University of Alberta

Improving the Efficiency, Productivity, and Cost-Effectiveness of Modular Design and Construction Processes

by

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ABSTRACT

This thesis provides a methodology to incorporate building information modeling (BIM), lean construction, and simulation modelling into a cohesive package in the context of modular manufacturing. BIM was used to construct a three dimensional model from which the wall and object properties were extracted. The methodology provides an efficient and effective method of estimating wall fabrication and erection probabilistic productivity rates by completing and analysing a time study to produce a realistic model for validating proposed changes to the process design to decrease time and cost requirements. The methodology of this thesis was explored though a case study of a modular manufacturing company to illustrate the functionality of the simulation model and its benefits for decision making. A current state and future state model of the wall fabrication and wall erection stations was created based on the findings of a detailed kaizen. By altering the fabrication station layout to the future state, a 10.1% decrease in overall module wall fabrication and erection was predicted with a 5.2% reduction in overall man hour requirements in comparison to current state simulation values.

ACKNOWLEDGMENT

Dedicated to my family.

I would like to thank all of the individuals who have assisted and supported me throughout this endeavour. I am deeply indebted to my parents for supporting me and pushing me to further my education, whose encouragement and confidence have made such a moment possible. Special thanks to my wife, who has provided endless motivation and understanding throughout the process.

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INTRODUCTION

MOTIVATION

Encouraged by the remarkable productivity improvements achieved by the manufacturing industry, the construction industry has tried to gain similar benefits of manufacturing technologies with varying success. With the implementation of advanced software, modular construction has achieved unique and inspiring designs while increasing efficiency and cost savings over site-built construction. However, while the methods of constructing modular and manufactured buildings have evolved over several decades, many of the techniques used in manufacturing plants vary only slightly from those employed in traditional site-built construction. This significantly reduces the potential efficiency and cost effectiveness of modular construction. Therefore, production efficiency strategies and new technologies must continually be integrated and adapted to reshape the modular construction industry.

Permanent modular buildings are built to the same building codes and requirements as site-built structures. As a result, the markets for permanent modular construction are similar to the markets for site-built construction including educational, office, retail/hospitality, healthcare, storage, security, industrial/in-plant offices, and government buildings (Modular Building Institute 2010). In general, the market's perception of modular construction is increasingly positive as the industry progresses to a higher level of design and aesthetic appeal. As a result, it is expected that the modular industry will continue to grow and overtake a significant market share from site-built construction.

However, due to the economic downturn over the last several years, the modular industry's growth has decreased substantially. In 2009, Statistics Canada reported a 11.5% reduction in all construction activity; however, in Alberta, where the modular industry has the strongest presence, overall construction activity was down 25.9% (Modular Building Institute 2010). With the downturn in the overall construction industry, many owners are looking for alternative construction solutions to address their unique building requirements. Many are attracte4d to modular construction due to its time and cost saving advantages.

Modular construction has significant environmental benefits over traditional on-site construction. In terms of global warming, average on-site construction impacts were about 23% higher than off-site (Modular Building Institute 2010). On-site builders often have limited storage space at their construction sites, and do not always have an exact inventory of all necessary materials required at each construction stage, resulting in a much less effective material procurement and management. It is common for on-site construction to order 5 to 10% extra material which is rarely observed in modular construction.

Research in modular design and construction has been gaining significant interest in the past couple decades as it has developed into a viable solution for various construction requirements. There have been significant studies into various ideologies focusing on modular construction; however, much of the research has focused specifically on a single aspect of modular construction and failed to achieve a greater holistic appreciation for the holistic factory construction process, including detailed design and drafting, plant management strategies, and simulation to estimate and validate production.

RESEARCH OBJECTIVES

This research proposes to develop a methodology to integrate various tools from building information modeling (BIM), lean construction, and simulation modelling. The methodology of this thesis will be explored though a case study of a modular manufacturing company. The research objectives of the thesis are:

- To demonstrate the versatility of BIM by extracting various wall properties from a three-dimensional model;
- To integrate lean construction practices to continually improve the manufacturing process;
- To quantify statistically the productivity rates and probabilistic duration for each activity; and
- To develop a simulation model to estimate statistically the scheduling, resource allocation and cycle time of a modular manufacturing facility.

RESEARCH METHODOLOGY

To achieve the aforementioned research objectives, several procedures will be implemented. First, a BIM model of the case study buildings will be developed with the use of detailed design drawings, including those depicting the structural shell of the building. Next, the dimensional properties will be extracted from the BIM model for use as input parameters for the simulation model. A time study will be performed on five modules (two suites per module) to determine the production times of wall fabrication and wall erection stations. The time study data will be analyzed to determine statistical productivity and probabilistic duration for each activity. Using lean construction techniques, muda in the system will be identified and mitigation methods will be proposed. To validate the lean construction improvements, a simulation model will be developed which integrates the time study and BIM model data into a cohesive package. As a result, the statistical duration times to complete various modules can be determined depending on several resource allocation and station reconfiguration scenarios.

THESIS ORGANIZATION

This thesis is organized into five chapters. Chapter 2 (Literature Review) explores the current literature in the fields of Building Information Modeling (BIM), Lean Construction, and Simulation Modeling. Chapter 3 (Proposed Methodology) presents a problem description defined within the scope of a case study and develops a proposed methodology using characteristics of BIM, lean construction and simulation modeling.

Chapter 4 (Application of Improvement Methods to Case Study) implements the proposed methodology to the case study and validates the findings. Chapter 5 (Conclusion) summarizes the research results, describes the research contribution of the thesis, and proposes future research in the area.

LITERATURE REVIEW

INTRODUCTION

The purpose of the literature review is to identify the current knowledge of the concepts and theories implemented in this thesis. Three main concepts will be studied: Building Information Modelling (BIM), lean construction, and simulation modeling. The literature review will introduce the fundamentals of each concept as well as advanced, ongoing research.

BUILDING INFORMATION MODELLING (BIM)

The BIM handbook defines Building Information Modelling (BIM) as "a verb or adjective phrase to describe tools, processes, and technologies that are facilitated by digital machine-readable documentation about a building, its performance, its planning, its construction, and later its operation" (Eastmon, et al. 2008). Building Information Modelling was first introduced in 1987 by Graphisoft's ArchiCAD; however, it has only recently been widely accepted by the architectural and engineering communities. BIM is reshaping the roles and relationships among project teams and when implemented appropriately, BIM facilitates an integrated design and construction process that results in better quality buildings at reduced costs and project durations (Eastmon, et al. 2008).

Building Information Modelling software, such as Autodesk Revit, Graphisoft's ArchiCAD, and Vico Software, allows for a three dimensional model to be developed with various objects that contain their geometry, relations and attributes. Every object remains within its given parameters and relationships which ensures integrity within the model.

BIM has significant advantages over traditional computer-aided design software. The advancements in computer processing power has enabled detailed rendering of the three dimensional model which makes the building design more accessible to non-technical participants and stakeholders. As well, rapid and multiple design alternatives can be achieved due to the parametric relationships and behaviour intelligence, which maintain design coherence and automated generation and layout of detailed components (Eastmon, et al. 2008). Since every object's individual properties are integrated into the holistic model, model integrity is ensured within all drawing views, such as plan, elevation and detail sheets. If a change is made within one of the views, the change will be updated throughout the model. As well, geometric integrity is monitored within the software to check for any physical clashes between objects within the model.

BIM technologies allows for varying degrees of automation to generate initial drawings and documents, with most requiring only minor annotation input. Once the model is completed within a three dimensional interface, all the required data to produce plan elevation and sectional views are available and can be created by altering the model view. The fundamental benefit of BIM technology is that changes to one aspect of the design results in an entirely updated model. BIM technology allows for multiple parties to construct the model simultaneously while working on various structural components.

This speeds up the design process and increases communication between parties since a single model version can be utilized and updated. The model data can be used to predict building performance, or can be incorporated into structural engineering analysis tools, automated life cycle analysis and construction cost estimations. As well, construction plan alternatives can be rapidly generated and evaluated based on construction schedules.

However, there are significant challenges still faced by BIM technology development. The coordination and fabrication of the mechanical, electrical, and plumbing (MEP) systems in modular construction has always been one of the most challenging tasks encountered in the delivery process of modular construction (Lu and Korman 2010). There are three factors reasons contributing to the challenges of MEP fabrication:

- The process is highly fragmented between design and construction firms;
- The level of technology used in different coordination scenarios has historically varied significantly between engineers and construction contractors, and;
- Historically, the process did not provide a model for specialty contractors to plan prefabrication.

Furthermore, the current construction delivery model does not support modular construction techniques due to extensive project planning and MEP coordination, even though modular building technologies offer tremendous advantages to the construction industry (Lu and Korman 2010). Therefore, BIM software must be further developed and evolved for ever changing needs and markets.

LEAN CONSTRUCTION

Lean construction (production) is a concept that aims to eliminate wastes systematically, simplify production procedures, and speed up production (Ballard 1999). Lean thinking has gained recognition and success within the automotive sector based on the principles of the Toyota Production System (TPS), developed by Ohno and Shingo. Lean construction refers to the adaptation of the underlying principles of the Toyota Production System which were popularized by the books *The Machine that Changed the World* (Womack, 1990) and *Lean Thinking* (Womack, 1996). The goal of lean production is to do more with less – less time, less space, less human effort, less machinery, less material – while giving customers what they want (Dennis 2007). The principles of lean construction theory are (Koskela 2000):

- Reduce the share of non-value adding activities
- Reduce variability
- Reduce cycle time
- Increase output flexibility
- Increase process transparency
- Simplify the process by minimizing number of steps, parts or linkages
- Build continuous improvement into the process
- Balance flow improvement with conversion improvement
- Focus control on the complete process
- Increase output value through systematic consideration of customer requirement
- Benchmark

Lean construction has recently attracted considerable attention in the construction industry, which has been historically characterized as inefficient and wasteful of time and resources due to high levels of variability. In general, a wide range of benefits of implementing lean construction include reduction in waste, production costs and cycle time, labour and inventory; and improved capacity for existing facilities, quality, profits, system flexibility, and cash flow (Kotelnikov 2006).

In lean production, activities can be broken down into three categories: value added, non-value added, and waste. Value added activities are those that add value to products and services for which customers are willing to pay for where as non-value added activities do not create value but are still required to execute value-added work (Dennis 2007). Waste (Muda) is any activity that uses resources but adds no value from the customer's perspective and must be eliminated where ever possible. The eight basic types of waste are: motion, delay, conveyance, correction, over-processing, inventory, overproduction, and knowledge disconnect (Dennis 2007). The primary tool developed through lean construction for identifying and eliminating waste is Value Stream Mapping (VSM). VSM is defined as describing all activities, both value added and non-value added, currently required to bring a product through the main flows essential to every product, the production flow from raw material to customer and the design flow from concept to launch (Rother and Shook 1999). VSM applies a visual representation of the material and information flow for a product family to better understand the production process. Mapping the process gives a clean picture of wastes that inhibit flow by displaying the cycle time for each operation and the total lead time for a process.

VSM has been used to identify and eliminate waste in housing construction. However, compared to manufacturing, the home building industry poses some significant particularities, making the direct application of VSM impossible (Yu, et al. 2009). Instead of eliminating individual waste in the process, the research focused on creating a stable production flow with a FIFO-lane-based system which increased process reliability, improved quality, and reduced total lead time. By restructuring work packages, the number of handovers was reduced and the total lead time was reduced by 50% compared to previous methods.

Value Stream Mapping has also been used in conjunction with discrete event simulation to study and model the production process in a spool fabrication shop (Wang, et al. 2009). The process of producing a mix of unique spools made the analysis and improvement of the production system very challenging using the conventional VSM approach. Instead, key lean manufacturing techniques, such as levelling production flow, were implemented to assist in the construction of the future state map of the simulation model. The research demonstrated that the development of a simulation-based approach was a practical and more powerful tool than the VSM for modeling and quantitatively evaluating the performance of a complex and dynamic spool fabrication shop.

Another study focused on the implementation of a Safety and Lean Integrated Kaizen (SLIK) (Ikuma, Nahmens and James Unpublished). A kaizen event is a team event dedicated to quick implementation of a Lean manufacturing method in a particular area over a short period of time (Tapping, Luyster and Shuker 2002). The researchers and employees focused on the improvement of the lowest performing station of the assembly process, the base framing station. A detailed time study was conducted to determine how the workers were spending their time which was broken down into value added activities, idle, walking, measuring, material handling, assisting another worker, directions, tools, cleaning, break, inspection and not available. Layout improvements and revised standard procedures resulted in a 55% decrease in work hours required to complete one base frame, a shift in activates from non-value added to value-added of 16% and a decrease or elimination of specific safety hazards (Ikuma, Nahmens and James Unpublished). Work hours per base frame decreased mainly due to making activities more efficient and improving communication. The largest decrease in non-value added activity occurred in walking which decreased from 15-22% to less than 8%.

CONSTRUCTION SIMULATION

Over the past two decades, construction engineers have extensively focused on the creation and use of simulation modelling to represent repetitive construction projects such as highways, buildings, tunnelling, and earth moving. Simulation has been defined as the mathematical representation of the interaction of real-world objects (Farlex 2011). In the construction industry, simulation models are usually used to represent the production process by describing the activity logic and the resource allocation that are involved in producing the product. Simulation can be used to efficiently evaluate various production scenarios, which can verify productivity measurement, risk analysis, resource planning, performance assessment and design of construction methods (Han 2010). Simulation can assist in making informed decisions by rapidly allowing for multiple scenarios altering the activity logic and resource allocation to determine the most desirable result before implementation. Simulation models generally offer significant opportunities to model probabilistic phenomena that are often encountered in construction. Simulation is generally more effective than other tools when: (AbouRizk, Role of simulation in construction engineering and management 2010)

- Problems are characterized by uncertainty;
- Problems are technically or methodically complex;
- Repetition is evident;
- Flexibility in modeling logic and knowledge is required to formulate a model;
- An integrated solution is required; and
- Detail and accuracy matter.

There are two types of simulation methods, discrete and continuous event simulation, which differ in how they manage the independent variable of time. Discrete event simulation can be defined as the modelling of a system as it evolves over time by representing the instantaneous change of state variables as separated points in time (AbouRizk, Lecture: Discrete event simulation 2010). In discrete event simulation, the dependent variables change at a specific event time which changes the state of the model. In continuous event simulation, the dependent variables continuously change over time, such as the velocity of a car. In construction projects, discrete event simulation is commonly used since it models real world activities more effectively with less computational power. As well, discrete event simulation allows for the allocation of resources to specific tasks within the modeling elements.

In discrete event simulation, the activity logic defines the path of the entities (virtual objects) as they pass through the various modelling elements in the simulation. The modelling elements cause changes to the entities' properties, such as altering the variable of time, or other modelling elements as the entity passes through them. An example of a modelling element would be an activity, such as loading a truck with soil. An entity would represent a truck, and as it passes through the modelling element, it is captured for a period of time while it is being loaded. As well, resource elements, such as a loader, can be captured by the modelling element while loading to represent resource allocation within the model.

In previous studies, simulation has been used to improve the flow of modular housing manufacturing operations based on time and process studies. Using Arena 5.0, the results showed that several alternatives can be implemented in order to increase the production level by almost 40% and labour cost per module can be considerably reduced (Velarde, et al. 2009). The alternatives proposed were varying combinations of cross-training employees, implementing 5S from lean manufacturing, and altering the takt time. By cross-training employees, the overall production flow was levelled with much less idle time for individual employees as they would transfer between stations.

The 5S system in lean manufacturing is designed for organization and standardization of the workspace and consists of five activities: sort, set in order, shine, standardize, and sustain (Tapping, Luyster and Shuker 2002). The takt time, or the beat of the customer demand, was also altered; however, in the study, the buffers were removed from the assembly line in an attempt to reduce takt time which had a negative effect causing a decrease in the systems' output. The findings of the study are displayed in Table 1 and show a significant savings relative to the cost of implementation of the lean tool.

Table 1: Improvement levels and economic comparison between alternatives

Alternative	Production Improvement	Cost Reduction	Annual Savings	Associated Cost
Cross-Training	37.4% from 14.35 to 19.72 modules per week	27.2% per module	$1,131,000	$5,420
5S Implementation	5.0% from 14.35 to 19.72 modules per week	4.8% per module	$199,000	$12,050
5S Implementation 10%	7.4% from 14.35 to 19.72 modules per week	6.9% per module	$287,000	$35,000
Takt Time	No Improvement	No Improvement	No Improvement	-
Takt Time with Buffers	No Improvement	No Improvement	No Improvement	-
Takt Time with Buffers and Cross-Training	38.5% from 14.35 to 19.72 modules per week	27.8% per module	$1,156,000	$62,420

Cyclone (Halpin 1973) was the first simulation tool developed specifically for the modeling of construction operations, and is based on the three-phase activity scanning modeling paradigm using activity cycle diagrams (ACD). Since then, numerous general-purpose and special-purpose simulation systems have been developed including Simphony (Hajjar and AbouRisk 1999) which was developed under the Natural Science and Engineering Research Council (NSERC)/Alberta Construction Industry Research Chair Program in Construction Engineering and Management at the University of Alberta. It was developed with the objective of providing a standard, consistent, and intelligent environment for both the development and utilization of construction special purpose simulation tools (Hajjar and AbouRisk 1996). In this thesis, Simphony.Net 3.5 will be used to develop the simulation model for the wall fabrication and erection stations.

PROPOSED METHODOLOGY

INTRODUCTION

This chapter describes and summarizes how building information modelling, lean construction and simulation will be implemented. First, the problem description, case study background and research goal are defined. Next, a detailed procedure is described for the implementation of building information modelling, lean construction and simulation. Finally, a holistic approach is described to incorporate all three tools into a cohesive unit.

PROBLEM DESCRIPTION

Encouraged by the remarkable productivity improvements achieved by the manufacturing sector, the construction industry has a long history of trying to achieve the benefits of manufacturing technologies. While industrialized construction techniques, such as modular and manufactured buildings, have evolved over several decades, many of the core techniques used in prefabrication plants vary only slightly from those employed in traditional site-built construction. This clearly overlooks the significant advantages associated with modular construction. One significant advantage to modular construction is the inherent ability to control all aspects of the construction process, from drafting to erection.

By implementing building information modeling (BIM) as a drafting platform, designers have the ability to front end load the 3D-model with extensive detail, which reduces the chances of severe errors during fabrication. BIM enables visual communication between all stakeholders at early stages in design and allows for alternatives to be created with ease. Since all of the elements in BIM are objects with defined properties, it is straightforward to produce quantity takeoffs of the required material for each unit. However, at this time, BIM has been intended and optimized for traditional stick-build construction. The scheduling methods used in common software, such as AutoDesk Revit, are not intended for assembly line production.

To remain competitive and successful in the modular industry, companies must continuously strive to improve production efficiency. Modular construction applies efficiency strategies in the plant that cannot be replicated at the building site, thereby reducing or eliminating waste in all forms. By developing lean manufacturing strategies specific to the construction of multi-story structures, continuous process flow, pull processing, production levelling, perfect first-time quality, standardization, and continuous improvement will be achieved. This will result in reduced cycle time and enhanced quality of the finished product. However, changes to the production process can be timely and have significant costs if not properly examined before implementation.

Therefore, before any changes to the production process are implemented, multiple scenarios should be explored and validated through the use of simulation. Discrete event simulation allows for the abstraction of multiple real world variables and processes to be statistically modelled and analyzed. Simulation modeling maps the process logic and tracks entities as they travel through the system. To improve the production process, a thorough study can be performed on specified stations to determine the current production practise and propose lean manufacturing techniques to improve them. By using simulation modeling, proposed changes can be explored and validated before implementation on the production line.

CASE STUDY

This research will focus on a case study of the current processes and practices of BCT Structures, a modular manufacturing company located in Lethbridge, Alberta, Canada. BCT Structures specializes in the construction of workforce housing, office complexes, schools, lavatories, multi story buildings, affordable housing, kitchen facilities and other custom solutions (Duess Design 2011). BCT Structures was opened in 2007 and offers 140,000 square feet of construction space.

During the case study, Stony Mountain Plaza will be fabricated by BCT Structures for Wood Buffalo Housing & Development Corporation. Stony Mountain Plaza is an affordable housing development which consists of two multi-story low income seniors' complexes in Fort McMurray, Alberta, providing homes for 125 families. Unique to the project, geothermal and solar panel technology will be used which could reduce the energy usage by up to 70%.

Apartment A and Apartment B consist of 70 suites and 55 suites, respectfully, ranging from one to three bedrooms. Both buildings will be constructed in modules (two suites per module) at the BCT's manufacturing facility and transported 950 km to the erection site in Fort McMurray.

The case study will focus on the production of five modules from apartment complex B as they progress through the production line, specifically the wall manufacturing and erection process. The units that were studied are as follows:

- Unit 744 – consists of two 2 bedroom suits (Two Unit B's (785sf. each));
- Unit 746 – consists of a 1 bedroom and a 3 bedroom suite (Unit A (528sf.) and Unit D (902sf.), respectively);
- Unit 747 – consists of two 1 bedroom suites (Two Unit A's (528sf. each));
- Unit 749 – consists of two 1 bedroom suites (Two Unit A's (528sf. each)), and;
- Unit 750 – consists of a 3 bedroom and a 1 bedroom suite (Unit D (902sf.) and Unit A (528sf.), respectively).

The stations to will be studied include the wall fabrication station, storage station, and wall erection station.

RESEARCH GOAL

In this research, a methodology is proposed to incorporate building information modeling (BIM), lean construction, and simulation into a cohesive package. It aims to provide an efficient and effective method of estimating production flow capacity of wall fabrication and a realistic model for validating proposed changes to the process design to decrease time and cost requirements.

IMPROVEMENT METHODS

In an attempt to improve the current state practices and procedures of BCT Structures' wall fabrication process, a combination of components from building information modelling, lean construction and simulation will be implemented.

First, a three dimensional model will be developed using Autodesk's BIM software, Revit Architecture. The model will be based on the shop drawings produced for Apartment A and will be designed based on each studied module. From the model, wall properties will be extracted for each module including the linear length, surface area, number of doors, number of windows, and number of columns. Next, the construction of five modules will be monitored in a time study to determine the duration and labour requirements for each activity completed within the wall fabrication and wall erection stations. A statistical analysis of the time study data will determine a mathematical representation of the real-world duration and labour requirements. As well, a detailed kaizen will be conducted on the wall fabrication and erection stations to identify wastes in the system and potential improvement areas. Finally, all of the data will be combined within a simulation model using Simphony.NET 3.5 to estimate and predict the scheduling and resource allocation requirements for each constructed module. Figure 1 below represents the thesis progression graphically in a flow chart.

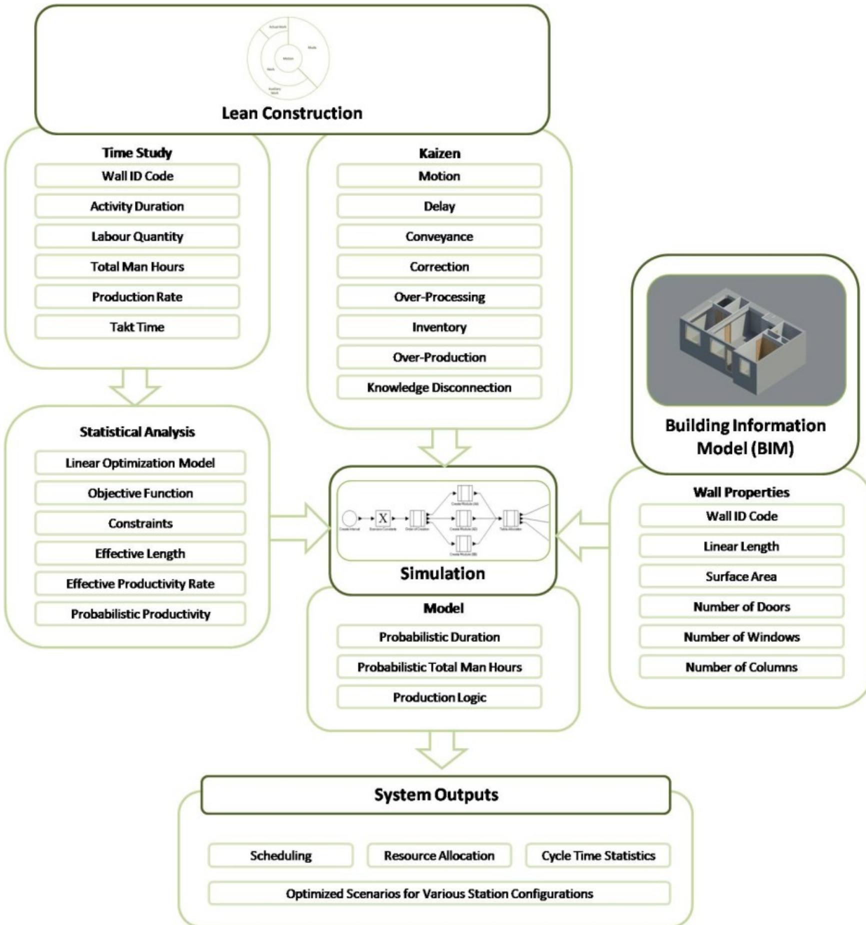


Figure 1: Overview Flow Chart

Building Information Modelling (BIM)

The proposed improvements to the manufacturing process start by changing from traditional 2D drafting to a much more robust BIM platform. Using BIM technology allows for the creation of intelligent models in terms of building elements and systems, such as walls, beams, columns, and MEP systems. BIM models have the capacity for extensive information on the component properties, such as geometry, associated components, location, suppliers, costs, and production schedules.

To limit the scope of the project, BIM will be only implemented as a tool to model and extract the property data of the apartment complexes. A three dimensional BIM computer model of the apartment complexes will be developed using AutoCAD Revit software. To create a cohesive model, all suite types will be drafted individually and later combined into a holistic model.

The first step in creating the model is to define the various wall types that will be used in the five modules studied. The wall type definitions with each unique combination of components can be found in Table 2 below.

Table 2: Wall Type Definition

Wall Type B
2x6" Double Top Plates - 16o.c. Framing
6 Mil Vapour Barrier
7/16" Vertical OSB Int. Sheathing
Single Layer 5/8" Type 'x' Drywall
Wall Type D
2x6" Double Top Plates - 16o.c. Framing
7/16" Vertical OSB Int. Sheathing
Single Layer 5/8" Type 'x' Drywall
Wall Type F
2x6" Double Top Plates - 16o.c. Framing
7/16" Vertical OSB Ext. Sheathing
Single Layer 5/8" Type 'x' Drywall
Wall Type H
2x4 - 16o.c. Framing
Single Layer 1/2" Type 'x' Drywall
Wall Type K
2x4 - 16o.c. Framing
Single Layer 1/2" Type 'x' Drywall
Wall Type M
2x6" - 16o.c. Framing
Single Layer 5/8" Type 'x' Drywall
Wall Type N
2x4 - 16o.c. Framing
Wall Type Q
2x6" Double Top Plates - 16o.c. Framing
7/16" Vertical OSB Ext. Sheathing

Once the walls have been created within the model, the window, column and door types and properties can be added to the model. However, for simplicity and focus of the model, the physical properties of the windows, columns and doors are not of concern, only the quantity that is contained within each wall.

Finally, the wall component property data can be extracted from the model, including the linear length, surface area, and number of windows, columns and doors.

Lean Construction

Two techniques developed within lean construction will be implemented in an attempt to improve the production flow and production rate, and minimize wastes within the processes.

A time study will be conducted on the current state of wall fabrication and erection stations to determine a benchmark for activity durations and labour requirements. The construction of five modules (Units 744, 745, 747, 749, and 750) will be studied and documented through all stations from floor construction to finishing details; however, due to the scope of the thesis, only the data from the wall fabrication and wall erection stations will be analysed in detail. In the wall fabrication station, the duration and labour requirement will be recorded for each activity. Each wall will be constructed based on the wall type defined in the shop drawings and is composed of varying activities including the framing method, vapour barrier, sheathing, and/or drywall. As well, the amounts of time and labour requirements to move and place the walls are tabulated. Table 3 below demonstrates a typical data entry form used to obtain the time study data.

Table 3: Sample Data Entry Form

		Linear Length (ft)	Linear Length (m)	Surface Area (ft^2)	Surface Area (m^2)	# of Doors	# of Windows	# of Columns	# of Workers	Time (min)	Total # of Man Hours (min)
Unit 744 (BB)											
WP01	Wall Type B										
WP01	2x6" Double Top Plates - 16o.c. Framing	25.00	7.62	200.52	18.63	1	2	2	3	67	201
WP01	6 Mil Vapour Barrier	25.00	7.62	200.52	18.63	1	2	2	3	9	27
WP01	7/16" Vertical OSB Int. Sheathing	25.00	7.62	200.52	18.63	1	2	2	3	29	87
WP01	Single Layer 5/8" Type 'x' Drywall	25.00	7.62	200.52	18.63	1	2	2	3	22	66
WP01	Place Wall	25.00	7.62	200.52	18.63	1	2	2	3	27	81
WP02	Wall Type B										
WP02	2x6" Double Top Plates - 16o.c. Framing	1.00	0.30	8.02	0.75	0	0	0	2	5	10
WP02	6 Mil Vapour Barrier	1.00	0.30	8.02	0.75	0	0	0	2	4	8
WP02	7/16" Vertical OSB Int. Sheathing	1.00	0.30	8.02	0.75	0	0	0	2	5	10
WP02	Single Layer 5/8" Type 'x' Drywall	1.00	0.30	8.02	0.75	0	0	0		...	
WP02	Place Wall	1.00	0.30	8.02	0.75	0	0	0			
WP03	Wall Type B										
WP03	2x6" Double Top Plates - 16o.c. Framing	20.75	6.32	166.43	15.46	0	2	4			
WP03	6 Mil Vapour Barrier	20.75	6.32	166.43	15.46	0	2	4			
WP03	7/16" Vertical OSB Int. Sheathing	20.75	6.32	166.43	15.46	0	2	4		...	
WP03	Single Layer 5/8" Type 'x' Drywall	20.75	6.32	166.43	15.46	0	2	4			
WP03	Place Wall	20.75	6.32	166.43	15.46	0	2	4			
WP04	Wall Type B										
WP04	2x6" Double Top Plates - 16o.c. Framing	1.00	0.30	8.02	0.75	0	0	0			
WP04	6 Mil Vapour Barrier	1.00	0.30	8.02	0.75	0	0	0			
WP04	7/16" Vertical OSB Int. Sheathing	1.00	0.30	8.02	0.75	0	0	0		...	
WP04	Single Layer 5/8" Type 'x' Drywall	1.00	0.30	8.02	0.75	0	0	0			
WP04	Place Wall	1.00	0.30	8.02	0.75	0	0	0			
	...		...				...			...	

To further improve and identify wastes in the construction process, a detailed kaizen will be conducted on the wall fabrication and wall erection stations. A kaizen is a focused and extensive review of a single process or station within an assembly line with the underline goal of continuous improvement and elimination of waste. The eight groups of waste that will be identified in the kaizen are: motion, delay, conveyance, correction, over-processing, inventory, over-production, and knowledge disconnection (Dennis 2007). Once the waste has been identified, potential solutions will be proposed to minimize the waste as much as possible.

A kaizen is typically completed by all labour and management directly affected by the station where ideas for improvement are discussed; however, due to the time and organizational pressures, group discussions were not possible for this research. Therefore, the kaizen will be completed solely by the author using only observations of the production process. As well, the kaizen cannot be implemented in the real-world due to managerial decisions, so the effects of changes will be modelled within the simulation.

Data Analysis

Once the data has been collected from the time study, it must be analyzed for each activity to determine the statistical representation of the total time required to complete the activity. A combination of a linear optimization models and statistical curve fitting will be conducted to represent the real-world results as accurately as possible.

Since there is significant variance in the duration of each activity, a probabilistic distribution will be used to represent the total time to complete an activity. It has been assumed that the productivity was not affected based on the number of workers that are assigned to a particular activity; therefore, the duration of an activity is directly proportional to the total time of the activity as the number of workers remains constant. Since the total time to complete an activity is a probability distribution, the duration will also be a probabilistic distribution. In general, the probabilistic duration of each activity within the simulation can be shown as:

Equation 1: Probabilistic Duration

$$\boldsymbol{PD = \frac{PTT}{W}}$$

$$PD = Probabilistic\,Duration$$

$$PTT = Probabilistic\,Total\,Time\,\{probability\,function\}\,[min]$$

$$W = Number\,of\,Workers\,Utilized$$

To determine a probabilistic total time for each activity, various specialized formulas were developed based on a time study of actual production and the wall properties. Each of these formulas will be broken down and discussed within the next subsections.

Since each wall varied substantially in dimensions, components, and materials used, the total man hours cannot be used exclusively to predict the duration of the wall construction. Within the study timeframe, there were eight wall composite types used with various combinations of materials to construct the modules as well as various components added. To easily obtain all of the necessary properties from each wall, they were extracted from the BIM model. The wall properties collected were:

- Wall Type;
- Linear length of wall;
- Surface area of wall;
- Number of doors;
- Number of windows, and;
- Number of columns.

The total time (or total man hours) to complete an activity is determined based on the productivity per worker and the size of the wall that is being constructed. However, since the workers' productivity fluctuates, it can best be represented as a probability distribution function. As well, each wall is constructed uniquely with various components, such as doors, windows and columns, so an effective length of each wall must be established so that they can effectively be compared. In general, the formula for calculating the probabilistic total time for framing is:

Equation 2: Probabilistic Total Time

$$\boldsymbol{PTT = \frac{EL}{PP}}$$

$$PTT = Probablisitic\,Total\,Time\,\{\text{probability function}\}\,[min]$$

$$EL = Effective\ Length\,[ft]$$

$$PP = Probabilistic\,Productivity\{probability\,function\}\,[ft/min]$$

The effective length is determined by the linear length of the wall plus the constant coefficients multiplied by each of the other wall properties. To calculate the effective length, the following formula has been used:

Equation 3: Effective Length

$$\boldsymbol{EL = LL + A * d + B * w + C * c}$$

$$EL = Effective\,Length\,[ft]$$

$$LL = Linear\ Length\,[ft]$$

$$d = Number\,of\ Doors$$

$$w = Number\,of\,Windows$$

$$c = Number\ of\ Columns$$

$$A, B, C = Wall\ Property\ Coefficients$$

Since the length of the wall is effectively changing, the productivity will change proportionately and can be represented by the following formula:

Equation 4: Effective Productivity

$$\boldsymbol{EP = \frac{EL}{TMH}}$$

$$EP = Effective\ Producitivity$$

$$EL = Effective\ Length$$

$$TMH = Total\ Man\ Hours\ [min]$$

To calculate the non-factored productivity, the un-factored length of the wall must be divided by the total man hours. Note that if the number of doors, windows and columns have no determinable effect on linear optimization, the effective productivity will be equal to the non-factored productivity. The non-factored productivity can be represented by the following formula:

Equation 5: Non-factored Productivity

$$\boldsymbol{P = \frac{LL}{TMH}}$$

$$P = Nonfactored\ Producvitiy$$

$$LL = Linear\ Length\ [ft]$$

$$TMH = Total\ Man\ Hours$$

From the time study, the amount of time and number of workers to complete each activity was collected. For every wall fabricated, the total man hours were calculated for each activity as follows:

Equation 6: Total Man Hours

$$\boldsymbol{TMH = W * T}$$

$$TMH = Total\ Man\ Hours\ [min]$$

$$W = Number\ of\ Workers$$

$$T = Time\ for\ completion\ [min]$$

To calculate each of the wall property constants, A, B and C, in the effective length formula, a linear optimization model was constructed. Since the goal is to linearize the effective production rate, the objective function is:

Equation 7: Linear Optimization

$$\boldsymbol{Objective\ Function = \min\left(\sum |EP - AEP|\right)}$$

$$EP = Effective\ Productivity\ [ft/min]$$

$$AEP = Average\ Effective\ Productivity\ [ft/min]$$

$$Decision\ Variables = A, B, C$$

$$Constraints = A, B, C \geq 0$$

Once the decision variables have been optimized and the effective length for each wall defined, the effective productivity rate still has some variance. Therefore, probabilistic productivity must be established to account for the inconsistency in the effective productivity. The probabilistic productivity for each activity will be defined as a two point exponential, gamma, triangular or uniform distribution function. EasyFit – Distribution Fitting software will be used to calculate these distributions. Each distribution function will be tested with a Kolmogorov-Smirnov goodness of fit to determine the optimum distribution for describing the real-world productivities. The probabilistic productivity can be expressed as follows:

Equation 8: Probabilistic Productivity

$$\boldsymbol{PP} = \boldsymbol{P}(\boldsymbol{EP})$$

$$PP = Probabilistic\ Productivity\{probability\ function\}[ft/min]$$

$$EP = Effective\ Productivity[ft/min]$$

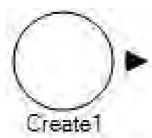
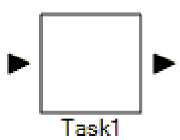
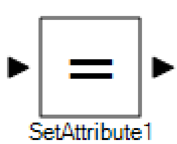
Simulation Modelling

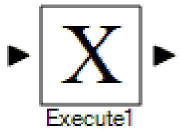
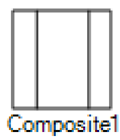
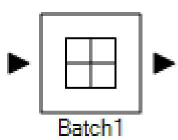
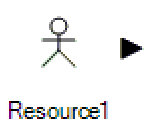
To verify and validate the changes to the manufacturing process, a simulation model will be created using Simphony.Net 3.5. Simphony.Net 3.5 is a construction oriented, general purpose discrete event simulation software developed at the University of Alberta that enables the user to model a system using process interaction concepts (Simphony.NET Development Team 2011). A general template of elements has been created which alters the properties of the entities as they pass through the system. To ensure consistency and readability, the general template will be used to construct the model.

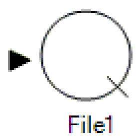
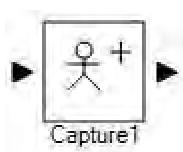
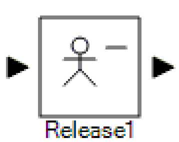
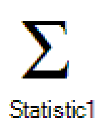
A brief description of the elements used within the simulation model is given in Table 4: Simphony.NET 3.5 General Template Elements which has been adapted from the User's

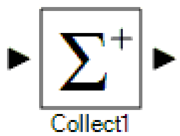
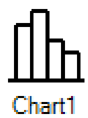
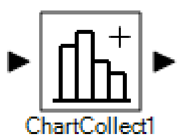
Guide for General Template in Simphony.NET 3.5 (Simphony.NET Development Team 2011).

Table 4: Simphony.NET 3.5 General Template Elements

Element Name	Symbol	Description
Create		The Create element produces entities that flow through the system. In the current simulation model, this element will define the quantity, order, and interval time spacing of the modules being called on the wall fabrication station.
Task		The Task element represents an activity in the model, such as framing, drywalling, or sheathing. A task delays the entity for a specified duration before continuing onto the next element. Within the simulation model, tasks will assign durations to each activity based on the statistical durations seen in a time study.
SetAttribute		The SetAttribute element allows the assignment of specific attributes to each of the entities that pass through them. These attributes can be referred to throughout the simulation by other elements. In the model, the SetAttribute element is used to assign the wall properties, such as linear length, number of

		doors, number of windows, and number of columns.
Execute		The Execute element is used within the general template to execute a coded expression as the entity passes through it. The Execute element allows for the coding of expressions that do not directly correlate to the other general template nodes.
Composite		The Composite element allows for a more meaningful user interface by grouping common elements together. Composites have been used mainly for grouping the SetAttribute elements for each wall within the modules and for grouping the logical order of module creation.
Batch		The Batch element combines a given number of entities and will release a single entity with either the first or last entity attributes intact. The Batch element has been used to recombine all of the wall entities into a single module entity.
Resource		The Resource element represents real-world resources such as labour or material which can simulate resource constraints within the system. The Resource element must be declared within a file that contains a queue that holds entities waiting for the resource. Capture and release elements are used to

		call for the Resource element's resources. Within the model, the resource element will represent the fabrication labour for each table and wall erection labour. As well, the Resource element will represent the wall storage station.
File		The File element defines the waiting file queue for the resource element. The File can position the entities in the queue based on the priority associated with each of them. Within the model, all walls are given the same priority so a first in – first out queue will be enforced.
Capture		When an entity passes through the Capture element, the entity attempts to access the associated resource. If there is enough of the resource based on the entity's demand, it will capture the resource. If the demand of the entity is higher than the quantity of the resource, the entity is transferred into the file queue until the resource has been released.
Release		When the entity passes through the Release element, the entity will release the quantity of the associated resource.
Statistic		The Statistic element computes statistics on parameters of interest. A statistic can be declared as

		intrinsic (time dependent) or non-intrinsic (time independent). The statistics can be displayed as histograms, cumulative distribution functions, or as time charts.
Collect		The Collect element adds observations to the Statistic element as entities pass through. There can be several Collect elements per Statistic element.
Chart		The Chart element displays the data collected by the ChartCollect element. The Chart axis can be defined in any formula from the entities.
ChartCollect		The ChartCollect element computes a data point from each entity that is received and adds it to its associated chart element.

Simulation Construction – Current State

By combining the fundamental elements, the complete simulation model of the current state can be seen in Figure 2 which represents the fabrication and erection of the walls. The entities are created at the "Start" element, pass through the system to simulation fabrication and erection, and are finally destroyed as the module moves to the next station out of the scope.

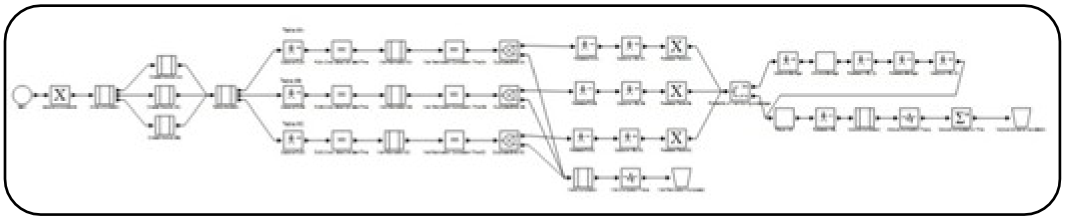


Figure 2: Simulation – Complete Current State Model

As the entities (walls) pass through the simulation model, they will capture and release various resource elements which can be seen in Figure 3. As well, the entity properties (floats, ints and strings) and statistical elements are displayed in Figure 3. To better understand and describe the simulation model, it has been broken into four sections of discussion: module creation, wall fabrication, wall fabrication completion, and wall erection.

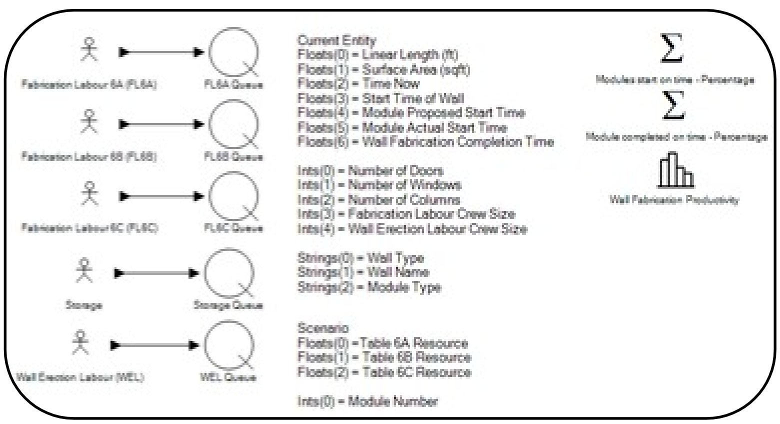


Figure 3: Simulation Model Resources and Entity Properties

Module Creation

To initiate the beginning of the model, a start element has been implemented that will create a module entity. The module entities are created at set intervals in time depending on the set flow rate of the production line. The module entity first passes through the scenario constraints element where the lengths of the framing tables are defined for the scenario. Next, the module entity enters the order of creation composite.

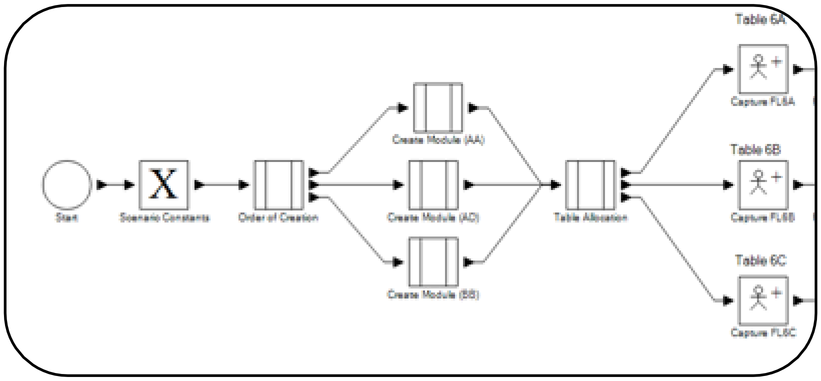


Figure 4: Simulation - Module Creation

The order of creation composite seen in Figure 5 defines which module types will be created and in which order. Within this study, three module types were produced, including modules with units AA, AD and BB types. The module entity first enters a conditional element which only allows a module to pass once the framing tables are ready to accept it. A statistic can be collected on the percentage of modules that start on time which is a good indication of the framing table's ability to maintain the designated production flow rate. Next, the module entity passes through various conditional elements to define which type of module is produced. Within the condition elements, a scenario counter is implemented to determine the order of creation. Once a module type has been chosen, a trace element displays the module type and start time of the module in the trace bar. If all of the modules have been created within the conditional statements, a trace will notify the user the simulation has been finished and destroy the module element.

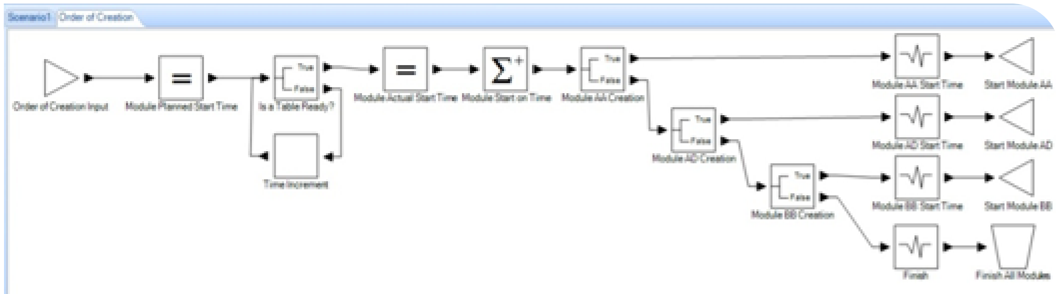


Figure 5: Order of Creation

The module entity exits the order of creation element to its respective module creation elements. A sample module creation composite can be seen in Figure 6 where the module entity is expanded into wall entities representing each wall within the module. The wall properties are defined within the entity properties including the linear length, surface area, number of doors, windows and columns, wall type, wall name and module type. Additional modules types could easily be modeled by adapting the module properties and wall types.

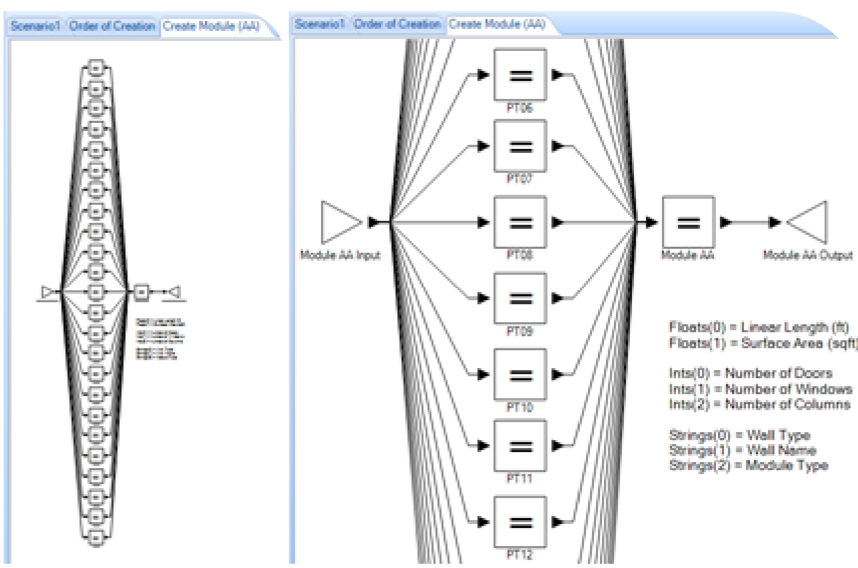


Figure 6: Create Module

Once the module entities have been created, they pass through the wall fabrication station which consists of three framing tables: 6A, 6B, and 6C seen in Figure 7. To determine the wall allocation to each table, the table allocation composite has been created.

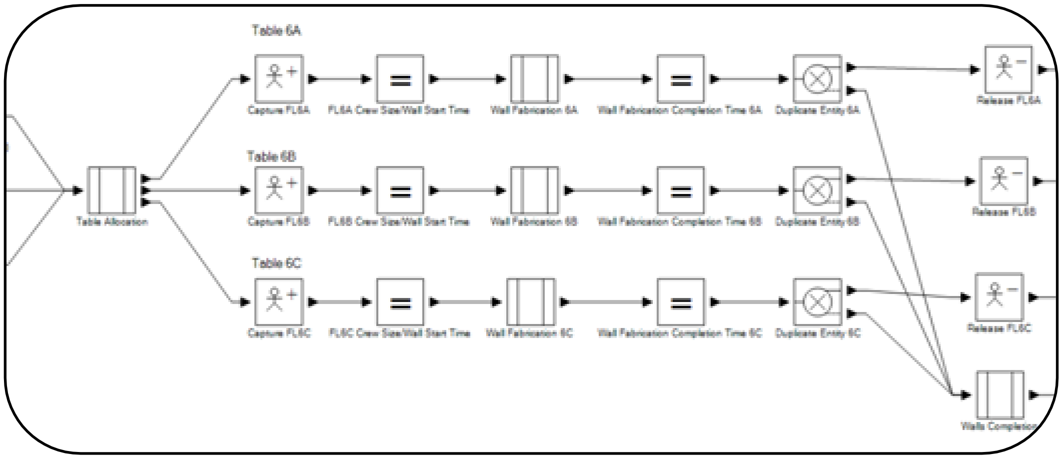


Figure 7: Simulation - Wall Fabrication

To determine the wall allocation to each framing table, a simple loop has been created. The governing factor of the table allocation is the linear length of the framing table, which has been set to 70 feet for each. If there is room on the framing table, the wall entity will be allocated to that table. If there is not room on the table, the wall entity will check if there is room on the next table. If all the tables are occupied, the remaining wall will continue through a loop with an added time increment until the table resource is available.

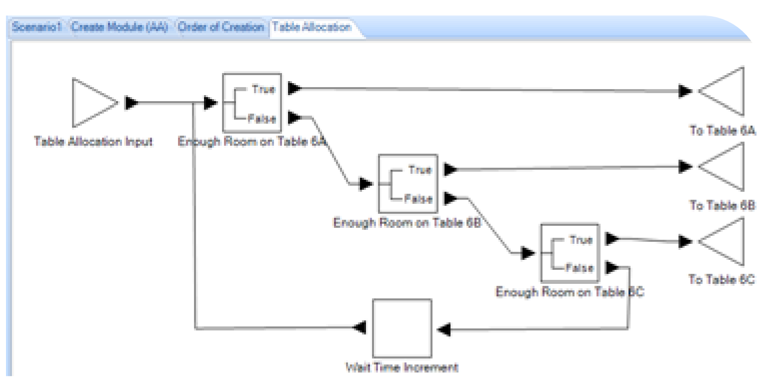


Figure 8: Table Allocation

Once a table has been assigned, a wall fabrication crew for the designated table can be selected to produce the wall. Wall fabrication crews have a defined crew size which has been set to three workers. Several crews can be assigned to a single table to each work on a separate wall; however, the crew sizes will not change. The wall start time is established and the wall enters the wall fabrication composite to be constructed. The wall entity passes through each stage of the fabrication process including framing, vapour barrier, sheathing, and drywalling. Depending on the wall type defined in the entity's properties, the duration of the fabrication is calculated based on the probabilistic total time and crew size defined in the Data Analysis section.

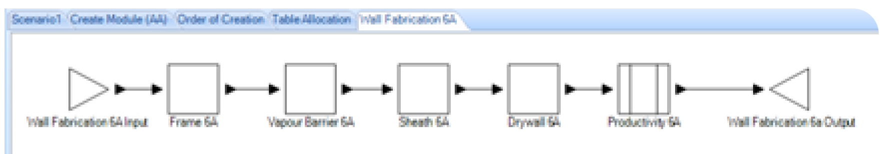


Figure 9: Wall Fabrication

To collect the wall fabrication productivity statistic based on wall type, the productivity composite has been created and can be seen in Figure 10. Each conditional element determines the wall type and directs it to its respective data collection element. If a wall type is not defined, a trace message is produced and the wall entity is destroyed.

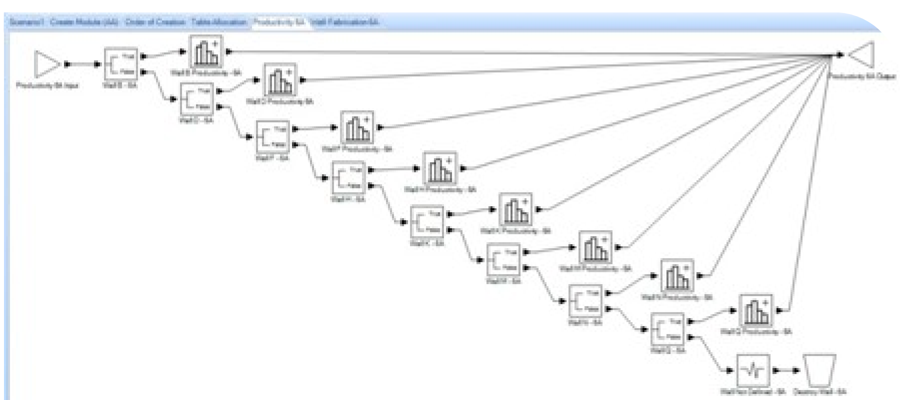


Figure 10: Fabrication Productivity

Once the wall has been fabricated, the fabrication crew is released to produce another wall. If the wall erection labour is available, they are captured and the wall is removed from the framing table, releasing the framing table resource. If the wall erection crew is unavailable, the wall will remain on the framing table and could potentially delay the production of the next wall entity. To collect a statistic on the completion time of all the module's walls, the wall entities are cloned after fabrication completion and enter the wall completion composite.

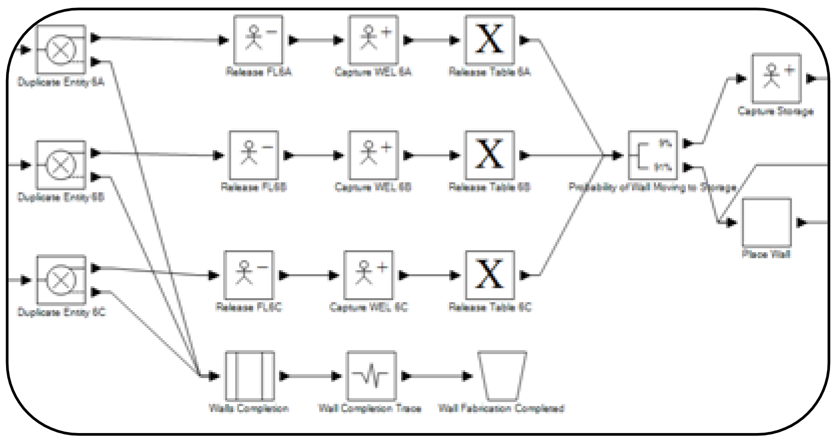


Figure 11: Simulation – Wall Fabrication Completion

The wall fabrication completion composite divides the wall entities into their perspective module types. The wall entities are batched until all walls from the module are collected and will release a single module entity. The completion time statistic is collected for each module type and the module entity is destroyed. This statistic can be used to systematically determine the probability of the duration to complete each type of module. The wall fabrication completion composite can be seen in Figure 12.

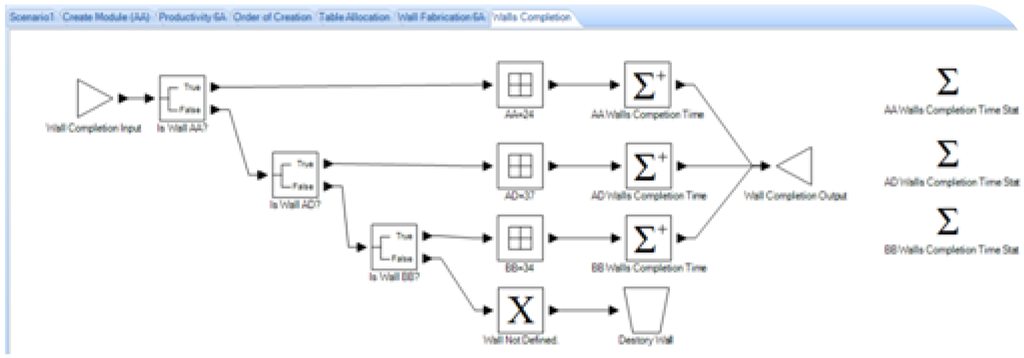


Figure 12: Wall Fabrication Completion

The final processes studied are the wall storage and wall erection stations. It was seen in the case study that 9% of the walls fabricated were sent to storage before being transferred to the wall erection station. To represent the storage time, a probabilistic element was used to direct wall entities to enter storage or move directly to wall erection. The labour requirements for both the storage and placement of walls will be based on the linear length of the wall entity as described in the Data Analysis section. Various numbers of crews and crew sizes can be implemented to determine the optimum balance between fabrication labour and wall erection labour depending on the overall production flow rate. Once the wall has been placed, the wall entity will enter the module completion composite to determine the module completion times.

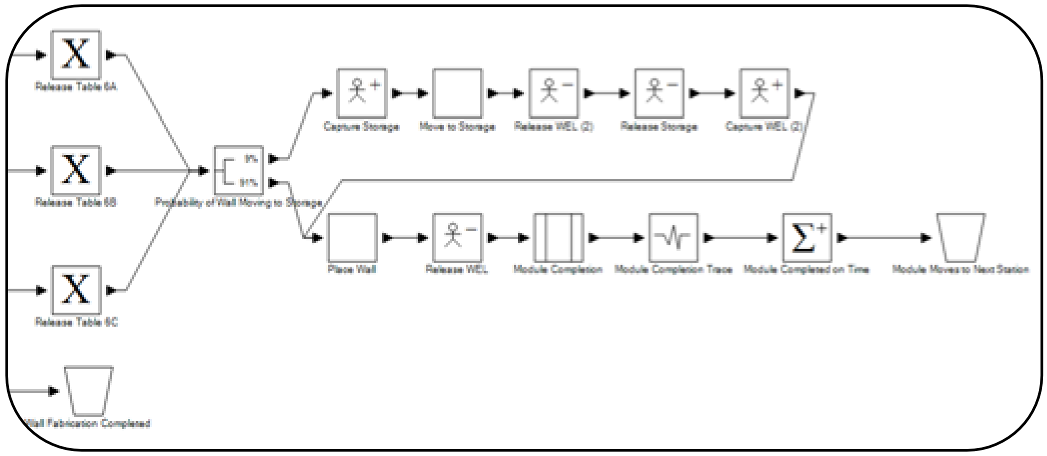


Figure 13: Simulation – Wall Erection

Figure 14 shows the module completion composite which determines the wall erection and module completion times. The module completion composite is designed similar to the wall fabrication completion composite. The wall entities are categorised based on module type and are batched until all wall entities are collected. Once all the wall entities are collected, a module entity is produced and sent to collect statistics.

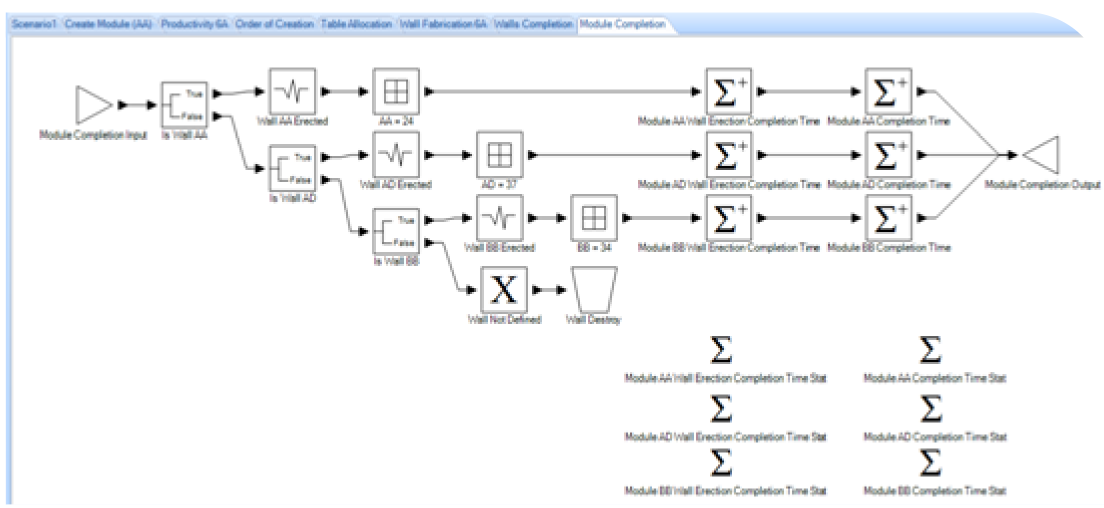


Figure 14: Module Completion

The final step in the model is to produce a trace stating the completion time of each module and collect a common statistic for the total completion time for all types of module.

Simulation Construction – Future State

To construct the future state simulation model, the principles of lean construction will be investigated and a kaizen will be implemented. In the kaizen, an alternative framing table layout will be proposed which reallocates Table 6B as a window and column fabrication station. To simulate this change, Table 6B has been removed from the simulation model, as seen in Figure 15. The increase in efficiency will mainly affect the framing task of the wall fabrication station and it has been estimated that the efficiency will be increased by 10% for this task. Therefore, only the duration of the framing task will be decreased and all other tasks will remain equivalent to the current state simulation. The wall fabrication simulation for the future state can be seen in Figure 16.

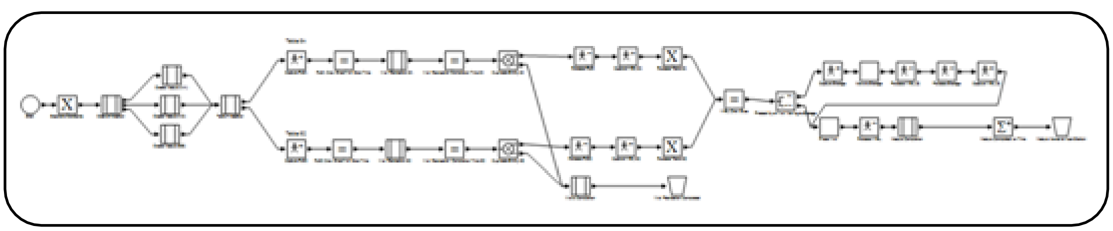


Figure 15: Simulation – Complete Future State Model

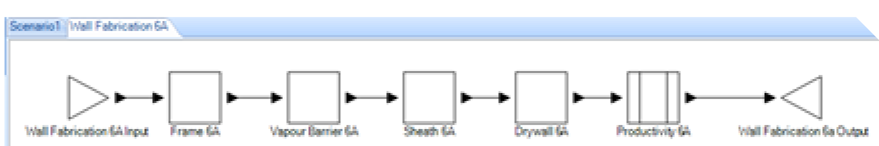


Figure 16: Wall Fabrication

APPLICATION OF IMPROVEMENT METHODS TO CASE STUDY

INTRODUCTION

The proposed methodology is implemented as a case study within this chapter. Before implementing the methodology, it is imperative to document the main stations and sub-tasks preformed in the current processes of the production line, including the wall fabrication, wall erection, and storage stations. Next, the model data will be created and extracted from the BIM model. A detailed time study and kaizen will be completed to develop improvements within the production process. The data from the time study will be statistically analyzed. Finally, a simulation model will be created in Simphony.Net 3.5 to validate the improvements.

BACKGROUND

The case study focuses on the wall manufacturing station of BCT Structures, which is one of the premier custom modular building companies in Southern Alberta. BCT Structures specializes in the construction of workforce housing, office complexes, schools, lavatories, multi-story buildings, affordable housing, kitchen facilities and other customized modular solutions. BCT Structures was opened in 2007 and offers 140,000 square feet of construction space.

The current project is the Stony Mountain Plaza by Wood Buffalo Housing, which consists of two multi-story low income seniors' complexes in Fort McMurray, Alberta. Apartment complex A and apartment complex B consist of 70 suites and 55 suites, respectfully, ranging from one to three bedrooms. Both buildings were constructed in modules (two suites per module) at the BCT factory and transported 950 km to erection site. The case study will focus on the production of 5 modules from apartment complex B as they progress through the production line, specifically the wall manufacturing station.

CURRENT PROCESS DESCRIPTION

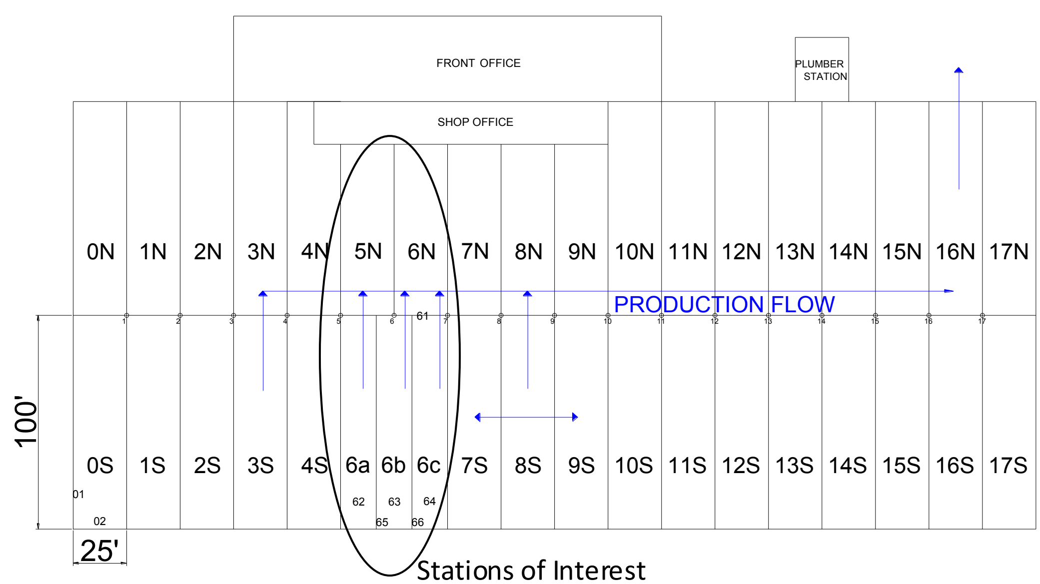


Figure 17: Manufacturing Plant Layout

Wall Fabrication Station

The wall fabrication station consists of three 70' long framing tables, stud storage, drywall storage, and two overhead cranes. It has been offset from the main flow of the production line and completed walls are lifted with the cranes. Typically, six workers are allocated to the framing tables (two per table); however, to expedite production, up to ten workers are used. To initiate the wall construction, the top and bottom plates are marked for the location of the studs, windows and doors. The layouts for all of the walls are marked prior to starting construction. The top and bottom plates are placed on the framing tables and the workers carry studs from the end of the middle table to the required locations. One worker on each side of the table nails the studs with a pneumatic nail gun at the layout locations. Second, the workers square the wall by measuring the diagonal lengths ensuring that they are equivalent. If required, a layer of ploy is applied with staples and silicone around door and window openings. Next, the workers carry the sheathing from behind the stud storage and place them on the wall. To fasten the sheathing in place, worker(s) will climb up onto the table and use a pneumatic staple gun. Since twelve foot lengths of drywall are extremely heavy, they are placed on a track that slides across the table where they are unloaded. Drywall screws secure the drywall to the wall. Using a router, the workers cut the openings for the doors and windows. Once assembled, the walls are transferred either to the wall erection station where they are attached to the floor, or placed in storage between the stations. If the wall is less than five feet in length, it is transported using one crane with a hook; however, if the wall is greater than five feet in length, rigging is bolted to the top plate of the wall for secure transport.

Figure 18: Wall Fabrication Station

Storage Station

If the walls have been completed but the wall erection station is behind, the walls are placed on the storage rack. The rack is designed to support up to three walls on each side; however, additional walls are added due to lack of space. If the storage rack is at or beyond capacity, walls are constructed on top of each other as seen in Figure 19: Storage Station. This practice of overproduction has caused damage to the surface of the drywall as well as greater potential for injury to the workers during transport and storage.

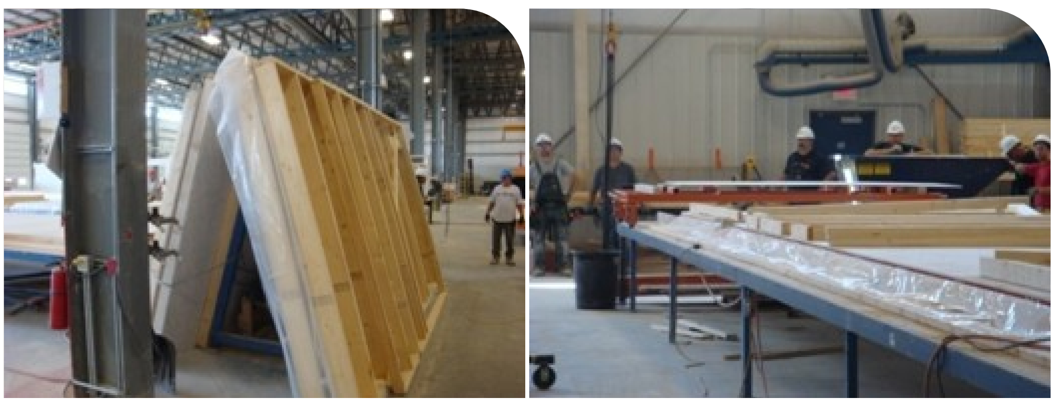


Figure 19: Storage Station

Wall Erection Station

The wall erection station is on the main assembly line and is preceded by the flooring station where the plumbing and heating systems are roughed in. To layout the wall locations, two workers manually chalk lines on the floor according to the drafting details. The first step in the wall erection process is to secure the wall to the crane with either the hook for smaller walls or rigging for larger walls. The walls can be taken from either the storage station or directly from the wall framing station as seen in Figure 20.

The first wall that is erected on each module is the WP01 which is the exterior facade of the building. The wall is positioned by two to five workers and is screwed to the flooring. If required, braces are added to support the wall before it is removed from the crane. Every additional wall is placed using the same method starting with the furthest from the framing tables. Once a sufficient number of walls have been placed, a single worker lag bolts the walls to the floor and at every joint for additional durability during transport. The final wall to be placed is the exterior corridor wall (typically WP03). Once all of the walls have been secured, the module is transported to the next station where preliminary electrical and drywall are completed.

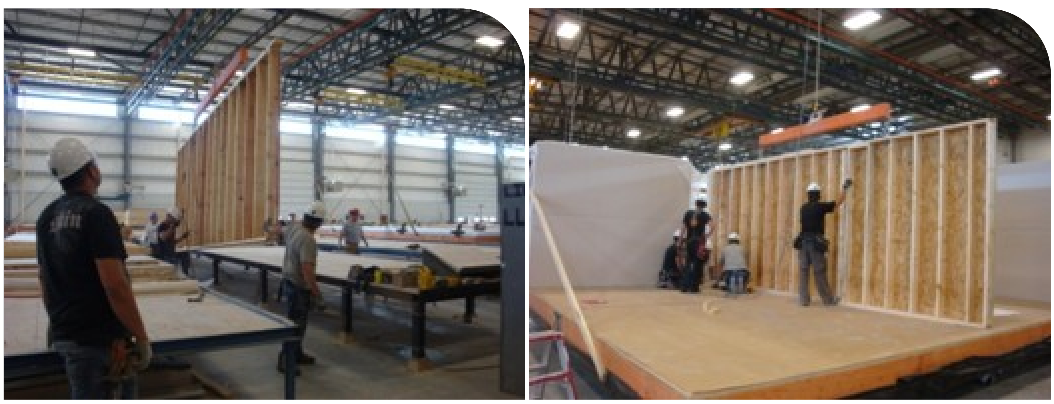


Figure 20: Erection Station

BUILDING INFORMATION MODELLING (BIM)

Using Autodesk Revit Architecture 2010, a BIM model was created for Stony Mountain Plaza apartment complex using the detailed manufacturing drawings supplied by BCT Structures in AutoCAD 2010. The first step was to create each wall type with the properties given from the manufacturing drawings. Next, the manufacturing drawings were imported into Autodesk Revit Architecture and the walls for each module were added. During the model building process, several mistakes were noted in the original manufacturing drawings due to design changes not being updated throughout each

AutoCAD drawing file. They were quickly noted and changed before production. Next, windows and doors were added with the same dimensions and materials used in the fabrication process to give a realistic look to the design. Additionally, flooring, roofing, cabinetry and finishes were added to several modules but have been omitted since only the wall properties are required for the scope of this project. Figure 21 demonstrates a simplistic view of a single unit of the model to demonstrate the wall properties that will be extracted.

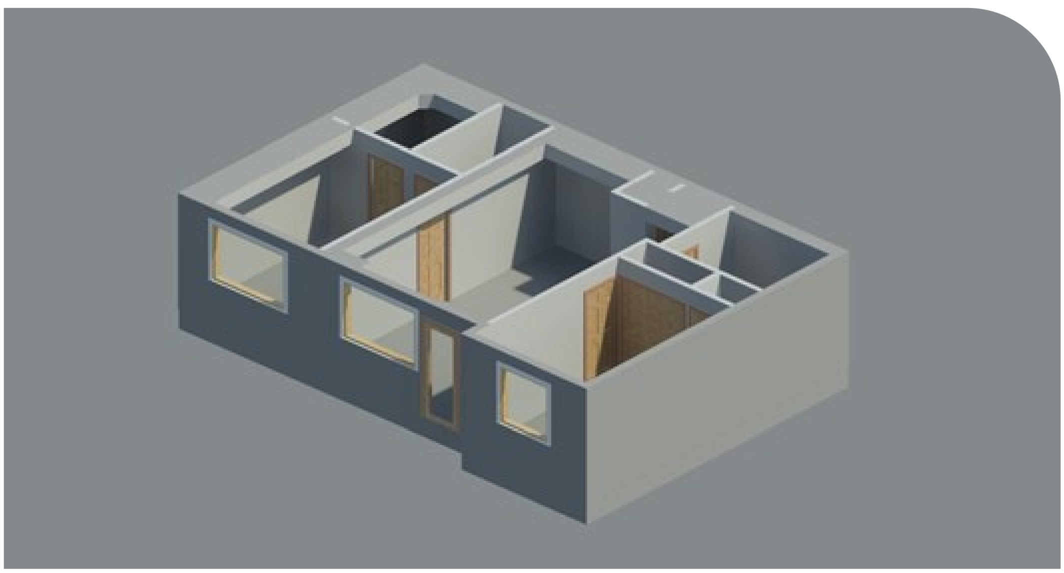


Figure 21: Typical BIM Model of Unit B

Since the company was initially unwilling to integrate BIM software into its daily applications due to software limitations, the model was produced to demonstrate that the vast capabilities of the software outweigh the limitations. However, several major software issues made it difficult to represent the modular construction process within the model. One of the main issues was the representation of wall construction in the wall fabrication station. In conventional construction, the entire structure is framed before drywall is installed, allowing for walls to be connected through their studs. However, within the wall fabrication station of modular construction, the walls are framed, and drywall is placed on one side on the framing table according to the manufacturing drawings' specifications. Once erected, the walls are joined with a layer of drywall between them. Unfortunately, common BIM software, such as Autodesk Revit, does not currently have the ability to alter the connection detail to the level desired by the industry. As well, since the walls are constructed on the framing table with only one side of drywall completed, it is imperative to relay which side is drywalled on the manufacturing drawings. However, there is no current method to alter the wall types to account for different scheduling times of wall component construction.

As well, the model was produced to effectively quantify the wall properties within each module. Table 5 through Table 9 detail the wall properties for unit 744, 746, 747, 749 and 750 that were extracted from the Revit model. The tables break down the wall number, wall type and dimensional properties, as well as the number of doors, windows, and columns. All data will be inputted into the simulation model to determine the production times. The benefits of BIM technology arise from one's ability to easily make changes to the model. If a change is made, the wall properties automatically change within the three dimensional model; however, there is currently no direct link between software packages, so the properties would have to be manually entered into the simulation model.

Table 5: Unit 744 Wall Properties

	Wall Number	Wall Type	Linear Length (ft)	Linear Length (m)	Surface Area (ft^2)	Surface Area (m^2)	# of Doors	# of Windows	# of Columns
Unit 744 (BB)									
	WP01	B	25.00	7.62	200.52	18.63	1	2	2
	WP02	B	1.00	0.30	8.02	0.75	0	0	0
	WP03	B	20.75	6.32	166.43	15.46	0	2	4
	WP04	B	1.00	0.30	8.02	0.75	0	0	0
	WP05	B	25.00	7.62	200.52	18.63	1	2	2
	WP06	D	20.81	6.34	166.93	15.51	0	0	0
	WP07	F	69.83	21.28	560.09	52.03	2	0	4
	WP08	D	20.81	6.34	166.93	15.51	0	0	0
	PT01	H	20.81	6.34	166.93	15.51	1	0	0
	PT02	H	10.48	3.19	84.06	7.81	2	0	0
	PT03	H	7.95	2.42	63.77	5.92	0	0	0
	PT04	H	3.00	0.91	24.06	2.24	0	0	0
	PT05	H	2.83	0.86	22.70	2.11	0	0	0
	PT06	H	6.50	1.98	52.14	4.84	1	0	0
	PT07	M	1.50	0.46	12.03	1.12	0	0	0
	PT08	N	2.33	0.71	18.69	1.74	0	0	0
	PT09	K	9.50	2.90	76.20	7.08	0	0	0
	PT10	H	2.17	0.66	17.41	1.62	0	0	0
	PT11	H	9.17	2.80	73.55	6.83	2	0	0
	PT12	H	14.00	4.27	112.29	10.43	1	0	0
	PT13	Q	20.81	6.34	166.93	15.51	0	0	0
	PT14	Q	20.81	6.34	166.93	15.51	0	0	0
	PT15	H	14.00	4.27	112.29	10.43	1	0	0
	PT16	H	9.17	2.80	73.55	6.83	2	0	0
	PT17	H	2.17	0.66	17.41	1.62	0	0	0
	PT18	K	9.50	2.90	76.20	7.08	0	0	0
	PT19	N	2.33	0.71	18.69	1.74	0	0	0
	PT20	M	1.50	0.46	12.03	1.12	0	0	0
	PT21	H	6.50	1.98	52.14	4.84	1	0	0
	PT22	H	2.83	0.86	22.70	2.11	0	0	0
	PT23	H	3.00	0.91	24.06	2.24	0	0	0
	PT24	H	20.81	6.34	166.93	15.51	1	0	0
	PT25	H	10.48	3.19	84.06	7.81	2	0	0
	PT26	H	7.95	2.42	63.77	5.92	0	0	0

Table 6: Unit 746 Wall Properties

	Wall Number	Wall Type	Linear Length (ft)	Linear Length (m)	Surface Area (ft^2)	Surface Area (m^2)	# of Doors	# of Windows	# of Columns
Unit 746 (AD)									
	WP01	F	64.88	19.77	520.35	48.34	2	0	6
	WP02	D	20.81	6.34	166.93	15.51	0	0	0
	WP03	B	64.88	19.77	520.35	48.34	2	5	4
	WP04	B	20.81	6.34	166.93	15.51	0	0	0
	PT01	H	3.00	0.91	24.06	2.24	0	0	0
	PT02	H	2.60	0.79	20.85	1.94	0	0	0
	PT03	H	6.50	1.98	52.14	4.84	1	0	0
	PT04	M	1.50	0.46	12.03	1.12	0	0	0
	PT05	N	2.33	0.71	18.69	1.74	0	0	0
	PT06	K	10.25	3.12	82.21	7.64	0	0	0
	PT07	H	10.25	3.12	82.21	7.64	2	0	0
	PT08	H	2.17	0.66	17.41	1.62	0	0	0
	PT09	H	14.33	4.37	114.94	10.68	1	0	0
	PT10	Q	20.81	6.34	166.93	15.51	0	0	0
	PT11	Q	20.81	6.34	166.93	15.51	0	0	0
	PT12	M	1.50	0.46	12.03	1.12	0	0	0
	PT13	N	2.33	0.71	18.69	1.74	0	0	0
	PT14	K	13.25	4.04	106.28	9.87	1	0	0
	PT15	H	9.67	2.95	77.56	7.21	2	0	0
	PT16	H	2.17	0.66	17.41	1.62	0	0	0
	PT17	H	2.17	0.66	17.41	1.62	0	0	0
	PT18	H	6.50	1.98	52.14	4.84	1	0	0
	PT19	H	2.33	0.71	18.69	1.74	0	0	0
	PT20	H	2.42	0.74	19.41	1.80	0	0	0
	PT21	H	5.25	1.60	42.11	3.91	1	0	0
	PT22	H	2.75	0.84	22.06	2.05	0	0	0
	PT23	H	8.81	2.69	70.68	6.57	0	0	0
	PT24	H	2.00	0.61	16.04	1.49	0	0	0
	PT25	H	5.33	1.62	42.75	3.97	1	0	0
	PT26	H	12.17	3.71	97.61	9.07	1	0	0
	PT27	H	2.00	0.61	16.04	1.49	0	0	0
	PT28	H	5.33	1.62	42.75	3.97	1	0	0
	PT29	H	3.42	1.04	27.41	2.55	1	0	0
	PT30	H	5.83	1.78	46.79	4.35	1	0	0
	PT31	H	7.92	2.41	63.53	5.90	0	0	0
	PT32	H	7.92	2.41	63.53	5.90	0	0	0
	PT33	H	14.00	4.27	112.29	10.43	0	0	0

Table 7: Unit 747 Wall Properties

	Wall Number	Wall Type	Linear Length (ft)	Linear Length (m)	Surface Area (ft^2)	Surface Area (m^2)	# of Doors	# of Windows	# of Columns
Unit 747 (AA)									
	WP01	F	48.00	14.63	385.00	35.77	2	0	4
	WP02	D	22.00	6.71	176.46	16.39	0	0	0
	WP03	B	48.00	14.63	385.00	35.77	2	4	4
	WP04	D	22.00	6.71	176.46	16.39	0	0	0
	PT01	H	3.00	0.91	24.06	2.24	0	0	0
	PT02	H	2.66	0.81	21.34	1.98	0	0	0
	PT03	H	6.50	1.98	52.14	4.84	1	0	0
	PT04	M	1.50	0.46	12.03	1.12	0	0	0
	PT05	N	2.33	0.71	18.69	1.74	0	0	0
	PT06	K	10.25	3.12	82.21	7.64	0	0	0
	PT07	H	10.25	3.12	82.21	7.64	2	0	0
	PT08	H	2.20	0.67	17.65	1.64	0	0	0
	PT09	H	14.33	4.37	114.94	10.68	1	0	0
	PT10	Q	22.00	6.71	176.46	16.39	0	0	0
	PT11	Q	22.00	6.71	176.46	16.39	0	0	0
	PT12	N	2.33	0.71	18.69	1.74	0	0	0
	PT13	M	1.50	0.46	12.03	1.12	0	0	0
	PT14	H	6.50	1.98	52.14	4.84	1	0	0
	PT15	H	2.66	0.81	21.34	1.98	0	0	0
	PT16	H	3.00	0.91	24.06	2.24	0	0	0
	PT17	K	10.25	3.12	82.21	7.64	0	0	0
	PT18	H	10.25	3.12	82.21	7.64	2	0	0
	PT19	H	2.20	0.67	17.65	1.64	0	0	0
	PT20	H	14.33	4.37	114.94	10.68	1	0	0

Table 8: Unit 749 Wall Properties

	Wall Number	Wall Type	Linear Length (ft)	Linear Length (m)	Surface Area (ft^2)	Surface Area (m^2)	# of Doors	# of Windows	# of Columns
Unit 749 (AA)									
	WP01	F	48.00	14.63	385.00	35.77	2	0	4
	WP02	D	22.00	6.71	176.46	16.39	0	0	0
	WP03	B	48.00	14.63	385.00	35.77	2	4	4
	WP04	D	22.00	6.71	176.46	16.39	0	0	0
	PT01	H	3.00	0.91	24.06	2.24	0	0	0
	PT02	H	2.66	0.81	21.34	1.98	0	0	0
	PT03	H	6.50	1.98	52.14	4.84	1	0	0
	PT04	M	1.50	0.46	12.03	1.12	0	0	0
	PT05	N	2.33	0.71	18.69	1.74	0	0	0
	PT06	K	10.25	3.12	82.21	7.64	0	0	0
	PT07	H	10.25	3.12	82.21	7.64	2	0	0
	PT08	H	2.20	0.67	17.65	1.64	0	0	0
	PT09	H	14.33	4.37	114.94	10.68	1	0	0
	PT10	Q	22.00	6.71	176.46	16.39	0	0	0
	PT11	Q	22.00	6.71	176.46	16.39	0	0	0
	PT12	N	2.33	0.71	18.69	1.74	0	0	0
	PT13	M	1.50	0.46	12.03	1.12	0	0	0
	PT14	H	6.50	1.98	52.14	4.84	1	0	0
	PT15	H	2.66	0.81	21.34	1.98	0	0	0
	PT16	H	3.00	0.91	24.06	2.24	0	0	0
	PT17	K	10.25	3.12	82.21	7.64	0	0	0
	PT18	H	10.25	3.12	82.21	7.64	2	0	0
	PT19	H	2.20	0.67	17.65	1.64	0	0	0
	PT20	H	14.33	4.37	114.94	10.68	1	0	0

Table 9: Unit 750 Wall Properties

	Wall Number	Wall Type	Linear Length (ft)	Linear Length (m)	Surface Area (ft^2)	Surface Area (m^2)	# of Doors	# of Windows	# of Columns
Unit 750 (DA)									
	WP01	F	64.88	19.77	520.35	48.34	2	0	6
	WP02	B	20.81	6.34	166.93	15.51	0	0	0
	WP03	B	64.88	19.77	520.35	48.34	2	5	4
	WP04	D	20.81	6.34	166.93	15.51	0	0	0
	PT01	H	5.33	1.62	42.75	3.97	1	0	0
	PT02	H	2.00	0.61	16.04	1.49	0	0	0
	PT03	H	8.81	2.69	70.68	6.57	0	0	0
	PT04	H	12.17	3.71	97.61	9.07	1	0	0
	PT05	H	2.00	0.61	16.04	1.49	0	0	0
	PT06	H	5.33	1.62	42.75	3.97	1	0	0
	PT07	H	3.42	1.04	27.41	2.55	1	0	0
	PT08	H	5.83	1.78	46.79	4.35	1	0	0
	PT09	H	7.92	2.41	63.53	5.90	0	0	0
	PT10	H	7.92	2.41	63.53	5.90	0	0	0
	PT11	H	2.83	0.86	22.70	2.11	0	0	0
	PT12	H	2.42	0.74	19.41	1.80	0	0	0
	PT13	H	5.00	1.52	40.10	3.73	0	0	0
	PT14	H	2.33	0.71	18.69	1.74	0	0	0
	PT15	H	6.50	1.98	52.14	4.84	1	0	0
	PT16	M	1.50	0.46	12.03	1.12	0	0	0
	PT17	N	2.33	0.71	18.69	1.74	0	0	0
	PT18	K	13.25	4.04	106.28	9.87	1	0	0
	PT19	H	14.00	4.27	112.29	10.43	0	0	0
	PT20	H	2.17	0.66	17.41	1.62	0	0	0
	PT21	H	2.17	0.66	17.41	1.62	0	0	0
	PT22	H	9.67	2.95	77.56	7.21	2	0	0
	PT23	Q	20.81	6.34	166.93	15.51	0	0	0
	PT24	Q	20.81	6.34	166.93	15.51	0	0	0
	PT25	M	1.50	0.46	12.03	1.12	0	0	0
	PT26	N	2.33	0.71	18.69	1.74	0	0	0
	PT27	H	6.50	1.98	52.14	4.84	1	0	0
	PT28	K	10.25	3.12	82.21	7.64	0	0	0
	PT29	H	2.17	0.66	17.41	1.62	0	0	0
	PT30	H	10.25	3.12	82.21	7.64	2	0	0
	PT31	H	14.33	4.37	114.94	10.68	1	0	0
	PT32	H	2.60	0.79	20.85	1.94	0	0	0
	PT33	H	3.00	0.91	24.06	2.24	0	0	0

LEAN CONSTRUCTION

To fully understand why the wall fabrication station and wall erection station were not maintaining a consistent production time, a kaizen was completed to identify the underlying wastes, or muda, in the system. In lean construction, a kaizen is a focused study on a specific task of a manufacturing process to achieve continual improvement. The typical kaizen should be completed by all management and workers that are associated with the work station; however, permission was not granted to interrupt production or management due to the timelines of the project. Therefore, the kaizen was completed strictly as an observational approach for the entirety of the construction of the five modules. The eight groups of waste that were identified in the kaizen are: motion, delay, conveyance, correction, over-processing, inventory, over-production, and knowledge disconnection (Dennis 2007).

Motion

Poor ergonomic design of a modular manufacturing facility can negatively affect productivity, quality and safety. Productivity suffers when there is unnecessary walking, reaching, or twisting, which can directly affect the quality as workers strain to complete their tasks. Ergonomic injuries comprise more than 50% of all workplace injuries in North America (Dennis 2007). Therefore, every task completed in the fabrication and erection of the walls should be reviewed to eliminate as much motion waste as possible.

In the wall fabrication station, significant motion waste was observed as workers carried all of the materials from the end of the framing table to their desired location, as seen in the current state configuration in Figure 22. Since the framing tables were seventy feet long, the transport of the studs took 36% of the total framing time with the workers carrying only two or three studs at a time. As walls were completed on the table, the workers would have to walk further to construct the next wall, significantly lowering the production rate of the framing. To minimize the waste in motion, the studs should be located central to the framing tables; however, site layout restricts such action with three long tables. Therefore, an alternative would be to remove the center framing table or shorten it to allow adequate space for material lay down area central to the framing tables. The shortened central table would be dedicated to producing window frames and columns for the exterior walls. The workers from the center line would be transferred to the other lines which would increase the productivity. The increased efficiency of the remaining two framing tables may offset the loss of the third table and produce a better just-in-time flow of walls to the wall erection station by decreasing the cycle time. The future state framing table configuration can be seen in Figure 24.

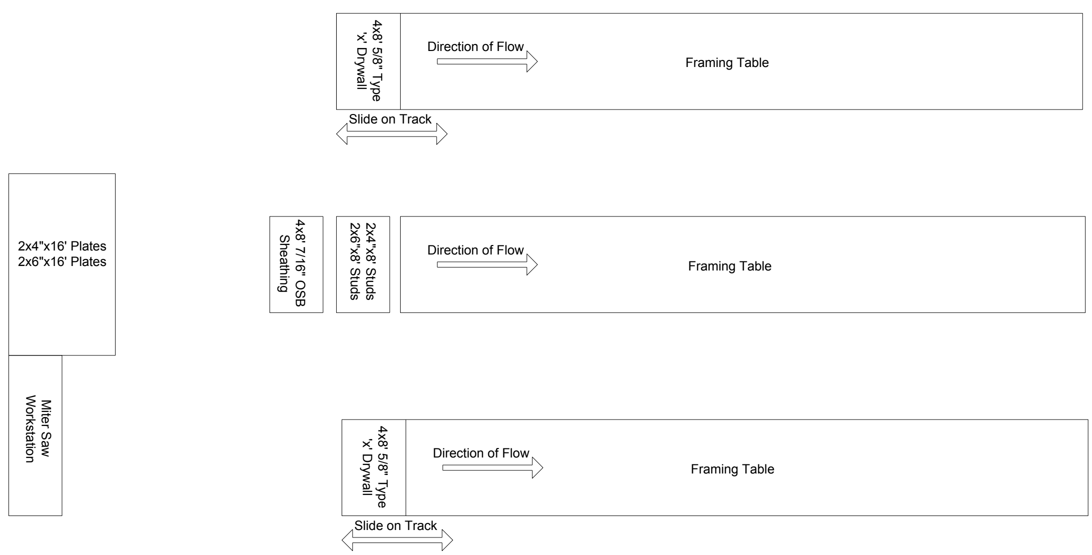


Figure 22: Faming Table Current State Configuration

Figure 23: Framing Table Current State Photos

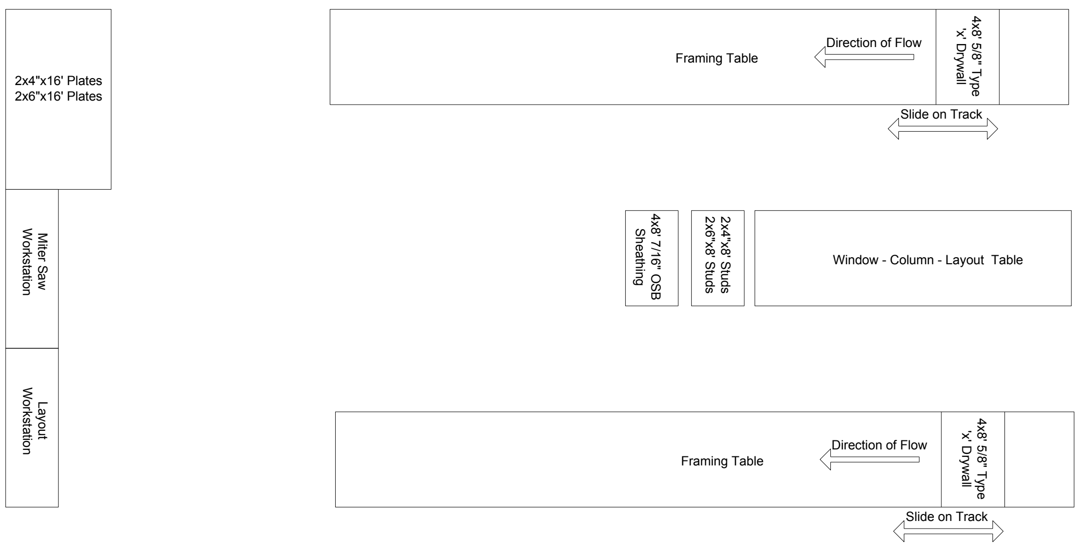


Figure 24: Framing Table Future State Configuration

Delay

A major source of muda was the delays in production due to an overall, non-balanced line flow. A key decision made by management was to construct the fourth floor modules in numerical order first and continue downward throughout the building. This decision was made for easier storage of the modules in the yard where a first in – last out system was utilized. However, this method does not consider the flow of production. To help balance the production flow, the unit schedule should start with the smaller square footage modules and progress to the larger ones. Since each module is a combination of two unit types, the amount of man hours required to construct each module differs substantially. In theory, by starting the smaller modules first, a pull system would be created where downstream stations would be ready for the next module when the line moved. However, in current practise, once the fourth floor is completed, the third floor larger modules are scheduled directly after the smaller fourth floor modules, causing a push flow and major time delays with earlier stations.

While studying the wall fabrication station, it became apparent that the flow of work was not consistent, and the workers were frequently idle until the production line progressed. At times, the wall fabrication station would be shut down for an entire day to allow the upstream stations to progress. However, once the wall fabrication station was reopened the next day, it would be behind and struggled to catch up, causing fluctuations in flow which rippled throughout the line. This delay in the overall production flow was mainly a result of a bottleneck created by the drywall mudding process which consistently slowed the line. Stony Mountain Plaza is the first residential housing project to use traditional drywall by BCT Structures. Furthermore, the majority of the labour was untrained and new so it is expected that a more balanced production flow will be achieved once labour requirements have been balanced between departments.

Conveyance

Conveyance waste is mainly observed in the transfer of the walls from the fabrication to the wall erection station. After the wall has been assembled, it is lifted with over-head cranes and transferred to the erection station. Typically, the first wall produced on the framing table is completed at the furthest point from the wall erection station since it is the closest point to the current material storage location. However, this positioning causes excessive conveyance waste since the majority of the wall is created at the furthest distance from the next step. To alleviate this conveyance waste, the wall fabrication station should be reconfigured, as proposed in the motion section, with the material location being transferred to a central location between the tables. As well, the first wall should be constructed at the closest point to the wall erection station, minimizing motion waste when moving the wall.

Correction

The correction of defective walls was the greatest source of waste observed during the manufacturing process. Common defects were seen on a continual basis, such as staples or screws not hitting the studs while installing the sheathing or drywall, there errors were due to an inexperienced and new workforce. By installing the sheathing and drywall on the framing tables, these defects are not seen until the wall is lifted for placement. Since each defect cannot be seen and corrected, walls had up to 96 staples which missed the stud and created extensive holes in the vapour barrier. These issues were corrected only after the wall had been erected in place, which caused a significant excess of work for the wall erection station. Typically, one or two workers were assigned exclusively to fixing mistakes created by the fabrication station. To balance the flow and increase consistency, the fabrication station must ensure perfection of each wall it produces before it is approved for and transferred to the wall erection station. To achieve this, a cultural change in the fabrication station must occur where continuous quality control checking is achieved. It is expected that the defects in the wall fabrication will decrease as the new workforce becomes better trained.

Over-Processing

Since all of the walls are constructed to specific Alberta Building Code standards, there is very little deviation in design from the given specifications. Therefore, the customer expects the finished product to abide by these specifications. All walls were eight feet and a quarter inch high with each stud placed at either sixteen or twenty-four inches on center depending on the location and function. However, while observing the wall framing, it was noted that time waste was occurring while squaring the walls. Once the studs have been nailed to the top and bottom plate, two workers must measure diagonally to the corners. If both diagonal lengths are equal, the wall is square within tolerances. For smaller walls, this process was fairly effective and would take between one to three minutes per wall. However, larger walls, such as exterior walls, were much harder to square once framed. At times, larger walls would require four workers with the use of a sledge hammer up to fifteen minutes to reposition the framed wall, accounting for an hour of total time. To limit this wasted time and energy, the framing tables should be fitted with standardized jigs that will accommodate both sixteen and twenty-four foot spacing and will automatically square the wall. Workers would only be required to position each stud in the correct jig location and it would be ready to nail to the bottom and top plates. As well, by using a jig, the layout time would be greatly reduced since only the location of doors and windows would be required. In the proposed redesign of the wall fabrication station, a shorter table 6B was introduced that was dedicated to the construction of windows and doors. Once the windows and doors are completed, they would be transferred onto framing tables A and C where they would be secured in place. By introducing stud spacing jigs, reconfiguring the table layout and function, and maintaining a steady flow, the over-processing of the wall fabrication will be minimized and value-added productivity will increase.

<u>Inventory</u>

While observing the operations of the wall fabrication station, it seemed that the inventory levels of raw materials, such as studs, sheathing and drywall, were adequate for the demand. There was space for approximately one shift worth of material located at the end of the framing tables; however, a signal to replenish the inventory was occasionally given too late and the remaining material would run out before it could be replenished. All of the raw material is stored away from the production line in a warehouse where forklifts transfer the materials by the pallet. It is up to the forklift operator to identify when the materials are getting low and to resupply the station. If the material reaches a critical level, the supervisor radios the forklift operator and requests delivery. This procedure is effective in the majority of instances; however, if the forklift operator is busy with another task, such as moving the line or restocking other areas, response delays as high as 45 minutes could occur. The current system fails to identify and convey the issue of material shortage at the appropriate time, causing delays which ripple through the entire production line flow. To correct this issue, a kanban, a small sign signalling the supply of the material, should be implemented at all of the stations in the plant. Three colors should be used: green, yellow, and red. Green would represent that all of the material is in good supply. A yellow sign would indicate that restocking is required in the next hour and a red sign would indicate that restocking is required immediately. This system would allow the forklift operators to glance over the production floor and determine the priorities of material delivery and ensure all inventory levels are maintained at effective levels.

Over-Production

A major form of waste is the excessive use of the storage station caused by over-production. If the fabrication station is over-producing relative to the wall erection station, the walls are continually placed in the storage station. As more walls are added to the storage station, the time required to ensure safe placement of each wall increases substantially. Almost all of the time spent placing and securing the walls in the storage station is waste and steps should be taken to minimize the use of the storage station. To achieve this, the wall fabrication and wall erection stations should balance their flow by creating a pull system. A new wall should only be fabricated once a completed wall has been taken from the table to be placed onto the floor. This will ensure that the wall is only moved once, minimizing the conveyance waste. Since the walls will be produced as single wall batches, the table effectively become the storage of completed walls to ensure a buffer. However, during the construction of larger walls, such as the exterior walls, the table must have enough room to accommodate the length of the wall. Therefore, all of the walls should be removed from the table and placed in the storage station while larger walls are being constructed, ensuring that the buffer remains between the two stations. By implementing this method, the number of walls in the storage station should never exceed two per side which will minimize the amount of time waste to secure the walls to the storage station.

Knowledge-Disconnect

As with many manufacturing industries, a significant knowledge-disconnect is present in the communication between the office and the manufacturing floor in the form of the 2D detailed design and drafting. The only document that was transferred from the office to the manufacturing floor was a detailed plan view of the module being constructed. For each module, the wall fabrication station supervisor would manually interpret the plans and choose the location of the studs depending on the separation requirements and the door and window locations. This was a tedious task which would take the supervisor on average 1.03 min/ft, resulting in a total time between 4.8 to 6.7 hours per module depending on the size. Since the calculations and layout were manually completed, each module would require the same amount of labour even though the entire complex was effectively composed of only four suite types. As well, there is a higher probability of defects in the layout due to the tediousness of the work. Therefore, significant gains could be achieved on the manufacturing floor if a more in depth set of drafting plans were supplied to the supervisor. To achieve better drafting, BIM was employed to create sophisticated 3D models of the suites which could model the stud locations without performing calculations on the shop floor.

DATA ANALYSIS

Since all of the activities in the wall fabrication station and erection station have similar processes involving labour and equipment, a standardized set of equations can be utilized to define the probabilistic productivity distribution for each. A detailed description and definition of all the equations used can be found in the proposed methodology. The main activities that will be analyzed are framing of the walls and installation of vapour barrier, sheathing, and drywall. As well, temporary storage and wall erection will be analyzed.

Calculation of Framing

Since there are various dimensional lumber and construction standards used depending on the wall type, several framing methods have been identified. Each wall of every module was constructed to one of the following framing methods.

- 2x6" Double Top Plates – 16o.c. Framing
- 2x4" – 16o.c. Framing
- 2x6" – 16o.c. Framing

The wall properties were isolated with their corresponding labour and time requirements to create a detailed analysis and determine the probabilistic productivity.

2x6" Double Top Plates – 16o.c. Framing

To determine the probabilistic productivity of 2x6" Double Top Plates – 16o.c. Framing, all of the walls with the given framing method have been tabulated in Table 10 below. The productivity rate of each wall production can easily be calculated from Equation 5 on page 29; however, there is a great amount of variability due to other factors such as the number of doors, windows and columns. Therefore, the effective length of the wall must be established to better represent the variability in the wall structure. To determine the effective length, the correction coefficients A, B, and C must be determined with the use of a linear optimization model. The goal is to adjust the coefficients to optimize a linear line of best fit through the data point while achieving as close to a steady production as possible. Therefore, the optimization function is determined to be the sum of the differences between the average productivity and the effective productivity for each wall. The findings for each wall can be seen in Table 10 with the coefficient values and objective function value found in Table 11.

Table 10: 2x6" Double Top Plate – 16o.c. Framing Productivity Rates

	Linear Length (ft)	Surface Area (ft^2)	# of Doors	# of Windows	# of Columns	# of Workers	Time (min)	Total # of Man Hours (min)	Production Rate (ft/min)	Effective Length (ft)	Effective Productivity Rate (ft/min)	Difference
2x6" Double Top Plates - 16o.c. Framing												
Unit 744												
WP01	25.00	200.52	1	2	2	3	67	201	0.12	38.42	0.19	0.18
WP02	1.00	8.02	0	0	0	2	5	10	0.10	1.00	0.10	0.28
WP03	20.75	166.43	0	2	4	3	55	165	0.13	30.75	0.19	0.19
WP04	1.00	8.02	0	0	0	2	5	10	0.10	1.00	0.10	0.28
WP05	25.00	200.52	1	2	2	3	72	216	0.12	38.42	0.18	0.20
WP06	20.81	166.93	0	0	0	3	26	78	0.27	20.81	0.27	0.11
WP07	69.83	560.09	2	0	4	4	84	336	0.21	90.65	0.27	0.11
WP08	20.81	166.93	0	0	0	3	24	72	0.29	20.81	0.29	0.09
PT13	20.81	166.93	0	0	0	2	25	50	0.42	20.81	0.42	0.04
PT14	20.81	166.93	0	0	0	2	18	36	0.58	20.81	0.58	0.20
Unit 746												
WP01	64.88	520.35	2	0	6	2	120	240	0.27	89.19	0.37	0.00
WP02	20.81	166.93	0	0	0	3	28	84	0.25	20.81	0.25	0.13
WP03	64.88	520.35	2	5	4	3	113	339	0.19	93.23	0.28	0.10
WP04	20.81	166.93	0	0	0	4	35	140	0.15	20.81	0.15	0.23
PT10	20.81	166.93	0	0	0	3	12	36	0.58	20.81	0.58	0.20
PT11	20.81	166.93	0	0	0	2	25	50	0.42	20.81	0.42	0.04
Unit 747												
WP01	48.00	385.00	2	0	4	2	110	220	0.22	68.82	0.31	0.06
WP02	22.00	176.46	0	0	0	2	31	62	0.35	22.00	0.35	0.02
WP03	48.00	385.00	2	4	4	1	110	110	0.44	74.84	0.68	0.30
WP04	22.00	176.46	0	0	0	1	31	31	0.71	22.00	0.71	0.33
PT10	22.00	176.46	0	0	0	1	36	36	0.61	22.00	0.61	0.24
PT11	22.00	176.46	0	0	0	2	16	32	0.69	22.00	0.69	0.31
Unit 749												
WP01	48.00	385.00	2	0	4	1	180	180	0.27	68.82	0.38	0.01
WP02	22.00	176.46	0	0	0	2	19	38	0.58	22.00	0.58	0.20
WP03	48.00	385.00	2	4	4	2	240	480	0.10	74.84	0.16	0.22
WP04	22.00	176.46	0	0	0	2	14	28	0.79	22.00	0.79	0.41
PT10	22.00	176.46	0	0	0	2	19	38	0.58	22.00	0.58	0.20
PT11	22.00	176.46	0	0	0	2	19	38	0.58	22.00	0.58	0.20
Unit 750												
WP01	64.88	520.35	2	0	6	2	123	246	0.26	89.19	0.36	0.01
WP02	20.81	166.93	0	0	0	2	39	78	0.27	20.81	0.27	0.11
WP03	64.88	520.35	2	5	4	2	124	248	0.26	93.23	0.38	0.00
WP04	20.81	166.93	0	0	0	2	45	90	0.23	20.81	0.23	0.14
PT23	20.81	166.93	0	0	0	2	55	110	0.19	20.81	0.19	0.19
PT24	20.81	166.93	0	0	0	2	32	64	0.33	20.81	0.33	0.05

Table 11: Equivalent Length Coefficients for 2x6" Double Top Plate – 16o.c. Framing

Equivalent Length Coefficients	
Door Coefficient (A)	6.92
Window Coefficient (B)	1.51
Column Coefficient (C)	1.75
Average Productivity (ft/min)	0.38
Sum of Differences	5.39
R^2	0.70

Therefore, the effective length of each wall using 2x6" double top plate framing can be represented in Equation 9.

Equation 9: Effective Length Formula for 2x6" Double Top Plates – 16o.c. Framing

$$EL = LL + 6.92d + 1.51w + 1.75c$$

Graphically, the linear length can be compared to the effective length results in Figure 25 below. It can be seen that the R-squared value for the linear length and the effective length are 0.62 and 0.70, respectfully. This demonstrates that data has been altered to better fit a constant productivity rate with the variations in wall construction taken into consideration. However, it should be noted that there is still great variability in the productivity rate so further analysis is required.

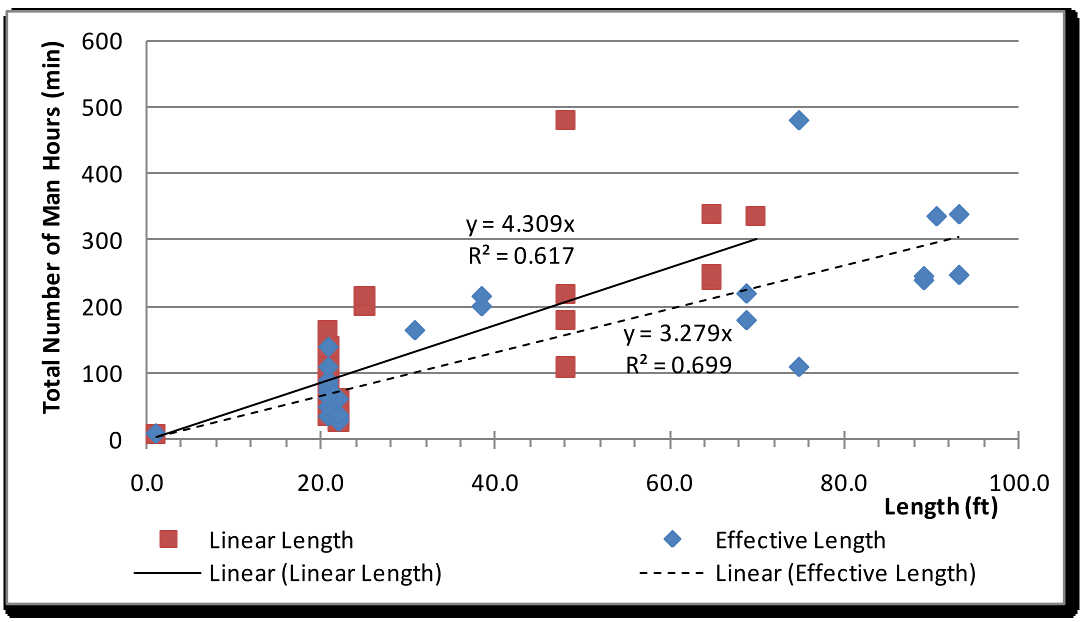


Figure 25: 2x6" Double Top Plate – 16o.c. Framing Linear Trend

With the use of EasyFit – Distribution Fitting software, a probability density function of the effective productivity was created to represent the natural variability in productivity rate. Triangular, uniform, exponential, and gamma distributions were fitted to the effective productivity rate and can be seen in Figure 26 below.

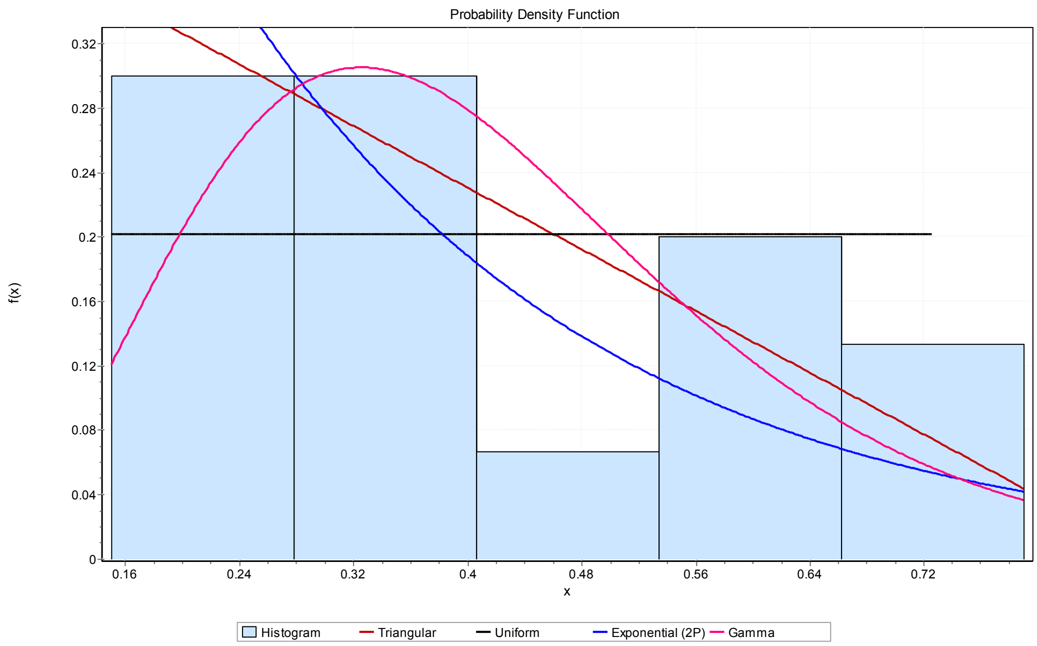


Figure 26: Probability Density Function for 2x6" Double Top Plate – 16o.c. Framing

To determine the most appropriate statistical model, the Kolmogorov-Smirnov goodness of fit test was used. The results can be seen in Table 12.

Table 12: Goodness of Fit for 2x6" Double Top Plate – 16.o.c. Framing

Goodness of Fit		
	Kolmogorov Smirnov	Ranking
Exponential (2P)	0.172	4
Gamma	0.169	3
Triangular	0.163	2
Uniform	0.145	1

From the goodness of fit test, the uniform distribution ranked the highest for representing the productivity rate, showing the variable nature of the production viewed, of 2x6” double top plate and can be calculated as follows:

Equation 10: Probabilistic Productivity Formula for 2x6” Double Top Plates – 16o.c. Framing

$$PP = Uniform\,Distribution$$

$$Low = 0.0903ft/min$$

$$High = 0.7257ft/min$$

2x4” – 16o.c. Framing

Since the same construction practices are used to construct 2x4” and 2x6” walls, a similar methodology was used to calculate the productivity of the 2x4” – 16o.c. framing. However, the major difference between the two wall types is the 2x6” walls are typically used as exterior and party walls while the 2x4” walls are typically used as partition walls within the suits. It should be noted that wall types with 2x4” framing will not have structural columns or windows as they are not found on the exterior of the module. Table 13 provides a full list of all 2x4” framed wall’s individual production rates for the five modules studied.

Table 13: 2x4" – 16o.c. Framing Productivity Rates

	Linear Length (ft)	Surface Area (ft^2)	# of Doors	# of Windows	# of Columns	# of Workers	Time (min)	Total # of Man Hours (min)	Production Rate (ft/min)	Effective Length (ft)	Effective Productivity Rate (ft/min)	Difference
2x4 - 16o.c. Framing												
Unit 744												
PT01	20.81	166.93	1	0	0	2	25	50	0.42	20.81	0.42	0.12
PT02	10.48	84.06	2	0	0	2	18	36	0.29	10.48	0.29	0.00
PT03	7.95	63.77	0	0	0	2	12	24	0.33	7.95	0.33	0.04
PT04	3.00	24.06	0	0	0	2	10	20	0.15	3.00	0.15	0.15
PT05	2.83	22.70	0	0	0	2	10	20	0.14	2.83	0.14	0.15
PT06	6.50	52.14	1	0	0	2	20	40	0.16	6.50	0.16	0.13
PT08	2.33	18.69	0	0	0	2	5	10	0.23	2.33	0.23	0.06
PT09	9.50	76.20	0	0	0	1	28	28	0.34	9.50	0.34	0.04
PT10	2.17	17.41	0	0	0		NA					
PT11	9.17	73.55	2	0	0	2	17	34	0.27	9.17	0.27	0.03
PT12	14.00	112.29	1	0	0	2	11	22	0.64	14.00	0.64	0.34
PT15	14.00	112.29	1	0	0	1	17	17	0.82	14.00	0.82	0.53
PT16	9.17	73.55	2	0	0	1	35	35	0.26	9.17	0.26	0.03
PT17	2.17	17.41	0	0	0		NA					
PT18	9.50	76.20	0	0	0	1	25	25	0.38	9.50	0.38	0.08
PT19	2.33	18.69	0	0	0	2	4	8	0.29	2.33	0.29	0.00
PT21	6.50	52.14	1	0	0	2	20	40	0.16	6.50	0.16	0.13
PT22	2.83	22.70	0	0	0	2	10	20	0.14	2.83	0.14	0.15
PT23	3.00	24.06	0	0	0	2	10	20	0.15	3.00	0.15	0.15
PT24	20.81	166.93	1	0	0	1	25	25	0.83	20.81	0.83	0.54
PT25	10.48	84.06	2	0	0	2	17	34	0.31	10.48	0.31	0.01
PT26	7.95	63.77	0	0	0	2	14	28	0.28	7.95	0.28	0.01
Unit 746												
PT01	3.00	24.06	0	0	0	2	6	12	0.25	3.00	0.25	0.05
PT02	2.60	20.85	0	0	0	2	6	12	0.22	2.60	0.22	0.08
PT03	6.50	52.14	1	0	0	2	19	38	0.17	6.50	0.17	0.12
PT05	2.33	18.69	0	0	0	2	6	12	0.19	2.33	0.19	0.10
PT06	10.25	82.21	0	0	0	4	6	24	0.43	10.25	0.43	0.13
PT07	10.25	82.21	2	0	0	4	7	28	0.37	10.25	0.37	0.07
PT08	2.17	17.41	0	0	0	2	6	12	0.18	2.17	0.18	0.12
PT09	14.33	114.94	1	0	0	4	8	32	0.45	14.33	0.45	0.15
PT13	2.33	18.69	0	0	0	2	7	14	0.17	2.33	0.17	0.13
PT14	13.25	106.28	1	0	0	2	26	52	0.25	13.25	0.25	0.04
PT15	9.67	77.56	2	0	0	2	16	32	0.30	9.67	0.30	0.01
PT16	2.17	17.41	0	0	0	3	4	12	0.18	2.17	0.18	0.12
PT17	2.17	17.41	0	0	0	3	4	12	0.18	2.17	0.18	0.12
PT18	6.50	52.14	1	0	0	2	18	36	0.18	6.50	0.18	0.12
PT19	2.33	18.69	0	0	0	2	6	12	0.19	2.33	0.19	0.10
PT20	2.42	19.41	0	0	0	2	7	14	0.17	2.42	0.17	0.12
PT21	5.25	42.11	1	0	0	2	23	46	0.11	5.25	0.11	0.18
PT22	2.75	22.06	0	0	0	2	8	16	0.17	2.75	0.17	0.12
PT23	8.81	70.68	0	0	0	2	26	52	0.17	8.81	0.17	0.13
PT24	2.00	16.04	0	0	0	2	10	20	0.10	2.00	0.10	0.20
PT25	5.33	42.75	1	0	0	2	20	40	0.13	5.33	0.13	0.16
PT26	12.17	97.61	1	0	0	2	17	34	0.36	12.17	0.36	0.06
PT27	2.00	16.04	0	0	0	3	4	12	0.17	2.00	0.17	0.13
PT28	5.33	42.75	1	0	0	2	22	44	0.12	5.33	0.12	0.17
PT29	3.42	27.41	1	0	0	2	19	38	0.09	3.42	0.09	0.21
PT30	5.83	46.79	1	0	0	2	26	52	0.11	5.83	0.11	0.18
PT31	7.92	63.53	0	0	0	4	14	56	0.14	7.92	0.14	0.15
PT32	7.92	63.53	0	0	0	4	16	64	0.12	7.92	0.12	0.17
PT33	14.00	112.29	0	0	0	2	17	34	0.41	14.00	0.41	0.12

By completing a linear optimization of the equivalent length formula, as presented in Table 14, it can be observed that the number of doors within a wall has no effect on the best fit optimized production rate. Therefore, the equivalent length will be equal to the actual length.

Table 14: Equivalent Length Coefficients for 2x4" – 16o.c. Framing

Equivalent Length Coefficients	
Door Coefficient (A)	0.00
Window Coefficient (B)	0.00
Column Coefficient (C)	0.00
Average Productivity (ft/min)	0.30
Sum of Differences	13.10
R^2	0.04

However, the extreme variability in the total man hours required per linear length of the wall can be seen in Figure 27 with an r-squared value of 0.04. From the results, it can be determined that there is effectively no relationship between the length of the wall and the construction time. The variability in the results can only be explained by the variations in the skilled labour. When the study was conducted, the majority of the workers had been recently hired due to the high project demands which skewed the results. Therefore, for simulation purposes, a probabilistic distribution must be used.

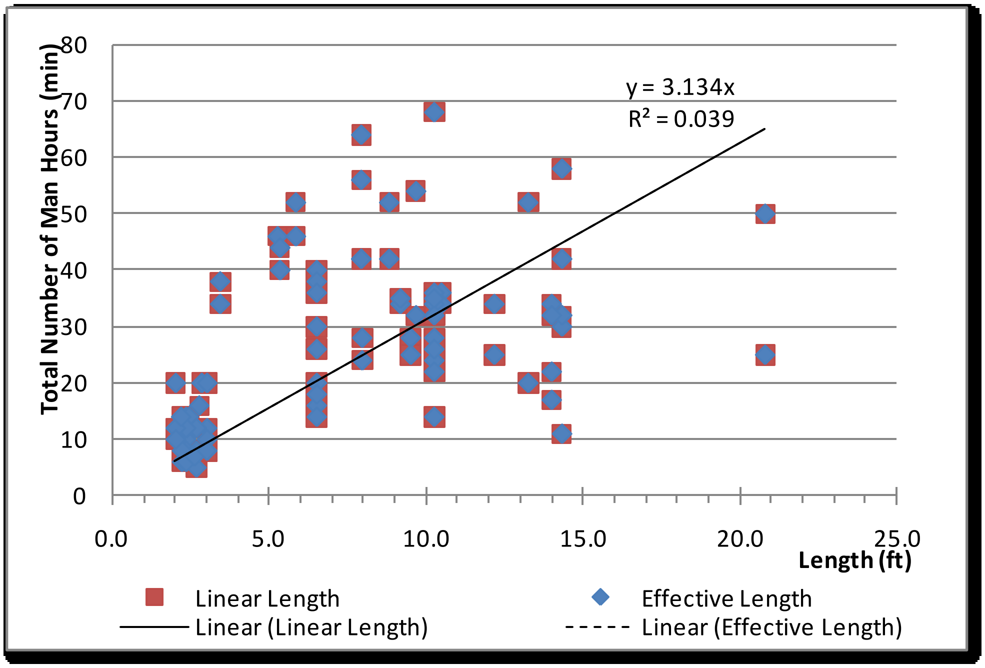


Figure 27: 2x4"– 16o.c. Framing Linear Trend

Figure 28 shows a probability density function for the 2x4" framing. It can be seen that the majority of the productivities range from 0.1ft/min to 0.4ft/min which is to be expected. To determine the best distribution, Kolmogorov-Smirnov's goodness of fit was implanted. Table 15 shows that a gamma distribution had received the best fit with 0.098.

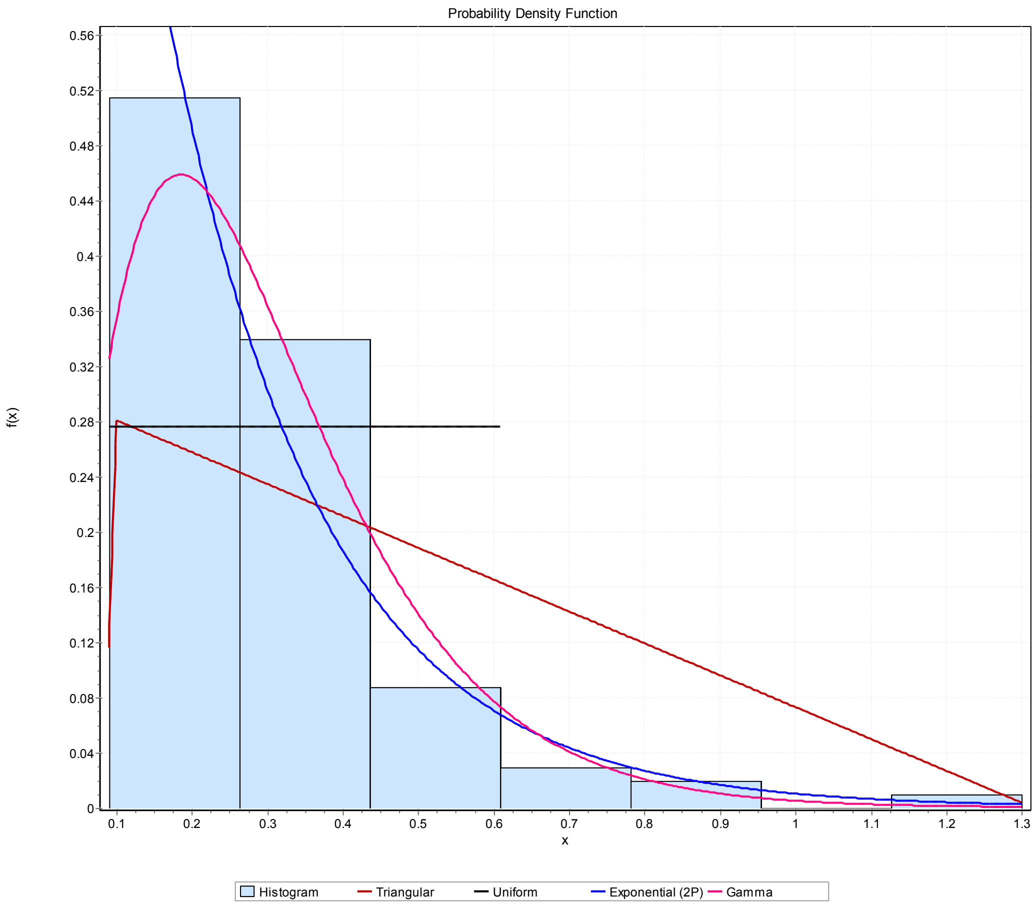


Figure 28: Probability Density Function for 2x4" – 16o.c. Framing

Table 15: Goodness of Fit for 2x4" – 16.o.c. Framing

Goodness of Fit		
	Kolmogorov Smirnov	Ranking
Exponential (2P)	0.128	2
Gamma	0.098	1
Triangular	0.39	4
Uniform	0.178	3

Finally, the probabilistic distribution can be represented as a gamma distribution, in Equation 11.

Equation 11: Probabilistic Productivity Formula for 2x4"– 16o.c. Framing

$$PP = Gamma\,Distribution$$

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

$$\alpha = 2.7248$$

$$\beta = 0.10933$$

2x6"– 16o.c. Framing

The 2x6" – 16o.c. wall framing type was only utilized as a false wall behind the tub within the suites. Since there are only two walls per suite that use this wall type, the overall effect on the construction duration is minimal; however, this information has been added for completeness of the model. All of the walls constructed had equivalent lengths of 1.50ft and did not have any other significant wall properties. Therefore, a linear optimization is not required, nor is a linear trend line. Table 16 shows the individual productivity rates for each wall constructed.

Table 16: 2x6" – 16o.c. Framing Productivity Rates

	Linear Length (ft)	Surface Area (ft^2)	# of Doors	# of Windows	# of Columns	# of Workers	Time (min)	Total # of Man Hours (min)	Production Rate (ft/min)
2x6" - 16o.c. Framing									
Unit 744									
PT07	1.50	12.03	0	0	0	2	4	8	0.19
PT20	1.50	12.03	0	0	0	2	6	12	0.13
Unit 746									
PT04	1.50	12.03	0	0	0	2	6	12	0.13
PT12	1.50	12.03	0	0	0	2	5	10	0.15
Unit 747									
PT04	1.50	12.03	0	0	0	2	7	14	0.11
PT13	1.50	12.03	0	0	0	2	7	14	0.11
Unit 749									
PT04	1.50	12.03	0	0	0	2	2	4	0.38
PT13	1.50	12.03	0	0	0	2	3	6	0.25
Unit 749									
PT16	1.50	12.03	0	0	0		NA		
PT25	1.50	12.03	0	0	0	2	4	8	0.19

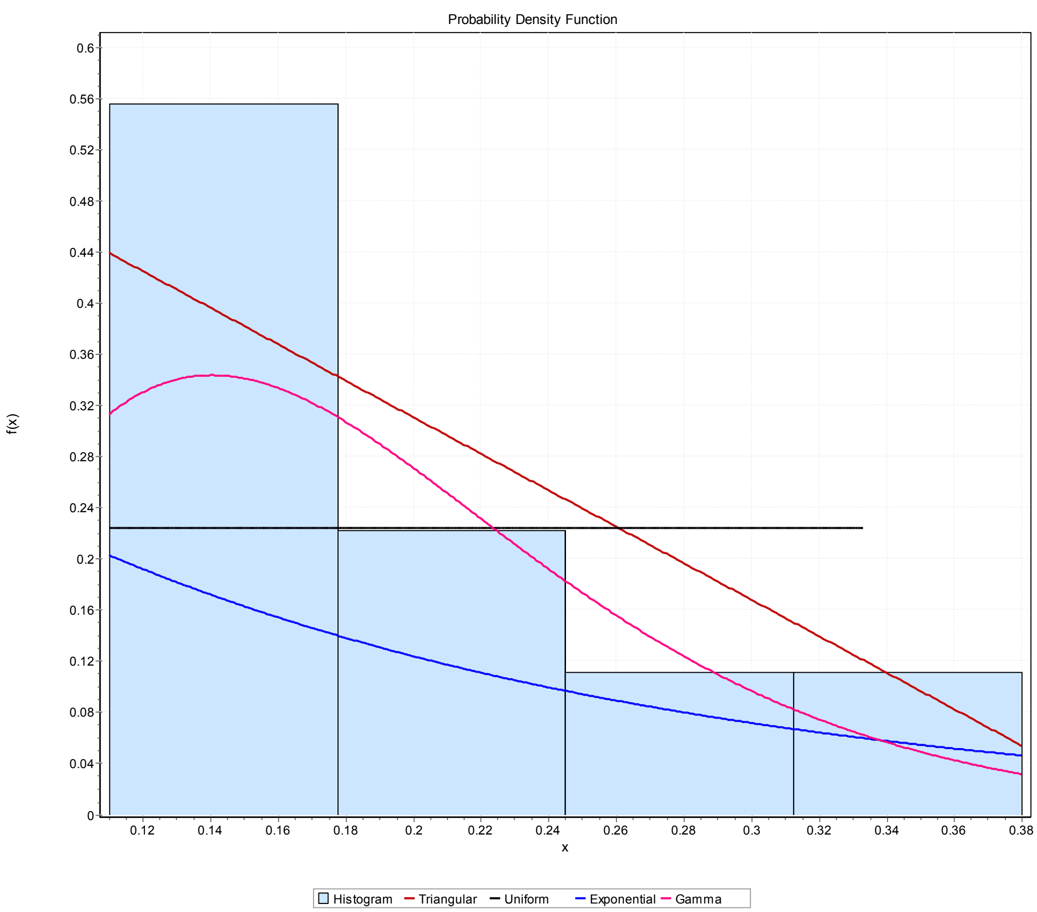


Figure 29: Probability Density Function for 2x6" – 16o.c. Framing

From Figure 29, it can be seen that the productivity of the walls constructed ranged from 0.11 to 0.38 ft/min. This large variation is mainly due to the minimal length of the wall being constructed. A small amount of change in the time to complete the wall significantly affected the productivity time. It can be seen in Table 17 that the gamma distribution provided the best fit for the probable productivity rate.

Table 17: Goodness of Fit for 2x6" – 16.o.c. Framing

Goodness of Fit		
	Kolmogorov Smirnov	Ranking
Exponential (2P)	0.453	4
Gamma	0.21	1
Triangular	0.325	3
Uniform	0.261	2

The probabilistic distribution can be represented in Equation 12 as a gamma distribution with the parameters α= 4.37263 and β= 0.04168.

Equation 12: Probabilistic Productivity Formula for 2x6"– 16o.c. Framing

$$PP = Gamma\,Distribution$$

$$PP = f(x;\alpha,\beta) = \begin{cases} \dfrac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-\frac{x}{\beta}} & , \quad x > 0 \\ 0 & , \quad elsewhere \end{cases}$$

$$\alpha = 4.3723$$

$$\beta = 0.04168$$

Table 18: Wall Framing Equation Summary

Wall Type	Equivalent Length Formula	Probabilistic Productivity Distribution Type	Parameters	
2x6" Double Top Plate - 16o.c.	EL = LL+6.92d+1.51w+1.75c	Uniform	Low=0.0903ft/min	High=0.7257ft/min
2x4" - 16o.c.	EL=LL	Gamma	α=2.7248	β=0.10933
2x6" - 16o.c.	EL=LL	Gamma	α=4.3723	β=0.04168

Table 18 summaries the three wall framing methods that were studied. To code this information into a simulation model, visual basic programming was implemented. The wall type has been stored within each of the entity's string(0). Once the appropriate wall type has been selected, the effective length and effective productivity are calculated based on individual wall properties. Finally, the duration of the framing task is calculated based on the effective length, effective productivity, and number of workers. After the required duration elapses, the entity is passed to the next task for completion. To program the wall framing task into Simphony.NET 3.5, the following coding was used.

Framing Coding

```
'Determine wall type
Select Case Context.CurrentEntity.Strings(0)

      '2x6" Double Top Plates - 16o.c. Framing (Wall Type B,D,F,Q)
      Case "B", "D", "F", "Q"
            EffectiveLength = context.CurrentEntity.Floats(0) +
                                    6.92*context.CurrentEntity.Ints(0) +
                                    1.51*context.CurrentEntity.Ints(1) +
                                    1.75*context.CurrentEntity.Ints(2)
            EffectiveProductivity = Uniform.Sample(0.0903,0.7257)
```

```
        '2x6 - 16o.c. Framing
        Case "M"
              EffectiveLength = context.CurrentEntity.Floats(0)
              EffectiveProductivity = Gamma.Sample(4.3723,0.04168)

        '2x4 - 16o.c. Framing
        Case "H", "N", "K"
              EffectiveLength = context.CurrentEntity.Floats(0)
              EffectiveProductivity = Gamma.Sample(2.7248,0.10933)

End Select

FrameDuration = EffectiveLength / (EffectiveProductivity *
                  context.CurrentEntity.Ints(3))
Return FrameDuration
```

6 Mill Vapour Barrier

To prevent moisture and air from passing through the walls, a 6 mil vapour barrier was installed on all exterior walls. In modular construction, the exterior walls are constructed on the interior side first, and the exterior insulation and sheathing is applied after the module has been erected. In contrast, site-built construction completes the exterior curtain before installing interior finishes. Since there were only five modules studied, there were significantly fewer data points recorded relative to other tasks. It can be seen in Table 19 that Unit 744 has five walls requiring a vapour barrier due to its corner position. As well, the individual productivities have been tabulated.

Table 19: 6 Mil Vapour Barrier Productivity Rates

	Linear Length (ft)	Surface Area (ft^2)	# of Doors	# of Windows	# of Columns	# of Workers	Time (min)	Total # of Man Hours (min)	Production Rate (ft^2/min)	Effective Area (ft^2)	Effective Productivity Rate (ft^2/min)	Difference
6 Mil Vapour Barrier												
Unit 744												
WP01	25	200.52	1	2	2	3	9	27	7.43	200.52	7.43	3.77
WP02	1	8.02	0	0	0	2	4	8	1.00	8.02	1.00	10.19
WP03	20.75	166.43	0	2	4	3	6	18	9.25	166.43	9.25	1.95
WP04	1	8.02	0	0	0	2	4	8	1.00	8.02	1.00	10.19
WP05	25	200.52	1	2	2	3	6	18	11.14	200.52	11.14	0.06
Unit 746												
WP03	64.875	520.35	2	5	4	3	15	45	11.56	520.35	11.56	0.37
WP04	20.8125	166.93	0	0	0	2	6	12	13.91	166.93	13.91	2.71
Unit 747												
WP03	48.00	385.00	2	4	4	1	19	19	20.26	385.00	20.26	9.07
Unit 749												
WP03	48.00	385.00	2	4	4	2	10	20	19.25	385.00	19.25	8.05
Unit 750												
WP02	20.8125	166.93	0	0	0	2	10	20	8.35	166.93	8.35	2.85
WP03	64.875	520.35	2	5	4	2	13	26	20.01	520.35	20.01	8.82

To determine the equivalent area of the wall in terms of the vapour barrier, the standard methodology was used; however, the column coefficient had no physical relationship to the vapour barrier installation and was determined to be zero. It can be seen in Table 20 that the optimum linear best fit line results in window and door coefficients of zero, making the effective area equivalent to the linear area. This is an expected result as the 6 mil poly is applied to the entire wall as a single piece. The windows and doors are cut out of the poly at the same time as the sheathing and drywall so no additional time is required.

Table 20: Equivalent Area Coefficients for 6 Mil Vapour Barrier

Equivalent Area Coefficients	
Door Coefficient (A)	0.00
Window Coefficient (B)	0.00
Column Coefficient (C)	0.00
Average Productivity (ft/min)	11.20
Sum of Differences	58.03
R^2	0.35

In Figure 30, it can be seen that the R-squared value for an average productivity rate is 0.35 which does not accurately represent the variability that was observed on the production floor. The variability in productivity rates can be described mainly by the varying experience levels of the workers. Therefore, the statistical representation must be implemented as with the other tasks.

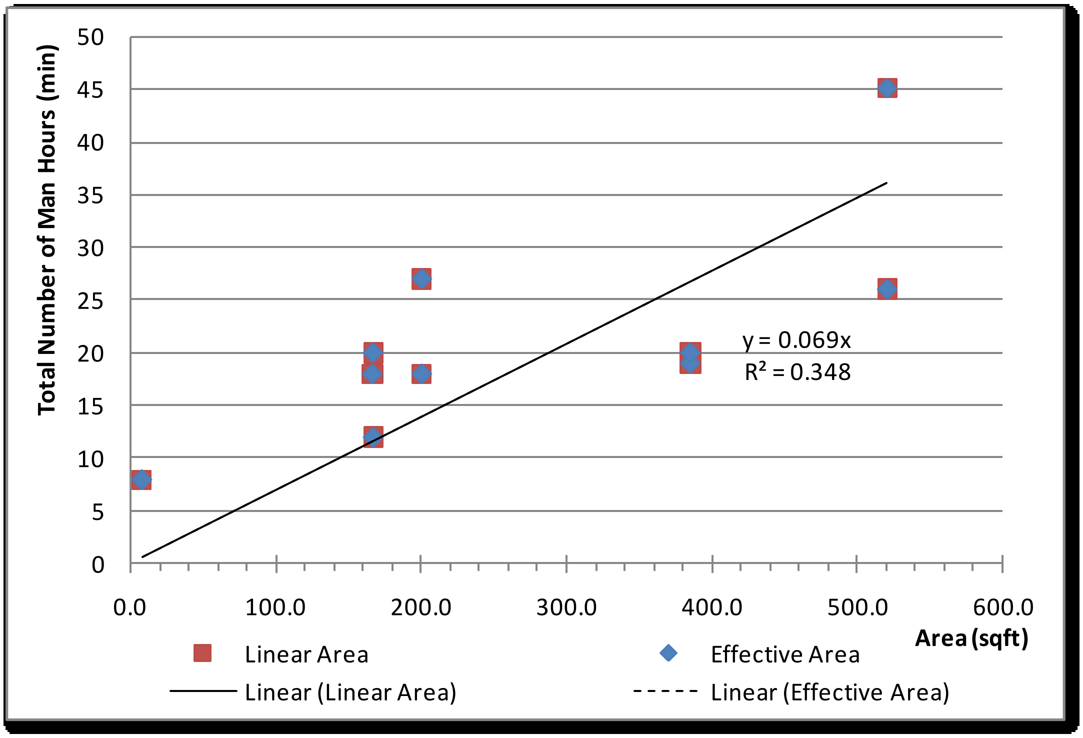


Figure 30: 6 Mil Vapour Barrier Linear Trend

The probability density function of the effective productivity rates can be seen in Figure 31. The productivity ranges substantially from $1ft^2$/min to $20.26ft^2$/min. Triangular, uniform, exponential and gamma distributions were fit to the data to determine the best representation of the vapour barrier task productivity.

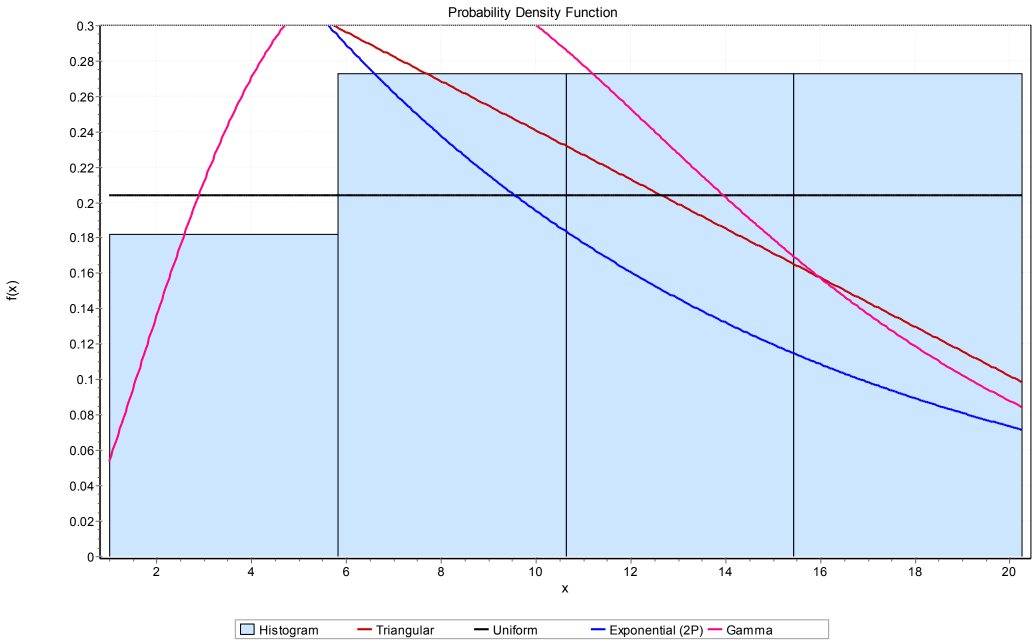


Figure 31: Probability Density Function for 6 Mil Vapour Barrier

To determine the best probability distribution, Kolmogorov-Smirnov's goodness of fit was used. Table 21 shows that a uniform distribution best describes the data.

Table 21: Goodness of Fit for 6 Mil Vapour Barrier

Goodness of Fit		
	Kolmogorov Smirnov	Ranking
Exponential (2P)	0.286	4
Gamma	0.177	2
Triangular	0.247	3
Uniform	0.159	1

The probabilistic productivity for the vapour barrier can be calculated as:

Equation 13: Probabilistic Productivity Formula for Vapour Barrier

$$PP = Uniform\ Distribution$$

$$Low = 1ft^2/min$$

$$High = 20.26ft^2/min$$

To represent the vapour barrier in the Simphony.NET model, the following coding was used within the vapour barrier task.

Vapour Barrier Coding

```
'Determine wall type
Select Case Context.CurrentEntity.Strings(0)

      'Vapour Barrier (Wall Type B)
      Case "B"
            EffectiveArea = context.CurrentEntity.Floats(1)
            EffectiveProductivity = Uniform.Sample(1,20.26)
            VapourDuration = EffectiveArea /
                                  (EffectiveProductivity *
                                  context.CurrentEntity.Ints(3))

      Case Else
            VapourDuration = 0
End Select
Return VapourDuration
```

<u>7/16" Vertical OSB Sheathing</u>

The next task within the wall construction station is to place and pneumatic staple the sheathing onto the framed wall. Sheathing is required on all exterior wall types and party walls, including wall types B, D, F, and Q. Wall type Q requires an additional layer of sheathing on the exterior for sound and fire separation regulation. Since the two party walls are erected directly beside each other, the sheathing must be placed before the wall, two values of sheathing duration can be seen for each of the party walls. The productivity rates for the individual walls can be seen below in Table 22.

Table 22: 7/16” Vertical OSB Sheathing Productivity Rates

	Linear Length (ft)	Surface Area (ft^2)	# of Doors	# of Windows	# of Columns	# of Workers	Time (min)	Total # of Man Hours (min)	Production Rate (ft/min)	Effective Length (ft)	Effective Productivity Rate (ft/min)	Difference
7/16" Vertical OSB Sheathing												
Unit 744												
WP01	25	200.52	1	2	2	3	29	87	0.29	29.50	0.34	0.21
WP02	1	8.02	0	0	0	2	5	10	0.10	1.00	0.10	0.45
WP03	20.75	166.43	0	2	4	3	20	60	0.35	29.76	0.50	0.05
WP04	1	8.02	0	0	0	2	5	10	0.10	1.00	0.10	0.45
WP05	25	200.52	1	2	2	3	29	87	0.29	29.50	0.34	0.21
WP06	20.8125	166.93	0	0	0	3	19	57	0.37	20.81	0.37	0.18
WP07	69.83	560.09	2	0	4	4	50	200	0.35	78.84	0.39	0.16
WP08	20.8125	166.93	0	0	0	3	26	78	0.27	20.81	0.27	0.28
PT13	20.8125	166.93	0	0	0	2	20	40	0.52	20.81	0.52	0.03
PT13	20.8125	166.93	0	0	0	3	18	54	0.39	20.81	0.39	0.16
PT14	20.8125	166.93	0	0	0	2	18	36	0.58	20.81	0.58	0.03
PT14	20.8125	166.93	0	0	0	3	15	45	0.46	20.81	0.46	0.09
Unit 746												
WP01	64.875	520.35	2	0	6	3	75	225	0.29	78.38	0.35	0.20
WP02	20.8125	166.93	0	0	0	3	20	60	0.35	20.81	0.35	0.20
WP03	64.875	520.35	2	5	4	3	57	171	0.38	73.88	0.43	0.12
WP04	20.8125	166.93	0	0	0	2	16	32	0.65	20.81	0.65	0.10
PT10	20.8125	166.93	0	0	0	3	16	48	0.43	20.81	0.43	0.12
PT10	20.8125	166.93	0	0	0		NA					
PT11	20.8125	166.93	0	0	0	2	30	60	0.35	20.81	0.35	0.20
PT11	20.8125	166.93	0	0	0		NA					
Unit 747												
WP01	48.00	385.00	2	0	4	2	57	114	0.42	57.01	0.50	0.05
WP02	22.00	176.46	0	0	0	2	19	38	0.58	22.00	0.58	0.03
WP03	48.00	385.00	2	4	4	3	27	81	0.59	57.01	0.70	0.15
WP04	22.00	176.46	0	0	0	2	24	48	0.46	22.00	0.46	0.09
PT10	22.00	176.46	0	0	0	1	32	32	0.69	22.00	0.69	0.14
PT10	22.00	176.46	0	0	0	2	11	22	1.00	22.00	1.00	0.45
PT11	22.00	176.46	0	0	0	2	20	40	0.55	22.00	0.55	0.00
PT11	22.00	176.46	0	0	0	2	14	28	0.79	22.00	0.79	0.24
Unit 749												
WP01	48.00	385.00	2	0	4	2	45	90	0.53	57.01	0.63	0.08
WP02	22.00	176.46	0	0	0	2	10	20	1.10	22.00	1.10	0.55
WP03	48.00	385.00	2	4	4	2	35	70	0.69	57.01	0.81	0.26
WP04	22.00	176.46	0	0	0	2	15	30	0.73	22.00	0.73	0.18
PT10	22.00	176.46	0	0	0	2	10	20	1.10	22.00	1.10	0.55
PT10	22.00	176.46	0	0	0	2	15	30	0.73	22.00	0.73	0.18
PT11	22.00	176.46	0	0	0	2	14	28	0.79	22.00	0.79	0.24
PT11	22.00	176.46	0	0	0	2	15	30	0.73	22.00	0.73	0.18
Unit 750												
WP01	64.875	520.35	2	0	6	2	100	200	0.32	78.38	0.39	0.16
WP02	20.8125	166.93	0	0	0	2	20	40	0.52	20.81	0.52	0.03
WP03	64.875	520.35	2	5	4	5	18	90	0.72	73.88	0.82	0.27
WP04	20.8125	166.93	0	0	0	2	30	60	0.35	20.81	0.35	0.20
PT23	20.8125	166.93	0	0	0	2	16	32	0.65	20.81	0.65	0.10
PT23	20.8125	166.93	0	0	0	2	26	52	0.40	20.81	0.40	0.15
PT24	20.8125	166.93	0	0	0	2	15	30	0.69	20.81	0.69	0.14
PT24	20.8125	166.93	0	0	0	2	22	44	0.47	20.81	0.47	0.08

Using linear optimization methodology, the door, window and column coefficients were found to be 0, 0, and 2.25, respectfully. In the physical world, the number of columns within a wall should not have a significant effect on the placement of the sheathing; however, columns are usually found in more complex exterior walls compared to interior party walls which could explain the variation based on the number of columns. Therefore, the column coefficient will be used to better fit the production to a constant rate.

Table 23: Equivalent Length Coefficient for 7/16" Vertical OSB Sheathing

Equivalent Length Coefficients	
Door Coefficient (A)	0.00
Window Coefficient (B)	0.00
Column Coefficient (C)	2.25
Average Productivity (ft/min)	0.55
Sum of Differences	7.77
R^2	0.78

Once the effective lengths have been calculated with using Equation 3, the linear and effective lengths can be plotted versus the total number of man hours. The linear slope of the line is equivalent to the best fit production rate. As seen in Figure 32, the r-squared values for the linear and effective length were found to be 0.75 and 0.78, respectfully. This demonstrates that the effective length fits much better to the expected steady production rate when the coefficient factors have been considered. However, there is still significant variability in the data so a statistical representation must also be used.

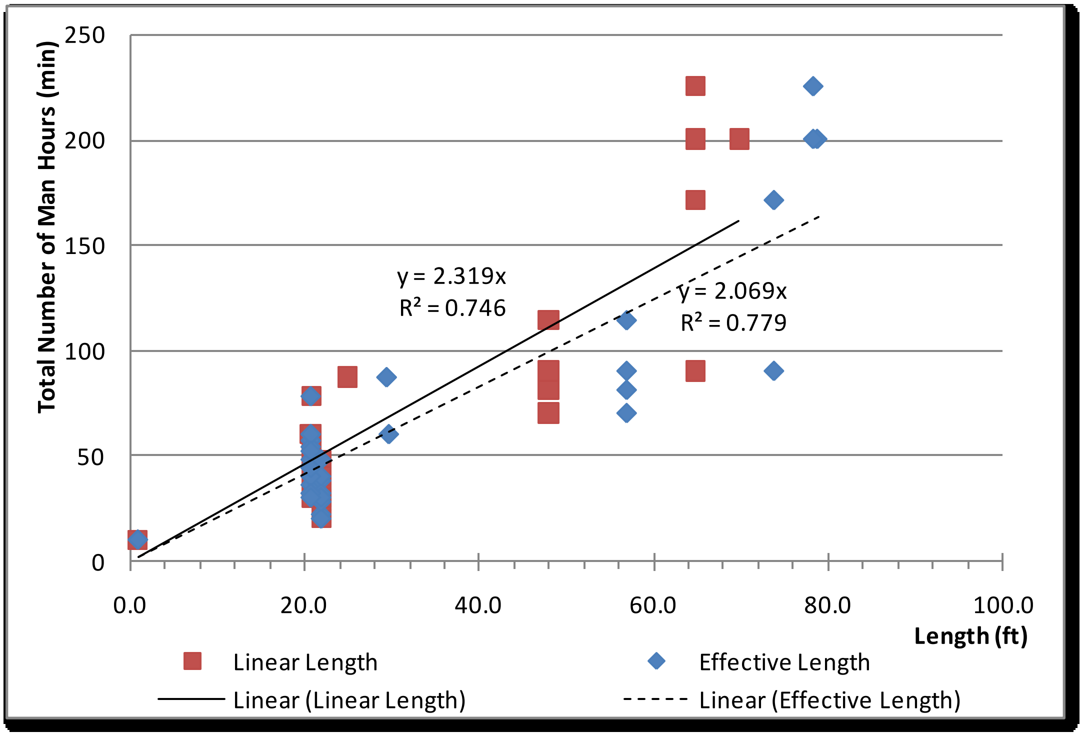


Figure 32: 7/16" Vertical OSB Sheathing Linear Trend

Figure 32 presents a probability density function which shows the likelihood of the various effective production rates. The x-axis displays the productivity rates observed ranging from 0.10 to 1.10 ft/min. This range suggests significant variation with production which was noted during the data collection phase. The best fit production rate was found to be 0.48ft/min.

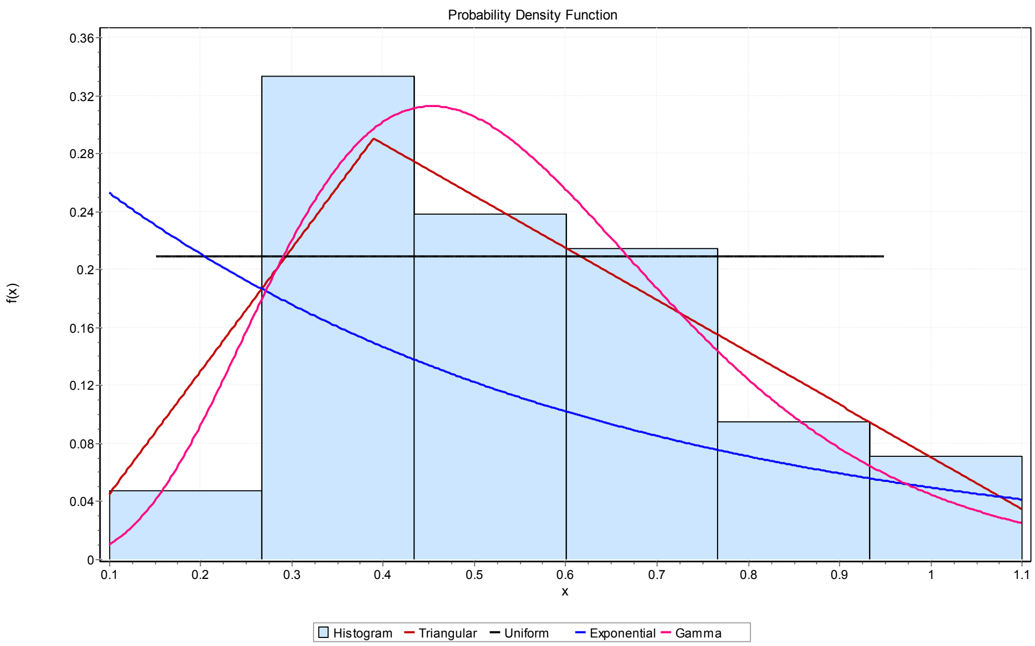


Figure 33: Probability Density Function for 7/16" Vertical OSB Sheathing

The goodness of fit test was completed to determine the best distribution for the probability density function in Figure 33. A gamma distribution with the parameters α=5.711 and β=0.0963 was most effective in modeling the data, with a goodness of fit of 0.108. Equation 14 below presents the parameters for the gamma distribution.

Table 24: Goodness of Fit for 7/16" Vertical OSB Sheathing

Goodness of Fit		
	Kolmogorov Smirnov	Ranking
Exponential (2P)	0.342	4
Gamma	0.108	1
Triangular	0.146	2
Uniform	0.165	3

Equation 14: Probabilistic Productivity Formula for Sheathing

$$PP = Gamma\ Distribution$$

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

$$\alpha = 5.7107$$

$$\beta = 0.09631$$

The 7/16" Vertical OSB Sheathing coding can be seen below, detailing the wall types which will receive sheathing and the duration associated with it.

7/16" Vertical OSB Sheathing Coding

```
'Determine wall type
Select Case Context.CurrentEntity.Strings(0)

      'Vapour Barrier (Wall Type B, D, F, and Q)
      Case "B", "D", "F", "Q"
            EffectiveLength = context.CurrentEntity.Floats(0) +
                              2.25*context.CurrentEntity.Ints(2)
            EffectiveProductivity = gamma.sample(5.7107,0.09631)

            SheathDuration = EffectiveLength /
                              (EffectiveProductivity *
                              context.CurrentEntity.Ints(3))

      Case Else
            SheathDuration = 0
End Select
Return SheathDuration
```

<u>5/8" Type 'x' Drywall</u>

The installation of 5/8" type 'x' drywall is required on all wall types with the exception of wall type N. Drywall is placed on the interior of every wall as the finishing surface base. For all partition walls, drywall is placed on a single side on the framing tables. Once each wall has been erected and secured, the electrical and plumbing is roughed in. Drywall is placed on the back of each wall in another stage of the manufacturing process using the traditional site-built methods. Therefore, only one instance of drywall installation was recorded per wall in the wall fabrication station. The productivity rates of each wall of module 744 and 746 can be seen in Table 25.

Table 25: 5/8" Type 'x' Drywall Productivity Rates

	Linear Length (ft)	Surface Area (ft^2)	# of Doors	# of Windows	# of Columns	# of Workers	Time (min)	Total # of Man Hours (min)	Production Rate (ft/min)	Effective Length (ft)	Effective Productivity Rate (ft/min)	Difference
Single Layer 5/8" Type 'x' Drywall												
Unit 744												
WP01	25	200.52	1	2	2	3	22	66	0.38	25.00	0.38	0.08
WP02	1	8.02	0	0	0	2	7	14	0.07	1.00	0.07	0.23
WP03	20.75	166.43	0	2	4	3	29	87	0.24	20.75	0.24	0.06
WP04	1	8.02	0	0	0	2	7	14	0.07	1.00	0.07	0.23
WP05	25	200.52	1	2	2	3	37	111	0.23	25.00	0.23	0.07
WP06	20.8125	166.93	0	0	0	3	25	75	0.28	20.81	0.28	0.02
WP07	69.83	560.09	2	0	4	4	78	312	0.22	69.83	0.22	0.08
WP08	20.8125	166.93	0	0	0	3	25	75	0.28	20.81	0.28	0.02
PT01	20.8125	166.93	1	0	0	2	22	44	0.47	20.81	0.47	0.17
PT02	10.48	84.06	2	0	0	2	23	46	0.23	10.48	0.23	0.07
PT03	7.95	63.77	0	0	0	2	13	26	0.31	7.95	0.31	0.01
PT04	3	24.06	0	0	0	2	15	30	0.10	3.00	0.10	0.20
PT05	2.83	22.70	0	0	0	2	15	30	0.09	2.83	0.09	0.20
PT06	6.5	52.14	1	0	0	2	18	36	0.18	6.50	0.18	0.12
PT07	1.5	12.03	0	0	0	2	5	10	0.15	1.50	0.15	0.15
PT09	9.5	76.20	0	0	0	1	32	32	0.30	9.50	0.30	0.00
PT10	2.17	17.41	0	0	0			NA				
PT11	9.17	73.55	2	0	0	2	11	22	0.42	9.17	0.42	0.12
PT12	14	112.29	1	0	0	2	16	32	0.44	14.00	0.44	0.14
PT13	20.8125	166.93	0	0	0	3	21	63	0.33	20.81	0.33	0.03
PT14	20.8125	166.93	0	0	0	3	24	72	0.29	20.81	0.29	0.01
PT15	14	112.29	1	0	0	1	39	39	0.36	14.00	0.36	0.06
PT16	9.17	73.55	2	0	0	2	12	24	0.38	9.17	0.38	0.08
PT17	2.17	17.41	0	0	0			NA				
PT18	9.5	76.20	0	0	0	2	12	24	0.40	9.50	0.40	0.10
PT20	1.5	12.03	0	0	0	2	8	16	0.09	1.50	0.09	0.21
PT21	6.5	52.14	1	0	0	2	37	74	0.09	6.50	0.09	0.21
PT22	2.83	22.70	0	0	0	2	15	30	0.09	2.83	0.09	0.20
PT23	3	24.06	0	0	0	2	15	30	0.10	3.00	0.10	0.20
PT24	20.8125	166.93	1	0	0	2	27	54	0.39	20.81	0.39	0.09
PT25	10.48	84.06	2	0	0	2	20	40	0.26	10.48	0.26	0.04
PT26	7.95	63.77	0	0	0	2	13	26	0.31	7.95	0.31	0.01
Unit 746												
WP01	64.875	520.35	2	0	6	3	82	246	0.26	64.88	0.26	0.04
WP02	20.8125	166.93	0	0	0	3	22	66	0.32	20.81	0.32	0.02
WP03	64.875	520.35	2	5	4	3	63	189	0.34	64.88	0.34	0.04
WP04	20.8125	166.93	0	0	0	2	40	80	0.26	20.81	0.26	0.04
PT01	3	24.06	0	0	0	2	4	8	0.38	3.00	0.38	0.08
PT02	2.6	20.85	0	0	0	2	4	8	0.33	2.60	0.33	0.03
PT03	6.5	52.14	1	0	0	2	15	30	0.22	6.50	0.22	0.08
PT04	1.5	12.03	0	0	0	2	4	8	0.19	1.50	0.19	0.11
PT06	10.25	82.21	0	0	0	4	7	28	0.37	10.25	0.37	0.07
PT07	10.25	82.21	2	0	0	4	9	36	0.28	10.25	0.28	0.01
PT08	2.17	17.41	0	0	0	2	4	8	0.27	2.17	0.27	0.03
PT09	14.33	114.94	1	0	0	4	10	40	0.36	14.33	0.36	0.06
PT10	20.8125	166.93	0	0	0			NA				
PT11	20.8125	166.93	0	0	0			NA				
PT12	1.5	12.03	0	0	0	2	4	8	0.19	1.50	0.19	0.11
PT14	13.25	106.28	1	0	0	2	20	40	0.33	13.25	0.33	0.03
PT15	9.67	77.56	2	0	0	2	20	40	0.24	9.67	0.24	0.06
PT16	2.17	17.41	0	0	0	3	5	15	0.14	2.17	0.14	0.15
PT17	2.17	17.41	0	0	0	3	5	15	0.14	2.17	0.14	0.15
PT18	6.5	52.14	1	0	0	2	16	32	0.20	6.50	0.20	0.10
PT19	2.33	18.69	0	0	0	2	5	10	0.23	2.33	0.23	0.07
PT20	2.42	19.41	0	0	0	2	4	8	0.30	2.42	0.30	0.00
PT21	5.25	42.11	1	0	0	2	12	24	0.22	5.25	0.22	0.08
PT22	2.75	22.06	0	0	0	2	7	14	0.20	2.75	0.20	0.10
PT23	8.8125	70.68	0	0	0	2	16	32	0.28	8.81	0.28	0.02
PT24	2	16.04	0	0	0	2	8	16	0.13	2.00	0.13	0.17
PT25	5.33	42.75	1	0	0	2	33	66	0.08	5.33	0.08	0.22
PT26	12.17	97.61	1	0	0	2	26	52	0.23	12.17	0.23	0.06
PT27	2	16.04	0	0	0	3	5	15	0.13	2.00	0.13	0.17
PT28	5.33	42.75	1	0	0	2	15	30	0.18	5.33	0.18	0.12
PT29	3.417	27.41	1	0	0	2	13	26	0.13	3.42	0.13	0.17
PT30	5.833	46.79	1	0	0	2	16	32	0.18	5.83	0.18	0.12
PT31	7.92	63.53	0	0	0	4	10	40	0.20	7.92	0.20	0.10
PT32	7.92	63.53	0	0	0	4	17	68	0.12	7.92	0.12	0.18
PT33	14	112.29	0	0	0	2	15	30	0.47	14.00	0.47	0.17

By completing a linear optimization of the best fit line, the door, window, and column coefficients were all found to be zero, demonstrating that these factors had little effect on the productivity of the drywall installation. As with vapour barrier and sheathing installation, drywall is placed and screwed over the entire wall. Once secured to the wall, a worker cuts out the door and window openings with a router. This process takes minimal time since the router follows the opening contours while cutting and has little effect on the overall time to complete the drywall installation.

Table 26: Equivalent Length Coefficients for 5/8" Type 'x' Drywall

Equivalent Length Coefficients	
Door Coefficient (A)	0.00
Window Coefficient (B)	0.00
Column Coefficient (C)	0.00
Average Productivity (ft/min)	0.30
Sum of Differences	17.74
R^2	0.73

As seen in Figure 34, the linear length and effective length are equivalent and have an r-squared value of 0.73.

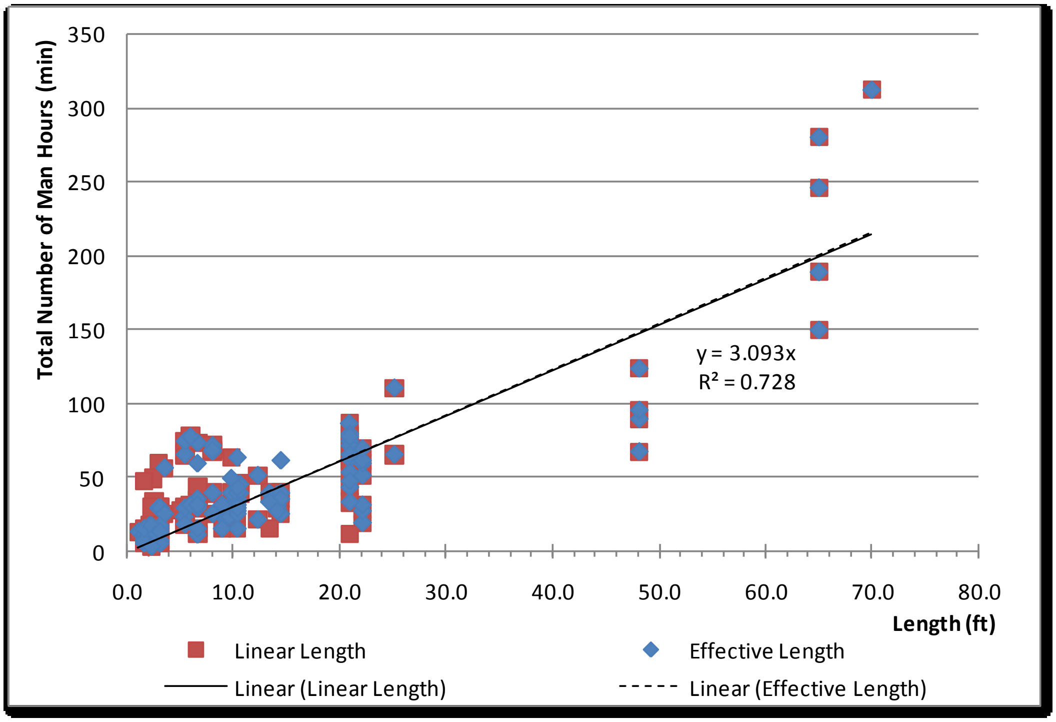


Figure 34: 5/8" Type 'x' Drywall Linear Trend

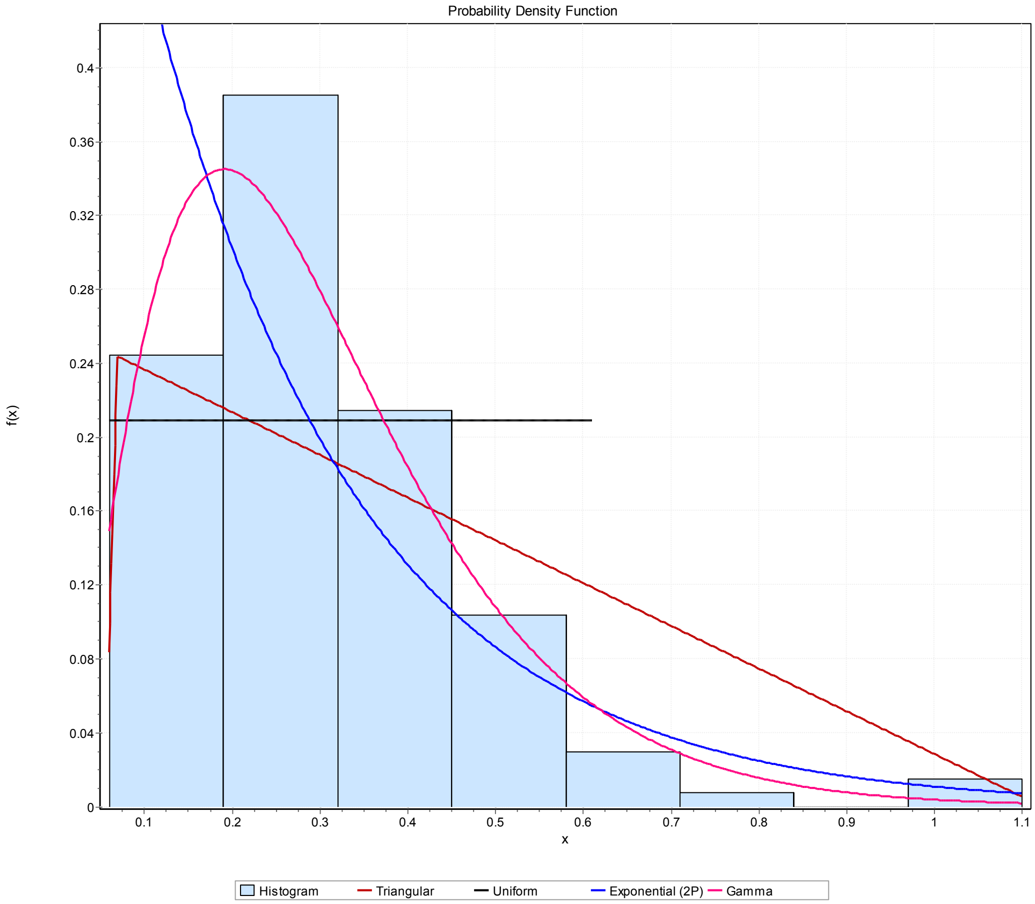


Figure 35: Probability Density Function for 5/8" Type 'x' Drywall

By performing a Kolmogorov-Smirnov goodness of fit test, it was seen that a gamma distribution with parameters $\alpha=2.7767$ and $\beta=0.10769$ was most effective in modeling the data. Equation 15 presents the parameters and formula for the gamma distribution.

Table 27: Goodness of Fit for 5/8" Type 'x' Drywall

Goodness of Fit		
	Kolmogorov Smirnov	Ranking
Exponential (2P)	0.23	3
Gamma	0.066	1
Triangular	0.264	4
Uniform	0.138	2

Equation 15: Probabilistic Productivity Formula for 5/8" Type 'x' Drywall

$$PP = Gamma\,Distribution$$

$$PP = f(x;\alpha,\beta) = \begin{cases} \dfrac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-\frac{x}{\beta}} & , \quad x > 0 \\ 0 & , \quad elsewhere \end{cases}$$

$$\alpha = 2.7767$$

$$\beta = 0.10769$$

5/8" Type 'x' Drywall Coding

```
'Determine wall type

Select Case Context.CurrentEntity.Strings(0)


      'Drywall (Wall Type B, D, F, H, M, K, or Q)

      Case "B", "D", "F", "H", "M", "K", "Q"

            EffectiveLength = context.CurrentEntity.Floats(0)

            EffectiveProductivity = gamma.sample(2.7767,.10769)


            DrywallDuration = EffectiveLength /

                                    (EffectiveProductivity *

                                    context.CurrentEntity.Ints(3))

      Case Else


            DrywallDuration = 0


End Select

Return DrywallDuration
```

Temporary Storage Placement

If the framing fabrication station is ahead of production relative to the wall erection station, walls are placed in the temporary storage so additional walls can be constructed. From observing the five modules' construction, 9.0% of the total number of walls were placed in storage. All of the walls placed in storage are presented in Table 28 below.

Table 28: Temporary Storage Placement Productivity Rates

		Linear Length (ft)	Surface Area (ft^2)	# of Doors	# of Windows	# of Columns	# of Workers	Time (min)	Total # of Man Hours (min)	Production Rate (ft/min)
Move to Temporary Storage										
Unit 746										
	PT19	2.33	18.69	0	0	0	2.00	6.00	12.00	0.19
Unit 747										
	PT09	14.33	114.94	1	0	0	2.00	4.00	8.00	1.79
	PT20	14.33	114.94	1	0	0	2.00	5.00	10.00	1.43
Unit 749										
	WP03	48.00	385.00	2	4	4	2.00	12.00	24.00	2.00
	PT03	6.50	52.14	1	0	0	2.00	2.00	4.00	1.63
	PT06	10.25	82.21	0	0	0	2.00	2.00	4.00	2.56
	PT07	10.25	82.21	2	0	0	2.00	2.00	4.00	2.56
	PT09	14.33	114.94	1	0	0	2.00	2.00	4.00	3.58
	PT12	2.33	18.69	0	0	0	2.00	3.00	6.00	0.39
	PT14	6.50	52.14	1	0	0	2.00	2.00	4.00	1.63
	PT15	2.66	21.34	0	0	0	2.00	2.00	4.00	0.67
	PT17	10.25	82.21	0	0	0	2.00	3.00	6.00	1.71
	PT20	14.33	114.94	1	0	0	2.00	2.00	4.00	3.58
Unit 750										
	PT04	12.17	97.61	1	0	0	2.00	3.00	6.00	2.03

Since every wall was moved similarly using the over-head cranes, the number of door, window, and column coefficients had no physical relation to the productivity rates observed. Therefore, these coefficients will not be considered. However, there is still variability in the productivity rates so a statistical representation of the data has been produced in Figure 36.

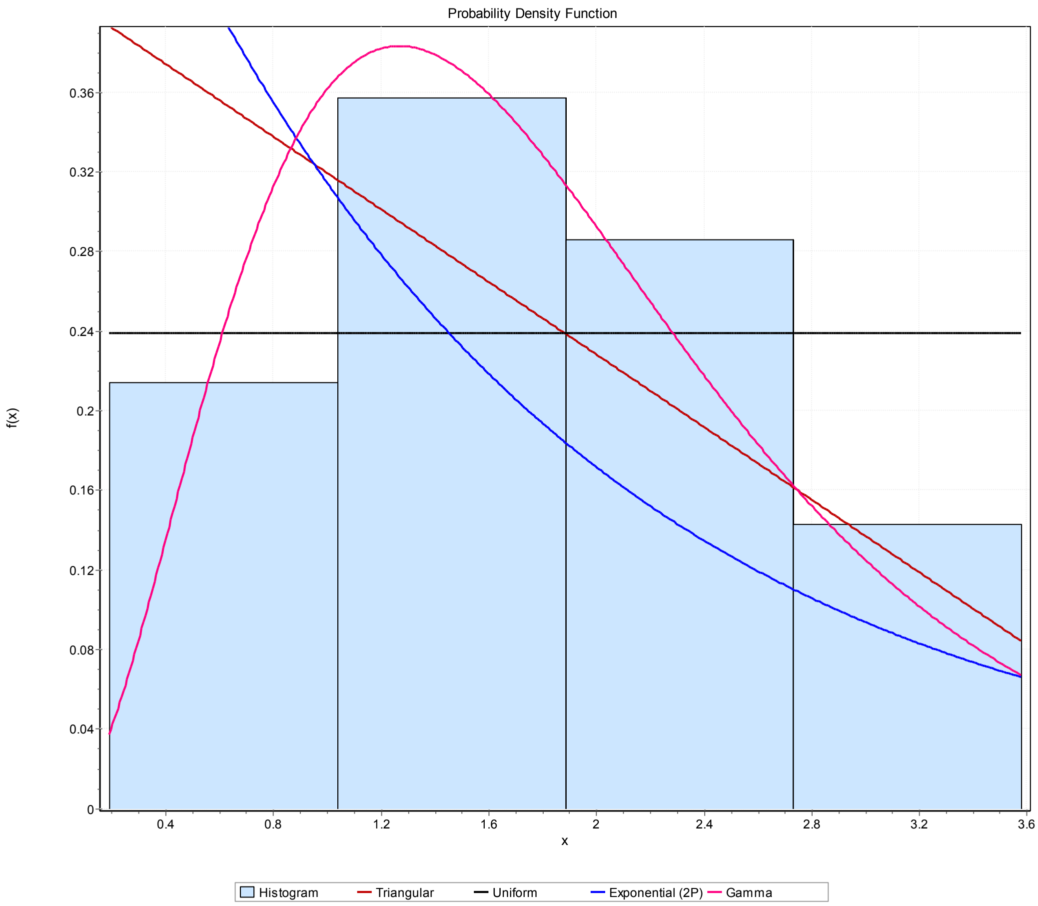


Figure 36: Probability Density Function for Temporary Storage Placement

From the triangular, uniform, exponential, and gamma distributions above, a goodness of fit test shows that the uniform distribution best fits the productivity rate data.

Table 29: Goodness of Fit for Temporary Storage Placement

Goodness of Fit		
	Kolmogorov Smirnov	Ranking
Exponential (2P)	0.314	4
Gamma	0.205	2
Triangular	0.278	3
Uniform	0.17	1

Therefore, the probabilistic productivity can be calculated as:

Equation 16: Probabilistic Productivity Formula for Temporary Storage Placement

$$PP = Uniform\,Distribution$$

$$Low = 0.0662 ft/min$$

$$High = 3.6124 ft/min$$

Temporary Storage Placement Coding

```
    Length = Context.CurrentEntity.Floats(0)
    Productivity = uniform.sample(0.0642,3.6141)'(ft/min)
    Duration = Length/Productivity
Return Duration
```

Wall Erection

The wall placement and temporary storage placement represent similar real world tasks so a similar methodology has been used. There is no significant difference in the method used to transport walls with varying characteristics; however, once a wall reaches a linear length of over six feet the method of attaching the wall to the crane changes. If a wall is less than six feet, a hook can be used to lift the wall from the top plate and directed by two workers. If a wall is greater than six feet long, the wall must be attached to the crane with bolts and rigging to ensure greater safety. Therefore, the productivity of the walls placement should be defined by the linear length of each wall. The wall placement productivity rates for each wall can be seen in Table 30.

Table 30: Wall Placement Productivity Rates

	Linear Length (ft)	Surface Area (ft^2)	# of Doors	# of Windows	# of Columns	# of Workers	Time (min)	Total # of Man Hours	Production Rate (ft/min)
Wall Placement									
Unit 744									
WP01	25	200.52	1	2	2	3	27	81	0.31
WP02	1	8.02	0	0	0	2	10	20	0.05
WP03	20.75	166.43	0	2	4	3	33	99	0.21
WP04	1	8.02	0	0	0	2	7	14	0.07
WP05	25	200.52	1	2	2	3	22	66	0.38
WP06	20.8125	166.93	0	0	0	3	14	42	0.50
WP07	69.83	560.09	2	0	4	3	42	126	0.55
WP08	20.8125	166.93	0	0	0	3	16	48	0.43
PT01	20.8125	166.93	1	0	0	4	19	76	0.27
PT02	10.48	84.06	2	0	0	2	10	20	0.52
PT03	7.95	63.77	0	0	0	2	13	26	0.31
PT04	3	24.06	0	0	0	2	6	12	0.25
PT05	2.83	22.70	0	0	0	2	7	14	0.20
PT06	6.5	52.14	1	0	0	4	7	28	0.23
PT07	1.5	12.03	0	0	0	2	8	16	0.09
PT08	2.33	18.69	0	0	0	2	4	8	0.29
PT09	9.5	76.20	0	0	0	4	16	64	0.15
PT10	2.17	17.41	0	0	0	4	8	32	0.07
PT11	9.17	73.55	2	0	0	4	16	64	0.14
PT12	14	112.29	1	0	0	4	18	72	0.19
PT13	20.8125	166.93	0	0	0	3	42	126	0.17
PT14	20.8125	166.93	0	0	0	3	28	84	0.25
PT15	14	112.29	1	0	0	4	25	100	0.14
PT16	9.17	73.55	2	0	0	4	11	44	0.21
PT17	2.17	17.41	0	0	0	4	14	56	0.04
PT18	9.5	76.20	0	0	0	4	7	28	0.34
PT19	2.33	18.69	0	0	0	2	8	16	0.15
PT20	1.5	12.03	0	0	0	2	8	16	0.09
PT21	6.5	52.14	1	0	0	4	10	40	0.16
PT22	2.83	22.70	0	0	0		NA		
PT23	3	24.06	0	0	0		NA		
PT24	20.8125	166.93	1	0	0	3	25	75	0.28
PT25	10.48	84.06	2	0	0	2	10	20	0.52
PT26	7.95	63.77	0	0	0	2	14	28	0.28

Since the wall placement productivity is based on the number of man hours and linear length, the variation can be represented in the probability density function in Figure 37.

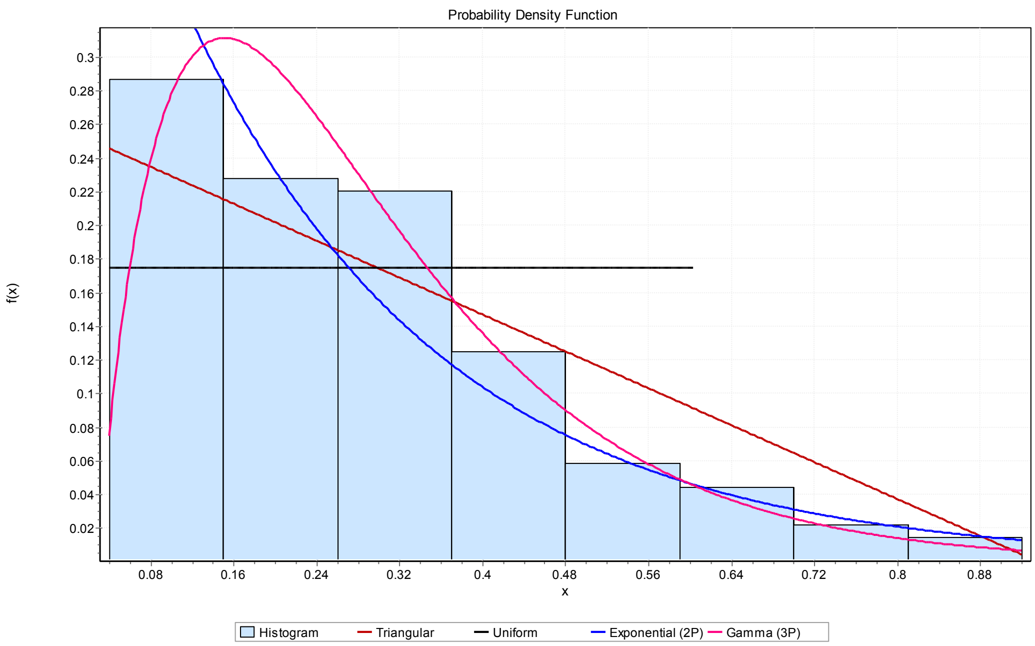


Figure 37: Probability Density Function for Wall Placement

From the Kolmogorov-Smirnov goodness of fit test, a gamma distribution with the parameters α=2.52 and β=0.115 provides the best representation of actual productivity rates.

Table 31: Goodness of Fit for Wall Placement

Goodness of Fit		
	Kolmogorov Smirnov	Ranking
Exponential (2P)	0.162	4
Gamma	0.06	1
Triangular	0.152	3
Uniform	0.131	2

The probabilistic productivity of the erection of the walls can be calculated as:

Equation 17: Probabilistic Productivity Formula for Wall Placement

$$PP = Gamma\ Distribution$$

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

$$\alpha = 2.5178$$

$$\beta = 0.11451$$

Wall Placement Coding

```
    Length = context.CurrentEntity.Floats(0)

    Productivity = Gamma.Sample(2.5178,0.11451)'(ft/min)

    Duration = Length/Productivity

Return Duration
```

Summary of Probabilistic Productivity

The probabilistic productivity for each task will be used within the simulation model to statistically represent the real life production flow of BCT Structures' wall fabrication and erection station. The probabilistic productivities for each task can be seen in Table 32.

Table 32: Summary of Probabilistic Productivity

Summary for Probabilistic Productivity					
Task		Equivalent Length Formula	Type	Probabilistic Productivity Distribution Parameters	
Wall Type	2x6" Double Top Plate - 16o.c.	EL = LL+6.92d+1.51w+1.75c	Uniform	Low=0.0903ft/min	High=0.7257ft/min
	2x4" - 16o.c.	EL=LL	Gamma	α=2.7248	β=0.10933
	2x6" - 16o.c.	EL=LL	Gamma	α=4.3723	β=0.04168
6 Mil Vapour Barrier		EL=LL	Uniform	Low = 1ft^2/min	High=20.26ft^2/min
7/16" Vertical OSB Sheathing		El = LL+2.25C	Gamma	α=5.7107	β=0.09631
5/8" Type 'x' Drywall		EL=LL	Gamma	α=2.7767	β=0.10769
Temporary Storage Placement		EL=LL	Uniform	Low = 0.0662ft^2/min	High=3.6124ft^2/min
Wall Erection		EL=LL	Gamma	α=2.5178	β=0.11451

SIMULATION RESULTS

Two simulations were proposed within this study. The first simulation models the current state of the production using the existing layout of the wall fabrication and erection stations. The goal of the first simulation is to optimize the labour force size and allocation based on the simulation parameters to provide a base line for the future state model. The second simulation model represents a change in the wall fabrication layout based on the lean manufacturing concepts discussed earlier and has eliminated Framing Table 6B and alternatively created a window and column fabrication table as well as moved the studs to the center of the two remaining framing tables. The goal of the second simulation will be to optimize the labour force size and allocation based on the same simulation parameters, as well as, provides justification for the change in the fabrication station layout.

Simulation Scenario 1 – Current State

To determine the optimum labour allocation for the framing and wall erection station for the current state of production, multiple simulation runs were completed. It was determined that to be effective, the wall fabrication crew size should be composed of between 2 and 4 workers. Two workers were required to place the sheathing and drywall and over four workers would increase inefficiencies in the fabrication. A maximum of three crews could be allocated to each table as that is typically how many walls could be placed on each table. The wall erection crew size varied substantially throughout the study so a range of crew sizes were modeled. A minimum of two crew members were required to move a wall for safety restrictions and up to six workers could be working on a wall. Since there are only two cranes to move the walls, there can only be one or two wall erection crews. The crew parameters can be seen in Table 33.

Table 33: Crew Size and Number of Crew Parameters

Crew Parameters		
	Minimum	Maximum
Wall Fabrication Crew Size	2	4
Number of Wall Fabrication Crews	2	3
Wall Erection Crew Size	2	6
Number of Wall Erection Crews	1	2

As well, the combination of wall fabrication and wall erection crew members could not exceed 26 due to congestion within the stations. Therefore, for the current state of the manufacturing, 28 configurations of workers for the wall fabrication and erection stations are possible ranging from 14 to 26 employees. A simulation was ran for each scenario to determine the wall fabrication, wall erection and complete module construction time for the three types of modules in the study. The mean and 95^{th} percentile times were recorded and are presented in Table 34.

Table 34: Current State Module Completion for Various Crews

Simulation	1	2	3	4	5	6	7	8	9	10
Seed	100	100	100	101	100	100	100	100	100	100
Run Count	100	100	100	100	100	100	100	100	100	100
Simulation Constraints										
Wall Fabrication Crew Size	2	2	2	2	2	2	2	2	2	2
Number of Wall Fabrication Crews	2	2	2	2	2	2	2	2	2	2
Wall Erection Crew Size	2	2	3	3	4	4	5	5	6	6
Number of Wall Erection Crews	1	2	1	2	1	2	1	2	1	2
Total Number of Workers	14	16	15	18	16	20	17	22	18	24
Table Length (3 Tables)	70	70	70	70	70	70	70	70	70	70

Simulation Results										
Module AA										
Wall Fabrication										
Mean Duration	477.3	458.6	453.9	485.6	453.9	457.5	496.7	452.3	447.9	439.0
Standard Deviation	179.7	235.6	193.8	397.7	193.8	197.7	697.5	179.6	159.1	159.8
95^{th} Percentile	772.9	846.2	772.7	1139.8	772.7	782.7	1644.1	747.7	709.6	701.9
Wall Erection										
Mean Duration	911.7	658.1	678.7	584.1	678.7	551.1	566.1	493.3	490.9	470.3
Standard Deviation	373.3	344.0	370.9	400.3	335.7	208.4	691.9	190.9	157.9	179.4
95^{th} Percentile	1525.8	1224.0	1288.8	1242.6	1230.9	893.9	1704.3	807.3	750.6	765.4
Module Completion										
Mean Duration	923.1	670.6	690.8	597.0	690.8	563.9	578.6	505.3	502.8	482.6
Standard Deviation	373.0	343.4	335.7	399.9	335.7	208.2	695.0	190.6	157.9	179.6
95^{th} Percentile	1536.7	1235.5	1243.0	1254.8	1243.0	906.4	1721.9	818.8	762.5	778.0
Module AD										
Wall Fabrication										
Mean Duration	733.9	597.3	628.7	589.9	628.7	607.5	658.2	608.7	596.8	601.2
Standard Deviation	519.8	146.8	187.2	171.7	187.2	270.1	712.7	242.3	179.1	191.3
95^{th} Percentile	1589.0	838.8	936.6	872.3	936.6	1051.8	1830.6	1007.3	891.4	915.9
Wall Erection										
Mean Duration	1197.4	828.1	864.5	701.7	864.5	734.1	746.2	659.3	662.9	631.6
Standard Deviation	560.6	290.0	265.5	217.5	265.5	306.5	716.1	276.1	186.6	198.8
95^{th} Percentile	2119.6	1305.2	1301.2	1059.5	1301.2	1238.3	1924.2	1113.5	969.9	958.6
Module Completion										
Mean Duration	1206.4	838.4	873.6	710.9	873.6	743.1	755.1	668.5	671.7	640.5
Standard Deviation	560.9	290.2	265.5	217.6	265.5	306.3	715.9	276.1	186.7	198.9
95^{th} Percentile	2129.1	1315.8	1310.3	1068.9	1310.3	1247.0	1932.8	1122.7	978.8	967.7
Module BB										
Wall Fabrication										
Mean Duration	947.8	610.1	700.4	604.4	700.4	633.3	604.6	642.9	606.1	778.6
Standard Deviation	260.6	182.2	456.1	233.5	456.1	362.0	168.1	363.7	285.0	202.3
95^{th} Percentile	1376.5	909.8	1450.7	988.5	1450.7	1228.8	881.1	1241.2	1074.9	1111.4
Wall Erection										
Mean Duration	1463.2	827.6	964.7	712.7	964.7	753.6	696.8	688.0	662.6	815.1
Standard Deviation	239.0	271.6	478.0	263.1	478.0	388.9	188.0	381.2	293.5	202.3
95^{th} Percentile	1856.4	1274.4	1751.0	1145.5	1751.0	1393.3	1006.1	1315.1	1145.4	1147.9
Module Completion										
Mean Duration	1478.5	834.2	971.4	652.5	971.4	760.9	703.4	694.5	668.9	589.2
Standard Deviation	255.2	271.4	478.7	64.7	478.7	389.2	187.7	381.1	293.9	141.1
95^{th} Percentile	1898.3	1280.7	1758.9	758.9	1758.9	1401.1	1012.2	1321.4	1152.4	821.3

To better represent the results in Table 34, the module completion duration times can be seen in Figure 38 for each of the three module types. As expected, the common trend for the module completion duration is to decrease as more labour is introduced;

however, the labour must also be balanced between stations to ensure balanced flow. The lowest duration times for each of the module types can be seen with a combination of two fabrication crews per table with three workers in each and two erection crews with four workers in each, resulting in the maximum number of workers of twenty-six. The average duration for each module is 6.2, 8.4, and 7.8 hours for Module AA, Module AD, and Module BB, respectfully. However, a large variation min production times was seen during the time study analysis for most of the tasks. Therefore, the 95th percentile completion time for each module is 10.9, 16.2, and 13.4 hours for Module AA, Module AD, and Module BB, respectfully.

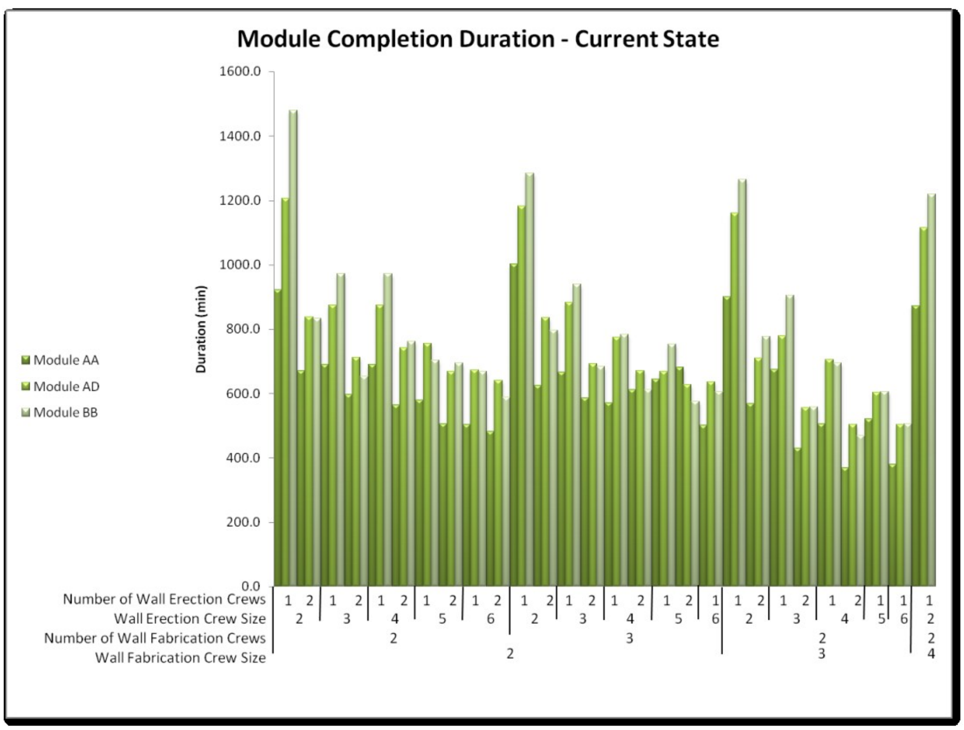


Figure 38: Module Completion Duration – Current State

However, by only using the total duration to determine the crew sizes, the optimum efficiency of workers will not be obtained as some will not be utilized for complete duration. Therefore, the total number of man hours to complete each module will provide a much better optimization technique to ensure the work force is balanced between stations. Table 35 shows the total number of man hours per module for both the mean and 95th percentile. Figure 39 shows the average number of man hours for a combination of the module types to demonstrate the optimum crew composition. Simulation 9 composed of two fabrication crews with two workers each and a single wall erection crew with six workers (18 workers total) proved to be the optimum crew selection to minimize the total man hours to 184.3 and 289.4 hours for the mean and 95th percentile, respectfully. Since fewer workers have been implemented, the 95th percentile total duration time has increased to 12.7, 16.3, and 19.2 hours for each of the module types.

Table 35: Total Number of Man Hours per Module – Current State

Total Man Hours to Complete Module (min)										
Simulation	1	2	3	4	5	6	7	8	9	10
Module AA	12923.4	10729.6	10362	10746	11052.8	11278	9836.2	11116.6	9050.4	11582.4
Module AD	16889.6	13414.4	13104	12796.2	13977.6	14862	12836.7	14707	12090.6	15372
Module BB	20699.28	13347.2	14571	11745	15542.4	15218	11957.8	15279	12040.2	14140.8
Average of Modules	16837.43	12497.07	12679	11762.4	13524.27	13786	11543.57	13700.87	11060.4	13698.4

Total Man Hours to Complete Module (95th Percentile) (min)										
Module AA	21513.59	19767.89	18645.4	22587.04	19888.42	18127.78	29271.88	18014.41	13725.82	18673.01
Module AD	29807.13	21052.46	19655.21	19239.34	20965.56	24939.27	32856.84	24699.06	17618.79	23224.57
Module BB	26576.54	20490.45	26382.92	13660.77	28141.78	28022.68	17206.83	29071.01	20742.58	19711.43
Average of Modules	25965.75	20436.93	21561.18	18495.71	22998.59	23696.58	26445.18	23928.16	17362.4	20536.34

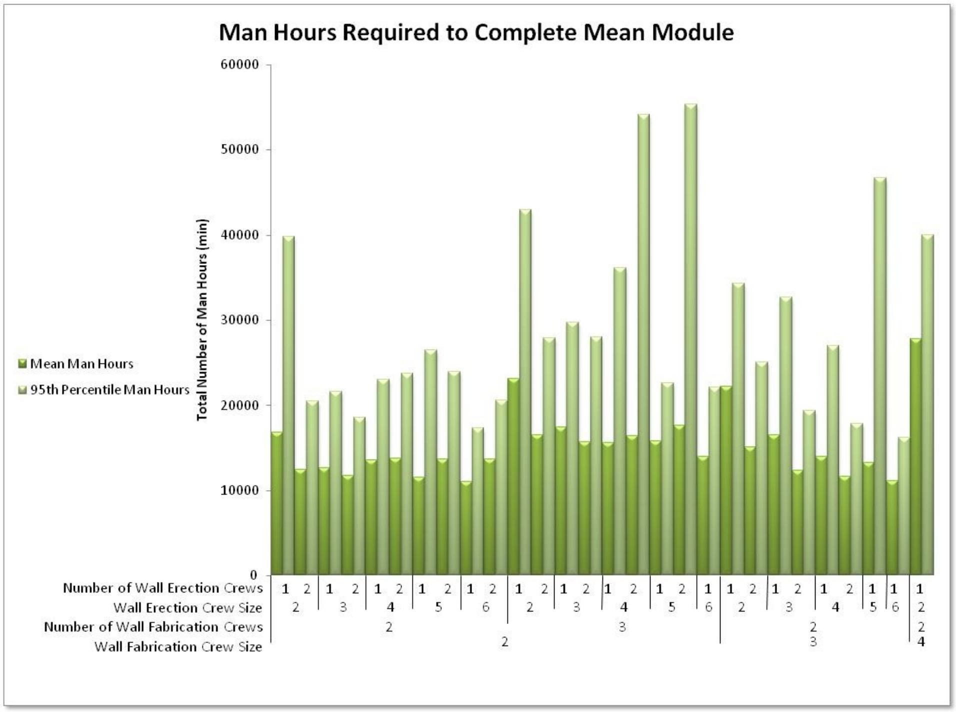


Figure 39: Man Hours Required to Complete Mean Module – Current State

Since Simulation 9 was determined to have the optimum crew composition, further analysis will be conducted. Figure 40 through Figure 48 show the statistical probabilities of completing the tasks in each station for each module. The simulation completed 300 runs of the model for each module and recorded the wall fabrication, wall erection and total completion time. For each of the figures, it can be seen that the majority of observations are localized within a specified range; however, due to the variant nature of the case study observations, a few observations extend well beyond the normally expected results which could be described as breakdowns on the production floor and extend the overall duration for each module.

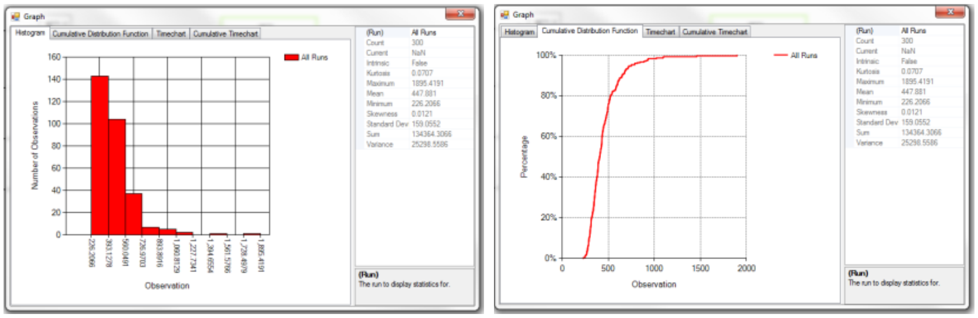


Figure 40: Current State – Simulation 9 – Wall Fabrication Time for Module AA

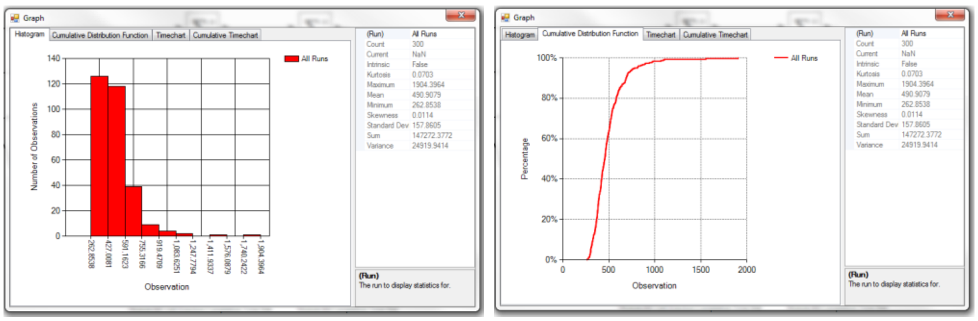


Figure 41: Current State – Simulation 9 – Wall Erection Time for Module AA

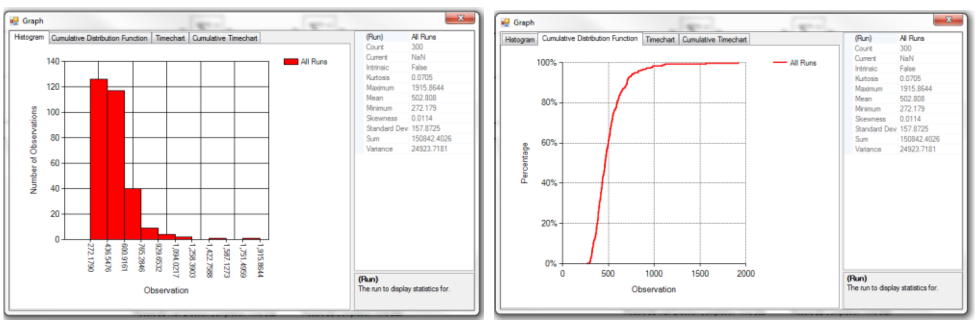


Figure 42: Current State – Simulation 9 – Module Completion Time for Module AA

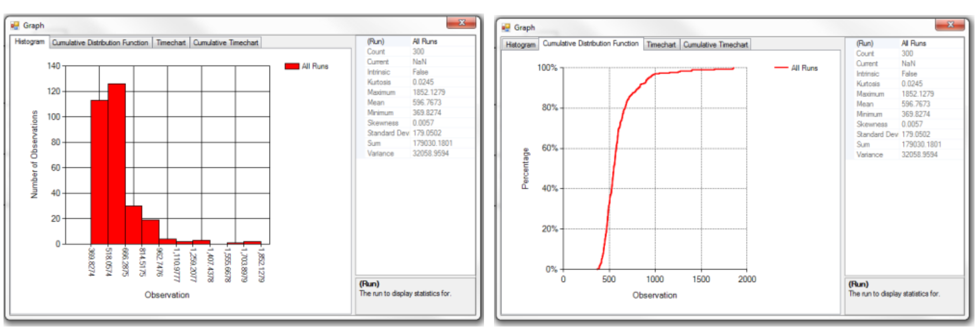


Figure 43: Current State – Simulation 9 – Wall Fabrication Time for Module AD

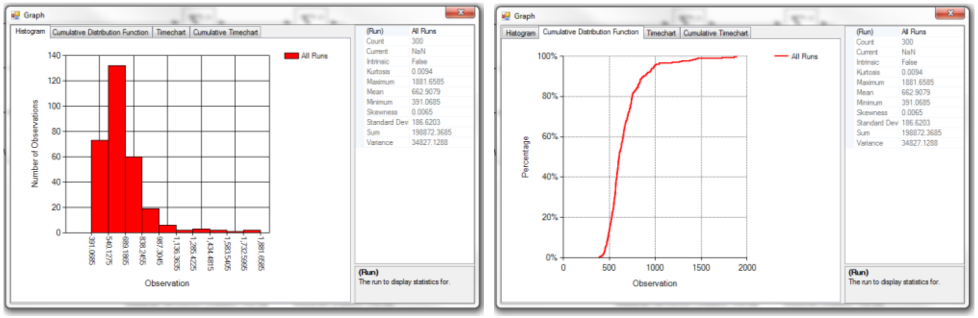


Figure 44: Current State – Simulation 9 – Wall Erection Time for Module AD

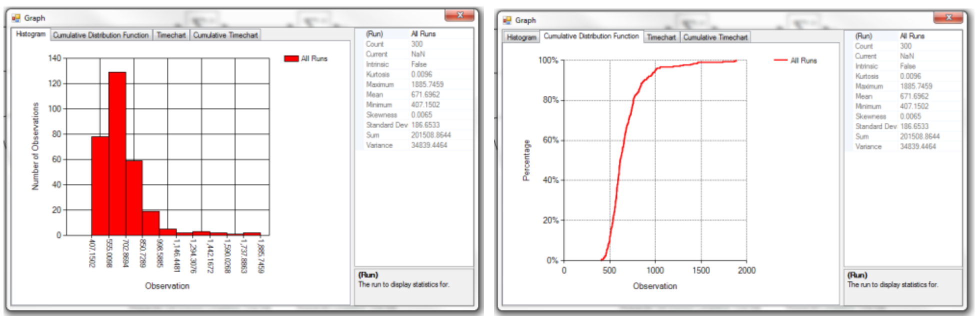


Figure 45: Current State – Simulation 9 – Module Completion for Module AD

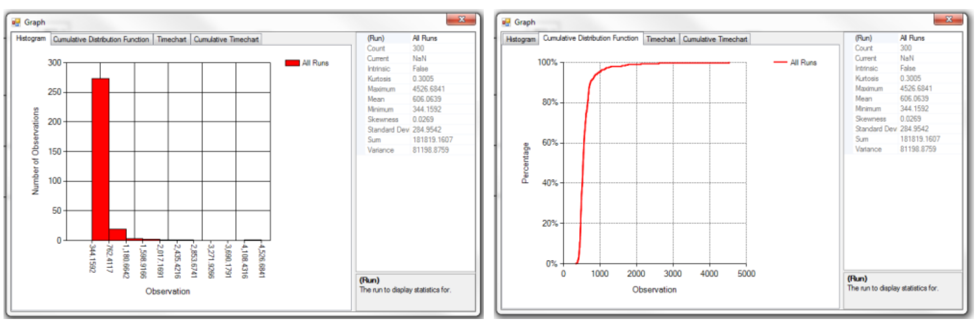


Figure 46: Current State – Simulation 9 – Wall Fabrication Time for Module BB

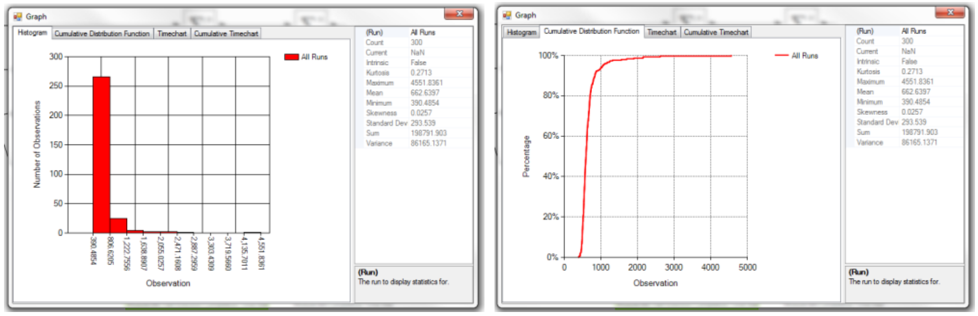


Figure 47: Current State – Simulation 9 – Wall Erection Time for Module BB

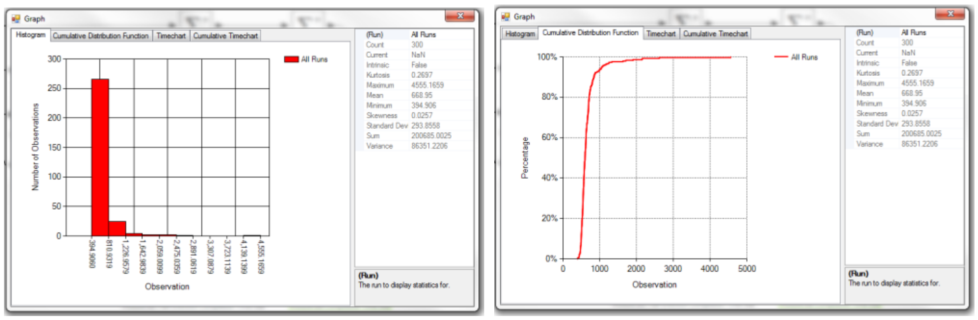


Figure 48: Current State – Simulation 9 – Module Completion Time for Module BB

The main power of the simulation technique comes from the ability to probabilistically determine the duration of production for each module based on the Cumulative Distribution Function. The management can decided the percentage of on-time module completions they wish to obtain which will determine the takt time for the entire production. Within the case study, a 95th percentile on-time completion was assigned which would make a takt time of 19.2 hours (approximately 2 days) for the entire manufacturing plant. Conversely, a takt time can be assigned to the wall fabrication and erection stations and the probability of on-time completion can be predicted based on the simulation. To balance the flow with the rest of the production line, a takt time goal of one and a half days (fifteen working hours) has been given to complete each module. From analysing Figure 40 through Figure 48, the probability of on-time completion would be 97%, 90% and 86% for Module AA, Module AD and Module BB, respectfully. Therefore, due to the large variations in fabrication and erection times, both Module AD and Module BB are unable to be produced within the allotted time 95% of the time. To ensure on-time completion and an optimized work force, alternative crew layouts must be used.

Simulation Scenario 2 – Future State

To stay consistent in the analysis, the same parameters discussed in Table 33 will be used to perform the future state analysis of the wall fabrication and erection stations. As well, a maximum of 26 workers between the two stations will be enforced to ensure productivity will not be affected due to overcrowding. Even though the parameters remain the same, the removal of a framing table has allowed for 48 different simulation scenarios to be created based on various combinations of work force allocations. Within the future state simulation, the total number of workers ranges from 10-26 workers. Each of the simulation scenarios were ran to determine the wall fabrication, wall erection and complete module construction time for the three types of modules in the study. The mean and 95th percentile times were recorded and are presented in Table 36.

Table 36: Future State Module Completion for Various Crews

Simulation	20	21	22	23	24	25	26	27	28	29	30
Seed	100	100	100	100	100	100	100	100	100	100	100
Run Count	100	100	100	100	100	100	100	100	100	100	100
Simulation Constraints											
Wall Fabrication Crew Size	2	3	3	3	3	3	3	3	3	3	3
Number of Wall Fabrication Crews	3	2	2	2	2	2	2	2	2	2	2
Wall Erection Crew Size	6	2	2	3	3	4	4	5	5	6	6
Number of Wall Erection Crews	2	1	2	1	2	1	2	1	2	1	2
Total Number of Workers	24	14	16	15	18	16	20	17	22	18	24
Table Length (2 Tables)	70	70	70	70	70	70	70	70	70	70	70

Simulation Results											
Module AA											
Wall Fabrication											
Mean Duration	446.5	573.3	381.1	427.4	341.1	385.8	328.5	354.4	319.6	366.6	339.7
Standard Deviation	145.4	784.7	187.7	142.5	114.5	144.0	95.5	103.1	99.0	121.2	155.5
95th Percentile	685.7	1864.1	689.9	661.8	529.5	622.7	485.6	524.0	482.5	566.0	595.5
Wall Erection											
Mean Duration	410.0	934.7	567.8	591.8	407.9	473.9	361.7	396.4	346.2	392.5	340.5
Standard Deviation	152.4	826.1	281.8	188.5	152.8	155.7	130.6	111.6	138.8	125.7	166.0
95th Percentile	660.7	2293.6	1031.4	901.9	659.3	730.0	576.5	580.0	574.5	599.3	613.6
Module Completion											
Mean Duration	482.8	973.7	607.1	627.5	450.1	511.2	402.3	436.2	384.8	427.6	379.0
Standard Deviation	151.0	825.3	280.6	187.9	151.1	153.9	126.3	110.5	135.2	125.3	163.5
95th Percentile	731.2	2331.3	1068.7	936.6	698.7	764.4	610.1	618.0	607.2	633.7	648.0
Module AD											
Wall Fabrication											
Mean Duration	738.5	833.6	555.0	670.6	537.6	623.8	523.1	601.4	525.3	563.5	520.9
Standard Deviation	214.1	215.3	125.2	181.3	159.3	486.7	147.4	347.5	126.8	159.1	120.9
95th Percentile	1090.7	1187.8	761.0	968.8	799.6	1424.4	765.6	1173.1	733.9	825.2	719.8
Wall Erection											
Mean Duration	810.8	1185.0	779.3	843.5	706.3	736.2	604.9	670.9	586.1	617.4	566.1
Standard Deviation	288.6	338.8	250.6	231.0	304.5	487.8	168.9	347.7	147.3	163.0	135.9
95th Percentile	1285.5	1742.3	1191.5	1223.5	1207.2	1538.6	882.7	1242.9	828.4	885.5	789.7
Module Completion											
Mean Duration	817.5	1194.2	790.2	853.5	717.0	745.7	614.9	680.8	597.1	627.5	575.8
Standard Deviation	288.8	339.0	250.7	231.0	304.4	487.6	169.2	348.6	148.0	162.9	135.5
95th Percentile	1292.6	1751.9	1202.6	1233.5	1217.7	1547.8	893.2	1254.2	840.6	895.5	798.7
Module BB											
Wall Fabrication											
Mean Duration	1019.7	1139.4	750.2	877.9	658.7	836.0	676.3	729.9	576.0	627.5	662.3
Standard Deviation	363.9	219.4	197.0	185.9	448.6	629.8	1274.4	516.6	153.7	128.7	976.2
95th Percentile	1618.3	1500.3	1074.3	1183.7	1396.6	1872.0	2772.7	1579.7	828.8	839.2	2268.1
Wall Erection											
Mean Duration	1082.2	1344.6	957.3	1045.2	789.5	927.1	776.0	808.0	646.9	689.5	723.8
Standard Deviation	363.7	273.7	338.0	430.0	465.1	631.8	1275.9	517.3	162.7	139.7	976.4
95th Percentile	1680.5	1794.8	1513.3	1752.6	1554.6	1966.4	2874.9	1659.0	914.5	919.3	2330.0
Module Completion											
Mean Duration	1088.6	1349.0	961.6	1049.4	793.9	931.6	780.3	811.9	651.0	693.5	727.9
Standard Deviation	363.8	273.8	337.8	430.4	464.9	631.6	1275.9	517.2	162.7	139.7	976.3
95th Percentile	1687.1	1799.4	1517.3	1757.4	1558.7	1970.6	2879.2	1662.7	918.6	923.3	2333.9

To better display the results, Figure 50 shows the mean duration to construct each module for each crew allocation. As the crew sizes and number of crews increase, the expected trend is for the total duration to decrease proportionately; however, it can be seen that the allocation of work force within the crews plays a more substantial role in determining the duration of the module construction. By creating a more balanced flow between stations, each station will actually increase their own production rates as each station is interconnected. If the wall fabrication station has an over-allocation of workers in comparison to the wall erection station, an over production of wall will occur and the fabrication crew will be required to wait until their tables are empty to continue producing walls.

From Figure 49, the minimum durations for the wall fabrication of for Module AA, Module AD and Module BB was seen in Simulation 46 with a mean module completion time of 5.7, 8.0, and 9.1 hours, respectfully. Simulation 46's workforce is composed of four workers in two crews per framing table with five workers in two crews for the wall erection station resulting in a total of twenty-six workers. The key to the reduction in module completion times compared to the current state simulation is the additional allocation of work force to the wall erection station. By creating a pull system and increasing the wall erection station's productivity rate slightly higher than the productivity rate of the wall fabrication station, the variability in probabilistic productivity rates will have a lesser effect on the overall production rate. However, Simulation 46 implements the maximum number of workers to obtain the minimum duration possible which does not necessarily optimize the work force productivity.

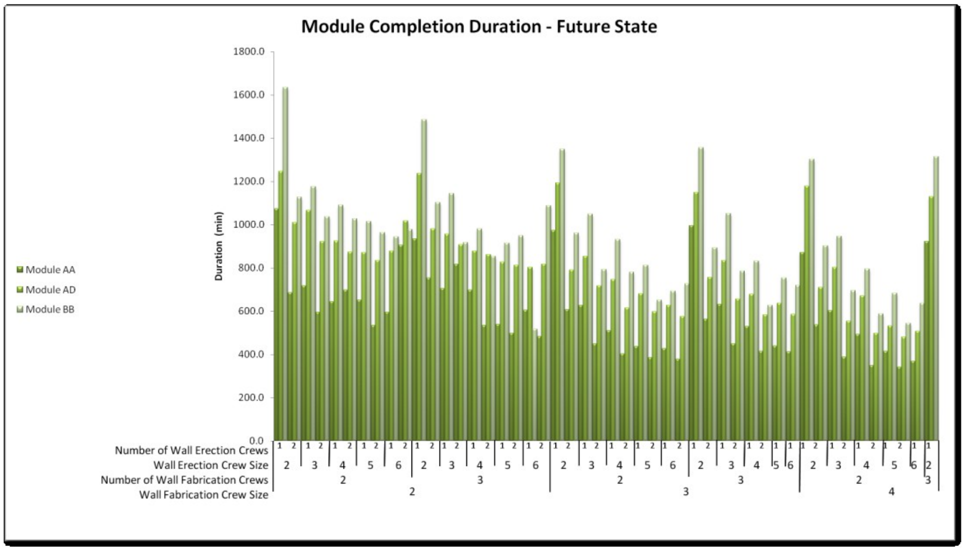


Figure 49: Module Completion Duration – Future State

To determine the optimum work force allocation, a similar method to the current state optimization was use which determined the total number of man hours required to fabricate and erect the walls for each module. The total number of man hours (in minutes) can be seen in Table 37 for each of the 48 simulations conducted. Simulation 29 was found to have the lowest mean total number of man hours which were 128.3, 188.3, 208.1 hours for each of the modules, respectfully. Figure 51 shows the average number of man hours for a combination of the module types to demonstrate the optimum crew composition. Simulation 29's work force is composed of three workers in two crews per table and six workers in a single wall erection crew, resulting in a total labour force of 18. This crew layout is very similar to the optimum crew size in the current state scenario with the exception that the additional workers from Table 6B have been disbursed to the other two tables. The total mean duration for Module AA, Module AD and Module BB is 10.0, 14.7, and 15.3 hours with a 95th percentile duration of 10.6, 14.9, and 15.4 hours, respectfully.

By comparing the total number of man hours and the total duration of the wall fabrication and erection processes between the current and future states, the overall gains can be estimated prior to implementation on the production floor. From the simulations, the average total number of man hours saved from the future state simulation was 9.9 hours which equates to a 5.2% reduction in labour. As well, the average duration to complete a module was reduced by 0.92 hours which equates to a 10.1% reduction in fabrication time. Since the optimized work forces for both the current and future state are equivalent, the production efficiencies obtained can be attributed to the reallocation of labour and the increase in framing productivity due to lean construction implementation.

Table 37: Total Number of Man Hours per Module – Future State

Total Man Hours to Complete Module (min)											
Simulation	20	21	22	23	24	25	26	27	28	29	30
Module AA	11587.2	13631.8	9713.6	9412.5	8101.8	8179.2	8046	7415.4	8465.6	7696.8	9096
Module AD	19620	16718.8	12643.2	12802.5	12906	11931.2	12298	11573.6	13136.2	11295	13819.2
Module BB	26126.4	18886	15385.6	15741	14290.2	14905.6	15606	13802.3	14322	12483	17469.6
Average of Modules	19111	16412	12581	12652	11766	11672	11983	10930	11975	10492	13462

Total Man Hours to Complete Module (95^{th} Percentile) (min)											
Module AA	17548.68	32638.46	17098.99	14048.93	12575.87	12229.85	12201.27	10505.53	13358.49	11406.93	15550.98
Module AD	31021.82	24525.97	19241.62	18502.43	21919.28	24764.83	17864.68	21322.2	18492.32	16118.47	19168.74
Module BB	40489.22	25191.61	24276.5	26361.12	28055.89	31529.31	57583.11	28265.8	20210.11	16619.52	56013.92
Average of Modules	29687	27452	20206	19637	20850	22841	29216	20031	17354	14715	30245

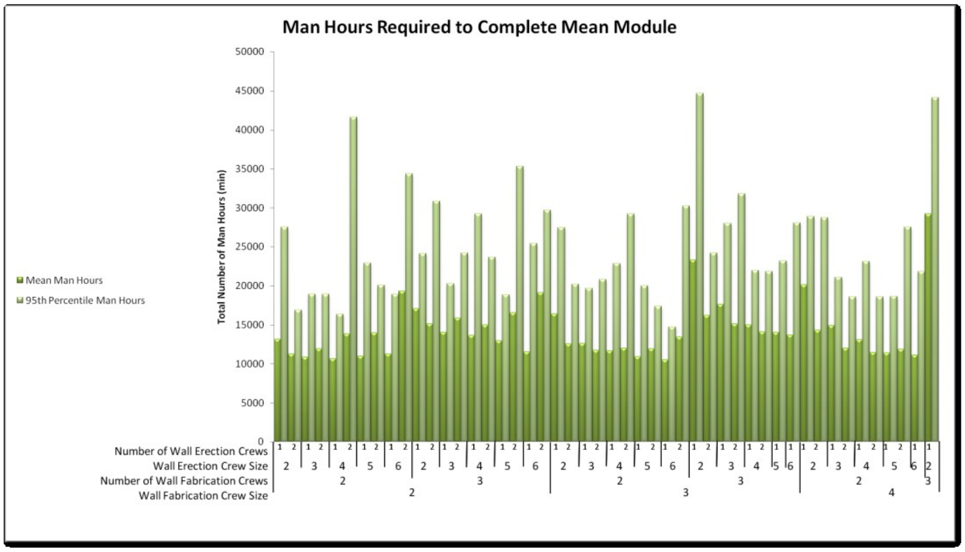


Figure 50: Man Hours Required to Complete Mean Module – Future State

Since Simulation 29 was determined to have the optimum crew composition for the future state, a complete analysis of the findings will be presented. Figure 51 through Figure 59 shows the statistical probabilities of completing the tasks in each station for each module. Similar to the current state optimum, the simulation completed 300 runs of the model for each module and recorded the wall fabrication, wall erection and total completion time. It can be seen that the majority of the observations are localized within a specified range; however, unlike the current state model, fewer extreme results were observed for several of the Modules.

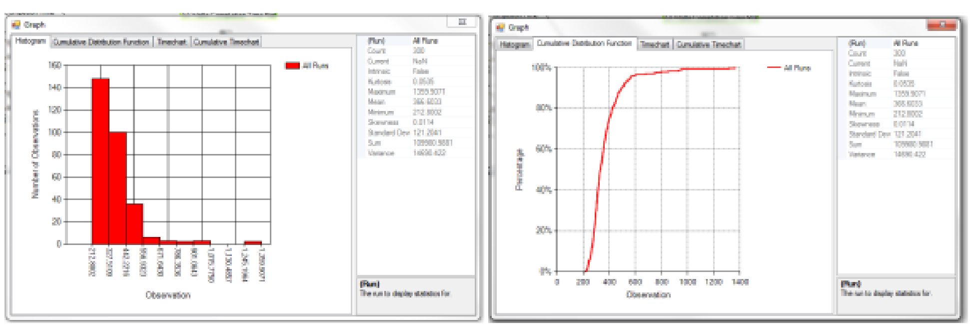


Figure 51: Future State – Simulation 29 – Wall Fabrication Time for Module AA

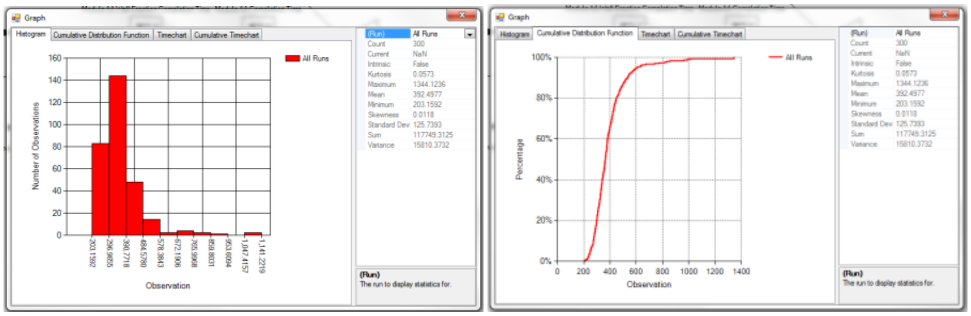


Figure 52: Future State – Simulation 29 – Wall Erection Time for Module AA

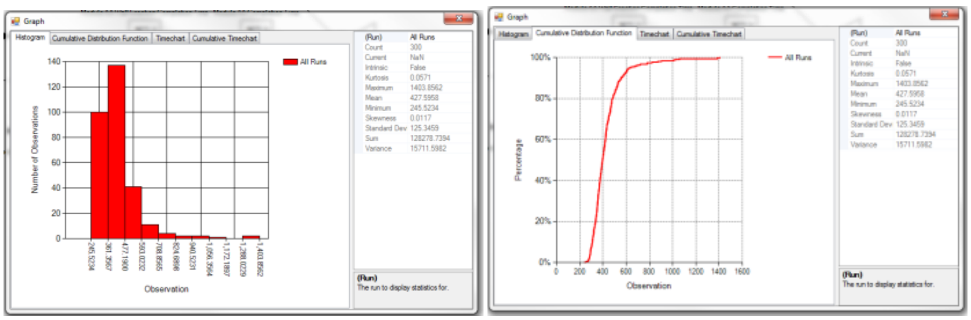


Figure 53: Future State – Simulation 29 – Module Completion Time for Module AA

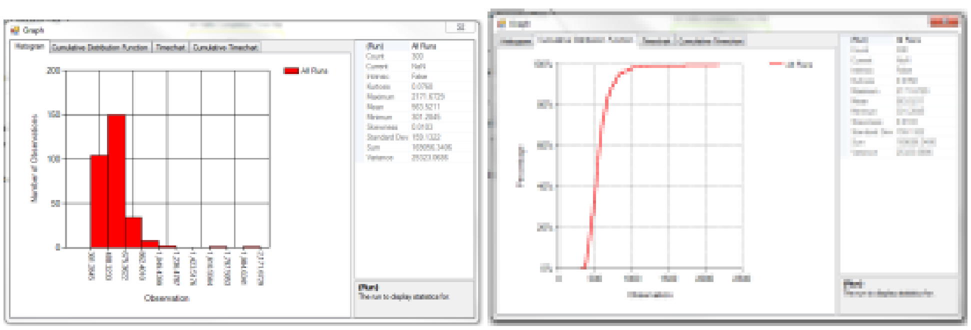


Figure 54: Future State – Simulation 29 – Wall Fabrication Time for Module AD

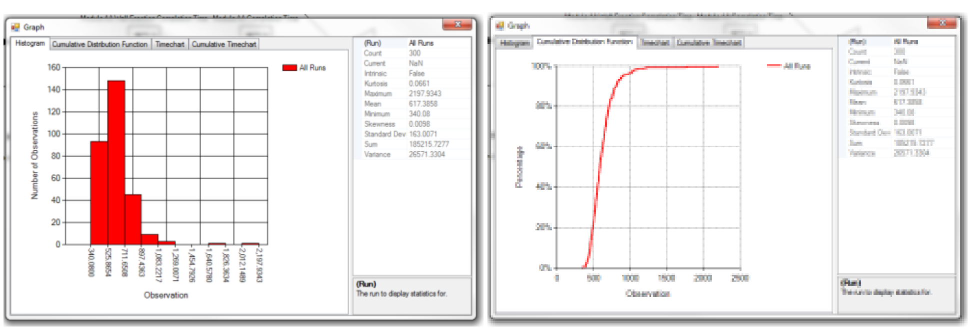


Figure 55: Future State – Simulation 29 – Wall Erection Time for Module AD

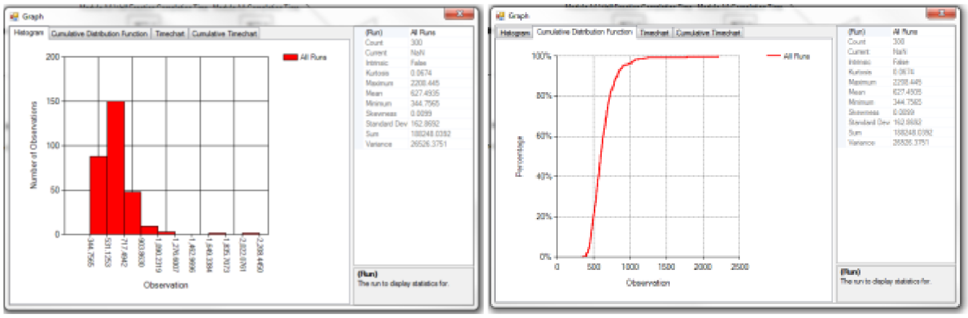


Figure 56: Future State – Simulation 29 – Module Completion for Module AD

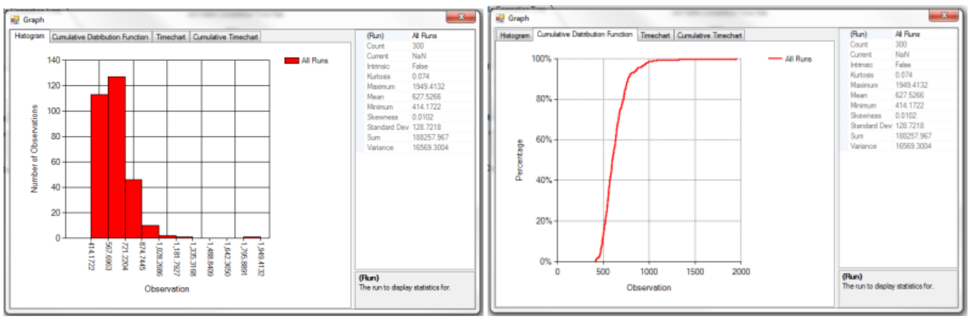


Figure 57: Future State – Simulation 29 – Wall Fabrication Time for Module BB

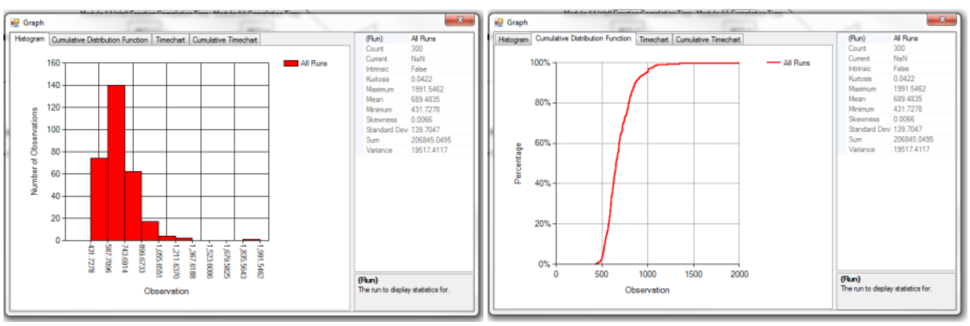


Figure 58: Future State – Simulation 29 – Wall Erection Time for Module BB

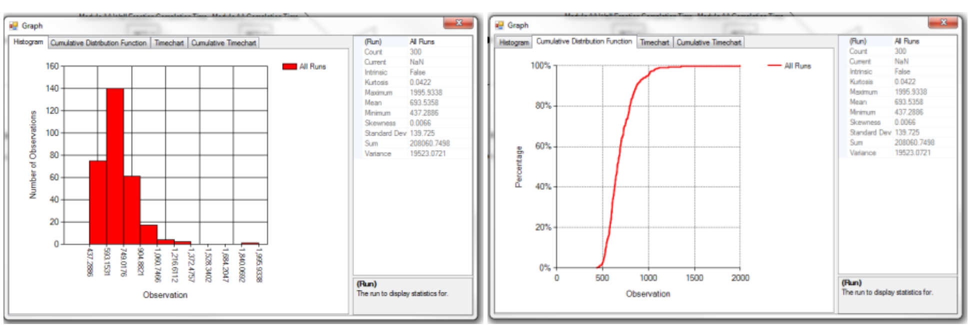


Figure 59: Future State – Simulation 29 – Module Completion Time for Module BB

By implementing the future state fabrication station layout, the management can decided the percentage of on-time module completions they wish to obtain which will determine the takt time for the entire production. Within the case study, a 95th percentile on-time completion was assigned which would make a maximum takt time of 15.4 hours (approximately 1.54 days) for the entire manufacturing plant. Conversely, the takt time can be assigned to the wall fabrication and erection stations and the probability of on-time completion can be predicted based on the simulation. To balance the flow with the rest of the production line, a takt time goal of one and a half days (fifteen working hours) has been given to complete each module. From analysing Figure 51 through Figure 59, the probability of on-time completion would be 99.5%, 95.3% and 92.9% for Module AA, Module AD and Module BB, respectfully. Although Module BB does not meet the 95th percentile takt time requirement of 15 hours, the on-time completion percentage is fairly close. By implementing the lean manufacturing techniques, it is predicted that the variance between task durations will be minimized and Module BB will be able to obtain a 95th percentile on-time completion with a total work force of eighteen in the wall fabrication and erection stations.

CONCLUSION

GENERAL CONCLUSION

This thesis described a methodology to improve the efficiency, productivity and cost effectiveness of a modular manufacturing production line by implementing and unifying several disciplines, including building information modelling (BIM), lean construction, and simulation modeling. To validate the proposed methodology, a case study of the current processes and practices of a modular manufacturing plant was conduct in collaboration with BCT Structures, IMR Reality, and the University of Alberta on the Stony Mountain Plaza Housing Project.

Within the case study, the various disciplines were integrated to produce a holistic representation of the wall fabrication, storage and wall erection stations of the modular manufacturing plant. A detailed BIM model was developed based on the detailed manufacturing drawings which allowed the dimensional and object properties to be extracted for use as input parameters for the simulation model. To implement lean construction, a time study and a kaizen were conducted on the wall fabrication and wall erection stations. A time study was conducted on 5 modules to determine the production durations and labour requirements of the wall fabrication and wall erection stations. The time study data was analyzed and the probabilistic productivity was determined for each task based on the wall type, number of windows, number of doors, and number of columns. The probabilistic productivity for each wall type was represented by either a gamma, uniform, exponential, or triangular distribution. A detailed kaizen was conducted in an attempt to eliminate muda from the system by identifying the eight forms of waste: motion, delay, conveyance, correction, over-processing, inventory, over-production, and knowledge disconnection. To validate the lean construction improvements, a simulation model was developed which included the time study and BIM model data into a cohesive package. Figure 1 has been reproduced below which identifies the flow and integration of each of the disciplines into a cohesive package.

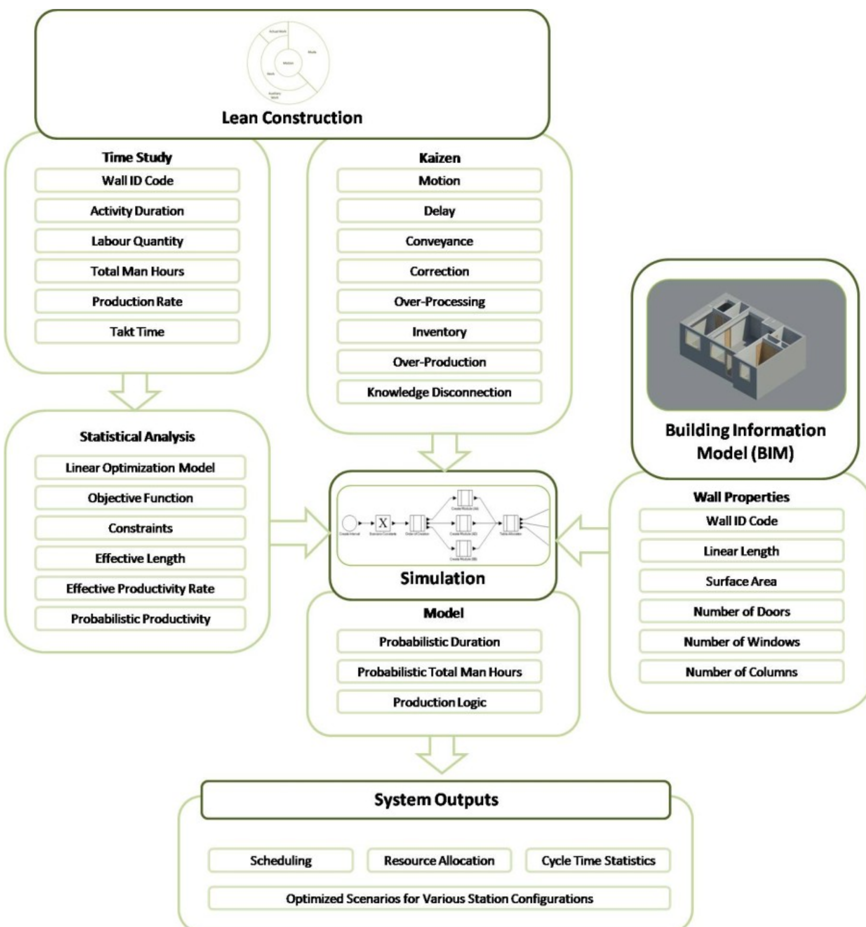


Figure 60: Overview Flow Chart

The current and future state simulation analysis provided key validation for the proposed methodology. The current state of the fabrication station can be represented by Figure 22 and the future state framing station can be represented by Figure 24. Through the analysis of the simulations, it was determined that the optimum total number of workers for both the current and future state was eighteen. In the future state, the optimum distribution of workers was to have two crews of three workers on each wall fabrication table and six workers in a single crew for the wall erection station. By altering the fabrication station layout to the future state, a 10.1% decrease in overall module wall fabrication and erection was predicted with a 5.2% reduction in overall man hour requirements in comparison to current state simulation values. The simulation has shown that it can provide decision makers, managers and workers with detailed information before implementing the proposed changes in the real production line. Unfortunately, there was not an opportunity to verify the results with real world changes to the production line.

RESEARCH CONTRIBUTION

The contributions of this research can be summarized as follows:

- Efficiently conveyed the relationship and advantages of combining building information modeling, lean construction, and simulation modeling;
- Demonstrated the versatility of BIM by extracting various wall properties from a three-dimensional model;

- Integrated lean construction practices including a time study and kaizen to continually improve the modular manufacturing process;
- Statistically quantified the productivity rates and probabilistic duration for a wall fabrication and wall erection station of a modular manufacturer to provide a base line for other companies; and
- Developed a simulation model that is used to statistically estimate the scheduling, resource allocation and takt time of a modular manufacturing facility.

PROPOSED FUTURE RESEARCH

To further pursue this research, modifications to the methodology could provide additional functionality. The following is a list of recommendations for future developments:

- To expand the methodology to all other stations within the modular manufacturing facility to provide a holistic model of the processes and relationships between stations;
- To add 3D visualization to the simulation model to better convey and understand the results obtained;
- To develop a more realistic simulation model including variations in the productivity rate of individual workers based on the number of workers on each station and number of hours worked; and,
- To verify and validate the simulation model predictions with real world changes to the production line by performing an additional time study.

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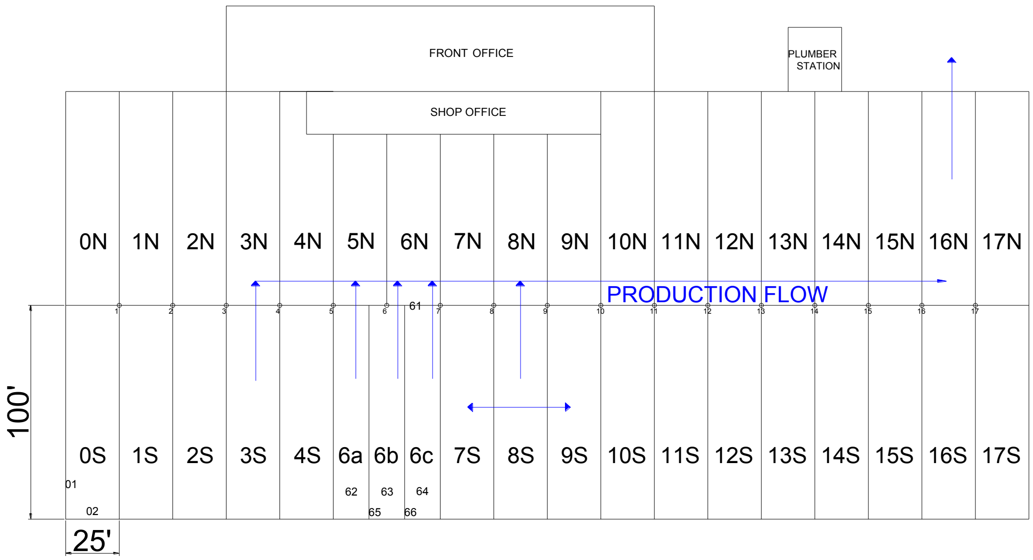
APPENDIX

FULL DESCRIPTION OF PLANT LAYOUT



Location	Photograph	Description
0S-1S		**Compile Lumber for Roofs** • Roof's 2x10 joists are cut to the unit's width with a mitre saws located at 01 and 02 • Joists are stacked and bound • Joists moved with fork lift over to 8S when ready to construct the roof

2S		**Storage for Roof and Flooring** • Storage of nails, screws, tools, ¾" sub-floors, sound reducing boards, etc. • 2 – 2 ton cranes connect 1S and 1N
3S		**Construct Floor** • Mark out joist location on 2x4 spacers that span the entire length of the floor • Carry joists to proper location • Nail joists to spacers • Place LVL (orange beams) around joists • Screw ¾" subfloor • Staple sound reducing board • Place paper on top (to protect the sound reducing board from mud later) • Plumbers mark out location of heating and plumbing pipes • 2 – 10 ton cranes move floor from 3S to 3N
4S		**Additional Floor Bay** • Not utilized, only 2 – 5 ton cranes so unable to lift the floor (used with 12' wide trailers) • Mark out of spacers has been completed here on occasion if 3S is behind

6a, 6b, 6c		**Framing Tables** • 3 framing tables to frame, poly, sheath, and drywall the walls (as required) • For exterior walls, all steps above are completed, leaving the "outside" of the wall exposed for electrical wiring • Partition walls are only framed and drywall on one side • All materials are stored on the south end of the tables. 12' – 1/2" drywall is stored on carts that role on top of the tables (62 and 64). 2x4 and 2x6 studs and sheathing are stationary stored at 63 and workers carry them to the correct location • 12' 2x4 and 2x6 dimensional lumber is stored at 65 with at mitre saw at 66 to mark out and cut the top and bottom plate • 1 long and 1 short exterior walls are constructed first, followed by partition walls, and finally the other 2 exterior walls • Walls are moved with cranes, 4 – 1 ton cranes between column 5 and 6 with access to 6a, 2 – 2 ton cranes between column 6 and 7 with access to 6b and 6c • If walls are completed before the floor is in position, they are stored at 61 or walls are built on top of each other on the tables

7S, 8S, 9S

Roofing

- A fork lift brings the joists from 0S and places them at the north end of 7S or 9S
- Workers construct and mark-out the side beams for the location of the joists
- Carry and nail joists in proper location
- The roof is built upside down, so all the framing is mirrored of what the plans show
- After framing, 2 pieces of 1x6 are nailed to the perimeter of the roof (provide space for the drywall)
- 2 layers of drywall are screwed to the roof
- The roof is flipped over with 2 – 5 ton cranes
- Electrical and fire sprinklers are installed while on the floor
- When ready, the roof is lifted onto the unit from 8S to 8N

10S - 17S

Storage of Materials

- 10S and 11S are shelves for electrical
- 12S is storage and cutting of drywall and sheathing
- 13S is storage of windows and building wrap
- 14S is storage of hot water tanks and mass storage of drywall
- 15S is storage of drywall materials (mud and ceiling texture) and doors and trim
- 16S is storage of trim and misc. Shelves
- 17S is work station with table saw and mitre saw. As well, the shipping and

		receiving office is in the south east corner of the building
0N-1N		**Storage of Materials** • Storage of insulation, plumbing supplies and LVL board for flooring
2N		**Immediate access materials for Plumbing and Floors** • Immediate use materials stored for use in 3N • LVL cut to length before moving to 3S
3N		**Plumbing, Heating, and Insulate Floor** • Plumbing crew runs pipe from the sinks, tubs, etc. To the mechanical shaft in each suite. As well, they run copper heating pipes under the windows, to the mechanical closet (with the hot water heater) and to the mechanical shaft to be connect to the boiler • After completion, a 1 hour pressure test is placed on the pipes. During the test, insulation is placed wherever there is no pipe (if there is a problem, they need the pipe exposed). If it passes the test, rest of insulation installed. • Black under wrap to hold in the insulation.

4N

Floor Storage

- The floor is stored with very little work completed; it provides a buffer for the wall department

5N

Place 1st Walls

- Place tubs in rough location before the walls are installed
- Place exterior wall built on 6a which is the west wall on the assembly line. Wall is transported by a 2 – 1 ton cranes bolted in place and supported with bracing
- Place exterior wall built on 6b which is the north wall on the assembly line.

6N

Install rest of walls

- Install all partisan walls starting with the NW and moving to the SE. Walls usually come directly from the tables but if the wall department is ahead, they can also be on the storage rack.
- Final wall to be installed is the long exterior wall because it has the most forgiveness to error

7N

Electrical Through Walls

- All electrical boxes are placed and wired to each other. Since the roof is not installed yet, only minimal wiring can be completed.
- Backing is installed for cabinetry
- If the drywall crew is ahead, might mud over drywall screws (fairly trivial task).

8N		**Installation of the Roof** • Moved from 8S to 8N with 2 – 5 ton cranes • The move from lifting to placement takes 10 min; however, accurate positioning and securing has been taking several hours • After it is secured, it is lag bolted in place around the perimeter and all partisan walls • This is a critical point in the factory because many activities cannot be started until the roof has been placed (such as placing drywall on the other side of the walls, bulkhead, electrical, etc.)
9N		**Electrical and Installing Drywall** • Drill the holes in the roof and pull the wire through to the electrical boxes (includes electrical, cable and phone lines) • Install drywall once electricians are completed • Install insulation on exterior once electricians are completed • 9N is always the busiest and most conflicting unit because the drywall installation crew is too fast and backing up the line. The electricians are constantly working around cut drywall

10N		**Building Exterior and Initial Interior** • Once completed insulation, sheathing is placed around the exterior perimeter. Styrofoam building wrap is stapled and taped to all sides of the module that will be on the exterior of the building. Windows are installed and taped for water-proofing • First coat of tape and mud is applied to the joints and screws • HRV (heat recovery ventilation) and hood vents installed • Bulkheads placed around HRV and hood vents
11N		**Complete Roof, 2nd Coat Mud** • Insulate, sheath and wrap roof (This is sometimes completed in 10N if the line is not moving) • 2nd coat of mud on the drywall
12N		Since the units are oversize in comparison to the stations, 12N is omitted as a station.
13N		**Final Coat of mud, Texture ceiling** • Final coat of mud checked with bright LCD lights for flaws • Texture ceiling • Paint around kitchen so cabinets can be installed in 14N • On north side of 13N, plumbers have a station to do all pre-installation cooper work for tubs

14N		**Installation of Cabinets, Paint, Flooring** • Install cabinets in kitchen and bathroom • Paint entire unit. Flaws in walls are touched up with mud and repainted • Install flooring (all vinyl tiles) takes about ½ a day; however, it must sit overnight to cure with no one able to enter the unit
15N		**Finishing Plumbing, Paint, Doors and Trim** • Final paint and touch ups • Install hot water tank, sinks, toilet, etc. • Install doors and place trim around • Install pre-painted base boards
16N		**Finishing Work and Ship Out** • Complete any unfinished tasks • Install range and refrigerator • Lift unit with air pressure jacks, back in trailer, and move the unit out to storage
17N		**Storage of finishing materials** • Storage of doors, ranges, and refrigerators