cost and require only a slight change to production, while others are costlier and more disruptive to operations. The implementation of all these changes was found to produce significant benefits for the plant. Once most changes have been completed, production should be further evaluated through time studies to confirm assumptions and time saving estimates. Using the time data, bottlenecks and areas of inefficiency can be identified for future improvements. This research only included timings for productive tasks, while a large part of the time spent was on non-productive tasks. A future study of non-productive time may be beneficial to identify causes and help shift this into productive time. Limited observations were a factor during this research; therefore, additional task timings would be valuable to fit all task durations to a distribution rather than using an average or constant value for the tasks with limited observations.

4.10 Acknowledgements

The authors would like to thank everyone at Selenium in Edmonton, AB, Canada, for allowing us to observe their actions at the facility in order to collect the data needed for this study. We would like to specifically thank Selene Yuen and Mike Booth for organizing visits and providing information. Additional thanks to Riphay Al-Hussein and Scott Penner for organizing this project. The research is funded by Natural Sciences and Engineering Research Council of Canada Engage Grant (EGP 532044-18).

Chapter 5: Evaluation of Multi-Skilled Labour in an Off-Site Construction Facility Using Computer Simulation

5.1 Introduction

Off-site construction uses production lines to produce building components in a controlled factory setting. By shifting construction activities to an off-site environment, many manufacturing principles can be employed, including the use of multiple work stations to produce components. Typically, each work station has a specialized labourer working only at the one station. Those work stations in the production line with the longest productive and wait times highly influence the throughput of the line. Often, some labourers are sitting idle while other stations are backlogged. This paper investigates the use of multi-skilled labour to reduce idle times and increase productivity by balancing cycle times. Take-off quantities from BIM models and computer simulation are used to determine the required duration and locations of multi-skilled labourers in the production line. Furthermore, the optimal number of multi-skilled labourers is found by balancing the costs of training multi-skilled labourers with facility overhead costs.

5.2 Literature review

Shifting construction to off-site facilities has become increasing popular due its productivity, quality, efficiency, and safety benefits (Modular Building Institute 2010). This is achieved by borrowing concepts and knowledge from the manufacturing industry (Zhang et al. 2016). Modular construction is a popular method of off-site construction in which building components are constructed into two dimensional panels, then the panels are assembled into a volumetric unit either in the factory or on-site. The building components are assembled on production lines comprised of work stations. Project management assigns labourers with individual specializations to each station. Labourers do not migrate from their assigned stations, which results in bottlenecks at the stations with the greatest work content, and in turn this has substantial impacts on the progress rate of projects (Arashpour et al. 2014).

It has been found that multi-skilled labour resources decrease project duration, increase job stability for workers, and allow for higher flexibility in task assignment (Wongwai and Malaikrisanachalee 2011). However, there is a cost to training labourers to be multi-skilled and this cost must be balanced with the production gains, and there still exists a lack of information as to the actual benefits in terms of the use of multi-skilled labour of how to address it.

Arashpour et al. (2014) analysed process integration strategies for the utilization of multi-skilled labourers. This study found that borrowing labourers from underutilized stations to help at over utilized stations smooths the capacity imbalance on the production line. If the production process is found to have work stations with a high variability in production times, then indirect skill chaining (multi-skilled crews that operate over a limited zone of the production line) was the optimal solution.

Moghadam (2014) outlines numerous methods to apply lean to the modular construction industry. It identifies production levelling, scheduling, and production flow as key areas of focus to improve the manufacturing process. In each of these areas it is suggested that the effect of multi-skilled labour in a modular building construction facility would be beneficial. Through the use of stationary labourers supported by a group of multi-skilled labours, it would be possible to adjust takt times to better handle the variability of projects and allow for non-fixed activity durations.

This group of multi-skilled labours is required to move into any station along the production line as needed. The upstream migration of multi-skilled personnel through the production line would balance labour requirements and reduced lead time of a module. The multi-skilled labourers would provide a flexible allocation of resources into the most complex stations (longest duration), which will allow for complex products to be produced at a similar pace as the simpler products. Hence, there is a clear need for a systematic method to address the use of multi-skilled labour in modular construction facilities.

Barkokebas et al. (2015) evaluated the effect of incorporating dynamic workstations (work stations comprised of multi-skilled labourers) for the floor and wall production lines in an off-site construction facility. The study used discrete event simulation (DES) and continuous simulation to prove that multi-skilled labour balanced fluctuations in workflow and improved overall production without increasing the number of labourers. While multi-skilled labour was found to shorten production time, questions remain with respect to the added cost of hiring and training highly skilled labourers. Hence, this study still lacks information regarding the financial impact of the use of multi-skilled labour in the production line. In fact, the financial impact is addressed as a multi-dimensional problem in which there is a significant investment and still no clear trade-off between investment and benefits in this solution. Moreover, other aspects are also important to address such as space constraints; each station is limited by the amount of space available, which limits the number of workers performing simultaneously at a given time.

Computer simulation is an effective tool that can be used to evaluate the effect of multi-skilled labour on production. Simphony.NET is an integrated environment for simulating construction activities that was developed by AbouRizk and Mohamed (2000). In this program, discrete event and continuous simulation are used to evaluate production scenarios in a virtual environment prior to real production (Altaf et al., 2018a). Several studies have been published using simulation in modular construction manufacturing to assess various risk factors (Li et al. 2014) and system efficiency (Hammad et al. 2002). Brito et al. (2011) indicates the combination of discrete event and continuous simulation, referred to as hybrid simulation, is potentially the optimal approach for problems when simulation requires both a low level of abstraction (e.g., predicting a start and end to a task provided by DES) and a higher level of abstraction (e.g., a dynamic change to the production rate of an activity due to an increase or decrease of resources).

This paper presents a case study of a well-established modular home manufacturer. The objective is to determine the optimal number of multi-skilled labourers in the facility and quantify the line balancing, lead time, and productivity benefits from the introduction of the multi-skilled labourer(s). Based on material data gathered from Moghadam (2014) and the results generated from discrete and continuous (hybrid) simulation, multi-skilled labour will be evaluated on a cost-benefits basis.

5.3 Methodology

The methods applied in this research are presented in this section and summarized in Figure 5.1 below. The plant layout containing the number of stations and its precedence is modelled along with the respective number of resources (i.e. fixed labour) for each. Man-hour requirements are added in the model through a labour database that calculates the labour requirements dependent upon project's attributes such as size, number of elements, etc. Hourly cost for direct (fixed and multi-skilled labour) and indirect (factory overhead such as utilities, space rental, etc.) labour are added in the model so a financial assessment can be performed. A comparison between the current and potential improvements in time and cost are important criterion to determine a good trade-off for the use of multi-skilled labour in the production line while space constraints (e.g. maximum number of labourers that can fit in a station) help determine the feasibility of each scenario. The shift length determines how often multi-skilled labourers are allowed to move between stations and how long they will work in there. Moreover, the research is based on two assumptions: (1) the productivity of fixed and multi-skilled labour is the same, and (2) there is no space constraint between stations (i.e. stations will not stop work due to queue length ahead).

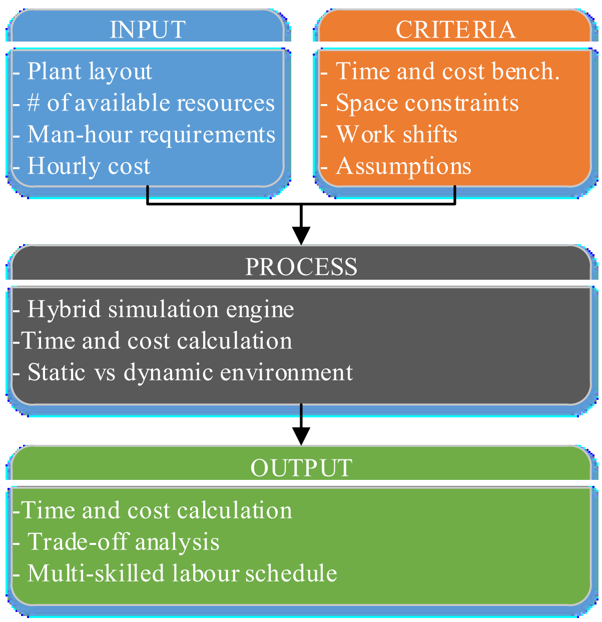


Figure 5.1 Methods overview

With all this information at hand, man-hour requirements for each project are added to the simulation engine, which consists of a combined discrete and continuous environment (hybrid). The simulation model is developed using Simphony.NET as per the given layout with projects being modelled as entities in a discrete environment and fixed labour (worker which will not leave their stations) being modelled as discrete resources. Each project (entity in the project) enters the simulation model with parameters referring to each man-hour requirement for the modelled stations. These man-hour requirements are turned into stocks in the continuous environment and the multi-skilled labour is assigned to the station that satisfies Equation 5.1 below.

$$Station_i = Max\left(\frac{Stock_i^1}{f_i^1+m_i^1} + \cdots + \frac{Stock_i^n}{f_i^n+m_i^n}\right) \qquad 5.1$$

where:

$Station_i$: Station where the multi-skilled labourer will work at period *i*

$Stock_i^1$: Stock of station n at period *i*

f_i^1: Fixed labour of station n at period *i*

m_i^1: Multi-skilled labour of station *n* at period *i*

As per Equation 5.1, the multi-skilled labourer is assigned to the station with the highest amount of man-hours left taking in consideration the labour assigned (fixed and multi-skilled) at the given time assuming fixed and multi-skilled labour have the same productivity. In order to make scheduling of multi-skilled labour a realistic effort for modular contractors, Equation 5.1 is applied to each available multi-skilled labourer at the beginning the production line's shift (i.e., where each multi-skilled labourer should work for the given shift). Moreover, the logic for the allocation of multi-skilled labour is also dependent of the context provided in the given layout, such as space constraints, and which stations should allow for the use of multi-skilled labour as will be discussed in the next section.

The total cost is calculated as per Equations 5.2, 5.3 and 5.4 below taking in consideration the direct and indirect costs incurred from the use of multi-skilled labour in the production line. Due to its extra training and expertise, it is assumed multi-skilled labour has a higher hourly rate paid by the employer. As observed in the equations below, the total cost consists of the sum of direct and indirect cost, which is represented by the product of man-hours spent by fixed and multi-skilled and its unit rates and factory's overhead represented by the product of total production time and factory's hourly overhead rate.

$$Total\ Cost = Direct\ Cost + Indirect\ Cost \qquad 5.1$$

$$Direct\ Cost = MHr_f \times \$_f + MHr_m \times \$_m \qquad 5.2$$

$$Indirect\ Cost = T_m \times \$_i \qquad 5.3$$

where:

$Total\ Cost$: Total cost in production line

$Direct\ Cost$: Cost incurred from labour in all stations

$Indirect\ Cost$: Cost incurred from overhead and fixed cost from the factory

MHr_f: Total man-hours worked by fixed labour in all stations

$\$_f$: Hourly rate for fixed labour

MHr_m: Total man-hours worked by multi-skilled labour in all stations

$\$_m$: Hourly rate for multi-skilled labour

T_m: Total simulation time

$\$_i$: Hourly rate for factory's overhead

By collecting station times and total cost, different scenarios are calculated by changing the number of available multi-skilled labourers in the simulated environment starting from a static (no multi-skilled labour) and moving to a dynamic (use of multi-skilled labour) environment. After simulation is performed, the results are analyzed as a trade-off between the overall cost and time spent to manufacture all simulated projects. After selecting the best scenario, a schedule is provided for each multi-skilled labourer indicating which station he should be at during each worked shift. The presented methods will be better described in the next section through a case study.

5.4 Case study

The case study consists of a wood-frame modular facility in Edmonton, Alberta, Canada with labour intensive operations that rely on a few cranes and traditional construction equipment. The introduction of multi-skilled labour can represent a significant improvement in production lines such as this in which workers are the main driver of production. Figure 5.2 demonstrates the addressed layout in this paper with its stations and respective fixed resources. The first identified bottleneck in the addressed layout is Station 2 since, in order to begin, both Stations 1a and 1b need to be completed (i.e., if one finishes before the other, it will remain idle while Station 2 will also be waiting for work commencement). The other identified bottleneck is in Station 3 due to idleness in the preceding Stations 1c and 2 when one finishes before the other, which potentially affects the remaining production. Hence, this research will evaluate the impact of multi-skilled labourers at the wall, floor, and roof framing stations (1a, 1b and 1c, respectively), which are considered the bottlenecks of the production line as highlighted in Figure 5.2 below.

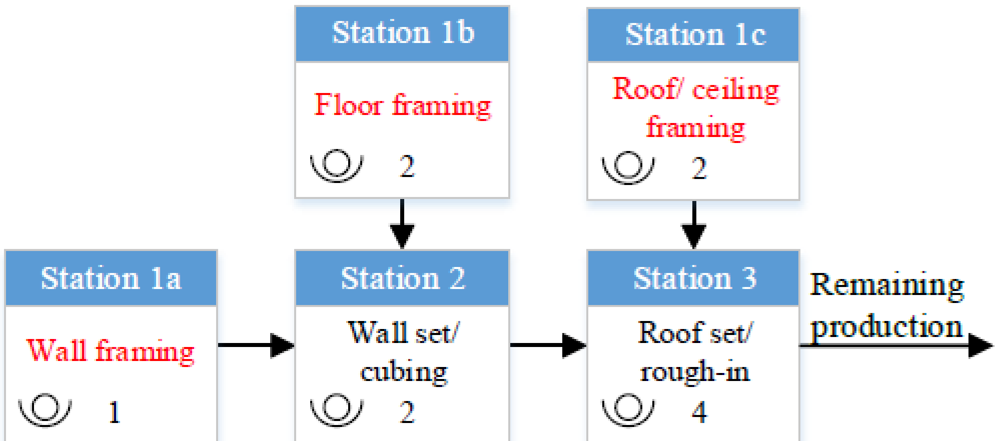


Figure 5.2 Addressed layout in the case study

The simulation model is first run with a scenario in which no multi-skilled labours are used (static scenario) in order to determine the current state of the production facility as a benchmark cost and time-wise. After the benchmark is established, the simulation is re-run under different (dynamic) scenarios in which fixed labour is substituted by multi-skilled labour (i.e. Station 1c will be given one fixed and multi-skilled labour) and multi-skilled labourers are added in the production line. Based on the given layout and resources allocated, the logic for allocation of multi-skilled labour is demonstrated in Figure 5.3 below. As demonstrated in Figure 5.3, the roof station is given preference for the use of multi-skilled labour if the walls and floors of the project are already finished. If that is not the case, the work to be performed in the addressed stations (wall, floor and roof stations) are compared and the multi-skilled labourer will help the station that satisfies Equation 5.1 at the given time. This analysis is simulated for every multi-skilled labourer after the end of each shift. In the case of this particular case study facility, workers work a total of 8 hours a day divided into 4-hour shifts.

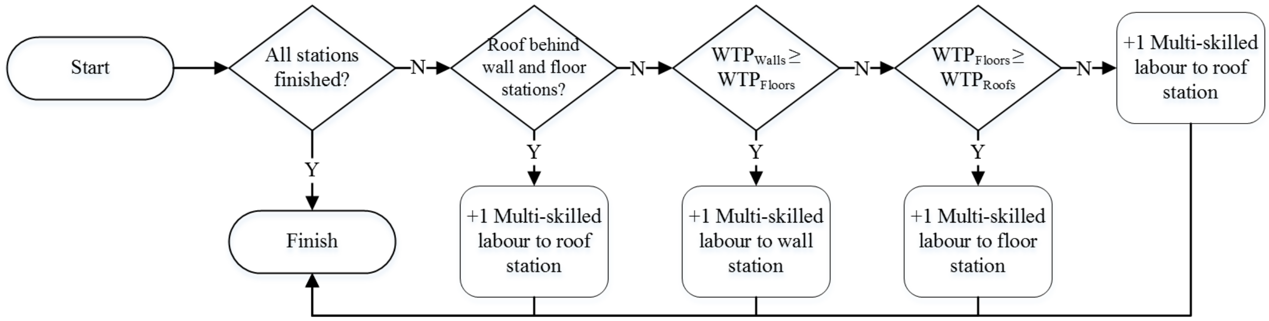


Figure 5.3 Proposed logic for multi-skilled labour

Man-hour requirements for each station and project are added in the simulation model from a labour database containing time studies performed as per statistical analysis in the case study manufacturing facility by Moghadam (2013). The projects, and their man-hour requirements for each station are described in Table 5.1 below, which consists of a combination of residential, commercial, and office spaces built using wood-frame structural members. The order in which these projects will be manufactured, and their impact in balancing the production, will not be addressed in this research as this decision is not taken by the production team but rather based on commercial and client deadline requirements.

Table 5.1 Project addressed in case study

ID	Total Area (m^2)	Total man-hours per station				
		1a	1b	1c	2	3
420A	65.59	18	17	16	18	20
420B	64.85	16	16	18	16	20
432	147.16	24	22	46	32	32
433	122.63	21	18	32	31	28
434	147.16	22	20	54	30	32
442A	61.78	10	14	13	12	16
442B	61.78	12	14	14	16	12
443A	61.78	7	14	12	12	12
443B	61.78	11	12	15	15	12
431A	61.32	12	14	12	12	12
431B	56.58	14	11	26	11	12
SUM	**912.41**	**167**	**172**	**258**	**205**	**208**

As observed in Table 5.1, a total of 11 modules from 7 different projects (e.g., project 420 consists of modules A and B) are addressed in the simulation model. A large discrepancy can be observed between the man-hour requirements of different modules due to the high variability of projects attributes (number of openings, walls, etc.) thus producing an unbalanced production line with significant idle time between stations. Moreover, additional input data such as the hourly cost for fixed labour, multi-skilled labour, factory overhead, and the maximum number of workers allowed to work at the stations are displayed in Table 5.2. Since no multi-skilled labour is currently used on the production line, there is no evidence of its actual cost. Hence, the multi-skilled labour rate is assumed to be the same initially and, in subsequent simulations, possible additional labour costs (e.g., extra training, expertise, etc.) are addressed in increments of 20% to the hourly rate until it reaches double the fixed labour cost (i.e., $50/ hr). Also shown in Table 5.2, the factory overhead cost includes all stations depicted in Figure 5.2 while the maximum number of workers to work in the multi-skilled stations is 7 due to space constraints (i.e., not enough space for more workers to work in these stations). The results of the analysis are presented in the next section.

Table 5.2 Input data used in case study

Hourly Rates	
Cost for fixed labour	$25 /hr
Base cost for multi-skilled labour	$25 /hr
Increments for multi-skilled labour	Base cost + 20%
Factory overhead	$750/ hr
Max number of workers allowed	7 workers

5.5 Model validation and results

This section presents the results of the case study while providing insightful information regarding the impact of multi-skilled labour given the current factory layout. Initially, the simulation will run with the current factory state in which no multi-skilled labour is used as per Figure 5.2. Results are then compared for model validation and alternative scenarios with the use of multi-skilled labour are simulated for further analysis. Finally, a scenario will be selected for further detailing and a schedule for multi-skilled workers will be developed based on simulation results. For the validation process, the developed model simulated the production line under the same conditions as the model used by Moghadam (2013) to validate the productivity of the modular facility being studied. In this previous work, a simulation model was developed to validate the current production time (without multi-skilled labour) through comparing the model and actual production. The results of the developed model are compared with the previously validated model by the company and the results are 167.27 and 167 man-hours, respectively, with an error of less than 1%. Therefore, the developed model is validated through a comparison with previously validated models and actual results.

For the presentation of scenarios, the terminology for scenario names is SC 5-0 where the first and second number represent the number of fixed and multi-skilled labour used in the scenario, respectively. By adding multi-skilled workers and also using them to replace fixed labour, scenarios are developed respecting the maximum number of workers allowed in the stations as per Figure 5.2.

Figure 5.4 demonstrates the total time and cost of alternative scenarios against the current state (SC 5-0). As per Figure 5.4, all scenarios indicate reduction in both time and cost when using multi-skilled labour in the modular construction facility. Also, the increase in the number of workers (fixed and multi-skilled) in the scenarios presents the lowest cost, which indicates that indirect cost (i.e., facility amenities, rental, administration, etc.) is a significant portion of overall cost. The lowest total time and cost are found in scenarios SC 5-2 and SC 4-3 where 2 additional multi-skilled workers are hired, and an extra multi-skilled worker could be trained from the original staff or could be a new hire as well. Also, there is no clear evidence of the impact of an hourly rate increase, which is the premium for multi-skilled work; therefore, a more detailed analysis is required to better understand the true impact of multi-skilled labour on the overall cost of the production in the modular construction facility. Figure 5.4 demonstrates a sensitivity analysis of the scenarios with their respective number of fixed workers in each station, multi-skilled labour, total time, and the cost difference from the current baseline, which is SC 5-0 (5 fixed labourers only) as per Figure 5.2 and Equations 5.2, 5.3 and 5.4.

SC #	Fixed labour			MS Labour	Total Time (hr)	Cost difference & rate increment for multi-skilled labour					
	1a	1b	1c			+0%	+20%	+40%	+60%	+80	+100%
SC 5-0	1	2	2	0	179	0%	0%	0%	0%	0%	0%
SC 5-1	1	2	2	1	136	-25%	-25%	-25%	-24%	-24%	-24%
SC 5-2	1	2	2	2	128	-29%	-29%	-28%	-28%	-27%	-27%
SC 4-1	1	1	2	1	147	-19%	-19%	-18%	-18%	-17%	-17%
SC 4-2	1	1	2	2	139	-24%	-23%	-23%	-22%	-21%	-21%
SC 4-3	1	1	2	3	128	-29%	-29%	-28%	-27%	-26%	-26%
SC 3-1	1	1	1	1	155	-15%	-15%	-15%	-14%	-14%	-13%
SC 3-2	1	1	1	2	140	-23%	-22%	-22%	-21%	-21%	-20%
SC 3-3	1	1	1	3	132	-27%	-26%	-25%	-25%	-24%	-23%

Figure 5.4 Sensitivity analysis of the scenarios

Figure 5.4 confirms the better results of scenarios *SC 5-2* and *SC 4-3* with a cost reduction of 29% for each, while indicating that premiums on multi-skilled labour do not contribute significantly to the overall cost in the production line: there is only a 3% increase in the total cost when multi-skilled labourers earn twice as much as fixed labour workers. However, it is important to note the developed simulation addresses the production at its natural state and it does not simulate the impact of these changes during implementation stages. Hence, it is reasonable to forecast an additional cost due to the implementation of changes and adaptation of workers to new environment and workflow. Moreover, both scenarios indicate a reduction of 29% in comparison to the current production time (*SC 5-0*), the scenario against which all comparisons are being performed. Another remaining question is the impact of direct and indirect cost when addressing the use of multi-skilled labour in modular construction facilities. In order to do that, a scenario will be chosen for further analysis. Although results from both scenarios *SC 5-2* and *SC 4-3* are similar, the first scenario of those scenarios is chosen for further analysis since it provides less change in the current state of the production line (i.e., re-training currently employed labourers would not be necessary, which means the modular contractor can hire 2 additional multi-skilled workers). Figure 5.5 shows the cost breakdown between direct and indirect costs represented by the work in stations and factory overhead, respectively, while the chart on the right describes the cost contribution between fixed and multi-skilled labour for the stations being considered in this case study.

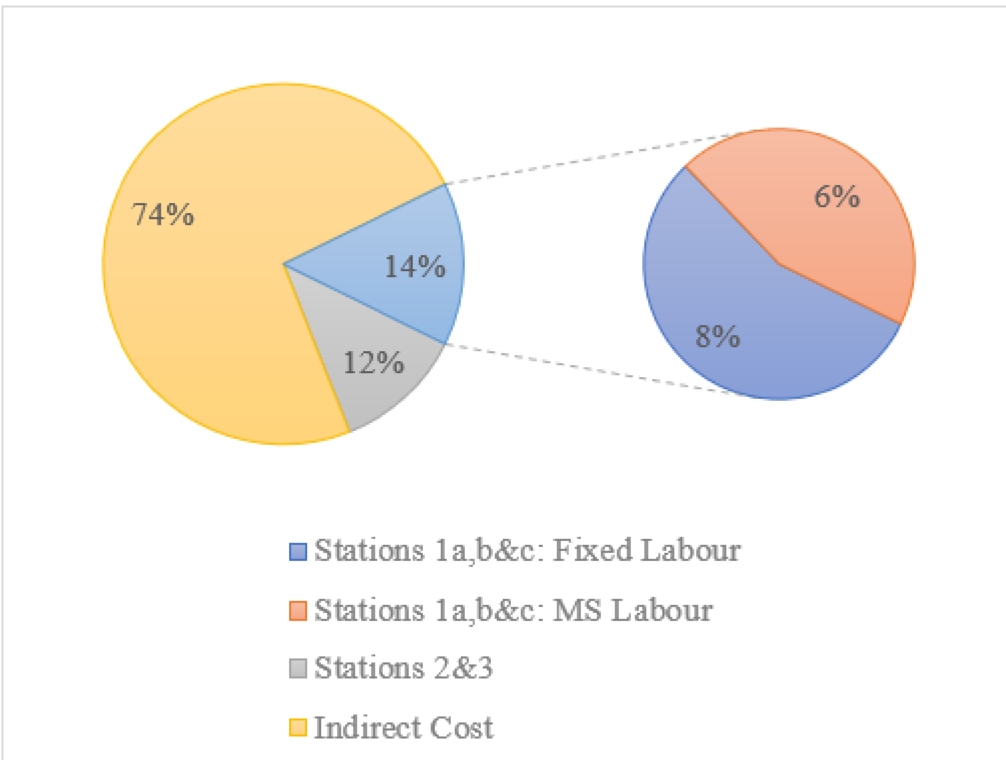


Figure 5.5 Cost breakdown of scenario 5-2

As shown in Figure 5.5, the less favorable scenario in which multi-skilled labourers are paid twice as much as fixed labourers is taken into consideration in order to provide the modular contractor a broader insight into the difficulties of involving multi-skilled labour in its production line. From the graph, it is clear the indirect cost is the highest contributor, representing almost two thirds of the overall production cost. Even considering the worst case, in which the hourly rate premium for multi-skilled labour is at the highest amount considered in this study, the use of multi-skilled labour only impacted the overall cost by 6%, where, when the multi-skilled rate is the same as the rate for fixed labour, the impact is reduced to as low as 3%. Considering the cost reduction of 29% between the current production cost and the evaluated scenario (SC 5-0 and SC 5-2, respectively), it is safe to recommend the use of multi-skilled labour in the modular construction facility. Moreover, Figure 5.5 indicates that in order to significantly reduce the overall cost, future improvement should be focused on reducing overall production time in order to minimize indirect cost that represents the factory's overhead (functioning hourly cost). To finalize the proposed work, a schedule for the proposed multi-skilled labour suggested in SC 5-2 is developed based on simulation results and the needs for multi-skilled workers at the stations as per Equation 5.1.

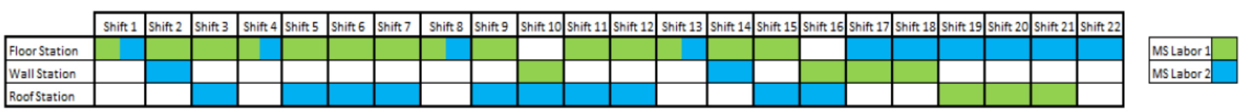


Figure 5.6 Proposed multi-skilled labour schedule for scenario 5-2

Figure 5.6 shows the schedule for SC 5-2 in which two multi-skilled labourers assist the respective stations in the plant for each 4-hour shift needed to complete the 11 simulated modules. This schedule was developed assuming 5 fixed labourers and assuming that the multi-skilled labourers are able to work freely between the floor, wall and roof stations. The schedule highlights the need for dynamic labour to balance the production lines. As variability in projects is encountered, the production rate of the lines shifts to accommodate this.

5.6 Conclusions

The research intends to address the impact of multi-skilled worker in modular construction facilities while addressing the particular context of each production line and its limitations. Through the development and validation of a hybrid (discrete and continuous event) simulation, several scenarios were developed taking into consideration the maximum number of workers allowed due to space constraints, direct cost, multi-skilled work premiums and indirect cost such as factory's overhead. Moreover, 11 modules from 7 different projects were simulated taking into consideration each module's attributes and variability. Despite what many people often assume, the addition of more workers contributes to a decrease in the overall cost and production time. It was shown here that adding 2 multi-skilled workers to work in 3 different stations as per required at the end of each work shift reduces the total production time by 29% when compared with the current production time, which uses 5 fixed labourers who only work at their respective stations.

Moreover, it is concluded that by adding 2 multi-skilled workers to the production line the overall cost is reduced by 29%, while the cost attributable to multi-skilled labour only represents 6% of the total. In fact, the main contributor for the overall cost is the indirect cost, which is responsible for almost 75% of the total thus suggesting the modular contractor develop other solutions to reduce total production time and cost. After the trade-off analysis is performed and suitable scenarios are selected, a schedule for the multi-skilled labourers is developed in order to provide better scheduling for floor managers regarding where to allocate labour resources. The information from the schedule is extracted from the simulation model and later modified to fit the manager's preference following the shift's duration at the modular facility. Although this study provides interesting insights in regards to the use of multi-skilled labour in modular construction facilities, the simulation model still has certain assumptions limiting its capacity such as: (1) adequate space to store idle panels between stations, (2) fixed and multi-skilled labourers have the same productivity rates. Moreover, this work does not consider the implementation and adaptation process of introducing the multi-skilled labour in the production line, nor integrated new projects attributes in a systematic manner for further analysis. Hence, the authors intent to explore and address these assumptions in future research.

5.7 Acknowledgements

The authors would like to acknowledge everyone at the case study company for their contributions, hard work, and for allowing us to observe their actions at the facility in order to collect the data needed for this study. We would like to specifically thank Mansooreh (Mana) Moghadam for her invaluable collaboration in this work.

Chapter 6: Manufacturing of Gable-to-Gable Roofs in an Offsite Construction Facility

6.1 Abstract

Industrialized construction employs concepts borrowed from the manufacturing industry in the production of building components. However, industrialized construction practitioners often do not apply manufacturing principles correctly and instead simply employ traditional construction methods used on jobsites to an indoor manufacturing facility without changing construction techniques. This practice is inefficient since it does not improve productivity to optimum levels. This paper presents the methods used to translate traditional construction methods into a manufacturing format in an offsite construction facility. In this research, a case study of the roof assembly line of a well-established offsite construction company is analyzed. This assembly process currently employs traditional on-site construction techniques that must be changed in order to take advantage of lean principles and utilize existing production lines. To change this process, a new gable-to-gable roof made up of two-dimensional panels, designed to be manufactured on the wall assembly line is tested. This new panelized design is tested by first developing a simulation model for both the roof assembly and wall assembly lines to provide a baseline, then future state simulation of the panelized roof is used to determine the effects that the panelized roof has on productivity. This comparative analysis will determine the production implications from transferring gable-to-gable roof construction from the roof assembly area to the same machines used in the wall assembly line. This production change resulted in the reduction of lead times for gable-to-gable roof projects, while freeing up resources for the remaining traditional roof assemblies. Improved production balancing and man-hour savings were also achieved.

6.2 Introduction

Industrialized construction is an innovative industry that utilizes techniques from the construction and manufacturing industries to produce buildings. Transferring construction operations to off-site facilities has been growing in popularity due to significant benefits in terms of productivity, quality, efficiency, lower labour requirements on-site, and safety (Modular Building Institute, 2010). The construction methods used to build residential buildings have the potential to be innovated, and offsite, modular, and industrialized construction techniques have been regarded as possible solutions in terms of increasing productivity and reducing environmental impacts. Productivity benefits are directly attributable to the concepts and knowledge borrowed from the manufacturing industry over the past decades (Zhang et al., 2016). Panelized construction is a popular offsite construction method in which building components are constructed as two-dimensional panels, then the panels are assembled into a volumetric unit either in the factory or on-site. This approach transfers most construction activities traditionally performed on the site into production tasks performed in a factory (Liu et al., 2015).

Modelling industrialized offsite construction after manufacturing has proven difficult due to the belief that construction is fundamentally different than manufacturing because each project is different from the next. The large scale of the projects, the specific precedence between activities, and the complexity and variation in structure types have been identified as the barriers to truly modelling construction after manufacturing (Zhang et al., 2015). By understanding these challenges, utilizing lean principles, and capitalizing on modern manufacturing technologies, offsite construction companies can bridge the gap between “stick build under a roof” and construction manufacturing.

Lean manufacturing principles were first applied to the construction industry in Koskela's (1992) paper in which concepts from the Toyota Production System were adapted to present an initial set of principles for lean construction. This new production philosophy aimed to eliminate or reduce non-value-added activities and increase the efficiency of value-added activities. More recent studies have applied lean techniques such as value stream mapping, 5S, facility layout, continuous improvement, and process mapping to offsite construction facilities resulting in numerous production benefits (Yu et al., 2013; Ritter et al., 2016; Brown et al., 2019). These studies have successfully used lean with computer simulation in offsite construction facilities to further translate traditional assembly methods into methods that better reflect a true manufacturing process.

Moghadam's (2014) doctoral thesis adapted current lean concepts to meet the production efficiency requirements of a modular construction manufacturer. Bottlenecks were identified through current state analysis of the facility, then "lean-modular" strategies were applied to these areas to meet efficiency requirements. The current state was analyzed to identify non-value-added activities and to expose bottlenecks, then future-state modelling was used to show the improved production efficiency. A combination of lean and simulation was used to efficiently evaluate potential scenarios and to find the near-optimum results for workflow balancing. Ritter et al. (2016) and Brown et al. (2019) performed similar studies of production improvements in offsite construction facilities using lean and simulation. Manual observation was used to collect data from the facility and identify potential process improvements, then discrete event simulation was used to quantify the productivity gains and aided management in decision making. The process improvements tested were presented to management and used to further refine the production lines to better reflect a construction manufacturing process. Altaf (2016) developed a framework to simulate the wall panel production process as well as a simulation–based optimization model for production scheduling. This framework aided in leveling the production process and improving the productivity of the prefabrication of panelized homes.

Production line balancing is vital to the success of prefabricated home construction since numerous production lines are utilized in order to manufacture the components required for the final assembly of the house. The manufacturing process for these components must be complete at close to the same time to ensure high productivity and as little idle time as possible (Boysen et al., 2006).

In each of these cases, computer simulation plays an important role in understanding the effect of process improvements on production. First, current state simulation is done to establish a baseline. In order to gather information to establish the baseline, observations of the construction process and activity timings must be gathered and analyzed. Next, lean and manufacturing principles are applied to develop potential process improvements within the manufacturing facility and tested in a simulated environment. In this environment, discrete event simulation (DES) is used as a cost-effective method to test these changes before they impact the factory floor and to provide a decision support tool that allows management to precisely examine different approaches in order to complete a project in the most efficient manner (Altaf et al., 2015).

The complexities of roof assemblies of residential homes have hindered the process of applying manufacturing principles to their construction. The translation of roof production into a panelized process would aid in bridging this gap, making the construction methods used in offsite facilities more closely parallel manufacturing processes. This study quantifies the lead time, man-hour and production balancing benefits found when moving from traditional roof construction techniques to a manufacturing operation by utilizing existing machinery to produce a new panelized roof design for gable-to-gable roofs. By applying the production techniques and technologies used in the wall production line to the construction process of panelized roof design, it is possible to improve the productivity of roof construction to achieve significant benefits in terms of time, labour, and reduced waste.

6.2.1 Previous panelized roof construction

Altaf et al. (2018b) performed a case study of a prefabricated panelized roof system for a simple gable-to-gable roof for a single-family home. The roof design consisted of two horizontal prefabricated roof panels, multiple girder trusses to hold the panels in place, a roof cap for the roof peak, ceiling panels for drywall backing, and a platform for site installation (Figure 6.1). Additionally, the roof included a front roof panel and veranda roof, which were built traditionally. It was found that the panelized roof system resulted in a 5.7% increase in site installation time and a reduction of 29% in cycle time to produce the panelized roof system. This roof system was able to be loaded onto a single flatbed trailer, compared to the four trailers required for traditional volumetric construction (Figure 6.2). Although this case study shows promising results, numerous problems were encountered. The roof panels could not be produced on the automated wall line due to their size, meaning manual labour was required to construct these panels. The design time for each panel was long and required approval by an engineer for every roof. This solution would only be applicable in the case of a gable-to-gable roof, which is the easiest to build traditionally. Hipped roofs and hip-gable roofs do not fit this design. The time required to complete on-site tasks was longer for both the crane and the labourers, making panelized roof systems less economical because site labour is more expensive than factory labour. Although drawbacks were encountered in the case study by Altaf et al. (2018b), this paper investigates how panelized roof construction has the potential to be efficient and economical if the aforementioned problems are addressed. This research aims to resolve the limitations caused by manual panelized roof production by utilizing existing production lines to reduce lead times and man-hour requirements, while balancing production for gable-to-gable roof production.

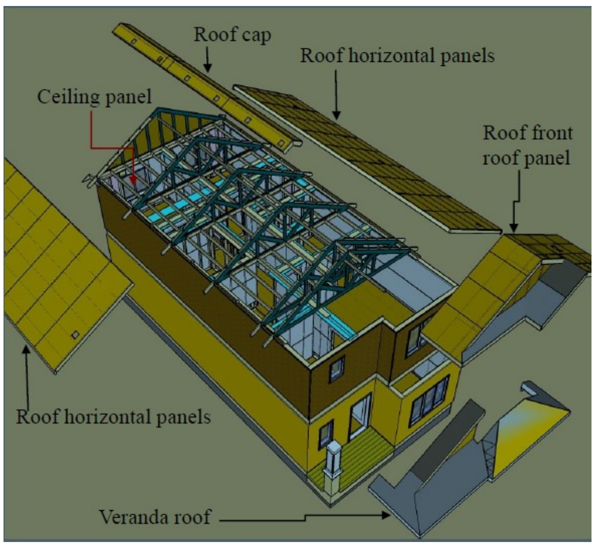


Figure 6.1 Panelized roof design (Altaf et al., 2018b)

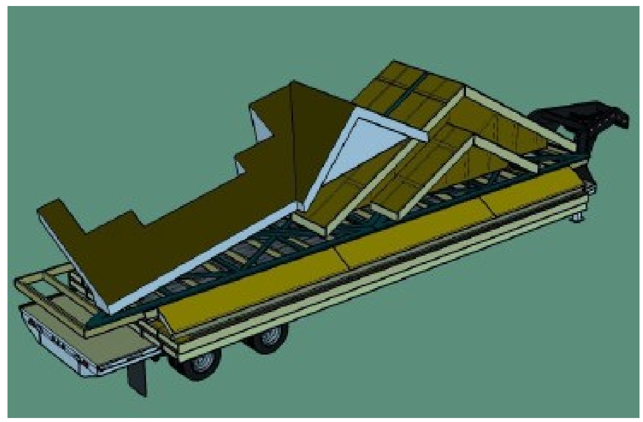


Figure 6.2 Single trailer for panelized roof system (Altaf et al., 2018b)

6.3 Methodology

The data for this study was collected through both manual observation and analysis of video recordings. 14 roof assemblies were observed from start to finish; these included roofs for single family detached homes, single family attached homes, and townhomes. 6 of these roof assemblies are simple gable-to-gable roofs that are compatible with the panelized roof design. Figure 6.3 describes the overall methodology used for this study in which MPDM is used to determine productivities for each activity, which are then inputted into a computer simulation model and validated by comparing the results to actual man-hour data. Further details are provided in this section.

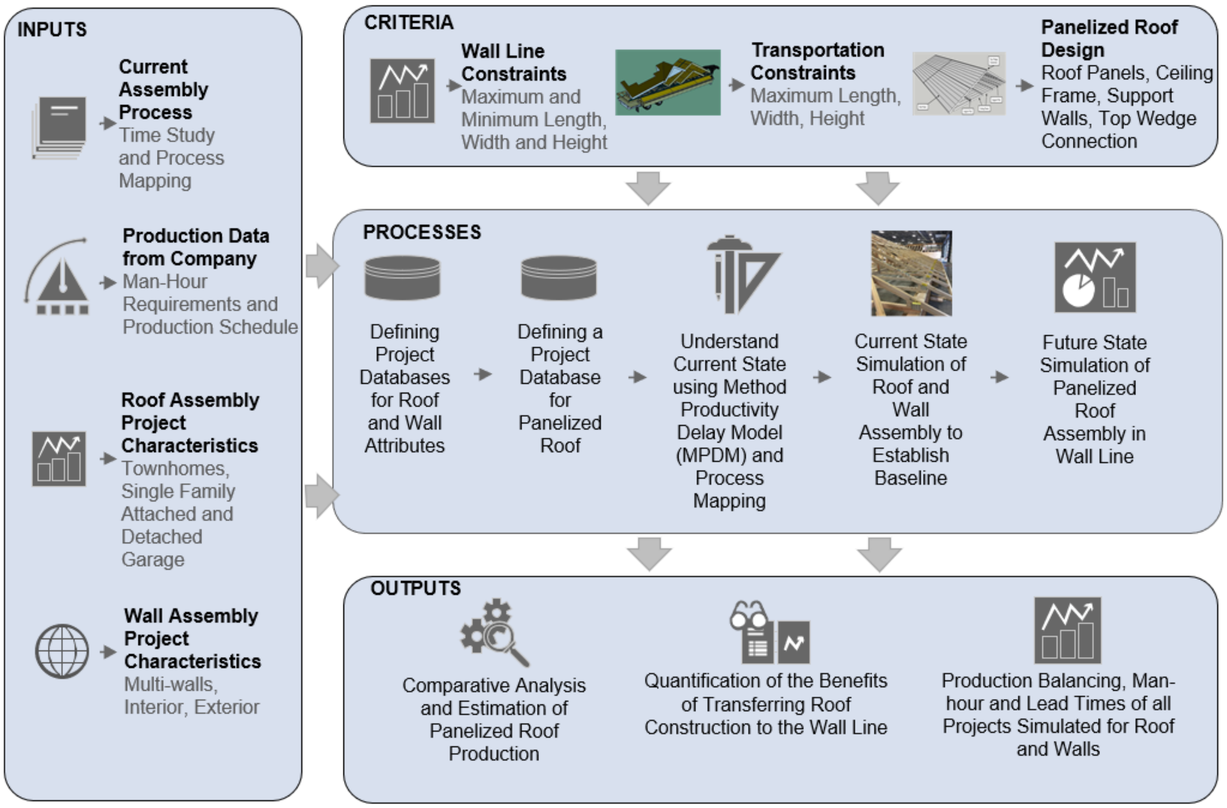


Figure 6.3 Methodology diagram

6.3.1 Current assembly process

In order to increase the production capacity of roof assemblies in the manufacturing facility without increasing the size of facility, the current construction process must be industrialized. The current roof assembly process employs traditional on-site construction methods inside the manufacturing facility. Roof construction is entirely manual with some assistance from overhead cranes. The overall assembly method starts with unloading trusses into the facility, then standing the gables faces and roof trusses, followed by bracing. Next, the roof is sheeted, papered, and then loaded onto trailers for shipment to site. A detailed breakdown of each step of the current state roof assembly process is shown in Appendix A.

6.3.2 Method productivity delay model (MPDM)

The Method Productivity Delay Model (MPDM) (Adrian and Boyer, 1976) is used to measure and predict productivity. This method is used to combine the time study and productivity measurement for the roof assembly. The results from this analytical method are used to determine production rates for each activity in the current state roof assembly process. In addition to providing a measure of productivity, this method is used to indicate the major sources of delays and their relative contribution to the lack of productivity (Dozzi and AbouRizk, 2011). The MPDM consists of five major phases. The first phase is the identification of the production unit and production cycle. For example, a finished roof panel was chosen as the production unit for the lifting panel activity and the production cycle is defined from the lifting to the securing of a single roof panel onto the truck. The second phase is the identification of the lead resource. For example, the overhead crane was the leading resource since operations cannot continue if the crane breaks down or is unavailable. The third phase is the identification of delay types that may be encountered; four general delays have been defined in Table 6.1 that may be encountered during roof assembly.

Table 6.1 Definition of delay types

Delay ID	Delay Type	Description
1	Equipment	Equipment is busy; cranes, trucks, or roof jigs
2	Labour	Labour is needed elsewhere during an activity
3	Material	Material must be modified or redone in order to proceed with task
4	Management	Plans must be reviewed with drafter or production manager

The fourth phase is data collection, which is the observation of each production unit and cycle made either in person or by manual analysis of videos. The occurrence and type of delays are manually recorded by the observer during the production cycles. The fifth phase is data processing and model analysis. In this phase, delay durations, productivity, variability, and likelihood of delay occurrences are calculated. Equations 6.1 to 6.4 are used to calculate durations and the likelihood of each type of delay.

$$ADPO_{Delay\ ID} = \frac{\left(\sum_{cycle=1}^{n} DD\right)_{Delay\ ID}}{(DO)_{Delay\ ID}} \quad 6.1$$

$$LO_{Delay\ ID} = \frac{\left(\sum_{cycle=1}^{n} DD\right)_{Delay\ ID}}{n_{total}} \quad 6.2$$

$$DPC_{Delay\ ID} = (ADPO_{Delay\ ID}) \times (\ LO_{Delay\ ID}) \quad 6.3$$

$$DF_{Delay\ ID} = (DPC_{Delay\ ID}) \times (\ ACT) \quad 6.4$$

where:

ADPO = average delay per occurrence for each delay type

LO = likelihood of occurrence for each delay type

DPC = delay per cycle for each delay type

DF = delay factor for each delay type

DD = delay duration for each delay type

DO = delay occurrences for each delay type

n_{total} = total number of cycles

ACT = average cycle time

Equations 6.5 and 6.6 are used to calculate the ideal and overall method productivity of the roof assembly process, respectively. The ideal productivity provides an initial value that will be used to determine productivities in the simulation model.

$$IP = \frac{3600}{ANDCT} \quad 6.5$$

$$OMP = IP * \left(1 - \sum_{1}^{4} DF_{Delay\ ID}\right) \quad 6.6$$

where:

IP = ideal productivity

OMP = overall method productivity

ANDCT = average non-delay cycle time

Equations 6.7 and 6.8 are used to calculate the cycle variability in the roof assembly process. The higher the ideal and overall cycle variability, the less dependable the productivity prediction will be (Adrian and Boyer, 1976).

$$ICV = (\textstyle\sum_{1}^{n}(NDCT_{Cycle} - ANDCT)/\ n_{nondelay}\ )/\ ANDCT \quad 6.7$$

$$OCV = (\textstyle\sum_{cycle=1}^{n}(CT_{Cycle} - ACT)/\ n_{total})/\ ACT \quad 6.8$$

where:

ICV = ideal cycle variability

OCV = overall cycle variability

NDCT = non-delay cycle time

$n_{non\text{-}delay}$ = total number of non-delay cycles

CT = cycle time for each cycle

6.3.3 Roof assembly current state simulation model

The current state roof assembly simulation model was developed through discrete event simulation in Simphony.NET, a program developed by AbouRizk and Mohamed (2000). The current state simulation model is shown in Figure 6.4 and follows the logic shown in Figure 6.5.

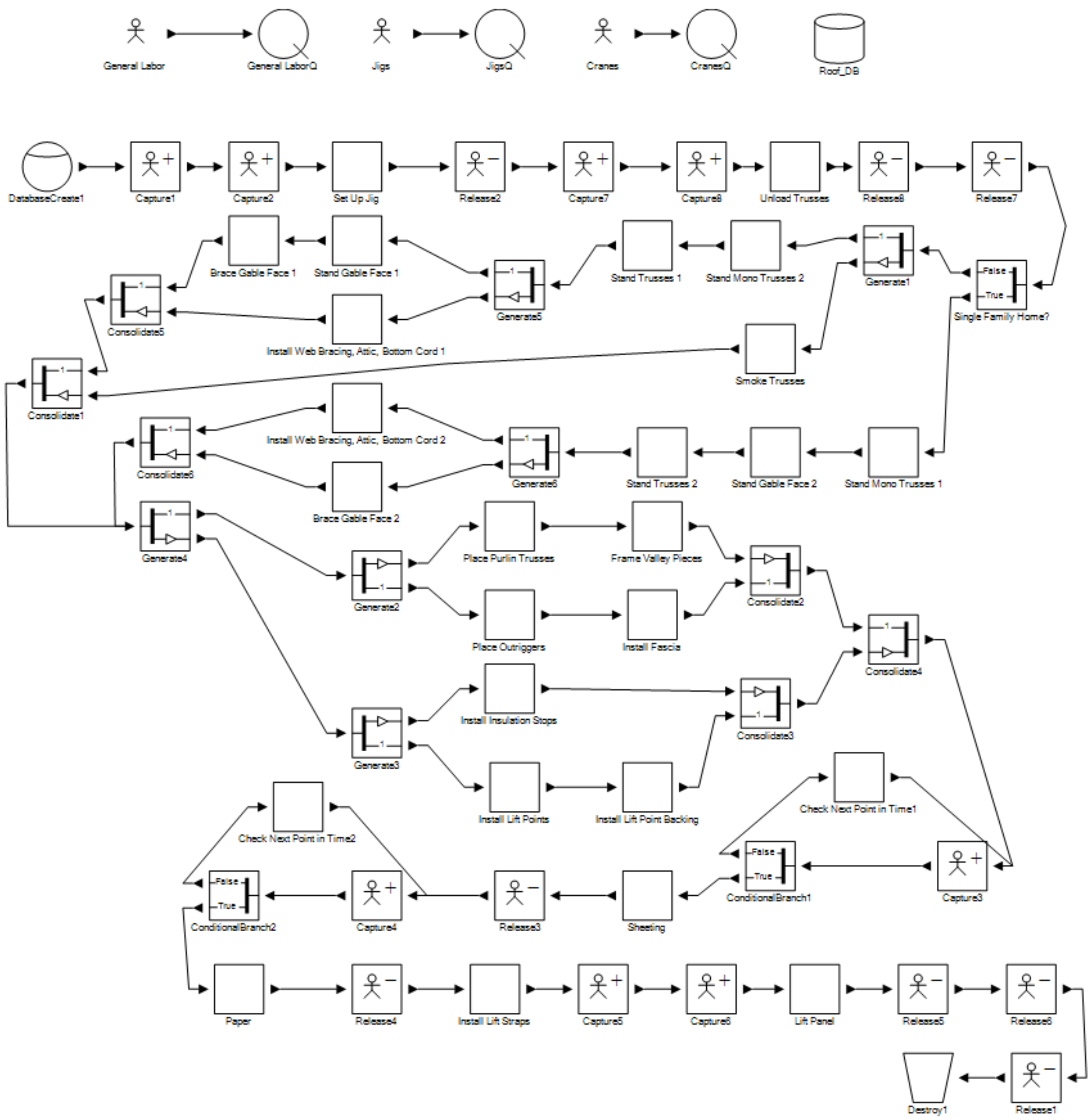


Figure 6.4 Current state roof simulation model

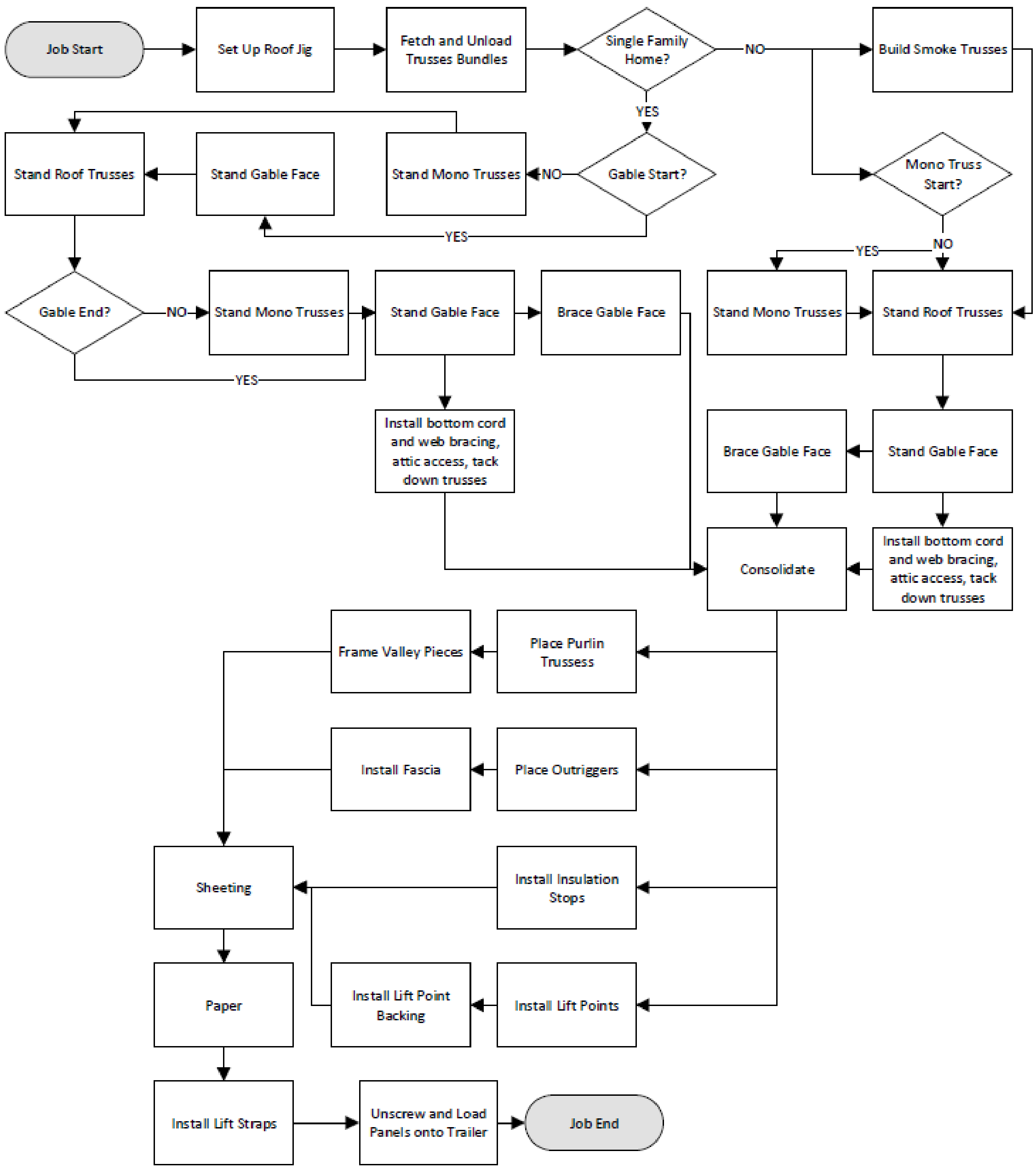


Figure 6.5 Current state roof assembly process flow diagram

The duration of each activity is represented by a triangular distribution and is defined in Equation 6.9. The 95% confidence interval for the student t-distribution around the productivities found from the Method Productivity Delay Model is defined in Equation 6.10. The student t-distribution was chosen because the sample size was less than 20 in all cases. The assumption used for this model is no specialized labour (i.e., general labourers are able to do every task) and job priority is first come first serve.

$$triangular(a, \bar{x}, b) \qquad 6.9$$

$$\bar{x} \pm t_{n-1}\frac{s}{\sqrt{n}} \qquad 6.10$$

where:

$\bar{x}$ = Population average productivity

t_{n-1} = t-distribution value for 95% confidence interval

s = standard deviation

n = sample size

a = $\bar{x} - t_{n-1}\frac{s}{\sqrt{n}}$

b = $\bar{x} + t_{n-1}\frac{s}{\sqrt{n}}$

A Microsoft Access database containing all characteristics of the 14 simulated roof projects is used to generate the attributes for the model. Every attribute is multiplied by the corresponding productivity of that activity to get duration. The simulation model focuses on single family homes with attached or detached garages and townhomes (custom homes are not considered). In the simulation model, projects are released in the order they are listed in the database and the lead time for a project begins once it starts the first task, which is setting up the roof jig. If a single-family home is being produced, one jig will be captured, if a townhome is being produced then two jigs are captured. Once the project has been loaded on flatbed trailers the lead time ends and the jig will be released to allow the next project to begin. For the sheeting and paper activities, a range of general labourers are captured. If a general labourer is available, it is captured and allocated to these tasks. If no labourers are available, the simulation model keeps checking the next point in time until one becomes available. This process continues until a maximum of four labours are working on these together or the task is completed. For the simulation model validation, man-hour requirements for each project from the simulation results were compared with actual production data taken from the company database. Equation 6.11 was used to determine the man-hours required for each project based on the duration found from the simulation. Ten general labourers were available in the simulation model with an average utilization of 67.1%. The average percent error between the company actual man-hour data and simulated results is 4.82%. Therefore, the developed model is validated through a comparison between simulation results and actual production data. The simulation results and validation are shown in Table 6.2.

$$SMH = (T \times N \times U)/60 \qquad 6.11$$

where:

SMH = simulated man-hours

T = simulation duration (min)

N = number of general labourers

U = average utilization of general labourers

Table 6.2 Roof simulation results and validation

Job number	Company man-hours	Simulation duration (min)	Simulation man-hours	Error
GLR-11-001-006	330.25	3018.21	337.53	2.21%
20MCR-19-006	87.5	749.02	83.76	4.27%
20LAG-19-0007	91.5	843.98	94.38	3.15%
TWB-06-020-025	173.75	1517.5	169.71	2.33%
10WSM-19-0019	97.5	939.06	105.02	7.71%
10WSM-19-0013	105	974.64	109.00	3.81%
20LAG-19-0003	82.5	780.6	87.30	5.81%
20LAG-19-0004	86	818.04	91.48	6.38%
TWB-03-030-034	246.5	2025.25	226.49	8.12%
TWB-04-008-013	254.2	2321.1	259.58	2.12%
20GRH-19-0008	92	885.22	99.00	7.61%
20GRH-19-0002	98	909.47	101.71	3.78%
20GRH-18-0055	83.5	795.59	88.97	6.56%
20MCR-18-0006	84.5	783.09	87.58	3.64%
			Average:	**4.82%**

6.3.4 Panelized roof design

The panelized roof design focuses on constructability. It consists of roof panels, ceiling frames, support walls, and a top wedge connection. Figure 6.6 shows the difference between the panelized roof design and a traditional roof. This design is for gable-to-gable single family home which fits 6 of the 14 roof assembly projects analyzed in this study. The roof panels and ceiling frames are designed to be manufactured on the wall production line. Each roof panel is made from 2×6 lumber with 600 mm spacing and OSB on one side. The ceiling frame consists of 2×10 outside studs and 2×6 inside studs with 600 mm spacing. The total area of the ceiling frames must equal the area of the second floor. The support walls are produced manually in the manufacturing facility because the height of the support walls is less than the minimum wall height that the wall production line can accommodate. The support walls are made of 2×6 lumber with 600 mm spacing. Figure 6.7 shows the generic width of the roof panels and height of the support walls. In Figure 6.7, the roof slope and roof span (S) are known from the architectural drawings. The top wedge connection is a V-shaped piece of glulam made to fit at the peak of the roof through the use of a CNC machine. Table 6.3 describes the constraints that the panelized roof design must adhere to.

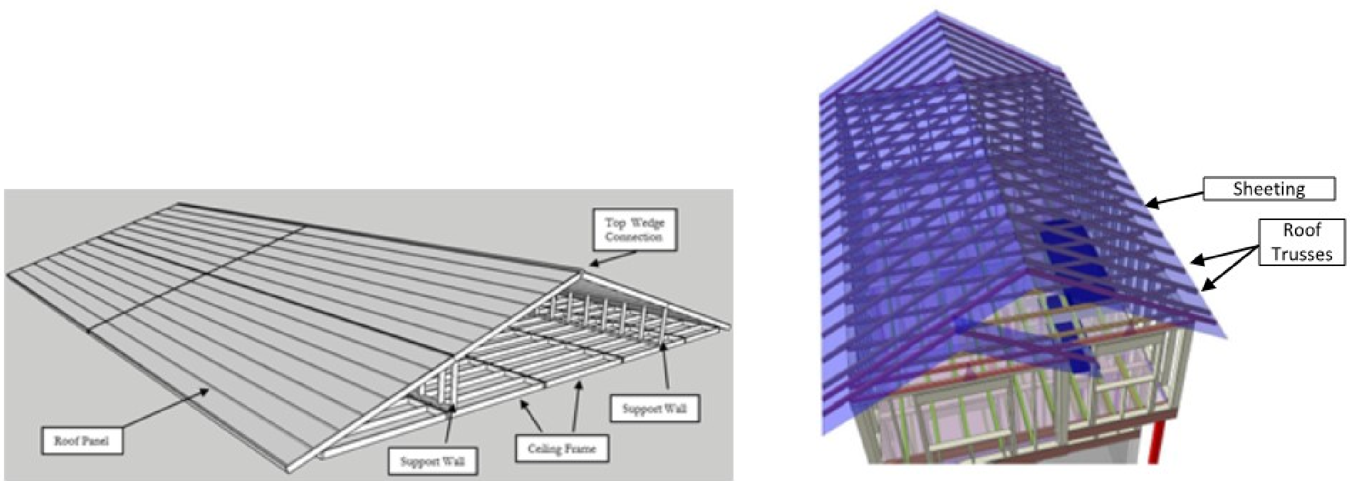


Figure 6.6 Panelized roof design vs. traditional roof

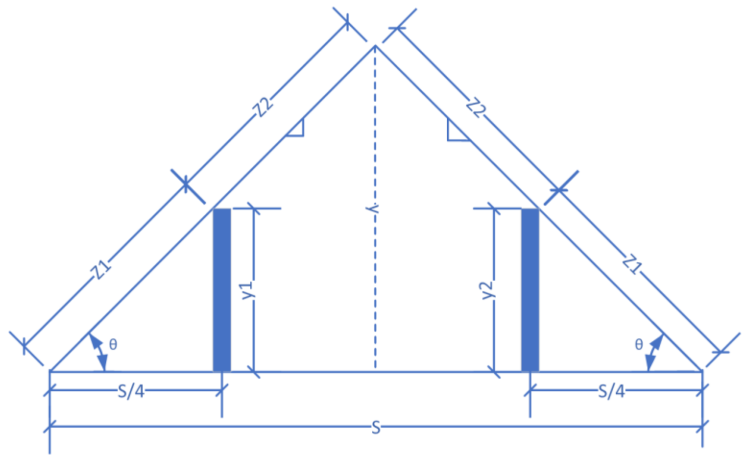


Figure 6.7 Support wall height and panel width calculation diagram

Table 6.3 Wall production line and transportation constraints

	Wall production line		Transportation	
	mm	feet	mm	feet
Maximum height	3200	10.5	2400	8
Maximum length	12200	40	14600	48
Minimum height	1600	5.25	n/a	n/a
Minimum length	1200	4	n/a	n/a

The roof panels and ceiling panels are subject to the height and length constraints of the wall production line and the flatbed trailer used to transport the components to site. The support walls are only subject to the transportation constraints. The lead times for the roof panels and ceiling frames are determined from the simulation results because these components are manufactured on the wall production line. For the support walls, the time required to manually frame the support walls is modified based on Equations 6.12 and 6.13, which were developed and validated in

Moghadam's (2014) doctoral dissertation for the framing of exterior walls. This can be used to estimate the support wall man-hour requirements because the exterior walls and the support walls are framed in a similar manner, with the only major difference being the reduced height of the support walls. In this analysis, the total number of wall components is equal to the number of studs because there are no exterior window or door openings.

$$CL(E) = (\alpha \times C) + (\beta \times L) \quad 6.12$$

where:

CL(E) = wall converted length (ft)

C = total number of wall components

L = linear length of wall (ft)

α = 0.87 = wall converting coefficient

β = 0.2 = wall converting coefficient

$$TMhr = (\alpha \times CL(E)) - \beta \quad 6.13$$

where:

TMhr = total man-hour requirement (mhr)

CL(E) = wall converted length (ft)

C = total number of wall components

α = 2.7 = productivity rate (mhr/C)

β = 47.2 = Statistical Constant

6.3.5 Wall assembly current state simulation model

The wall assembly current state simulation model consists of composite elements that represent each station in the production process (Figure 6.8). Within each composite element are numerous deterministic task elements that represent the activities and a probabilistic chance of delay for that station. In this simulation model there is specialized labour for each station, i.e., labourers cannot move in-between stations. This model was verified and validated by Altaf (2016). A quantity take-off was undertaken to gather the required attributes for the simulation model containing the relevant wall characteristic for each project. This input is then fed into the simulation model using the characteristics of each project as the attributes needed for the simulation model to determine project duration and labour productivity. The roof panels and ceiling frame of the panelized roof are designed to be manufactured on the wall assembly line. 6 gable-to-gable roofs are able to be transferred to the wall assembly line. The characteristics of each panel are entered into a separate database that the simulation model uses for its attributes. In this analysis, the simulation is run separately for the addition of each project up to the maximum of 6 roof projects added to the wall assembly line. The attributes used for the walls and panelized roof are listed in Table 6.4.

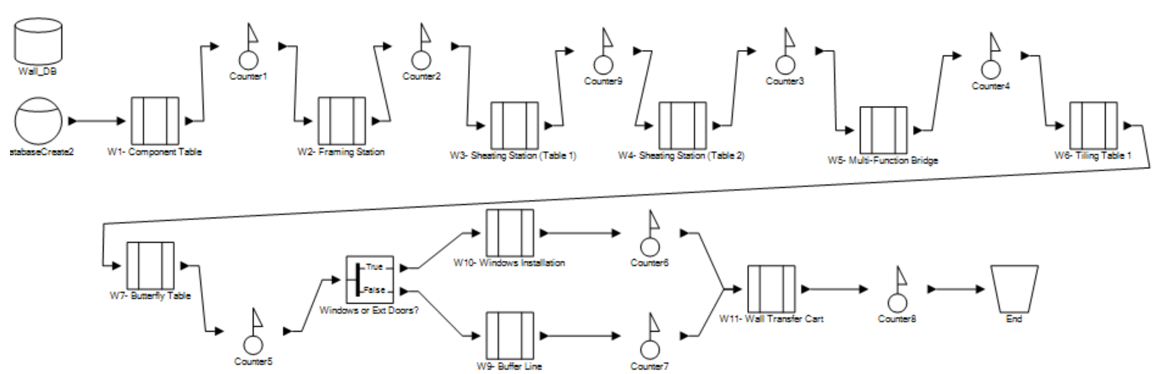


Figure 6.8 Current state wall simulation model

Table 6.4 Attributes for wall and panelized roof simulation

Characteristic	Wall	Panelized roof
Small window	✓	
Regular window	✓	
Large window	✓	
Regular door	✓	
Regular studs	✓	✓
Garage door	✓	
Interior doors	✓	
Blockings	✓	
OSB sheets	✓	✓
Corner components	✓	
Intersection components	✓	
Cut zones	✓	✓
OSB nail lines	✓	✓
OSB nails	✓	✓
Type of wall (interior or exterior)	✓	✓
Wall area	✓	✓

6.4 Results

The results were determined by running all 14 projects together in the model to simulate a production period rather than an individual assembly. The projects are all released to the model in order and the lead time for each project starts once the first task begins. Next, the gable-to-gable roofs are taken out of the roof assembly simulation model and introduced as panelized roofs into the wall assembly simulation model. The lead times for the wall and roof assemblies for the baseline (current state production) and 6 panelized roof projects are shown in Table 6.5. An analysis for lead times, man-hours and production balancing is done for every case; however, the baseline production and the 6 panelized roofs production will be the focus of the comparative analysis because they highlight the greatest difference in lead time, production balancing and man-hour requirements between the two methods. It was found that transferring roof production for the 6 gable-to-gable roof projects to the wall assembly line caused these projects to have a lead time reduction of 38% on average. When accounting for the projects transferred to the wall assembly line and the remaining projects in the roof assembly area, a reduction in lead times of 16% on average was found across all 14 roof projects. By transferring roof projects to the wall production line, the simulation shows there is a decrease in the production time for all remaining roof projects because the over utilized resources (workers and jigs) in the roof assembly area are now more available. It was found that transferring 6 of the 14 roof assemblies to the wall assembly line caused an increase in lead time of 34% on average for the walls. However, the wall production times are still less than the production times for the corresponding traditional roofs, and production times are similar for the walls and the corresponding panelized roofs. These lead time changes are highlighted in Figure 6.9 and Figure 6.10. The change in the average lead times of the two lines helps to balance production, and when cumulative lead times of the baseline and 6 panelized roof projects are compared, the difference between the wall assembly line and roof assembly is reduced on average by 20% as shown in Figure 6.9 and Figure 6.10. The total man-hours across all projects for the roof assembly were reduced by 28% and the wall assembly man-hour requirements increased by only 3%. This is due to the labour-intensive methods required for the roof assembly and the highly automated production lines in the wall assembly. By introducing automation to the numerous roof projects, a significant number of man-hours and human errors can be eliminated from the production process. While the man-hour requirements for the roof panels and ceiling frames are determined from the simulation results, the support walls man-hour requirements must be calculated based on the length of each support wall, which is shown in

Table 6.6. The production times for the three components of the panelized roof are shown in Figure 6.11.

Table 6.5 Project lead times

	Baseline (min)		Panelized roof designs (min)	
Job number	**Roof duration**	**Wall duration**	**Roof duration**	**Wall duration**
10WSM-19-0013	1004.24	291.47	1101.44	302.67
10WSM-19-0019	1062.79	337.32	1043.11	358.68
20GRH-18-0055	797.14	332.15	242.27	352.32
20LAG-19-0003	845.42	328.41	339.07	466.33
20LAG-19-0004	995.88	362.69	953.73	530.67
20LAG-19-0007	846.35	355.01	281.32	619.10
20MCR-18-0006	778.29	730.09	617.02	973.52
20MCR-19-0006	897.04	444.60	851.53	694.15
GLR-11-001-006	3435.12	1028.83	3294.58	1340.38
TWB-03-030-034	2067.30	793.04	2094.20	1122.96
TWB-04-008-013	2248.92	1017.23	2310.31	1392.74
TWB-06-020-025	1373.33	1287.70	1431.03	1647.10
20GRH-19-0002	1359.45	1397.34	1257.20	1518.02
20GRH-19-0008	1533.28	1598.69	1443.63	1613.67

= Panelized Roof Design

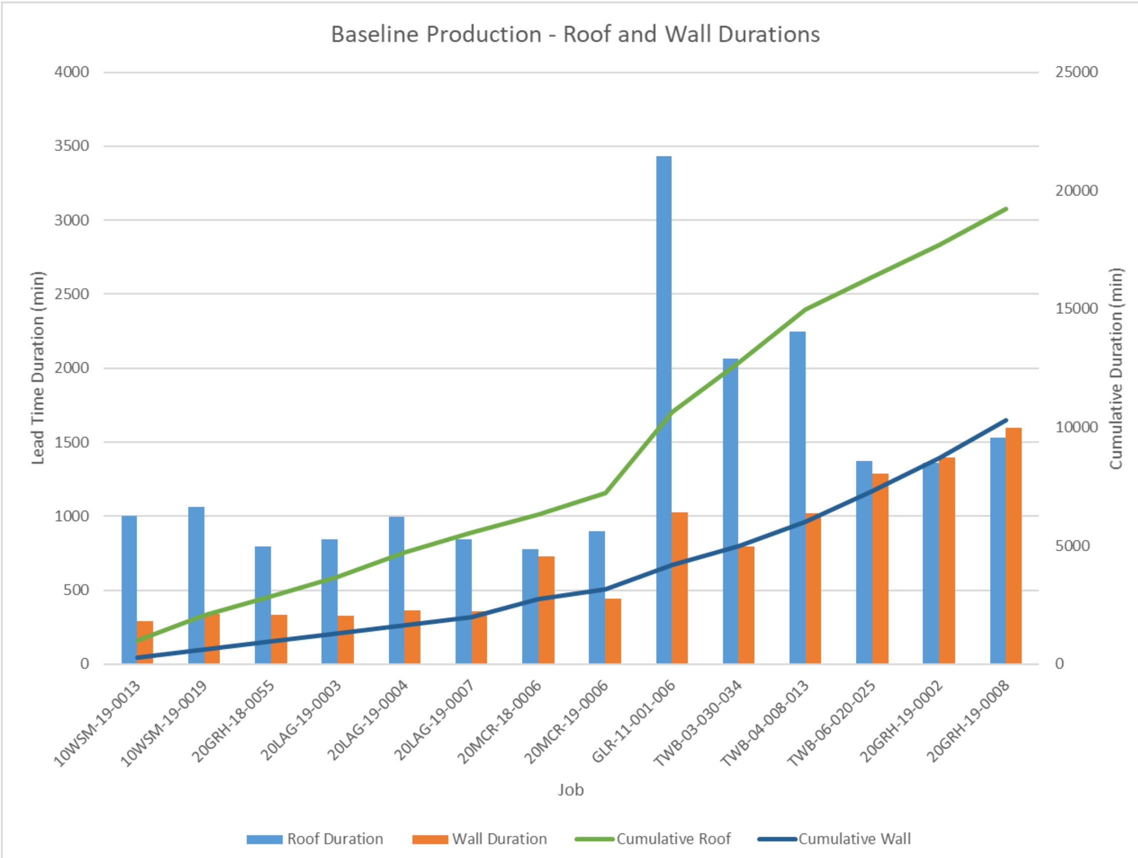


Figure 6.9 Baseline production

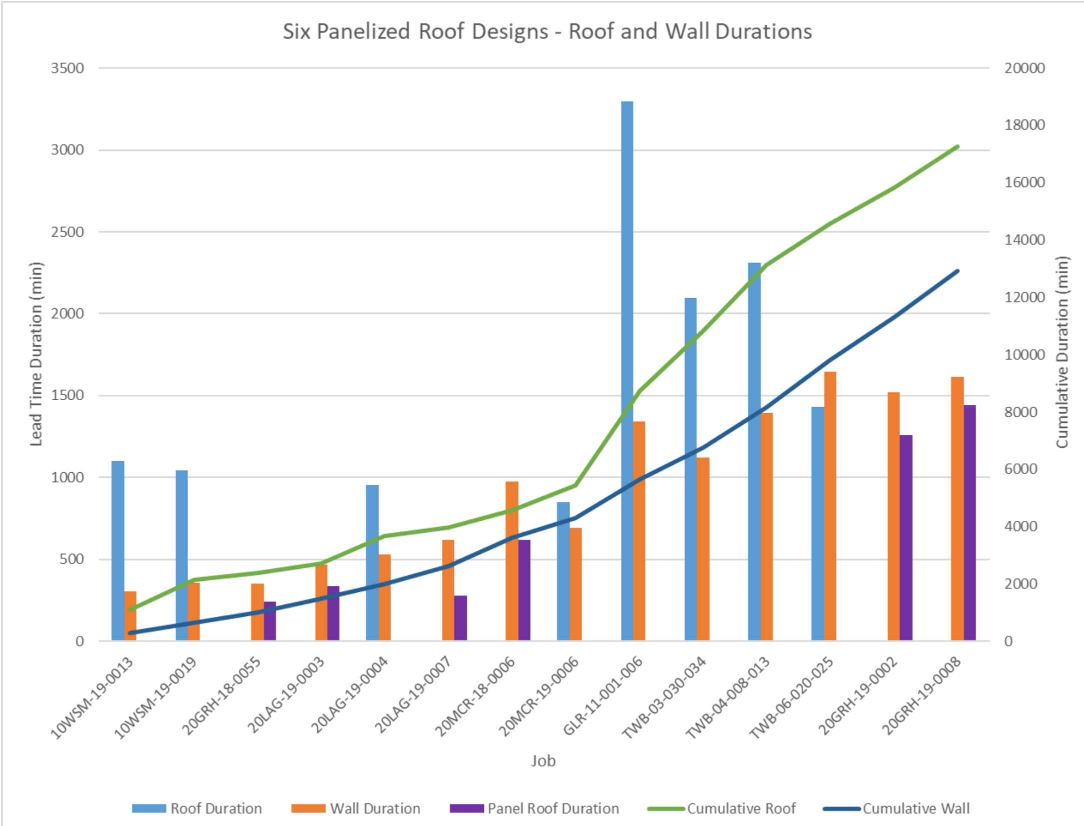


Figure 6.10 Panelized roof production

Table 6.6 Man-hour requirements for support walls

Job number	Support wall	Length (ft)	Components	Converted length (ft)	Man-hours (man-hr)	Total man-hours (man-hr)
20GRH-19-0002	SW1	26.5	15	18.35	2.345	**9.92**
	SW2	26.5	15	18.35	2.345	
	SW3	27	15	18.45	2.615	
	SW4	27	15	18.45	2.615	
20LAG-19-0007	SW1	20.5	16	18.02	1.454	**6.896**
	SW2	20.5	16	18.02	1.454	
	SW3	21.5	16	18.22	1.994	
	SW4	21.5	16	18.22	1.994	
20LAG-19-0003	SW1	21.5	16	18.22	1.994	**6.896**
	SW2	21.5	16	18.22	1.994	
	SW3	20.5	16	18.02	1.454	
	SW4	20.5	16	18.02	1.454	
20GRH-19-0008	SW1	24.5	15	17.95	1.265	**6.14**
	SW2	24.5	15	17.95	1.265	
	SW3	25.5	15	18.15	1.805	
	SW4	25.5	15	18.15	1.805	
20GRH-18-0055	SW1	19.5	16	17.82	0.914	**3.656**
	SW2	19.5	16	17.82	0.914	
	SW3	19.5	16	17.82	0.914	
	SW4	19.5	16	17.82	0.914	
20MCR-18-0006	SW1	21.25	16	18.17	1.859	**7.436**

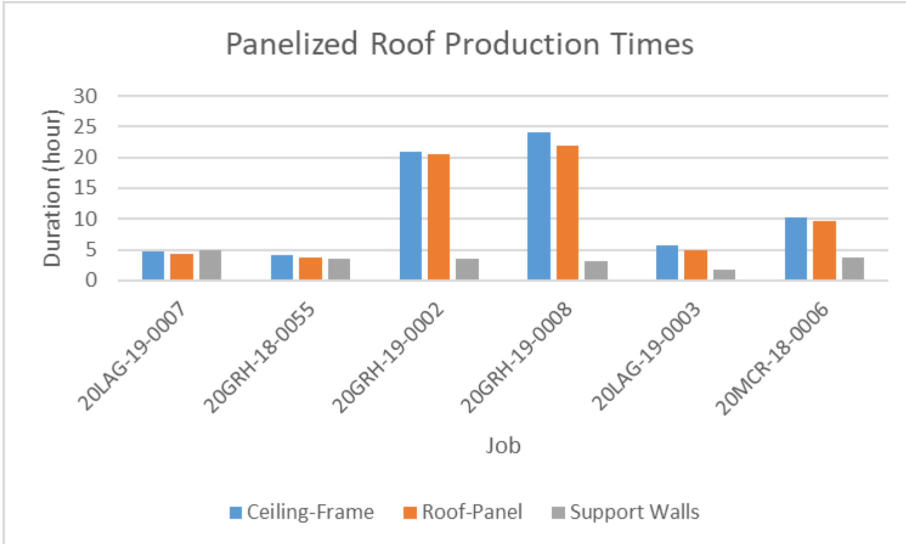


Figure 6.11 Panelized roof production times

It was found that the limiting resource for the baseline scenario in the roof assembly are the roof setup jigs since they have highest utilization, followed by the roof general labour. The labour utilization for the baseline wall assembly is relatively low, meaning there is capacity for additional production. In the transfer of the 6 roofs to the wall assembly line, it was found that the resource utilizations associated with the roof assembly decreased because of the reduced number of projects. When the 6 projects are transferred, the wall assembly line reaches capacity at the framing station, which is now the bottleneck of the production line. The utilization rate of the labour in the other stations increases but does not reach capacity and is therefore not a limiting factor. The resource utilizations for the baseline and 6 panelized roof assemblies are shown in Table 6.7.

Table 6.7 Resource utilization

	Resource	Average utilization (%)	
		Baseline	Panelized roof designs
Roof assembly	Cranes	18.5	13.6
	General Labour	74.7	64.9
	Jigs	90.3	81.2
Wall line	W1 Station	57.9	66.6
	W2 Station	73.9	98.6
	W3 Station	24.9	30.0
	W4 Station	12.4	16.5
	W5 Station	22.7	31.5
	W6 Station	14.4	19.5
	W7 Station	24.0	32.5
	W9 Station	29.8	34.2
	W10 Station	21.5	24.8
	W11 Station	22.9	31.0

6.5 Conclusions

In terms of production, this research intends to address the impact of introducing an innovative panelized roof design to the production line of a well-established offsite facility. Data were collected through manual observations at the case study manufacturing facility, then productivities were determined using the Method Productivity Delay Model. A simulation model was developed for the roof and wall production areas to analysis the effect of transferring gable-to-gable roofs to the wall assembly line. 14 projects of single-family homes and townhomes were simulated in the roof assembly area and wall assembly line to establish a baseline (current state). Next, 6 gable-to-gable roof projects were transferred to a panelized roof design, then the simulation model was run with 6 roof assemblies being transferred to the wall assembly line and the remaining roof assemblies staying in the roof assembly area. It was found that transferring roof production for the 6 panelized roofs to the wall assembly line caused a lead time reduction of 38% on average for the roofs. When accounting for the roof projects in the wall assembly line and those remaining in the roof assembly area, a reduction in lead times of 16% on average was found across all 14 roof projects. The change in lead times of the roof assembly and wall assembly line allowed for better production balancing resulting in a 20% reduction in the difference between the two. Man-hour savings of 28% in the roof assembly area were realized while only increasing the wall assembly line man-hour requirements by 3%. This is because the panelized roof design utilizes the automation in the wall assembly line and the labour-intensive methods used in the roof assembly are reduced. Through this research, the implications of manufacturing the new panelized roof design have been presented and will allow for management to make informed decisions when changing their production methods.

6.5.1 Limitations and future work

This work is limited by the ability to observe and perform a time study of the on-site assembly. Once a panel roof has been completed, the on-site assembly time needs to be evaluated. It is known that the on-site assembly time will likely be higher than current state methods, but this additional on-site time needs to be measured against the savings found from the reduced production time for the panelized roof design. Additionally, this on-site assembly time needs to be monitored because it should decline as personnel become more familiar with the installation. The designs consist of roof panels and ceilings frames, which are able to be produced on the wall production line; however, the support walls must be manually produced since the height of these walls is shorter than the minimum height the wall production line can accommodate. This will hinder the production efficiency of the panelized roof design. In the future if the panelized roof becomes mass produced, then specialized machinery should be put in place to accommodate this design requirement. This research is also limited by the small roof component assembly station that was not considered in the simulation model. The small roof component assembly process was not observable due to the facility's production schedule interfering with other projects that needed to be observed. This may cause small discrepancies between actual and simulated production durations when producing panelized roofs on a large scale.

6.6 Acknowledgements

The authors would like to acknowledge everyone at the case study company for their contributions, hard work and for allowing us to observe their actions at the facility in order to collect the data needed for this study. We would like to specifically thank Beda Barkokebas for his knowledge and contributions to this work and Md Saiful Islam for his contributions. Additionally, we would like to thank Mohammed Sadiq Altaf for his invaluable collaboration in this work.

Chapter 7: Predicting Performance Indicators Using BIM and Simulation for a Wall Assembly Line

7.1 Introduction

Off-site home construction allows for the construction of building components to be completed in an off-site facility. The floors, walls, and roof are constructed on separate production lines, then shipped together to site for installation. This type of home construction presents a good opportunity to utilize lean manufacturing principles allied with simulation methods to better industrialize the home building process. This paper presents a case study of a well-known panelized residential home manufacturer, where the focus is the wall assembly line. Multiple key performance indicators (KPIs) are calculated in order to forecast production for each project and key result indicators (KRIs) are used to predict the outcomes of multiple projects. The predicted performance indicators are found through a simulation model of the production line using quantity take-offs extracted from BIM models. The analysis of these performance indicators will be used to evaluate project feasibility when the project is built in an off-site construction facility.

7.2 Literature review

The construction industry suffers from poor productivity and high levels of waste. The industrializing of construction has long been thought of as a solution to this (Koskela, 1992). Bjornfot and Stehn (2004) define industrialization as a streamlined process promoting efficiency and economic profit. By modelling construction after manufacturing, lean can be applied to construction to solve the shortcomings of traditional stick-built methods. Bjornfot and Stehn (2004) go on to define lean construction as a methodology aiming at streaming the whole construction process while product requirements are realized during design, development and assembly. Therefore, the concept of industrialization and the philosophy of lean tie into one another seamlessly. Off-site construction derives its root from the manufacturing industry: entire stick-built construction projects are broken down into components that are easy to manufacture on factory production lines (Zhang et al, 2016).

Ritter et al. (2016) performed a study of the floor area of an off-site construction company (the same company used for the present case study) that focused on the analysis of directly and indirectly productive tasks to determine possible process improvements of the floor production line. By simulating the facility's current state operations, then applying multiple lean improvements to the model, productivity gains were quantified. The results of the future state simulation showed productivity increases and aided management in decision making.

Moghadam (2014) did a similar study of another modular home manufacturing facility. This study focused on the application of lean tools to the manufacturing process, and included studies of the floor, wall, and roof station timings to assist in production levelling. The use of multi-skilled labour was identified as a solution to balancing of the production lines since labourers could move between stations to maintain equal production rates.

Each of these studies provides valuable input on how to make a process more efficient, but does not provide an overall view of the whole manufacturing process. Performance indicators give a clearer representation of the benefits of lean since utilizing traditional accounting methodology is not always obvious (Bhasin, 2008). Performance indicators are used to measure the success of the manufacturing process. Key performance indicators (KPIs) are those indicators that focus on the aspects of organizational performance that are most critical for current and future success of the organization. Key result indicators (KRIs) summarize the activity of more than one team; it is a more overall look at the results of the activities that have taken place (Parmenter, 2010). Both of these performance measures are imperative for evaluating current and past production trends, as well as capturing the outcomes of the variability of project sizes. Through the use of performance indicators, lean improvements to the off-site manufacturing facility can be analysed.

The tools used to calculate these indicators are building information modelling (BIM) and computer simulation. BIM is a technology used to integrate the architectural and structural design, modularity concepts, and framing best practices into one model that helps the end-user during the decision-making process (Alwisy et al., 2012). Sacks et al. (2009, 2010) provided a conceptual framework for assessing the interconnections between lean and BIM and they identified 56 interactions through their developed matrix. Using the BIM model, it is possible to extract quantity take-offs that can be used in the simulation model.

Simphony.NET is an integrated environment for simulating construction activities that was developed by AbouRizk and Mohamed (2000). Simulation models are used to replicate complex operations and give valuable output regarding productivity, resource utilization, and material usage. Based on the output of the simulation model, it is possible to calculate these performance indicators and forecast manufacturing operations.

7.3 Motivation

The objective of this paper is to use performance indicators to predict the outcomes of building the walls of a construction project in an off-site construction facility. Based on material quantities extracted from BIM models and the results generated from computer simulation, many performance indicators are evaluated. The predicted key performance indictors give insight into project specific production (cost and productivity): these indicators aid management in determining if a project is feasible. The predicted key result indictors are used to evaluate production outcomes over multiple projects (material usage, time and cost). By comparing actual production measures to the predicted performance indicators, management can determine material, budget, and schedule deviances.

7.4 Methodology

This research combines BIM modelling and discrete event simulation to predict the performance indicators of a wall production line for potential projects. Figure 7.1 shows the overall process used to extract information from BIM models, organize the information into a database, and feed this information to a simulation model to get data for calculating KPIs and KRIs. The information is extracted from each BIM model through a Dynamo script and parsed through a developed add-on in two stages: (1) sequencing and combining of all panels in the project into panels of maximum length of 40 feet, and (2) addressing each panel's attributes relevant to the simulation model as per Barkokebas et al. (2017). All information is stored in Microsoft Access and imported in the simulation model for the development of KPIs of each project.

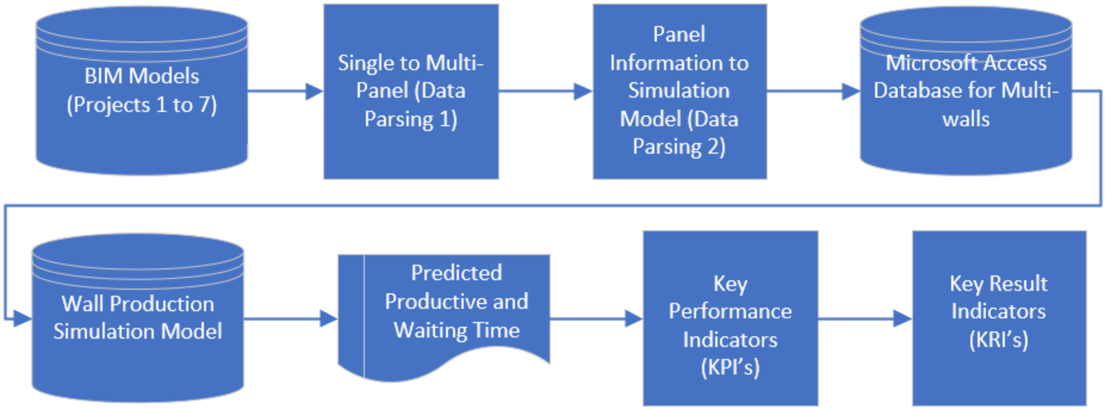


Figure 7.1 Process diagram of information flow

The first step is to construct a current state simulation model of the wall production assembly line as shown in Figure 7.2. The simulation model was developed through discrete event simulation in Simphony.NET, a program developed by AbouRizk and Mohamed (2000). The current production process consists of ten stations as outlined in Figure 7.2. To build the current state simulation model, each of the ten stations are broken down into multiple tasks with deterministic and heuristic durations dependent upon each panel's attribute such as number of openings, area, and use (exterior or interior). Each station also includes a probabilistic chance of delay that has a distributed duration. The tasks' durations are constant because of the high level of automation and standardization used in the manufacturing process. Simphony.NET is used to find the best fitting distribution for the delay durations based on the time study data gathered. Resource constraints for the number of labourers and equipment are also represented in the model. Altaf (2016) verifies and validates this simulation model in his doctoral dissertation. The inputs required for the simulation model are the number of window and door openings, studs, OSB sheets, corners and intersection and beam pockets. From this information the total wall area, number of multi-panel walls, and number of single panel walls are determined.

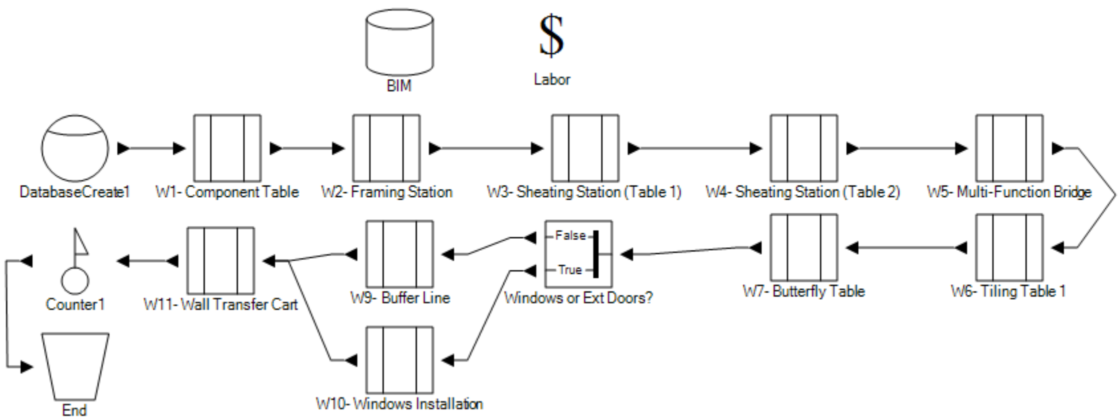


Figure 7.2 Wall production line simulation model

Table 7.1Wall production stations

Order	Station	Description	Crew Size (persons)
1	Component table	Opening rough-ins are assembled prior to framing	3
2	Framing station	Studs, plates, and pre-assembled components are nailed together	2
3	Sheathing Station 1	Label walls, and place hooks	3
4	Sheathing Station 2	Place blocks, OSB sheathing and vapour barrier	3
5	Multi-function bridge	Nail sheathing	1
6	Tilting table	Sheathing quality control	2
7	Butterfly table	Place rods, and cut exterior walls	2
9	Buffer Line	Backing and plastic wrap	3
10	Window/door installation	Installing windows and doors where it applies	5
11	Wall transfer	Flip wall	1

The next step is to gather all the take-off information from the BIM models. This is done by data parsing to gather the necessary information for every wall (single panel information). In order to efficiently construct the walls, the single panel walls must be arranged into multi-panel walls; this is done through the use of a greedy algorithm. This algorithm arranges single panel walls of the same size (2”x4”, 2”x6” or 2”x8”) to be as close as possible to the machine limit of 40’ in length. Data parsing is used again to gather the single and multi-panel data; this data is then exported to a

Microsoft Access database that feeds the information into the simulation model. In this study, the BIM models of 5 commercial projects and 1 residential house are used. The information extracted from the BIM models and used in the simulation model is shown in Table 7.2.

Table 7.2 Project information

Project ID	**Project**	**Number of Multi-Panel Walls**	**Number of Single Panel Walls**	**Total Wall Area (SF)**
1	BC Residential Housing	5	20	1785.33
2	Kamsack Liquor Store	18	25	5113.37
4	ATCO Site Office/Washroom	8	28	2006.18
5	ATCO Small Office/Washroom	3	8	559.07
6	ATCO Office Building	22	72	10587.35
7	Car Wash	4	8	607.73

Each project is put through the simulation model separately and for one thousand runs. All multi-walls of each project are released to station 1 at time zero. The simulation model outputs are: directly productive time (min) and waiting time (min) for each station. The hourly rate for crew workers is assumed to be $25/hr and the overhead rate for the facility is assumed to be $4500/hr. From the simulation results, the predicted KPIs are calculated as shown in Table 7.3. The predicted KRI values are calculated through the formulas shown in Table 7.4.

.

Table 7.3 Key performance indicators formulas

KPI	Formula
Total Project Cost ($)	$= \left[Directly\ Producitve\ Time\ (min) * Crew\ Size * 0.42 \left(\frac{\$}{min}\right)\right] + [75 \left(\frac{\$}{min}\right) * Lead\ Time(hr)]$
Productivity (SF/min)	$= \frac{Total\ Wall\ Area\ (SF)}{Project\ Lead\ Time\ (min)}$
Project Cost ($/SF)	$= \frac{Total\ Project\ Cost\ (\$)}{Total\ Wall\ Area\ (min)}$

Table 7.4 Key result indicators formulas

KRI	Formula
Total Material Usage	$\sum_{i=1}^{n}(\text{total wall area}_\text{i})$
Total Lead Time	$\sum_{i=1}^{n}(\text{project project time}_\text{i})$
Total Cost	$\sum_{i=1}^{n}(\text{project cost}_\text{i})$

7.5 Results

The simulation output for the productive and waiting times for each project are shown in Table 7.5 and Table 7.6. Figure 7.3 shows the total time per station for each project found by totaling the simulation results. The first spike in total time is due to significant waiting times found at stations 1 and 2 (component table and framing station, respectively). Wait times are highest here because all multi-walls are released at time zero to station 1, meaning there is a backlog of walls to begin with before they make their way down the assembly line. The second spike in total times occurs because of the long productive times of stations 9 and 10 (buffer line and window/door installation, respectively). Station 9 has a high productive time for the projects that need beam pockets, and is zero for projects that do not require them. The variability in the number of openings (windows and doors) strongly influences the productive time of station 10: if the multi-wall contains many openings, the productive time greatly increased. The simulation results identify stations that could be targeted for lean improvements to reduce project lead time. In this analysis, the stations with the highest wait times and productive times should be the focus of lean improvements. It is also important to note that the productive and wait times are highly variable due to the range of project sizes.

Table 7.5 Simulation results - productive time

Productive Time (min)										
Project ID	**@W1**	**@W2**	**@W3**	**@W4**	**@W5**	**@W6**	**@W7**	**@W9**	**@W10**	**@W11**
1	7.70	12.21	6.50	8.48	3.44	1.70	2.83	0.00	32.34	2.70
2	5.57	9.64	3.14	6.55	3.12	1.70	2.83	77.56	49.84	2.70
4	11.55	13.21	6.72	5.23	3.14	1.70	2.83	152.97	51.74	2.70
5	14.73	11.92	6.43	4.49	2.96	1.70	2.83	0.00	55.84	2.70
6	9.98	15.53	6.78	3.47	3.75	1.70	2.83	205.04	72.45	2.70
7	12.59	10.68	4.95	4.52	2.81	1.70	2.83	0.00	46.38	2.70
Average	10.35	12.20	5.75	5.46	3.20	1.70	2.83	72.60	51.43	2.70

Table 7.6 Simulation results - waiting time

Waiting Time (min)										
Project ID	**@W1**	**@W2**	**@W3**	**@W4**	**@W5**	**@W6**	**@W7**	**@W9**	**@W10**	**@W11**
1	17.46	12.29	0.00	0.00	0.03	0.00	0.01	0.00	0.00	0.00
2	69.61	67.63	0.00	0.00	0.25	0.00	0.09	0.00	0.00	0.24
4	55.98	12.39	0.00	0.00	0.27	0.01	0.09	0.00	0.09	0.14
5	14.90	0.38	0.00	0.00	0.02	0.00	0.02	0.00	0.00	0.08
6	109.35	82.59	0.00	0.00	0.23	0.00	0.01	0.00	0.00	0.12
7	23.59	7.39	0.00	0.00	0.35	0.02	0.15	0.00	0.00	0.00
Average	48.48	30.45	0.00	0.00	0.19	0.01	0.06	0.00	0.02	0.10

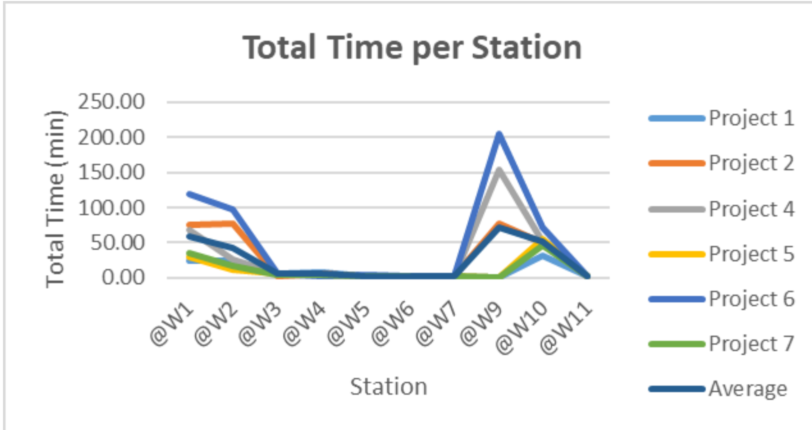


Figure 7.3 Total time for each project

The predicted KPIs for the wall assembly line are shown in Table 7.7. These predicted values can be compared on a per project basis with actual KPIs once a project has been completed to determine material, schedule, and budget deviations. It was found that as project size increases, productivity increases and cost per square foot decreases, along with the obvious total project cost and time increase. This productivity increase and cost per square foot decrease occurs because wait times do not significantly increase when a larger project is being worked on. This is due to resource utilization of each station not being maximized. Once resource usage is maximized, wait times will increase, causing productivity to decrease and cost per square foot to increase. Therefore, productivity and cost savings can be gained by constructing projects with higher square footages of wall area, until resource utilization is exhausted. Figure 7.4 plots project size vs productivity with a linear trend line, which has R2 = 0.6453. Figure 7.5 plots project size vs cost with a linear trend line, which has R2 = 0.5216. These R-squared values are seemingly low but do still provide proof of a correlation, given the small sample size. Furthermore, total project cost and project time vs project size (not shown graphically) were found to have R2 = 0.8245 and R2 = 0.8260, respectively. This reinforces results from the simulation model for the time and cost increases when constructing larger projects.

Table 7.7 Predicted key performance indicators

Project	Project Size (SF)	Productivity (SF/min)	Direct Cost ($)	Indirect Cost ($)	Project Cost ($)	Cost ($/SF)
1	1785.33	16.58	61.07	8076.57	8137.63	4.56
2	5113.37	17.02	154.50	22534.71	22689.21	4.44
4	2006.18	6.25	263.72	24057.65	24321.37	12.12
5	559.07	4.70	74.24	8924.97	8999.21	16.10
6	10587.35	20.50	336.08	38738.45	39074.54	3.69
7	607.73	5.04	64.63	9048.40	9113.03	15.00

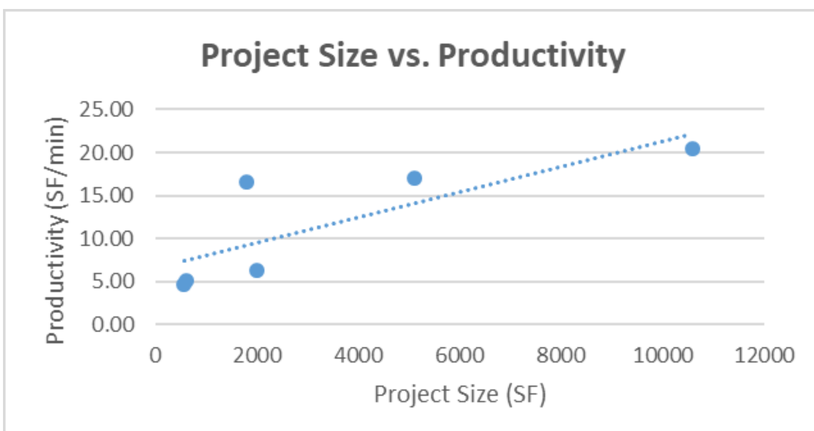


Figure 7.4 Productivity of each project

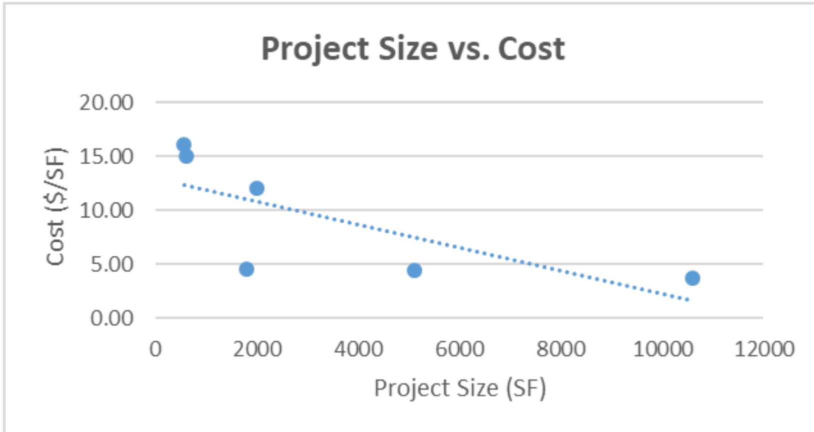


Figure 7.5 Cost of each project

Since each project produces a high variability of results further analysis into production over a specified time period is necessary. The predicted KRI values are shown in Table 7.8. These values are a summation of material, time, and cost requirements for completing all six projects. By comparing the predicted KRI values to actual material, time, and cost outcomes, production can be evaluated in terms of material, schedule, and budget deviations over the entire production period. Table 7.9 defines how to interpret the deviations of predicted vs actual KRI values. Evaluating production over numerous projects gives an overall analysis of facility performance rather than focusing on project-specific production.

Table 7.8: Predicted key result indicators

Total Material Usage (SF)	20659.03
Total Project Time (min)	1485.08
Total Cost ($)	112335.00

Table 7.9: Key result indicator interpretation

KRI	Δ = KRI_{actual} - $KRI_{predicted}$
Total Material Usage	+ Δ = material waste - Δ = material saving
Total Production Time	+ Δ = schedule delay - Δ = ahead of schedule
Total Cost	+ Δ = over budget - Δ = under budget

7.6 Limitations and future work

This research is limited by the separate simulation of each project. This method does not completely reflect actual production methods of releasing a new project to the floor once there is resource availability at the first station. The method of simulating production over multiple projects is preferable to simulating projects one at a time because rarely will a single project have the entirety of the factory floor. If only one project is simulated, the waiting time will only be accumulated due to the backlog of multi-walls of one project and not due to the wait time of projects catching up to one another. Calculating performance indicators based on only a single project will lead to a slight overestimate of production and underestimated costs. In the future, it would be useful to simulate production continuously over all projects in order to determine the additional wait time that would be accumulated. Furthermore, it would be ideal to simulate a larger number of BIM models in order to prove a stronger correlation between productivity and cost vs project size. If enough projects have been simulated, predictive data analysis techniques such as regression, clustering, or time series analysis can be used to predict the KPIs of possible projects without having to construct a BIM model to be used in the computer simulation model. Through the data analysis of performance indicators, it will be possible to efficiently evaluate the feasibility of potential projects in an off-site construction facility. Another limitation of this research is the focus on only the wall production line. In the future the same analysis should be done for the floor and roof production lines in order to determine the performance indicators of the whole projects, rather than just those for the wall production line.

7.7 Conclusion

Through BIM modelling and computer simulation the productive and waiting times for the wall assembly line was determined for six different projects. Using these times and information from the BIM model, numerous key performance indicators were predicted. Upon analysis of these KPIs it was found that as project size increased, productivity (SF/min) and cost ($/SF) decreased. Additionally, the predicted key result indicators for construction of all six projects was calculated. Based on these results, the feasibility and outcomes of producing walls through off-site construction can be measured. On a per project basis the predicted KPI values can be used to determine the schedule, budget, and material implications. While the predicted KRI values give an overview of the total material, schedule, and budget requirements of production over several projects.

7.8 Acknowledgements

The authors would like to thank everyone at the case study company for allowing us to observe their actions at the facility in order to collect the data needed for this study. We would like to specifically thank Antonio Cavalcante Araujo Neto, Mohammed Sadiq Altaf, and Mahmud Abushwereb for their invaluable collaboration in this work.

Chapter 8: Conclusion

8.1 General conclusions

This research has been motivated by necessity to improve the efficiency and operations of existing offsite construction facilities. Existing production methods are inefficient, wasteful, and closely resemble traditional on-site practices. This thesis investigates through numerous case studies how offsite construction facilities can transform their current state operations into a more efficient manufacturing process. In each case, current state operations are measured and then simulated using a construction modelling software. Process improvements targeting the inefficiencies within the facility are identified and tested in the simulated environment. Finally, proposed improvements are quantified and proposed to facility personnel. The challenge when improving offsite construction facilities is that each facility operates uniquely and cannot be transformed unless company-specific improvements are implemented for that facility. While lean and manufacturing principles are used as the basis for facility improvements, they must be refined and applied in a realistic way that differs between each offsite construction manufacturer. This thesis defines the following: (1) how current state operations of an offsite construction facility can be transformed through process mapping, lean principles, and computer simulation, and also how, by using manufacturing principles suitable for that particular facility and quantifying proposed improvements through simulation, the company personnel's confidence and willingness to implement change can be achieved; (2) how multi-skilled labour can be scheduled to level the production line and improve facility throughput; (3) how the production of new and innovative designs can be tested through computer simulation to understand the manufacturing-related effects on multiple production lines and facility throughput; and (4) how, through the use of computer simulation and performance indicators, it is possible to determine the manufacturing implications of producing projects in an offsite construction facility, and these performance indicators can then be used to determine budget, and time deviations in production.

8.2 Research contributions

The academic contributions of this research can be summarized as follows:

1. the utilization of discrete event simulation for facility layout and production sequence optimization.
2. the utilization of hybrid simulation to determine multi-skilled labour allocation and schedule.
3. the use of discrete event simulation to determine the manufacturing implications of producing new and innovative roof designs on multiple production lines.

The industry contributions of this research can be summarized as follows:

1. the application of process mapping and computer simulation to identify production inefficiencies and develop process improvements to update and optimize production.
2. the utilization of multi-skilled labour to reduce lead times, balance production and decrease costs.
3. an evaluation of the production benefits from implementation of a new and innovative roof design.

4. the use of performance indicators to predict facility performance for individual projects and production periods.

8.3 Research limitations

This research is subject to the following limitations:

- The researcher's capacity to perform a comprehensive time study of all facility operations. In each case study, manual observations are used to collect time data on production. Observations are limited to the work occurring during the time study, which creates a bias based on the observed days. The activities that do not occur on a regular basis or during the study do not have enough observations to develop a distribution for their cycle time. Instead, an average or fixed time was used for those activities, which does not accurately reflect reality.
- The researcher's capacity to study on-site assembly of offsite construction components. The inefficiencies found during on-site assembly can give important information about the problems within the production lines. All possible process improvements are not captured when focusing only on activities within the facility.
- Labour pools in the simulation models are assumed to have identical productivities and no learning curve.

8.4 Future research

The research serves to develop multiple methods for increasing production efficiency in offsite construction facilities. The following areas may require further research:

- Implementation and adaption process of introducing numerous changes and new designs to the production lines. Research should be conducted after process improvement have been implemented to validate and verify the outcomes of the changes.
- Analysis of on-site assembly to identify issues within the production lines that are not apparent until problems are encountered on-site. If these issues on-site can be studied, then this knowledge used to further refine the manufacturing process.
- Work with management to develop an implementation plan for production improvements. Process improvements must be introduced to the facility in a methodical and logical manner to maintain employee engagement and economics.

References

Abbasian-Hosseini, S., Nikakhtar, A. and Ghoddousi, P. 2014. Verification of lean construction benefits through simulation modeling: A case study of bricklaying process. KSCE Journal of Civil Engineering, 18(5).

Abdelhamid, T.S., El-Gafy, M.A. and Salem, O. 2008. Lean construction: fundamentals and principles, American Professional Constructor Journal, 4, pp. 8-19.

AbouRizk, S. 2010. The role of simulation in construction engineering and management, Journal of Construction engineering and Management, 136(10).

AbouRizk, S., and Mohamed, Y. 2000. Simphony-an integrated environment for construction simulation. Proceedings of the Winter Simulation Conference. Orlando, FL, USA, 10-13 Dec 2000, pp.1907–1914.

Abudayyeh, O., Young, A. D., and Jaselskis, E. 2004. Analysis of trends in construction research: 1985–2002, Journal of Construction Engineering and Management, 130(3).

Adrian, J.J. and Boyer, L. T. 1976. Modeling method-productivity. Journal of the Construction Division. 102(1).

Altaf, M. S., Bouferguene, A., Liu, H., Al-Hussein, M., and Yu H. 2018a. Integrated production planning and control system for a panelized home prefabrication facility using simulation and RFID. Automation in Construction, 85(1).

Altaf, M.S., Demirer, S., Han, S.H. Al-Hussein, M. 2018b. A case study: Prefabricated wood framed panelized roof system for single family home. Proceedings of the World Conference on Timber Engineering. Seoul, Republic of Korea, 20-23 Aug 2018, pp. 1–6.

Altaf, M.S. 2016. Integrated production planning and control system for prefabrication of panelized construction for residential building. Ph.D thesis, The Department of Civil and Environmental Engineering. The University of Alberta, Edmonton, AB.

Altaf, M.S., Liu, H., Zhang, Y., Al-Hussein, M. and Bouferguene, A. 2015. Discrete-event simulation modeling of prefabricated wall production line. Proceedings of the European Modeling and Simulation Symposium, Bergeggi, Italy, 21-23 September 2015, pp. 234–239.

Alvanchi, A., Azimi, R., Lee, S., AbouRizk, S., and Zubick P. 2012. Off-Site Construction Planning Using Discrete Event Simulation. Journal of Architectural Engineering, 18(2).

Alwisy, A., Al-Hussein, M., and Al-Jibouri, S. H. 2012. BIM approach for automated drafting and design for modular construction manufacturing. Proceedings of the Computing in Civil Engineering Conference. Clearwater Beach, FL, USA, 17-20 June 2012, pp. 221-228.

Arashpour, M., Wakefield, R., Blismas, N., and Minas, J. 2014. Optimization of process integration and multi-skilled resource utilization in off-site construction. Automation in Construction, 50(1).

Arif, M. 2009. Editorial – Special issue on offsite manufacturing, Construction Innovation, 9(1).

Barkokebas, B., Zhang, Y., Ritter, C., and Al-Hussein, M. 2017. Building information modelling and simulation integration for modular construction manufacturing performance improvement. Proceeding of the European Modelling and Simulation Symposium. Barcelona, Spain, 18-20 Sept 2017, pp. 409-415.

Barkokebas, B., Bu Hamdan, S., Alwisy, A. and Al-Hussein M. 2015. Evaluation of the impact of dynamic work stations versus static work stations in wood framing prefabrication using hybrid simulation. Proceedings of the Modular and Off-site Construction Summit. 19-21 May 2015, Edmonton, Alberta, Canada.

Bertelsen, S. and Koskela, L. 2004. Construction beyond lean: A new understanding of construction management. Proceedings of the Annual Conference of the International Group for Lean Construction, Elsinore, Denmark, 205 August 2004, pp.1-12.

Bhasin S. 2008. Lean and performance measurement. Journal of Manufacturing Technology Management, 19(5).

Bjornfot, A. and Stehn, L. 2004. Industrialization of Construction -A Lean Modular Approach. Proceeding of International Group for Lean Construction, Helsingor, Denmark, 3-5 Aug 2004, pp. 1-14.

Boyd, N., Khalfan, M. and Maqsood, T. 2013.Off-site construction of apartment buildings, Journal of Architectural Engineering, 19(1).

Boysen, N., Fliedner, M. and Scholl, A. 2006. A classification of assembly line balancing problems. European Journal of Operational Research, 183(1).

Brito, T.B., Trevisan, E.F.C., Botter, R.C. 2011. A conceptual comparison between discrete and continuous simulation to motivate the hybrid simulation methodology, Proceedings of the Winter Simulation Conference, Phoenix, Arizona, USA, 11-14 Dec 2011, pp. 3915-3927.

Brown, R., Ritter, C., and Al-Hussein, M. 2019. Simulation based approach for the industrialization of a cabinet manufacturing facility. Proceedings of the Modular and Offsite Construction (MOC) Summit, Banff, Alberta, Canada, 21–24 May 2019, pp. 301–308.

Dozzi, S., and AbouRizk, S. 2011. Productivity in construction. Available from https://pdfs.semanticscholar.org/5189/7ec6a4ff684f5d9b282f23d3498a98599cbd.pdf [cited 11 April 2019].

Hosseini-Nasab, H., Fereidouni, S., Fatemi Ghomi, S. and Fakhrzad, M. 2017. Classification of facility layout problems: A review study. The International Journal of Advanced Manufacturing Technology. 94(1-4).

Hosseini, S.A., Nikakhtar, A., Wong, K., Zavichi, A. 2012. Implementing lean construction theory to construction processes' waste management, Proceeding of the International Conference on Sustainable Design and Construction, Kansas City, Missouri, USA, 23-25 March 2012, pp. 414-420.

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

Kobayashi, K., Fisher, R. (2008). Business improvement strategy or useful tool? Analysis of the application of the 5S concept in Japan, the UK and the US. Avaliable from <https://doi-org.login.ezproxy.library.ualberta.ca/10.1080/14783360701600704> [cited Nov. 25, 2018].

Koskela, L. 2000. An exploration towards a production theory and its application to construction. Ph.D. thesis, Helsinki University of Technology, Espoo, Finland.

Koskela, L., 1992. Application of the New Production Philosophy to Construction. Technical Report No. 72, CIFE Department of Civil Engineering, Stanford University.

Lee, S., Han S., and Peña-Mora, F. 2009. Integrating construction operation and context in large-scale construction using hybrid computer simulation. Journal of Computing in Civil Engineering, 23(2).

Li, H. X., Al-Hussein, M., Lei, Z., and Ajweh, Z. 2013. Risk identification and assessment of modular construction utilizing fuzzy analytic hierarchy process (AHP) and simulation. Canadian Journal of Civil Engineering, 40(12).

Liu H., Altaf M.S., Lei Z., Lu M., and Al-Hussein, M. 2015. Automated production planning in panelized construction enabled by integrating discrete-event simulation and BIM. Proceeding of the 5th International/11th Construction Specialty Conference. Vancouver, British Columbia, Canada, 8-10 June 2015, pp. 1-10.

Lu, N., Ed. D. 2009. The current use of offsite construction techniques in the United States construction industry. Proceedings of the 2009 Construction Research Congress, Seattle, Washington, USA, 5-7 April 2009, pp. 946-955.

Manufactured Housing Research Alliance (2007). "Pilot Study: Applying Lean principles to Factory Home Building." <https://www.huduser.gov/portal/Publications/pdf/pilotstudy.pdf> [cited Nov. 20, 2018].

Martinez, J. C. 2010. Methodology for conducting discrete-event simulation studies in construction engineering and management, Journal of Construction Engineering and Management, 136(1).

Modular Building Institute. 2010. Improving Construction Efficiency & Productivity with Modular Construction. The Modular Building Institute, pp.1–16.

Moghadam, M. 2014. Lean-Mod: An approach to modular construction manufacturing production efficiency improvement. Ph. D. thesis, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, AB.

Moghadam, M., Aladdin A., and Al-Hussein, M. 2012. Integrated BIM/Lean base production line schedule model for modular construction manufacturing. Proceedings of the Construction Research Congress. West Lafayette, IN, USA, 21-23 May 2012, pp.1271-1280.

Mostafa, S., Chileshe, N. and Abdelhamid, T. 2016, Lean and agile integration within offsite construction using discrete event simulation: A systematic literature review, Construction Innovation, 16(4).

Parmenter, D. 2010. Key Performance Indicators: Developing, Implementing, and Using Winning KPIs, 2nd ed., John Wiley & Sons, New Jersey, USA. Report No. 72, CIFE Department of Civil Engineering, Stanford University, Stanford, California.

Poshdar, M., González, V.A, O'Sullivan, M., Shahbazpour, M., Walker, C.G. and Golzarpoor, H. 2016. The role of conceptual modeling in lean construction simulation. Proceedings of the International Group for Lean Construction, Boston, Massachusetts, USA, 20-22 July 2016, pp. 63-72.

RazaviAlavi S. and AbouRizk S., 2015. A hybrid simulation approach for quantitatively analyzing the impacts of facility size on construction projects, Automation in Construction, 60.

Ritter C., Li X., and Al-Hussein M. 2016. Production monitoring and process improvement for floor panel manufacturing. Proceedings of the Modular and Offsite Construction (MOC) Summit. Edmonton, Alberta, Canada, 29 Sept - 1 Oct 2016, pp.75-82.

Sacks, R., Koskela, L., Dave B. A., and Owen, R. 2010. Interaction of lean and building information modeling in construction. Journal of construction engineering and management, 136(9).

Sacks, R., Dave B. A., Koskela, L., and Owen, R. 2009. Analysis framework for the interaction between lean construction and building information modelling. Proceedings of the 17th annual conference of the international group for lean construction, Taipei, Taiwan, 2009, pp. 221-234.

Sacks, R. and Goldin, M., 2007. Lean management model for construction of high-rise apartment buildings, Journal of Construction Engineering and Management, 133(15).

Tam, V., Tam, C., Zeng, S. and Ng, W. 2007. Towards adoption of prefabrication in construction, Building and Environment, 42.

Wongwai, N., Malaikrisanachalee, S. 2011. Augmented heuristic algorithm for multi-skilled resource scheduling. Automation in Construction, 20(1).

Xu, H. and Wang, X. 2014. Optimization and control methods in industrial engineering and construction, Springer, Netherlands, pp. 179-196.

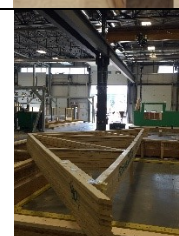
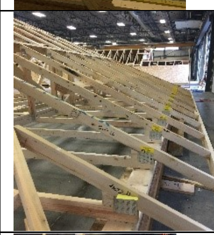
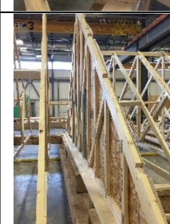
Yu, H., Al-hussein, M., Asce, M., Al-jibouri, S., and Telyas, A. 2013. Lean Transformation in a Modular Building Company: A Case for Implementation. Journal of Management in Engineering, 29(1).

Yu, H. 2010. An integrated approach toward lean for production homebuilders. Ph.D. thesis, University of Alberta, Department of Civil and Environmental Engineering, Edmonton, AB, Canada.

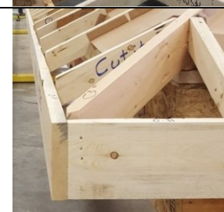
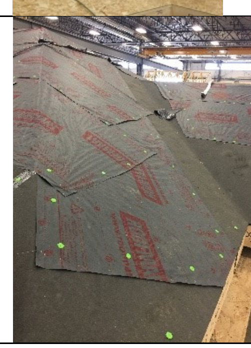
Zhang, Y., Fan, G., Lei, Z., Han, S., Raimondi, C., Al-Hussein, M., Bouferguene, A. 2016. Lean-based diagnosis and improvement for off-site construction factory manufacturing facilities. Proceeding of the International Symposium on Automation and Robotics in Construction. Auburn, AL, USA, 18-21 July 2016, pp.1090-1098.

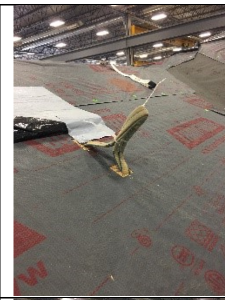
Appendix A

A. Current state assembly breakdown

Set up Jig: The jig is setup according to the dimensions of the second-floor plans. The jig is then squared.	Labour: 1 person	
Unload Trusses: Trusses are brought into the facility on a flat bed trailer. Truss bundles are offloaded using the overhead crane, typically on the far end of the jig.	Labour: 2 person	
Stand Mono-Trusses: Smaller trusses that are stood and tacked at the beginning and or end of the main roof truss standing.	Labour: 2 person	
Stand Gable Face: Gable face is stood and tacked to roof jig. Gable face is needed at the beginning and/or end of the main roof truss standing.	Labour: 1 person	
Stand Trusses: Roof trusses are stood, tack to the roof jig and tacked to a spacer and/or ridge block. At the panel split, trusses are screwed directly together.	Labour: 2 person	

Installing Web Bracing, Attic Access, Bottom Cord Bracing and Secure Trusses: Web bracing is added by nailing 2”x4” (51×102 mm) lumber to the web of specified trusses. Attic Access is nailed into place. Bottom cord bracing is nailed across the bottom of all trusses to provide stability and secure the trusses.	Labour: 1 person	 
Build and Stand Smoke Trusses: Drywall and install 2”x4” (51×102 mm) pieces to both sides of the roof truss. The overhead crane is then used to hoist the smoke truss onto the roof jig. Smoke truss is then tack to the jig and secured to its uring trusses.	Labour: 2 person	
Brace Gable Face: A measured piece of 2”x4” (51×102 mm) lumber is nailed from the top of the gable to the bottom chord.	Labour: 1 person	
Place Purlin Trusses: Purlin trusses are nailed to the top of the roof trusses in provide additional support.	Labour: 1 person	
Place Outrigger: Gable faces are notched, then outriggers are secured in these notches. Outriggers are used to secure the gable fascia.	Labour: 1 person	

Frame the Valley: 2”x4” (51×102 mm) pieces are nailed in roof valleys that are created between the purlin and main roof trusses.	Labour: 2 person	
Install Fascia: Fascia pieces are nailed across the ends of the roof trusses, mono trusses and outriggers.	Labour: 1 person	
Install Lift Points: Two 2”x6” (51×152 mm) pieces of lumber are layered and nailed to the under side and across the roof trusses to support the lift straps when lifting the panel.	Labour: 2 person	
Install Lift Point Backing: 2”x4” (51×102 mm) pieces are installed above and below the lift points to prevent the OSB sheets from ripping during crane hoisting.	Labour: 1 person	
Install Insulation Stops: Cardboard pieces are stapled in between and at the end of the roof trusses to prevent insulation from falling out of the roof.	Labour: 1 person	
Sheeting: OSB sheets are placed to cover the whole roof. Lift points, vent holes and plumbing stack locations are marked and cut.	Labour: 1-4 people	
Paper: Paper wrap is stapled to cover the OSB sheets. Lift points, vent holes and plumbing stack locations holes are cut.	Labour: 1-4 people	

Install Lift Straps: Straps are strung through the holes in the OSB sheets around the lift points.	Labour: 1 person	
Lift Panel: Trusses are unscrewed from one another and lift straps are attached to the overhead crane. The crane then hoists the panel on a flatbed trailer. The panel is then secured to the trailer, ready for delivery on-site.	Labour: 1 person