Process automation for flexible residential wall panel manufacturing

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in
Construction Engineering and Management

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ABSTRACT

Modular construction has gained momentum in North America as an emerging construction paradigm in recent years. Modular buildings are assembled from components that are prefabricated in manufacturing plants and transported to the construction site for assembly. The current manual-based approach to modular construction, which typically applies the traditional *stick-building-under-a-roof* building method, involves time-consuming and labour-intensive tasks. However, the application of automated prefabrication of components has the potential to significantly advance the productivity, worker safety, and competitiveness of the Canadian construction industry. This research, focusing on the construction of wood-framed panels, presents a methodology which allows intelligent wall panels with different design properties to be analyzed. By integrating external databases with building information modelling (BIM)-based software, generating wall panel combination plans and assembly information, and developing modularized wood wall-framing machinery, the automated machinery is able to implement the intelligent wall panel prefabrication target. Featuring a case study as the approach to identifying the advantages, the study of panels in a sample house from an Edmonton-based panel manufacturer is thus employed in order to explain the effectiveness of the proposed methodology.

Table of Contents

List of Tables

List of Figures

Chapter 1 Introduction

1.1 Research motivation

As reported by the Canada Mortgage and Housing Corporation (2015), there are approximately 200,000 housing starts in Canada each year. Wood is widely used as the primary construction material in North American residential construction, and a number of construction companies are fabricating wood-framed wall panels in their manufacturing plants as Figure 1.1. However, rather than using automated equipment for framing purposes, these manufacturing plants typically employ a manual process which can be described as *stick-building-under-a-roof*. Meanwhile, the Industry 4.0 concept was introduced by the German government in 2011, promoting the computerization and automation of manufacturing (Brettel et al. 2014); it is not difficult to foresee that it is crucial for the construction industry to adopt this paradigm.

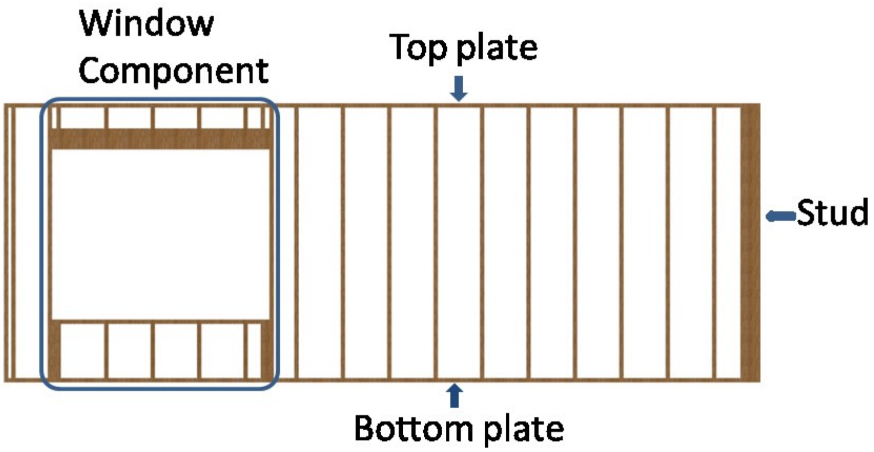


Figure 1.1: Wood wall panel configuration

Compared to the traditional stick-built approach, industrialized home building has several advantages such as shorter project schedule, lower costs, increased safety, enhanced quality control, and less dependence on skilled labour (Burke and Miller 1998; Nadim and Goulding 2010). Therefore, by transferring from the *stick-building-under-a-roof* method to an industrialized one—automated construction, the home building industry will be able to improve productivity to satisfy the potential market. The development of practical, automated equipment is thus in high market demand.

One of the challenges associated with industrializing construction in Canada is that the majority of the machines are developed in Europe, making them costly and difficult to customize in order to meet the specific needs of the Canadian industry. The development of a method to make these machines economically viable is a major concern for Canadian building manufacturers. Additionally, automated construction requires a high level of accuracy in the drafting and design documentation to ensure full compliance with the project pre-planning, project coordination, preliminary design, and transportation plan (Haas et al. 2000; Goodier and Gibb 2007). However, most design plans do not currently provide complete assembly information. The majority of Canadian homebuilders build without detailed construction drawings since the planning stage is time-consuming and costly. Therefore, they rely on the experience of their carpenters to build homes based on a rough structural design. Furthermore, although industrialized construction methods will benefit the construction process, these challenges still inhibit the application of construction automation in the Canadian homebuilding industry.

The introduction of proper construction guidelines to facilitate the shift from the *stick-building-under-a-roof* method to automated manufacturing of wood panels will help to overcome the shortage of skilled carpenters, reduce the high level of timber waste, and improve housing quality, while enabling reduced construction cycle time. This research consists of two central parts. First, guidelines are proposed for improved panel assembly practice, and the linkage between drafting (i.e., computer-aided design) and manufacturing (i.e., computer-aided manufacturing) is developed. The second part focuses on developing new machinery for modular prefabrication. The proposed software application will be capable of generating a wood wall-framing operation plan in a customized format with accompanying support from a BIM model.

Facilitated by industrialized construction methods, multi-panel wood wall-framing is applied in place of single-wall framing (as illustrated in Figure 1.2). A multi-panel arrangement, which is verified by mathematical optimization models, is utilized to reduce the machine set-up time. The multi-panel is partially pre-cut by the wood-framing table to provide easy separation into single-wall panels at a later stage. After loading the details in order to generate a 3D model, and then extracting information from the structural plan of the BIM model panels, the nailing, drilling, and cutting coordination are used to analyze and establish a guideline for further BIM-based construction assembly. The incorporation of intelligence from the BIM model ensures that the manufacturing process is less subject to the skill of carpenters, and therefore significantly increases the construction accuracy and improves quality.

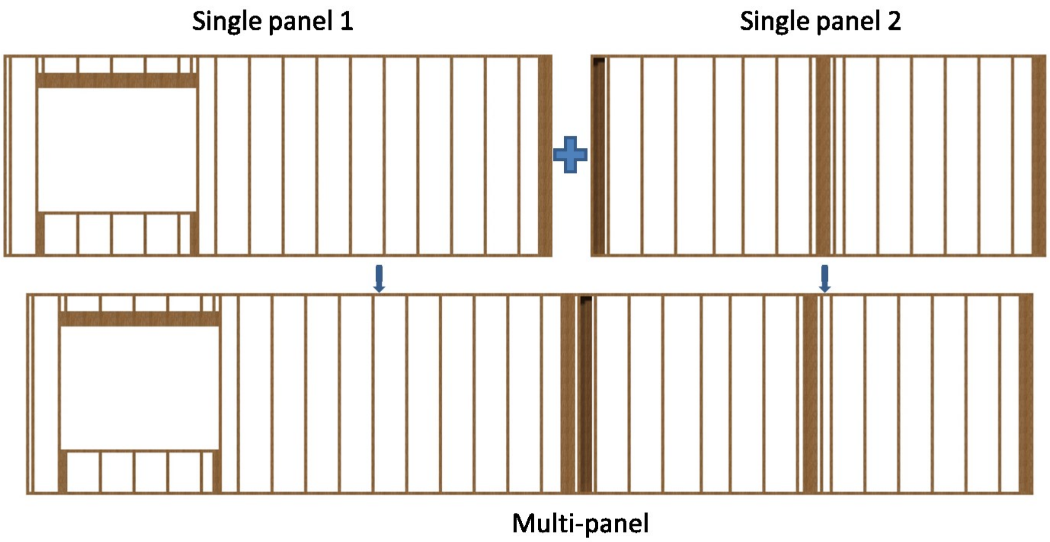


Figure 1.2: Multi-panel framing in place of single-panel wall framing

In order to satisfy the requirements of automated wall panel manufacturing, each station (feeding, nailing, drilling, and cutting) of wood wall-framing machinery must be designed accordingly. However, since the housing market is not stable enough for companies to justify the enormous investment cost of upgrading the entire factory production line at once, the framing machinery developed in this research is designed in the form of modularized components that can be selected and configured based on a company's particular manufacturing requirements. For successful modularization, each framing machine component is decoupled into subsystems with very few interdependencies. By analyzing the existing factory production line and manufacturing target, the upgrade plan can be built accordingly. Rather than changing the factory production line to accommodate the new machinery, the modularized wood-framing machine is customized to satisfy a company's manufacturing requirements thereby reducing the associated costs of increased automation. In addition, the BIM model with proper motion planning analysis provides sufficient information for automated multi-panel wall framing. The goal is to implement a production system that allows fewer labourers with less experience to complete the wall panel assembly affordably, efficiently, and accurately. The system also provides estimators with accurate and practical duration information for wood wall-framing activities (Manrique 2009).

This research involves the design of an operational system which integrates a mathematical algorithm with BIM to establish a complete multi-panel fabrication guideline, while reducing the manufacturing time and material waste associated with offsite construction. Also, it proposes a modularized wood wall-framing machine which can be customized according to company-specific requirements. This automated process for the prefabrication of panels also increases accuracy compared to what would be achievable manually.

1.2 Research objectives

This research is built on the following hypothesis:

"Modular-based machine development for residential building wall framing will permit increased automation and flexibility of framing manufacturing."

"Modular" in this thesis refers to the process of subdividing the wall framing manufacturing system into modules such as cutting, nailing and drilling. "Automation" refers to the use of a control system for wall framing machinery which necessitates minimal human intervention. "Flexibility" refers to the ability of the user to purchase or upgrade to a suitable production line based on their manufacturing requirements and financial capacity. To validate this hypothesis, the following research objectives are pursued:

- to gain an understanding of residential building wall framing technology;
- to challenge the current practice, which can be described as “stick-building-under-the-roof”;
- to develop modular machine operation to support automation of the framing process;
- to generate panel assembly information from the BIM model, such as nail, drill hole, and cut locations, for the purpose of control system development; and
- to build a simulation model in order to analyze the panel manufacturing process and support decision makers in determining the feasibility of purchasing or upgrading automated machinery.

1.3 Organization of thesis

Chapter 1 (Introduction) describes the research motivation and objectives, and provides an overview of the research. Chapter 2 (Literature Review) provides a description of the current state of the application of automated construction, building information modelling (BIM), and material optimization. Chapter 3 (Proposed Methodology) describes the proposed methodology to provide panel assembly guidelines and perform multi-panel manufacturing. Chapter 4 (Case Study) applies the developed methodology in an Autodesk Revit model for the purpose of validation. Chapter 5 (Conclusion) summarizes the research contributions, limitations, and direction of future work.

Chapter 2 Literature Review

2.1 Overview

This chapter reviews the existing literature on the application of automation in construction and industrialized home building. As the building information modelling (BIM) concept is central to this thesis, the literature review section also reviews the state of BIM development and implementation in the construction industry. Finally, since a panel manufacturing simulation model is used to evaluate the feasibility of the machinery, the literature related to simulation models developed for the construction industry is also reviewed.

2.2 Review of the state of the art in wood-framing home building

In the timber-rich northeastern United States, wood is traditionally the primary material for constructing buildings. In the colonial era, *half-timbering*, a heavy framing of squared timbers with "filling" between them was commonly used for building construction (Kniffen and Glassie 1966). From these origins, two basic stick-built construction methodologies were developed: the balloon framing method and the platform framing method. The balloon framing method was launched in Chicago in 1833 (Sprague 1981). The popularity of balloon framing during the 19th century occurred in response to the growth of American cities in less treed regions. Compared to the half-timbering method, balloon framing used lumber which was sawn into standard-sized boards at the mill and was then shipped throughout the West. This method not only made possible the sudden and rapid settlement of the western United States, but also allowed relatively unskilled workers to erect wood-framed buildings both quickly and soundly. Balloon framing improved the strength-to-weight ratio over the timber frame, and implemented both structural and material efficiency (Cavanagh 1997). However, the balloon framing method used vertical studs to cover the wall's full height, from slab on grade or on top of a wood floor to the ceiling, as shown in Figure 2.1. Some of the limitations of this method are material transportation, installation difficulty, and increased fire hazard potential. Thus, in the early 1920s, the platform framing method replaced the balloon framing method; the platform framing method, as illustrated in Figure 2.2, consists of single-height walls from floor to floor. Each wall, in turn, is composed of bottom- and top-plates which connect the vertical wood elements (studs) and window or door components. This method offers ease of assembly, less demand for natural resources and specialized skilled labour, easy material transportation, and lower construction cost (Manrique 2009) The platform framing method has undergone several modifications as residential construction has evolved, including the recent shift of a portion of the market share from on-site construction to factory-based construction (e.g., modular, panelized, etc.). Ideally, factory construction is to be promoted in the homebuilding industry because a controlled environment improves product quality and performance and lowers cost. Since the products are built in a factory, the principles of mass production can be applied to leverage the benefits of a manufacturing-based approach (Neelamkavil 2009). Mass production of housing components and systems reduces construction duration by half and cost by at least 20% (Alarcón 1997). However, when materials and information are defective or idle, manufacturing-based construction methods can lead to significant waste of resources. The implementation of lean tools to replace mass production involves industrializing home building to improve efficiency (Mullens 2004). In 2007, approximately 5% of new residential homes were built in factories either as panelized or modular in the United States (U.S. Census Bureau 2007). However, challenges still remain in making the process more lean, since home building involves a high level of customization and multi-faceted characteristics in the production process. Panels for a specific home possess a diversity of dimensions and design properties which require different amounts of processing time in the production line; the relatively low production volume of specific house models inhibits the full deployment of lean tools (Sabharwal et al. 2009). Meanwhile, as Bock (2015) has discussed, the conventional construction methodology has become stagnant and has reached its technical limits. Although efforts toward construction automation are still at the innovation stage, continued research and development targeting automation will propel construction into the growth phase.

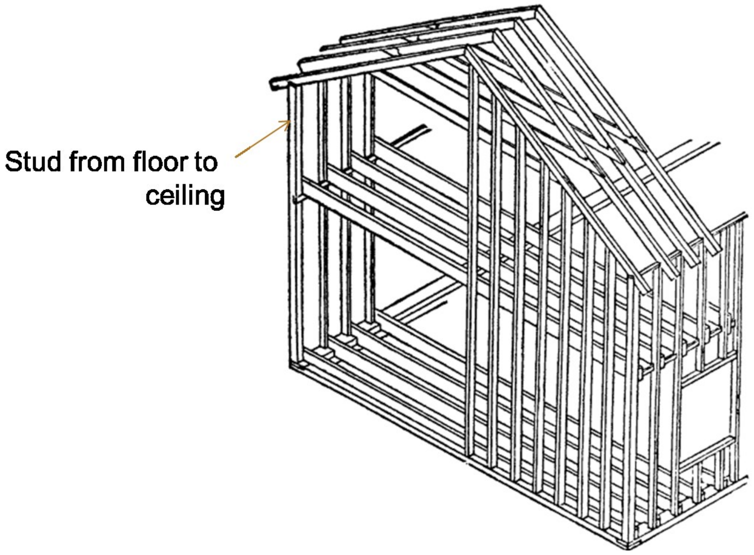


Figure 2.1: Balloon framing

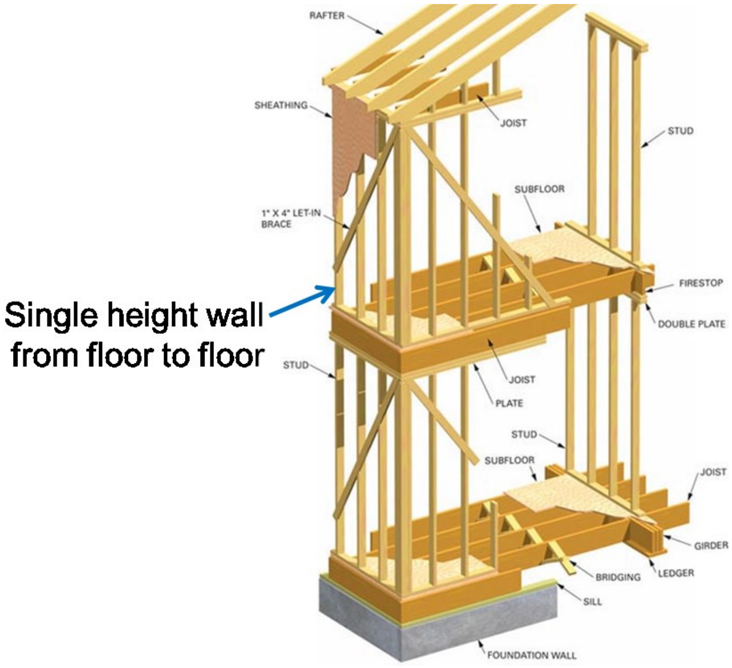


Figure 2.2: Platform framing

2.3 Review of the state of the art in building information modelling

Since construction involves multiple organizations, its success is highly dependent on the accuracy and timeliness of complex data and information exchange among project participants (Dawood, 2002). Traditional paper-based documents often cause unanticipated field costs, delays, and eventual lawsuits between the various parties in a project team. For overcoming such problems, several methods have been developed: alternative organizational structures (design-build method); use of real-time technology (project websites for exchanging documents and plans); and the implementation of 3D computer-aided design tools. Although these methods indeed reduce the information sharing time, the severity and frequency of conflicts caused by paper documents or their electronic equivalents still exist. It has also been noted that the critical assessments about a proposed design, such as cost estimates, energy-use analysis, and structural details, are typically carried out late in the process, when it is difficult to make important changes (Eastman 2011). Building information modelling (BIM) was introduced by van Nederveen and Tolman (1992), and has led to revolutionary change in the management of the entire lifecycle of a building project (Chen et al. 2013). BIM serves as an information database and allows users to create functional relationships between a building model and other integrated project elements. BIM is widely applied in architecture, engineering, and construction (AEC) estimation, and communication among project stakeholders (Liu et al. 2015). BIM aids in visualizing what is to be built in a simulated environment to identify any potential design, construction, or operational issues (Azhar 2011).

Autodesk Revit, as one type of BIM software, provides a means to generate and manage data based on user requirements. It is a tool utilized to improve the performance throughout the entire lifecycle of a building (Stine 2012). Revit provides a powerful .NET API that allows developers to perform the automation of repetitive tasks, extend the Revit core functions in simulation, implement conceptual design, and improve construction and building management (Autodesk 2015). Therefore, from the Revit model, the parameters of building walls can be easily extracted (Liu et al. 2015).

2.4 Review of the state of the art in simulation of construction

A simulation environment called CYCLONE was introduced by Halpin (1977), who presented the progress of the foundation of construction simulation. AbouRizk and Hajjar (1998) have presented a framework for the simulation application in construction which focused on construction practitioners, and proposed the special-purpose simulation (SPS) concept. SPS is a computer-based environment with special purpose capabilities which permits experts in specific areas to use the program without prior simulation knowledge. AbouRizk and Mohamed (2000) developed Simphony.NET as a system combining discrete-event simulation (DES) and continuous simulation. The major contribution of Simphony is the improvement of construction project management; the activities and resources involved in projects can be converted to a Simphony model following their original sequences, and it can provide various model outputs such as standard statistical averages, density functions, and time graphs. As AbouRizk (2010) has asserted, the model can be built to optimize construction methods, maximize resource utilization, and improve cost effectiveness. Therefore, simulation modelling enables engineers to compare different approaches and arrive at the best solution. In addition, simulation modelling allows production controllers to evaluate different scenarios of the construction process in order to complete a project in the most efficient way. Chau et al. (2005) have developed a construction management model for 4D site management (4DSMM). Al-Bataineh et al. (2013) introduced a case study which developed a simulation model in Simphony.NET for a tunneling project decision support system in Edmonton, Canada. A DES model of the steel girder bridge fabrication process has been developed by Alvanchi et al. (2012) to solve the complex process of planning off-site girder bridge construction.

Liu et al. (2015) have introduced a BIM-based simulation tool for construction planning (Figure 2.2). It implements information exchange among BIM, DES, and construction logic modelling. Wall panel information from the BIM model is stored in the database and can be read by the simulation model. The simulation model builds the linkage between panel parameters and the model entity directly. An SPS template has also been developed by Liu et al. (2015) to obtain custom building modelling elements such as workstation, storage, and equipment, thereby permitting efficient visualization and simulation of the production line. This simulation tool is used in this thesis to develop the decision support system for wood wall framing machinery purchase or upgrade.

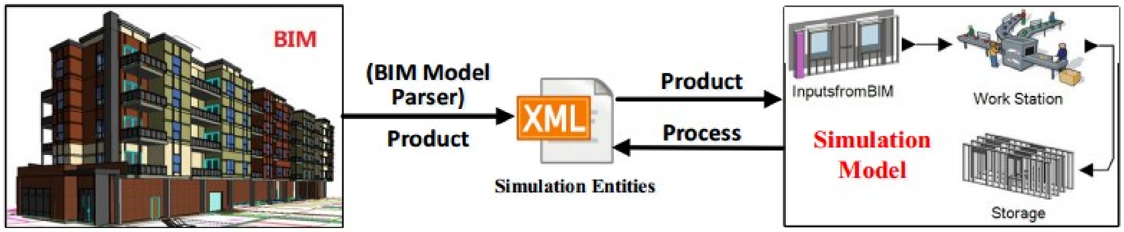


Figure 2.3: Information exchange between BIM model and simulation model

Chapter 3 Methodology

The key contributions of this methodology are the generation of panel assembly information guidelines, and the development of a wood wall-framing machinery operating system which implements intelligent wall panel industrialized manufacturing and is ready for programmers to establish computer numerical control (CNC) code.

Panels for wood-framed buildings entail a high degree of complexity since they have a range of different interconnections and component parts. Therefore, each panel has its own specified framing plan. Based on current assembly requirements for panels, the assembly process can be subdivided into three parts: (1) treating the stud as a consistent interchangeable part, simplify the process of loading and attaching them to one another; (2) drill the top- and bottom-plate, which will help facilitate lifting requirements in downstream stations; and (3) after assembly of a given panel is complete, the cut operation should proceed to precut the multi-panel. Thus, to successfully satisfy the above requirements for panel manufacturing, wood-framing machinery is designed by a research team at the University of Alberta. The design of smooth machinery operation is the major concern of this thesis. Therefore, the next step is to analyze each operation location and build panel manufacturing standardization guidelines.

The wood wall-framing machinery is designed to consist of two sets of dragging jaws and four modular stations: feeding, nailing, cutting, and drilling on each side as Figure 3.1 and Figure 3.2. Modularity adds flexibility, which allows manufacturing to upgrade to a higher level of automation at any time. Definitions of wood wall-framing table configurations and parameters used in this research for explaining the manufacturing process are described in Table 3.1 and Table 3.2. Table 3.2 also lists the parameters used in the equations for operation locations and for generating the wood wall-framing machinery motion planning.

Table 3.1 Definitions of machine configuration components

		Configuration	Description
Table B		Dragging Jaws (DJ)	A top and bottom jaw device draws the framework to the next operation point
		Belt	A continuous metal chain for moving the multi-panel during the assembling
Table A	Nailing station	Top Plate Sliding Stopper (TPSS)	A sliding device used to secure the top plate and stud *x*-direction during nailing
		Bottom Plate Sliding Stopper (BPSS)	A sliding device used to secure the bottom plate and stud *x*-direction during nailing
		Nailing Gun (NG)	Horizontal nail device used to connect top plate, stud, and bottom plate; only moves in the *z*-direction
		Top Plate Clamp (TPC)	A hydraulic device used to secure the top plate *z*-direction during nailing
		Bottom Plate Clamp (BPC)	A hydraulic device used to secure the bottom plate *z*-direction during nailing
		Stopping Pin (SP)	A pin to aid manual positioning of the stud and to hold stud before nailing
		Sliding Pin	A pushing device that slides the studs into position
		Top Clamp	A hydraulic device used to secure the bottom horizontal stud *z*-direction during nailing
		Machine Block	A block in the nailing station table able to move vertically to hold top horizontal stud during nailing
	Drilling station	Drill Clamp (DC)	A rotating clamp designed to secure top and bottom plate *y*-direction during drilling process
		Press Drill	Horizontal drill device used to drill hole on plates that are mounted horizontally
	Cutting station	Cutter Clamp (CC)	A hydraulic device used to secure the top and bottom plate both *y* and *z* directions during the cutting process
		Cutter	Automated device for cutting plates and sawing partial cut in multi-walls, moves vertically with the help of pneumatic actuator
	Feeding station	Top Barrier	A metal plate on feeding station to help hold the top plate in place
		Bottom Barrier	A metal plate on feeding station to help hold the bottom plate in place
		Roller	A series of rollers combined together to facilitate the transfer of studs and components easily

Table 3.2 Definitions of machine parameters

Type	Notation	Description
Constant parameter	Dn	Distance from nailing station machine to home position
	Zo	Nailing gun *z*-direction home position to the table edge
	Dd	Distance from drilling station machine to home position
	Dc	Distance from cutting station machine to home position
Parameter from drawing	j	Top-plate stud id
	k	Bottom-plate stud id
	hi	Header id
	b_j	j^{th} stud thickness
	b_k	k^{th} stud thickness
	d_j	j^{th} stud width
	d_k	k^{th} stud width
	Lhi	i^{th} header length
	X_j	#j top-plate stud *x*-direction midpoint coordinate
	Z_j	#j top-plate stud *z*-direction midpoint coordinate
	Xhi	#hi header *x*-direction midpoint coordinate
	Zhi	#hi header *z*-direction midpoint coordinate
	X_k	#k bottom-plate stud *x*-direction midpoint coordinate
	Z_k	#k bottom-plate stud *z*-direction midpoint coordinate
	NTS	Total number of studs touching top-plate
	NBS	Total number of studs touching bottom-plate
	c	Component id
	H	Multi-panel height
	i	Hole id
	L	Multi-panel length
	m	id of sub-wall on multi-panel
	COGm	m^{th} sub-wall COG to home position length
	Lswm	m^{th} sub-wall length
	XSWSm	m^{th} sub-wall start-point *x*-coordinate
	XSWFm	m^{th} sub-wall end-point *x*-coordinate
	SW	Number of sub-wall
User-defined parameter	N_j	Total number of nails on j^{th} stud (default 2)
	N_k	Total number of nails on k^{th} stud (default 2)
	Dm	m^{th} sub-wall drill hole number
	G	Gap between sub-walls
Calculated parameter	X_{jn}	#n nail on #j top-plate stud *x*-coordinate
	Y_{jn}	#n nail on #j top-plate stud *y*-coordinate
	Z_{jn}	#n nail on #j top-plate stud *z*-coordinate
	X_{kn}	#n nail on #k bottom-plate stud *x*-coordinate

Type	Notation	Description
Calculated parameter	Y_{kn}	#n nail on #k bottom-plate stud y-coordinate
	Z_{kn}	#n nail on #k bottom-plate stud z-coordinate
	XDi	i^{th} hole distance from home position
	$HSLB_j$	Horizontal j^{th} stud left boundary distance
	$HSRB_j$	Horizontal j^{th} stud right boundary distance
	$VSLB_j$	Vertical j^{th} stud left boundary distance
	$VSRB_j$	Vertical j^{th} stud right boundary distance
	$HSLB_k$	Horizontal k^{th} stud left boundary distance
	$HSRB_k$	Horizontal k^{th} stud right boundary distance
	$VSLB_k$	Vertical k^{th} stud left boundary distance
	$VSRB_k$	Vertical k^{th} stud right boundary distance
	X_c	a^{th} cut distance from home position
	Dwa	a^{th} movement of dragging jaws
	DW	Cumulative movement of dragging jaws
	DD	Panel drilling position to current dragging jaws position
	DC	Panel cutting position to current dragging jaws position
	DNT	Panel top-plate nailing position to current dragging jaws position
	DNB	Panel bottom-plate nailing position to current dragging jaws position
	Mn	Nailing gun vertical moving distance
	c	Cut id for multi-panel
	C	Total number of cutting
	Xhn	#n nail on #h header x-coordinate
	Zhn	#n nail on #h header z-coordinate
	Di	i^{th} drilling coordinate
	Cc	c^{th} cutting coordinate
	NTn	n^{th} top side nailing coordinates
	NBn	n^{th} bottom side nailing coordinates
	XThn	n^{th} nail on header x-coordinate
	YThn	n^{th} nail on header y-coordinate
	ZThn	n^{th} nail on header z-coordinate

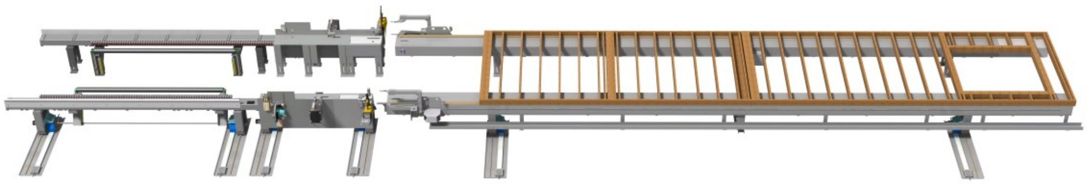


Figure 3.1: Wood-framing machine Table A and Table B

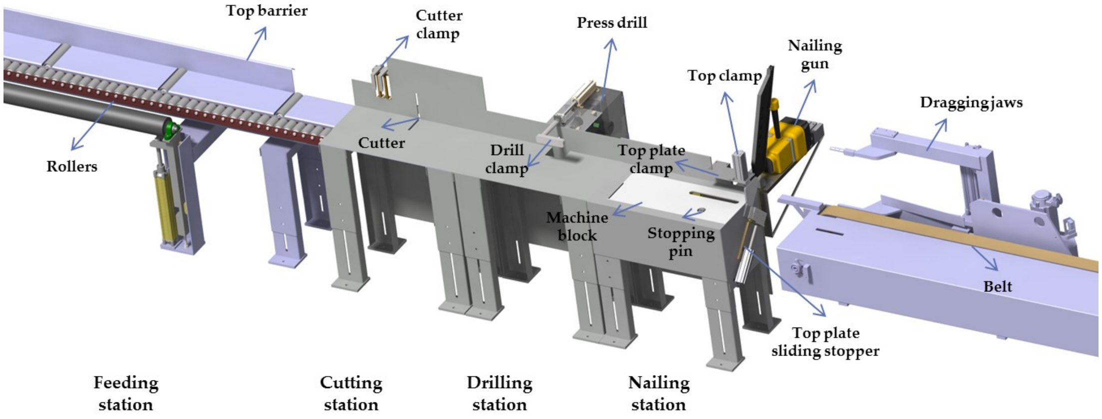


Figure 3.2: Table A (feeding, cutting, drilling, and nailing station) and Table B configuration

To achieve the research objectives, the methodology brings together the following five parts, as shown in Figure 3.3: (1) optimization of multi-panel design verified by mathematical optimization model; (2) generation of machinery assembly information for each machine module, and creation of guidelines for panel manufacturing practice; (3) visualization of wood-framing table operation sequences; (4) wood-framing machine motion plan, which ensures efficient machine operation; and (5) simulation, which evaluates 3D visualization of panel manufacturing operation to determine cycle time of panel manufacturing. In order for these modules to be implemented, the following input data is required: (1) BIM model containing wall framing details (e.g., for wall/window/door/floor elements) in order to provide information support for the automated wall panel manufacturing process; (2) an external add-on for Revit, developed by a research team at the University of Alberta, containing wall-framing details to provide information support for automated wall panel manufacturing (since the current Revit system does not offer a component to represent lumber); (3) wall labels, which refer to the locations of wall panels that will optimize multi-panel combinations; (4) available wall length, which is required in order to generate the multi-panel combination plan; and (5) wood-framing machine data, which provides the dimensions of each modular machine, allowing a 3D representation of the machine models to be constructed by the 3D model builder. Another input is the timeline for each operation, which allows the simulation model to analyze the manufacturing panel cycle time. The criteria required to implement the above modules are as follows: (1) onsite experience, to support the establishment of the panel manufacturing guidelines; (2) user-defined framing specifications, which are input by the user in order to generate the operation locations such as the nail number on a certain stud; (3) construction specifications; (4) maximum multi-panel length; (5) wall information, which refers to the wall-type parameters used to determine the feasibility of two-wall combinations; (6) wall labelling rules, which assist in identifying the wall base constraint; and (7) Greedy algorithm, which is used to optimize the multi-panel combination plan. The outputs are: (1) multi-panel optimization, i.e., optimized configuration of the various single panels that form multi-panels; (2) operation guidelines, which include nailing, drilling, and cutting locations; (3) 3D visualization of wood-framing table operation; (4) cycle times of manufacturing panels, which can assist in determining whether using automatic machinery rather than the manual approach will improve the production line efficiency.

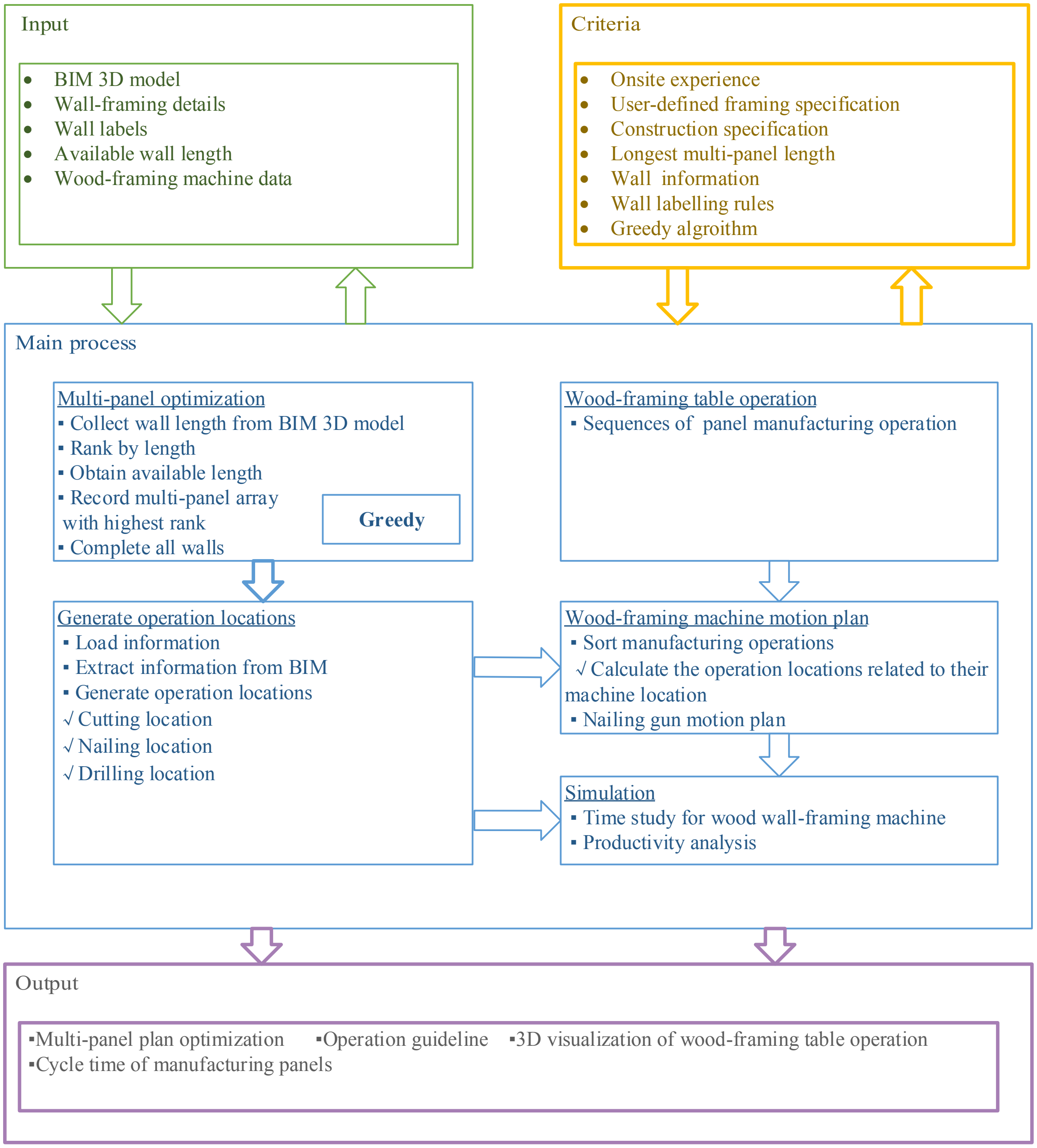


Figure 3.3: Research methodology

3.1 Multi-panel Optimization

Combining single walls together to manufacture multi-panels in the plant will improve the efficiency of the current construction process by reducing manufacturing time. These single walls will become the sub-wall for that particular multi-panel and framing in wood wall-framing machinery. The maximum capacity of multi-panel length for the wood wall-framing machinery introduced in this research is 40 ft. However, most house wall lengths are less than 40 ft. Instead of manufacturing single walls, as shown in Figure 3.4, producing multi-panels, as shown in Figure 3.5, at the wall assembly station will save setup time and increase the productivity of the machine. Additionally, fabrication in the form of multi-panels as an alternative to single walls may increase the utilization of downstream stations due to reduced idle time (Shafai 2012). In current practice, all wood wall panels from an entire house are combined together for analysis. However, if upper-level walls and lower-level walls are assembled together, the downstream station worker must spend time identifying and categorizing them. The inefficiency of this process can be attributed to the lack of predetermined multi-panel plans, which are necessary in order to establish an optimal methodology.

As presented in Figure 3.6, the multi-panel optimization procedures are as follows: (1) collect wall lengths from the BIM model and export them to Microsoft Excel; and (2) use a greedy algorithm to form the optimized multi-panel combination plan. There are five criteria involved in the implementation of this target: (1) the longest multi-panel length, which cannot exceed the machine's maximum design length (40 ft in the case of this research); (2) wall information, which refers to the wall-type parameters that determine the feasibility of two wall combinations, where only the same wall-type panel can be combined and manufactured together; (3) wall labelling rule, which adds clarity in identifying the *wall base constraint*; (4) greedy algorithm, which is used to determine the multi-panel combination plan; and (5) the gap between two panels, which is limited to 1″ in this research since the saw must have a certain amount of space in order to accurately pre-cut. The outputs are used to obtain multi-panel combination arrays, which include the panel mark, panel length, and wall type. Proper planning for multi-panel combinations will decrease redundant assembly processes in order to increase project efficiency, reduce waste, and increase profitability.

Figure 3.4: Single walls from sample house. Adapted from “A Framework for Design of panelized wood framing prefabrication Utilizing Multi-panels and Crew Balancing,” by Ziad Ajweh, 2014, 30. Copyright 2014 by Ziad Ajweh. Used with permission.

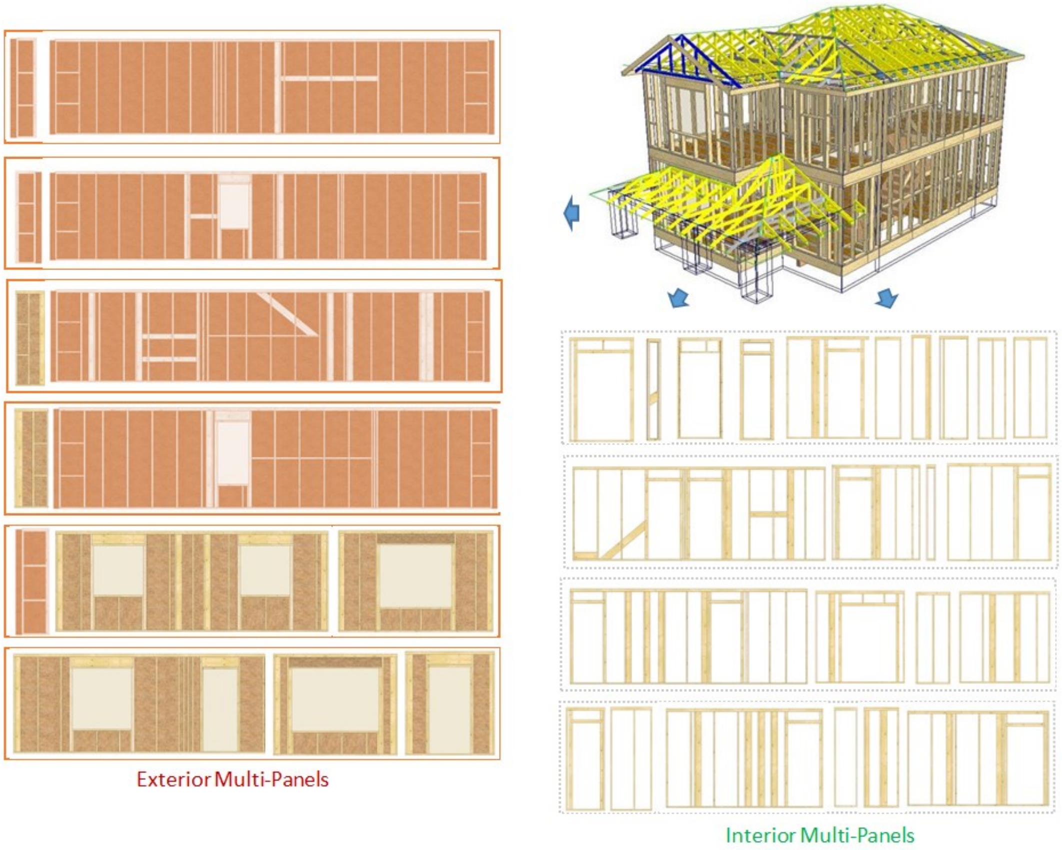


Figure 3.5: Combination of single walls into multi-panels. Adapted from “A Framework for Design of panelized wood framing prefabrication Utilizing Multi-panels and Crew Balancing,” by Ziad Ajweh, 2014, 30. Copyright 2014 by Ziad Ajweh. Used with permission.

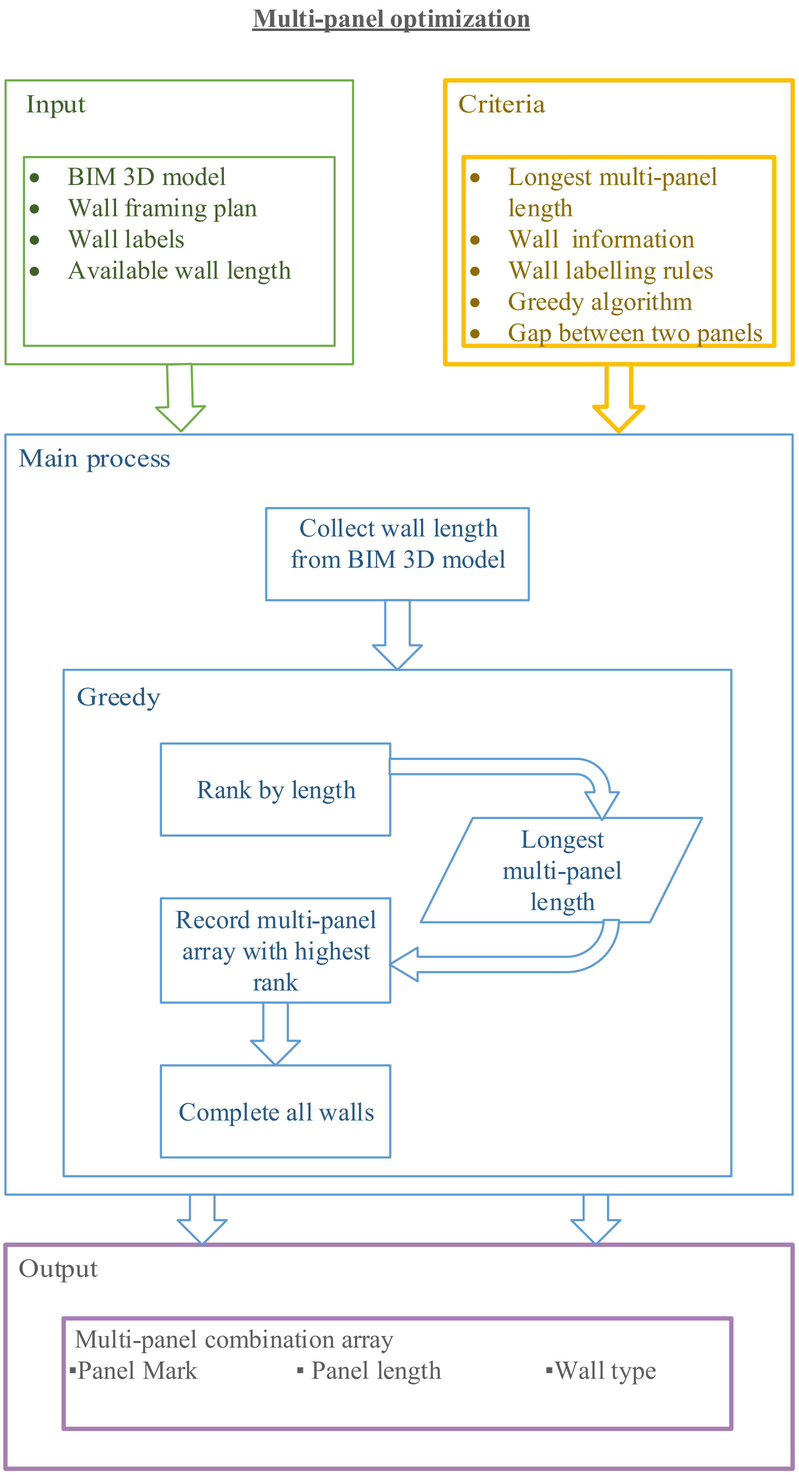


Figure 3.6: Multi-panel optimization methodology

3.1.1 Greedy algorithm

Greedy algorithm is employed to address the multi-panel optimization problem. After the Revit model wall-framing has been completed, the length of each wall can be extracted and utilized for wall-panel combination. First, the exterior walls and interior walls must be separated into two groups. Exterior and interior walls cannot be manufactured as one panel since they comprise different wall layers such as siding and building wrap. Next, matching interior wall types are collected and placed in the same pool. Finally, there are two scenarios for achieving the sub-wall grouping: (1) the wall grouping for the entire house is combined into one pool, as shown in Figure 3.7; or (2) the main floor wall grouping is combined into one pool and fills in the multi-panel arrays, then the same type of wall from the second floor will fill in the main floor pool, as presented in Figure 3.8.

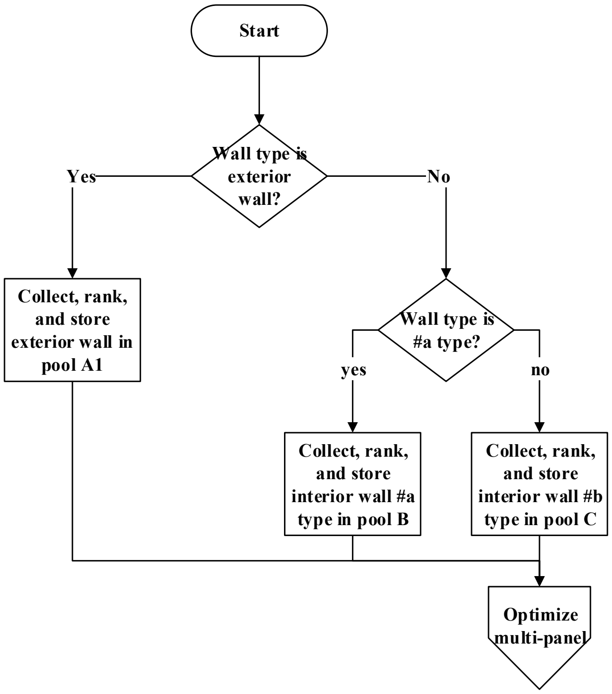


Figure 3.7: Scenario 1—Whole-house grouping

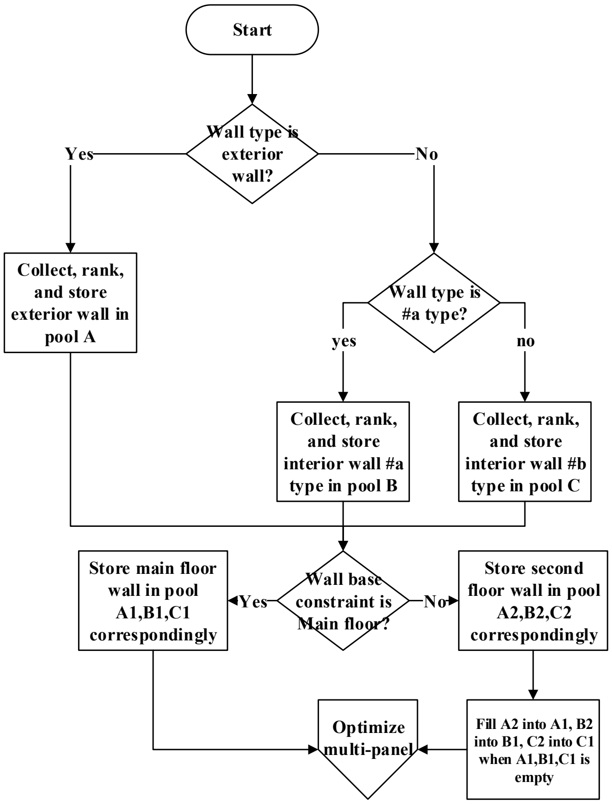


Figure 3.8: Scenario 2—Combining multi-panels for each floor

In each pool, sub-walls are ranked by length in descending order. Once all the sub-walls are collected in the pool, the sub-wall with the highest length is primarily selected to record the panel number in the multi-panel array (*X*). Next, based on the remaining part of multi-panel length, the current longest sub-wall in the pool, which has been maximized using the remaining multi-panel length, is selected and recorded. If the remaining portion of multi-panel is not long enough to hold the current longest sub-wall, this sub-wall is skipped and the same procedure begins on the following sub-walls. The process pauses when no sub-wall can be selected to fit the remaining part of the multi-panel; thus, the multi-panel array is complete. Thereafter, the sub-walls that remain in the pool resume being selected to the next multi-panel array, until all the sub-walls in the pool are exhausted. The same process is implemented for all existing pools. The flowchart of the multi-panel optimization is presented in Figure 3.9.

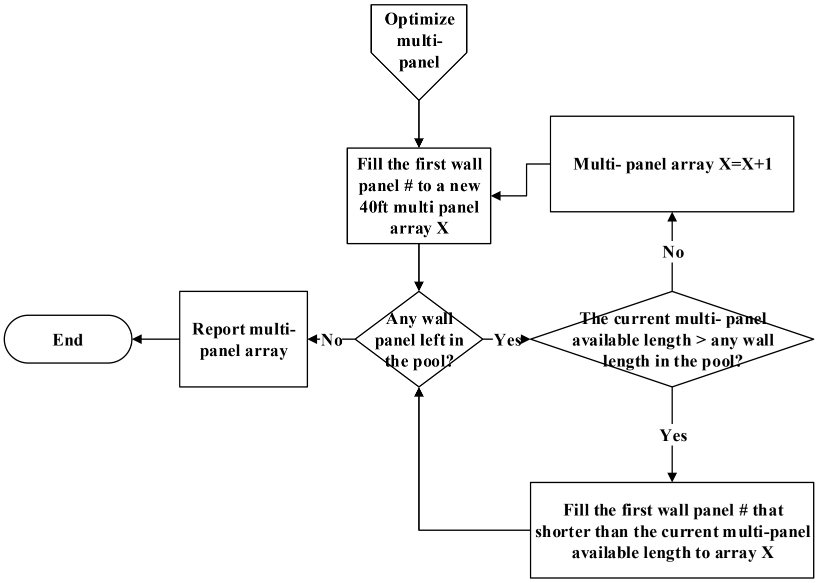


Figure 3.9: Flowchart of multi-panel optimization process

3.2 Generation of operation locations from BIM model

The BIM model provides rich information for wall assembly such as wall dimensions, stud details, and prefabricated opening component details. Based on the multi-panel optimization, which is explained in section 3.1, the information for single walls can be consolidated into multi-panel information. As shown in Figure 3.10, the methodology used to generate operation locations from the BIM model consists of the following three procedures: (1) load framing information into the BIM model; (2) extract framing information from the BIM model to Microsoft Excel; and (3) generate cutting, drilling, and nailing locations guideline based on real-world on-site experience and construction specifications. The output of this system is task coordination for nailing, cutting, and drilling.

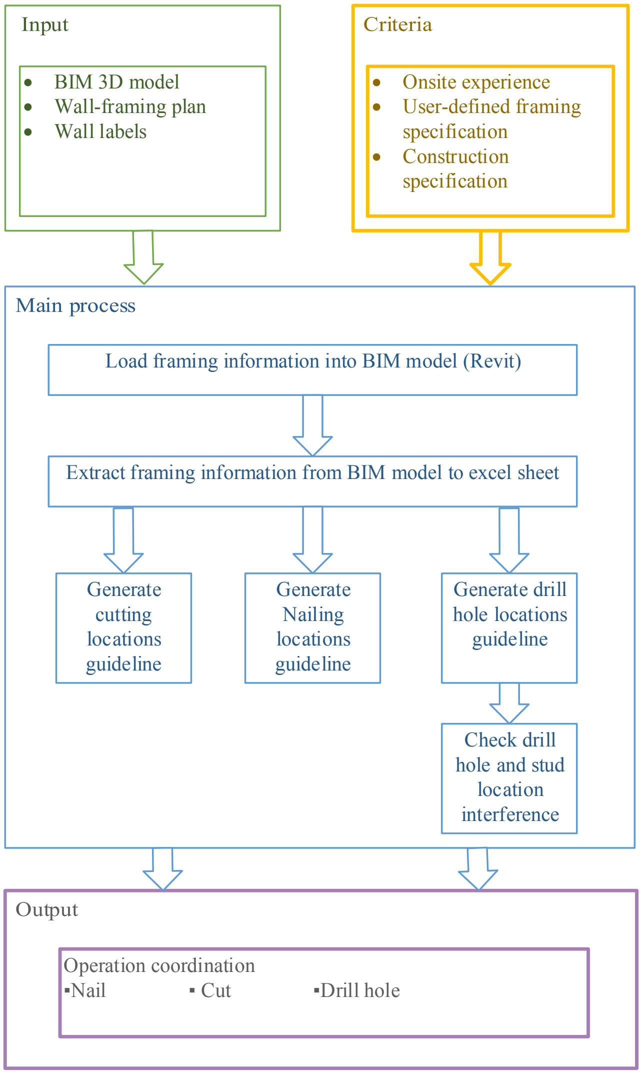


Figure 3.10: Methodology for generation of operation locations

3.2.1 Loading of information into BIM model

The goal for the automation of wall-framing manufacturing is to build a bridge between the housing wall layouts from the Revit software and the factory panel manufacturing process using *BIMSF_ID*, which is an identification tag for each wall framing. When generating the wall-framing layout using Revit, each *BIMSF_ID* is formed automatically for each wall panel using the Revit add-on. The factory plant will identify the BIMSF_ID and will assemble the panel based on the wall-framing layout; the same BIMSF_ID is used to label the finished panel.

3.2.2 Extraction of information from BIM model

According to the wood wall-framing table assembly requirements, the information being extracted from the BIM (Revit) model includes: (1) wall properties from the BIM model such as wall details (top- and bottom-plate length (L_{swm}), wall height (H), and wall thickness(b)), stud details (stud IDs (j&k), dimensions (b&d), and coordinates (*x,y,z*), prefabricated opening component details (component IDs (c), lower boundary coordinates, and upper boundary coordinates); (2) sub-walls IDs (m) contained within each multi-panel; (3) user-defined framing specifications such as number of nails per stud (N), gap between two sub-walls (G), and number of drill holes per wall (D_m). At this point, this data can be used to generate nail, cut, and drill locations, as well as IDs. The drill location must also contain stud location information in order to detect potential collisions, and thus can adjust accordingly.

The coordinates of each stud and each sub-wall belonging to the multi-panel can be extracted based on the origin, as shown in Figure 3.11. The absolute origin is set as the multi-panel's first stud outside boundary (home position) for $x = 0$; therefore, each stud's absolute *x*-coordinate is its *x*-direction center-point-to-home-position distance. Stud absolute *z*-coordinates represent each stud *z*-direction center-point touching top- or bottom-plate position facing up or down relative to the *z*-axis. Vertical orientation stud *z*-coordinate is set to be 0, as expressed in Figure 3.12(a). In this case, the stud orientation and position can be distinguished by the absolute *z*-coordinates. If the value of *z* is negative, this stud is horizontal and on the bottom edge of the top-plate, as seen in Figure

3.12(b). If the value of *z* is positive, this stud is horizontal and on the top edge of the top-plate as shown in Figure 3.12(c). The absolute *y*-coordinate of the bottom-plate outside boundary is set to 0; accordingly, the top-plate outside boundary *y*-coordinate will be the multi-panel height, h.

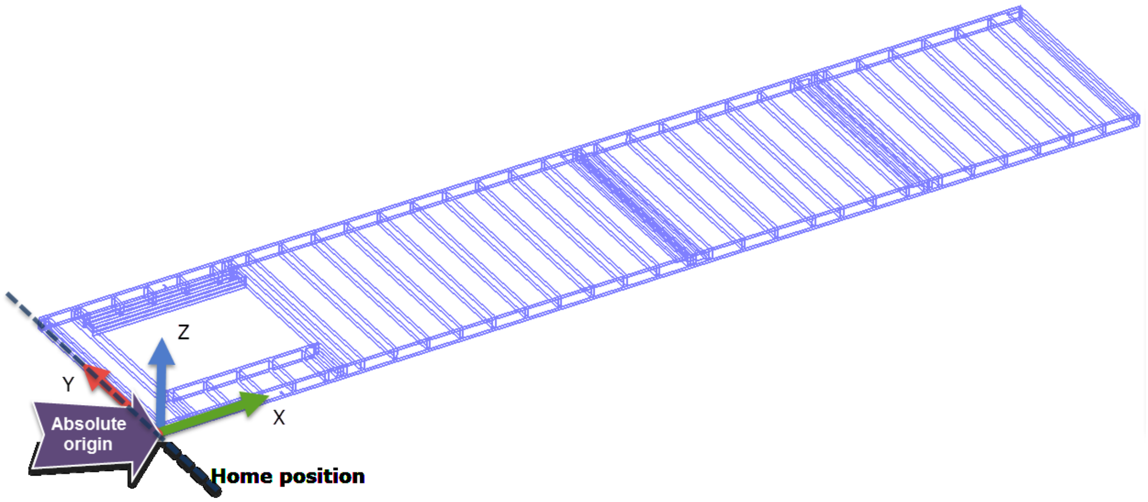


Figure 3.11: Multi-panel absolute origin and home position

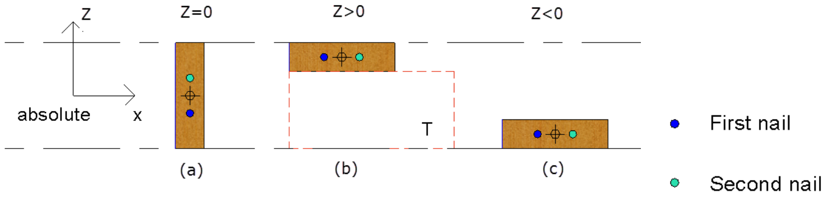


Figure 3.12: Stud absolute *y*-coordinate and position relationship

3.2.3 Generation of coordinates

Based on the information obtained from the BIM model, cutting, drilling, and nailing locations for multi-panels can be generated and prepared for the analysis of wood wall-framing operation procedures.

3.2.3.1 Generation of cut location and IDs

The first cut location depicted in Figure 3.13 is located at the end-point of one sub-wall and the second cut location is located at the start-point of the following sub-wall. A ranking of non-zero start and finish sub-wall *x*-coordinates will be used to obtain the cut locations. All cut locations will be partially cut as expressed in Eq. (3.1) and Eq. (3.2) except the last one, since it is coterminous with the multi-panel end-point. At that point, the cutting machine must cut and separate extra top- and bottom-plates completely, as Eq. (3.3). The cut locations are generated based on start and finish *x*-coordinates of sub-walls.

Location of partial cuts:

$$XC_a = XSWS_m - \text{Saw thickness}\ (XSWS_m \neq 0) \tag{3.1}$$

$$XC_a = XSWF_m\ (XSWF_m \neq L) \tag{3.2}$$

Location of complete cuts (Multi-panel end-point location):

$$XC_a = L \tag{3.3}$$

where:

a: cut ID for multi-panel

m: ID of sub-wall

XC_a: a^{th} cut distance from home position

$XSWS_m$: m^{th} sub-wall start-point *x*-coordinate

$XSWF_m$: m^{th} sub-wall end-point *x*-coordinate

L: multi-panel length

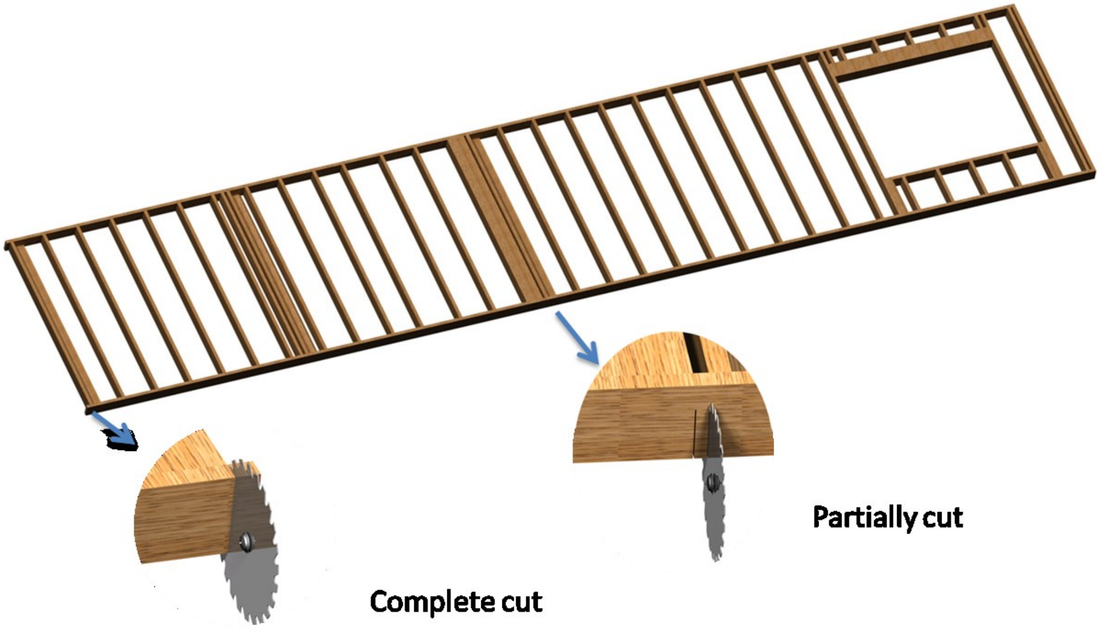


Figure 3.13: Sample multi-panel cutting location

3.2.3.2 Generation of nailing locations

Wall studs and pre-assembled window and door frames are joined with top- and bottom-plates using nails. Depending on the elements belonging to the wall, the top-plate stud number and location may be different from the bottom-plate. Figure 3.13 depicts an example of an opening component where the bottom cripples only touch the bottom-plate and do not connect with the top-plate. Therefore, the top- and bottom-plate nailing plans should be analyzed separately.

The default setting for the total number of nails on a stud is two. However, users can specify this setting if necessary, e.g., j^{th} stud on top (T) has N number of nails (NT_j), or k^{th} stud on footer (B) has N number of nails (NB_k). The y-coordinates of the bottom-plate nails will be 0 and top-plate nails y-coordinates will be H. Sample nailing x- and z-coordinates on the horizontal and vertical studs are shown in Figure 3.12. When the stud is horizontal ($Z \neq 0$), the nails on the *x*-axis position of that stud should be evenly distributed along the stud width. The *z*-coordinates of the nails should be the same as the *z*-coordinates of the stud since they are along the midpoint of the stud thickness. When the stud is vertical ($Z = 0$), the nails on that stud should be evenly distributed across the stud width throughout the *z*-axis. The *x*-coordinates of the nails should be the same as the *x*-coordinates of the stud since they are along the midpoint of the stud thickness. The methodology of nailing coordinate generation is presented in Figure 3.14, and expressed in Eq. (3.4) to Eq. (3.15).

Nail locations for horizontal studs at top-plate side ($YTj \neq 0$):

$$\mathbf{XTj_n} = [XT_j - (d/2)] + n \times [d / (NT_j + 1)] \tag{3.4}$$

$$\mathbf{YTj_n} = H \tag{3.5}$$

$$\mathbf{ZTj_n} = ZT_j \tag{3.6}$$

Nail locations for vertical studs at top-plate side ($YT_j = 0$):

$$\mathbf{XT_{jn}} = XT_j \tag{3.7}$$

$$\mathbf{YT_{jn}} = H \tag{3.8}$$

$$\mathbf{ZTj_n} = [Z_j - (d/2)] + n \times [d/ (NT_j + 1)] \tag{3.9}$$

Nail locations for horizontal studs at bottom-plate side ($YB_k \neq 0$):

$$\mathbf{XBk_n} = [X_k - (d/2)] + \{n \times [d / (NB_k + 1)]\} \tag{3.10}$$

$$\mathbf{YBk_n} = 0 \tag{3.11}$$

$$\mathbf{ZBk_n} = ZB_k \tag{3.12}$$

Nail locations for vertical studs at bottom-plate side ($YB_k = 0$):

$\mathbf{XBk_n} = XB_k$ (3.13)

$\mathbf{YBk_n} = 0$ (3.14)

$\mathbf{ZBk_n} = [ZB_k - (d/2)] + \{n \times [d / (NB_k + 1)]\}$ (3.15)

where:

H: multi-panel height

j: top-plate stud ID

k: bottom-plate stud ID

d: stud width

XT_j: #j top-plate stud *x*-direction midpoint coordinate

ZT_j: #j top-plate stud *z*-direction midpoint coordinate

XB_k: #k bottom-plate stud *x*-direction midpoint coordinate

ZB_k: #k bottom-plate stud *z*-direction midpoint coordinate

XTjn: #n nail on #j top-plate stud *x*-coordinate

YTj_n: #n nail on #j top-plate stud *y*-coordinate

ZTj_n: #n nail on #j top-plate stud *z*-coordinate

XBk_n: #n nail on #k bottom-plate stud *x*-coordinate

YBk_n: #n nail on #k bottom-plate stud *y*-coordinate

ZBk_n: #n nail on #k bottom-plate stud *z*-coordinate

NT_j: total number of nails on j^{th} stud (default 2)

NB_k: total number of nails on k^{th} stud (default 2)

Additionally, if the components in the multi-panel have headers that touch the top-plate, each ply of the header must be nailed to the top-plate. The *x*-direction of each nail location will be distributed at specific intervals across the header length leaving a small space from the header edge to avoid last nail is too far away from the edge. The header ply default *x*-direction of the nail location setting is 0.75″ from each end joint, and 16″ is the normal interval of the nailing pattern. The nail location *z*-direction will be at the center-point of each ply. From the BIM model, the *x*-coordinate of the center-point of each ply along the header top-plate is XT_{hi}, the *z*-coordinate is ZT_{hi}, and the ply length is $L_{hi.}$ The header start-point, therefore, will be the *x*-direction center-point (XT_{hi}) minus half of the header length (L_{hi}). The first nail is located at the start-point plus the edge space (0.75″), the last nail is located at the end-point minus the edge space (0.75″), and the *x*-direction locations of the remaining nails are added to the setting space as shown in Figure 3.14. The nail location *z*-direction is Z_{hi}.

Nail locations for header:

$$n_{max} = INT[(L_{hi} - 1.5'') / 16'' + 1] \tag{3.16}$$

$$\text{Setting space} = (L_{hi} - 1.5'') / (n_{max}-1) \tag{3.17}$$

$$XT_{hn} = (XT_{hi} - \tfrac{1}{2} L_{hi}) + 0.75'' + [\text{Setting space} \times (n - 1)] \tag{3.18}$$

$$ZT_{hn} = ZT_{hi} \tag{3.19}$$

$$YT_{hn} = H \tag{3.20}$$

where:

XT_{hn}: n^{th} nail of header *x*-coordinate

YT_{hn}: n^{th} nail of header *y*-coordinate

ZT_{hn}: n^{th} nail of header z-coordinate

XT_{hi}: i^{th} top-plate header x-direction midpoint

L_{hi}: i^{th} header length

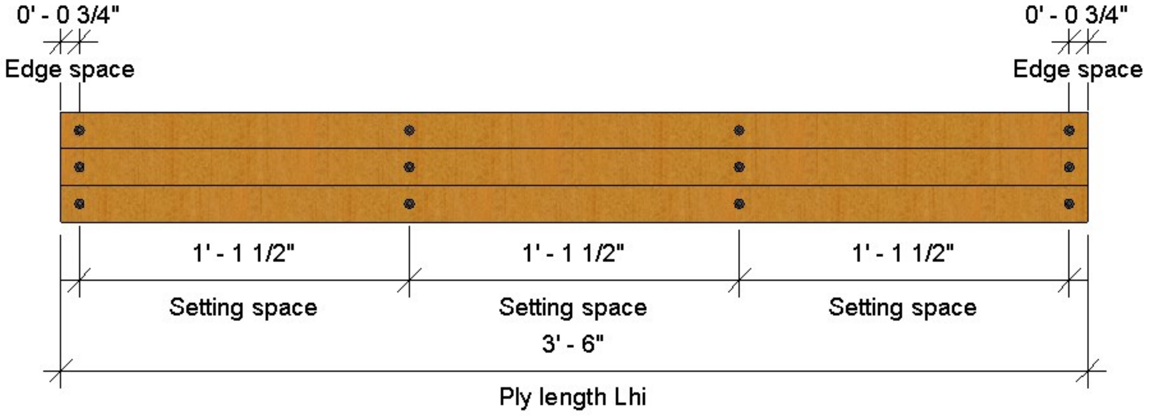


Figure 3.14: Header nail pattern example

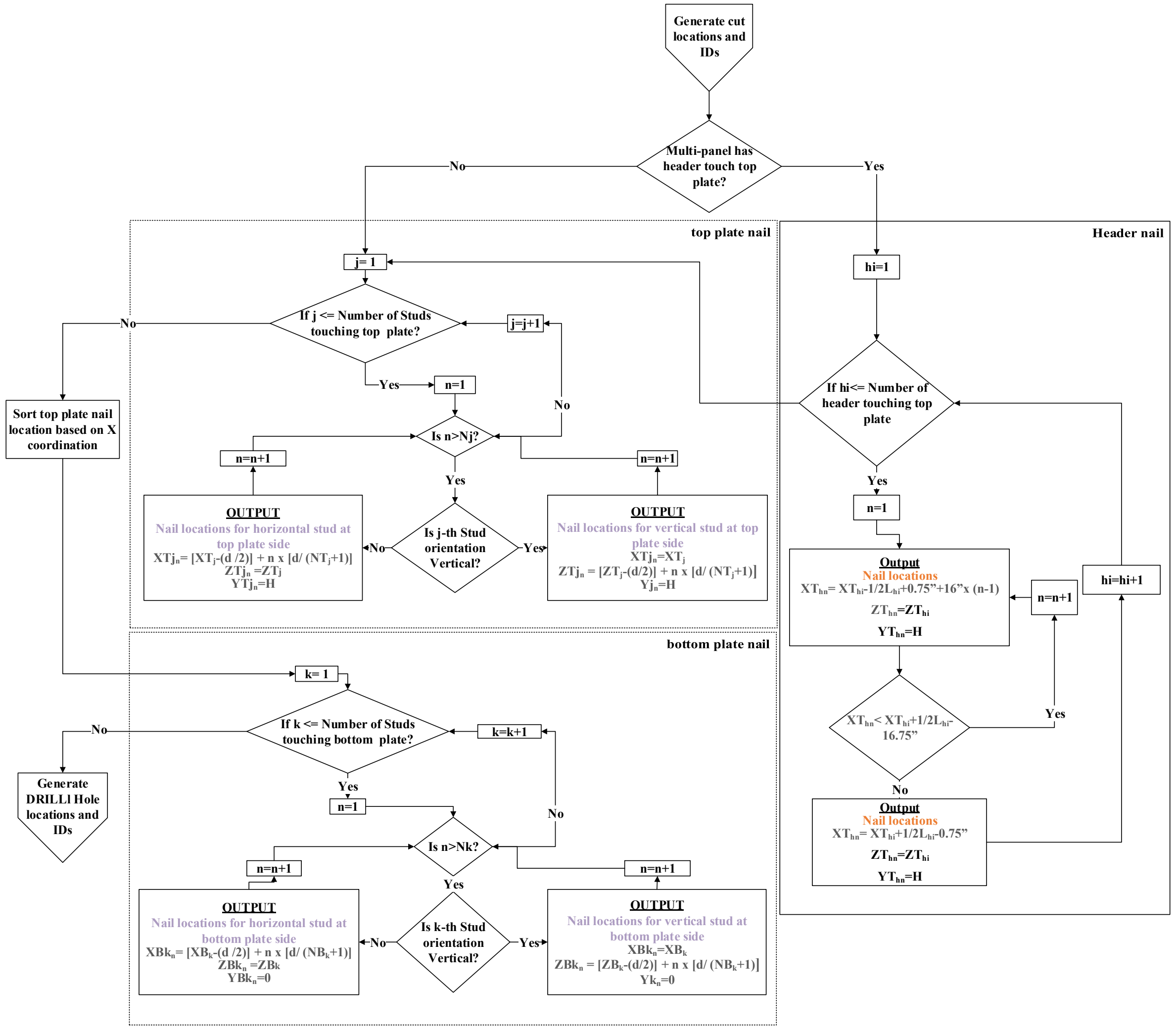


Figure 3.15: Methodology for determining nailing locations

3.2.3.3 Generation of drilling locations

There will be drill holes made on each sub-wall to facilitate any necessary lifting actions at further stations, and for transferring to site. The default setting for the number of drill holes on each sub-wall (D_m) is two; however, the user can define the settings to their own requirements. In analyzing the drill hole locations, the location of the center of gravity (COG) should be considered. If the sling legs are the same length, failure to establish precise COG will create an imbalance in the tension in each sling and cause the load to tilt during lifting. Therefore, the COG should be identified for each single panel first. The drilling points on either side should ensure that the COG is located at the exact midpoint between them to avoid any unplanned movement during lifting due to imbalance (Unirope Slingmax 2015). Since the multi-panel is not symmetrical, the COG may not be located exactly in the middle of the multi-panel. Therefore, in the research, the drill hole location could be anywhere in the range from the COG to the point permitting maximum lift capacity without spreader beam failure, and the optimal drill position will be the spreader beam length, as illustrated in Figure 3.16. Since the drill machinery has a certain distance to the panel home position, if the drill hole falls within that range then it should be drilled manually. The drill hole optimized locations are determined using Eq. (3.22), with the method summarized in Figure 3.16.

COG location:

$$COG_m = \sum(m_i \times l_i) / \sum m_i \qquad (3.21)$$

where i = 1,2,3…. total number of members (studs, plates, headers, etc.) in the m^{th} panel

Optimized drill hole location:

$$\mathrm{XD_i} = XSWS_m + COG_m + (-1)^i \times Spreader\ Beam\ length/2 \tag{3.22}$$

where:

$\mathrm{m_i}$: i^{th} member mass of the panel

$\mathrm{l_i}$: i^{th} member origin along the panel's x-axis

i: hole ID

$\mathrm{XD_i}$: i^{th} hole distance from home position

$\mathrm{COG_m}$: m^{th} sub-wall COG to home position length

$\mathrm{XSWS_m}$: m^{th} sub-wall start-point x-coordinate

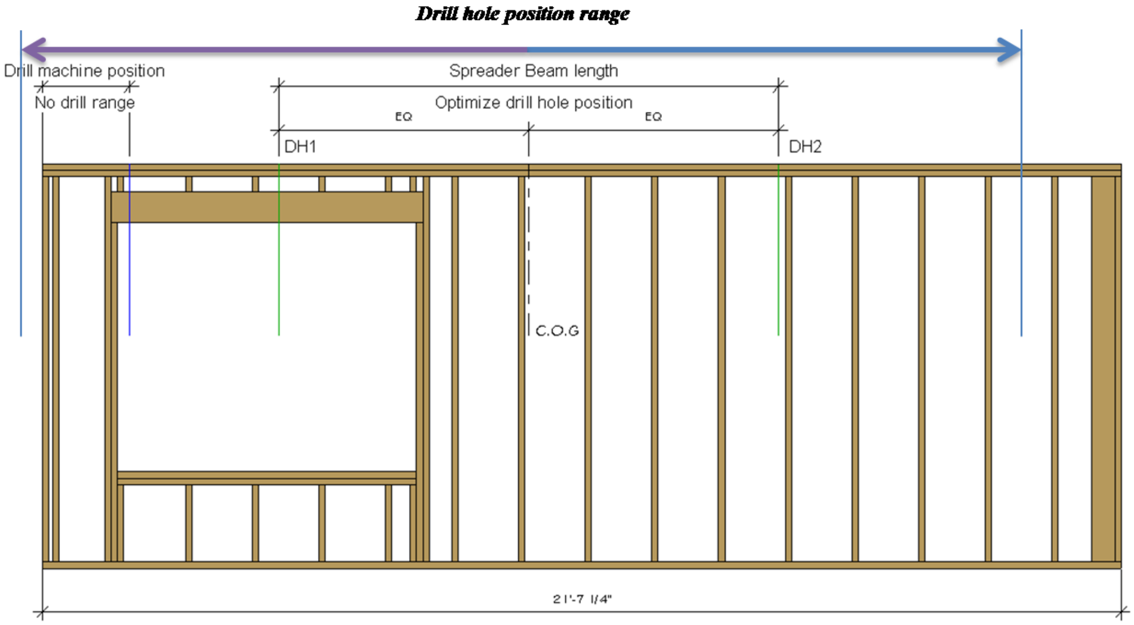


Figure 3.16: Sample panel of drilling location

3.2.3.2.1 Checking for drill hole and stud location interference

The drill hole and stud location should avoid interference. If one hole accidentally drills on the stud, the structure of the framing is no longer stable. Prior to the analysis, the stud location range should be determined. For vertical orientation stud, the stud left boundary is the stud midpoint location minus half of the stud thickness; the stud right boundary is the stud midpoint location plus half of the stud thickness. For horizontal orientation stud, the stud left boundary is the stud midpoint location minus half of the stud width; the stud right boundary is the stud midpoint location plus half of the stud width. The drill position is the middle of the drill hole; therefore, the stud location range must be extended in consideration of the maximum hole radius. In that case, the stud location range is measured from the stud left boundary, minus the maximum drill hole radius to the stud right boundary, plus the maximum drill hole radius. To avoid interference, whenever the drill hole position falls within the stud location range, the drill hole location will be justified depending on the coincident stud location. If that stud location is in the first half of the total multi-panel studs, the drill hole position will be moved toward the panel start-point by 1″; otherwise, it will be moved away from the panel start-point by 1″. The drill hole position will remain justified until it is outside of the stud location range. The methodology for operation location interference checking is shown in Figure 3.17 and expressed by Eq. (3.23) to Eq. (3.38).

Top side stud and drill hole checking:

$$HSLBT_j = X_j - \tfrac{1}{2}d \qquad (3.23)$$

$$HSRBT_j = X_j + \tfrac{1}{2}d \qquad (3.24)$$

$$VSLBT_j = X_j - \tfrac{1}{2}b \qquad (3.25)$$

$$VSRBT_j = X_j + \tfrac{1}{2}b \qquad (3.26)$$

If:

$$HSLBT_j - R \le XD_i \le HSRBT_j + R \qquad (3.27)$$

Or:

$$VSLBT_j - R \le XD_i \le VSRBT_j + R \qquad (3.28)$$

If that drill hole *x*-coordinate < the single-panel COG *x*-coordinate:

$$XDi = XDi + 1'' \qquad (3.29)$$

otherwise:

$$XDi = XDi - 1'' \qquad (3.30)$$

Bottom side stud and drill hole checking:

$$HSLBB_k = X_k - \tfrac{1}{2}d \qquad (3.31)$$

$$HSRBB_k = X_k + \tfrac{1}{2}d \qquad (3.32)$$

$$VSLBB_k = X_k - \tfrac{1}{2}b \qquad (3.33)$$

$$VSRBB_k = X_k + \tfrac{1}{2}b \qquad (3.34)$$

If:

$$HSLBB_k - R \le XD_i \le HSRBB_k + R \qquad (3.35)$$

Or:

$$VSLBB_k - R \le XD_i \le VSRBB_k + R \qquad (3.36)$$

If that drill hole *x*-coordinate < the single-panel COG *x*-coordinate, then:

$$XDi = XDi + 1 \tag{3.37}$$

otherwise:

$$XDi = XDi - 1'' \tag{3.38}$$

where:

D: number of drill holes per multi-panel.

R: drill hole maximum radius

i: hole ID

j: top-plate stud ID

k: bottom-plate stud ID

XD_i: i^{th} hole distance from home position

$HSLBT_j$: horizontal j^{th} stud left boundary distance

$HSRBT_j$: horizontal j^{th} stud right boundary distance

$VSLBT_j$: vertical j^{th} stud left boundary distance

$VSRBT_j$: vertical j^{th} stud right boundary distance.

$HSLBB_k$: horizontal k^{th} stud left boundary distance

$HSRBB_k$: horizontal k^{th} stud right boundary distance

$VSLBB_k$: vertical k^{th} stud left boundary distance

$VSRBB_k$: vertical k^{th} stud right boundary distance d: stud width

b: stud thickness

X_j: #j top-plate stud *x*-direction midpoint coordinate

X_k: #k bottom-plate stud *x*-direction midpoint coordinate

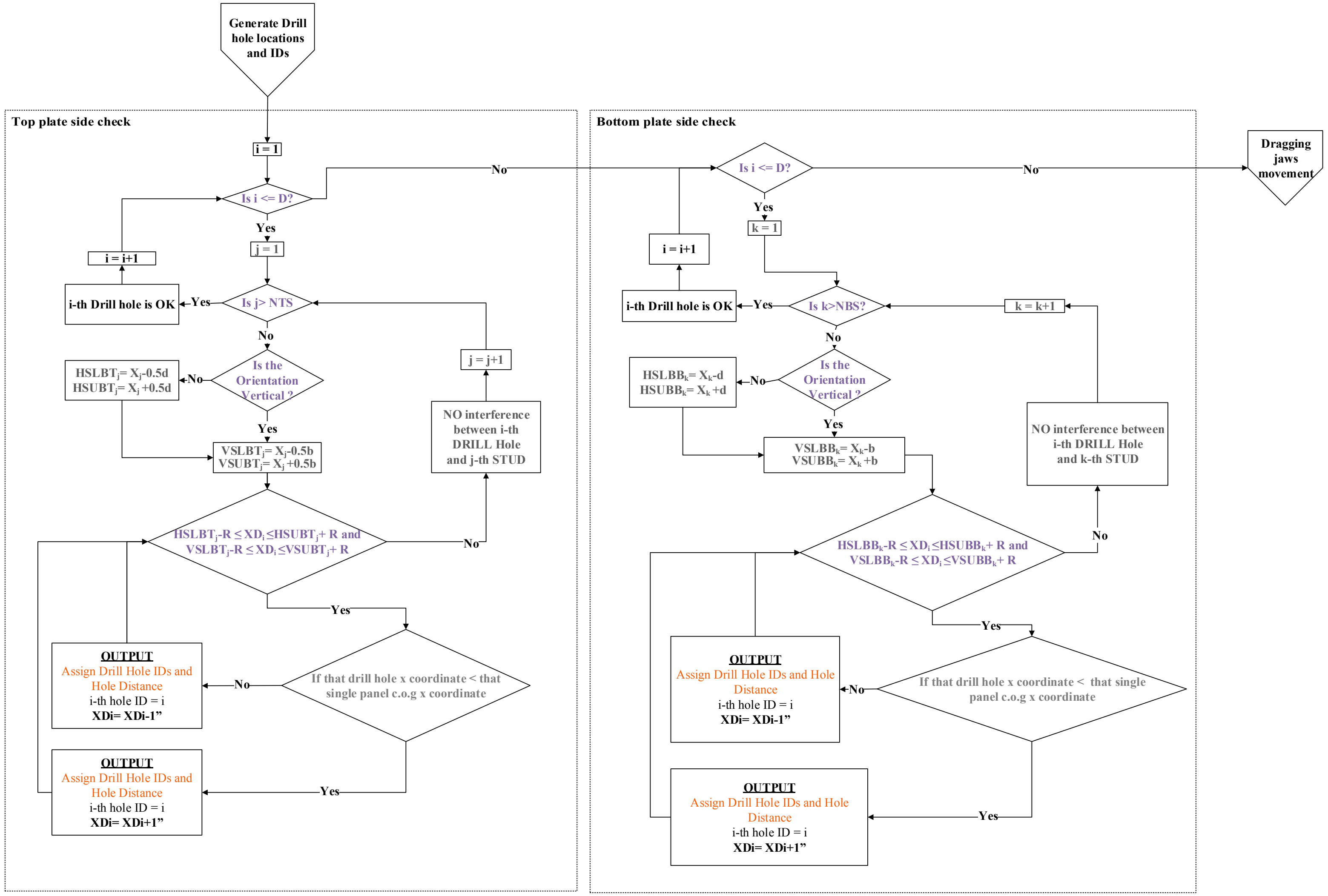


Figure 3.17: Methodology of operation interference

3.3 Wood wall-framing stations operation design

The machine is designed to complete the nailing, drilling, and cutting operations for the multi-panel assembly, as shown in Figure 3.18. The wall studs and prefabricated opening components should be joined to the top- and bottom-plate by nails. Multiple holes on the top- and bottom-plate must be drilled, which aid in the lifting of the panels at downstream stations in the manufacturing facility, and later transferring to the site. Since the multi-panels that are manufactured by the wood wall-framing machine consist of a number of sub-panels, which will be later separated into single panels at the on-site assembly stage, the wood top- and bottom-plates must be partially precut. Additionally, the top- and bottom-plate must be completely cut if there is extra material remaining when the multi-panel is complete.

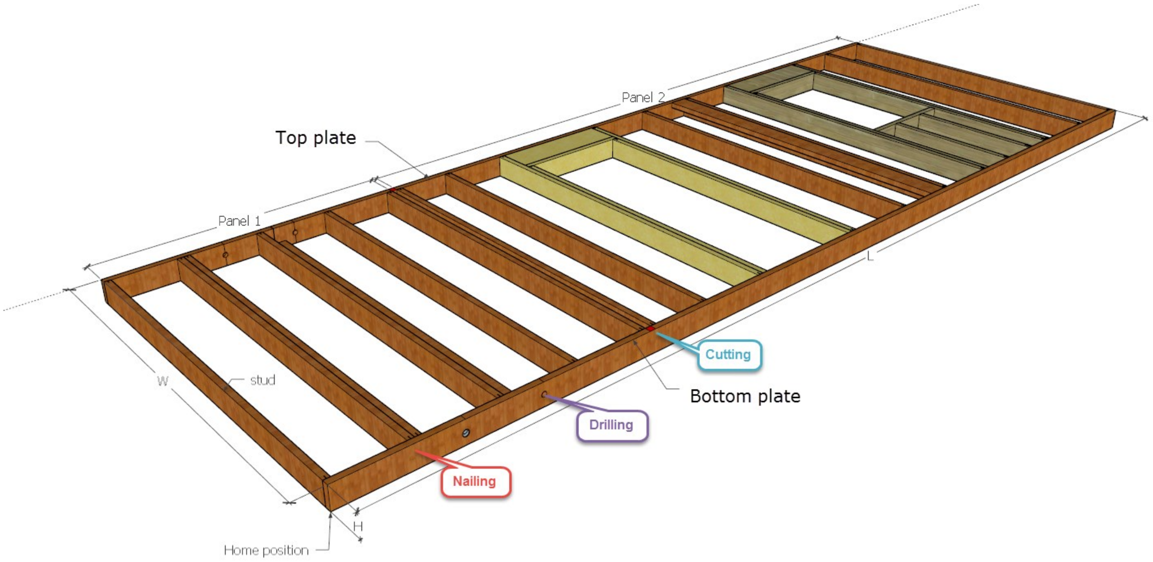


Figure 3.18: Sample multi-panel details

The methodology of wood wall-framing station operation design involves determining the operations of the dragging jaws and modular stations to finish the assembly procedures as presented in Figure 3.19. The machine must be pre-set (phase 1), and top- and bottom-plates must be placed on the table (phase 2). The dragging jaw movement (phase 3) is the key point for successful assembly. Facilitated by the motion planning, the dragging jaws will transport the entire panel to the next station, preparing for the next step in the operation. The next step in the operation (nailing, drilling, and cutting) is checked based on the established operation procedures, and the corresponding operation will proceed. After the operation process has been completed, the machine operation loops back to phase 3. If no operation process is required, the current multi-panel assembly is complete (phase 5).

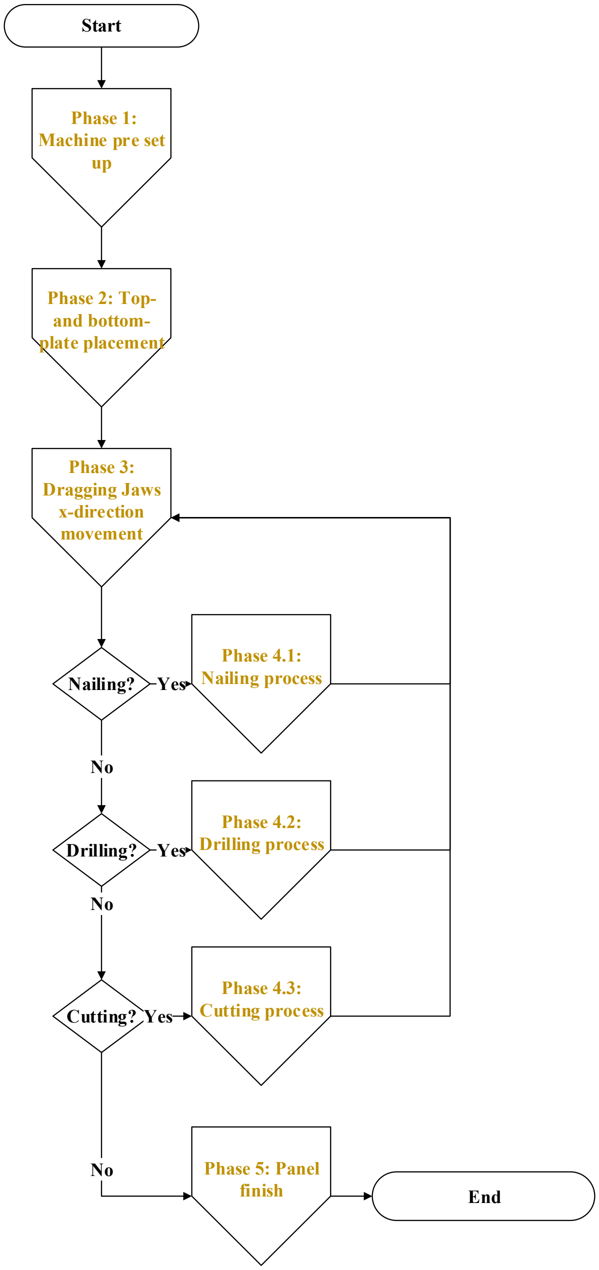


Figure 3.19: Wood wall-framing table operation methodology

3.3.1 Machinery pre-sets

The wood wall-framing machine must be pre-set before the manufacturing of each multi-panel can begin as Figure 3.20. The inputs consist of user-defined parameters, which are listed in Table 3.2. The multi-panel will lie on its side as it is pulled through the station to finish the assembly. Therefore, the right side of the machine will move toward the left side until both sides precisely fit the wall height securing the wall in place in preparation for the multi-panel assembly.

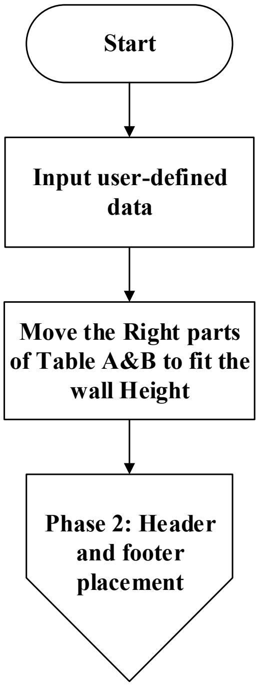


Figure 3.20: Machinery pre-set logic

3.3.2 Top- and bottom-plate placement

Top- and bottom-plates must be placed prior to the multi-panel assembly, the logic for the procedures are shown as Figure 3.21. The top- and bottom-plate sliding stoppers on table A will be active first. The top-plate is manually placed against the top sliding stopper on table A. A sensor is used to check that the top-plate is against the top sliding stopper. If contact is made (x-direction secure), the top side cutter clamp will push against the top-plate until the top-plate touches the top side barrier (y-direction secure). The top clamp applies pressure until it touches the top-plate (z-direction secure). Therefore, the top-plate will be secure in all directions and is thus ready for the next step in the process. After the bottom-plate has undergone the identical securing procedures as the top-plate, the dragging jaws will be activated and will secure the top- and bottom-plate in preparation for multi-panel assembly movement.

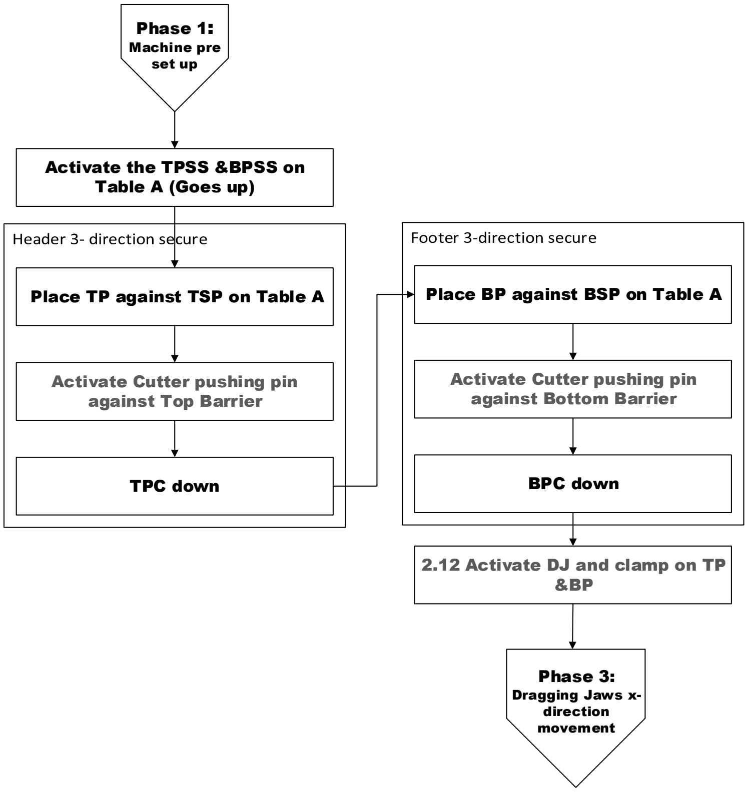


Figure 3.21: Top- and bottom-plate placement logic

3.3.3 Movement of dragging jaws

The dragging jaws will clip onto the multi-panel top- and bottom-plate and will move the multi-panel into position for each assembly station operation. The moving distances (D_{wa}) are based on the operation locations relative to their corresponding machine locations which will be explained in full in the Section 3.4.1.

3.3.4 Modular machine operations

The modular machines will operate independently of one another and implement assembly tasks based on the motion planning.

3.3.4.1 Nailing operation

Wall studs and prefabricated opening components are joined with the top- and bottom-plates using nails. At the nailing station, the nailing gun will trigger the nail into the top- or bottom-plate fastening the stud. The top-side stud number and locations may be different from the bottom component (e.g., the opening component in the sample multi-panel shown in Figure 3.19). Due to the opening in the sample wall, the cripples depicted in the figure only touch the bottom-plate and require nailing. Therefore, the bottom- and top-plate nailing plans should be analyzed separately. The logic and schematic of nail operation is presented in Figure 3.22 and Figure 3.23.

First, the user must check if the number of nails in the nailing gun is fewer than five. If so, the user must refill the nailing gun manually before operation begins. The top and bottom sliding stoppers must be in their resting positions, touching the top-plate and bottom-plate, respectively.

If the stud is the next assembly object, the machine will pause until the stud is manually placed on table A to touch the stopping pin. The sliding pin will activate when the sliding pin touches the stud, and the stopping pin will release. The sliding pin will continue to push the stud until the stud boundary touches both the top and bottom sliding stopper. If the stud is the top horizontal stud, the machine block must be raised, as shown in Figure 3.23 (c2). The top clamp and bottom clamp must both move down in order to secure the stud. If the current stud is the bottom horizontal stud, the extension clamp will activate and help secure the stud in position as shown in Figure 3.23 (c1). After the nailing gun moves vertically to each nail position, the nailing gun will moves toward the plate and active trigger. Since the stud nailing operation complete, all the stoppers and clamps will release as Figure 3.23(f).

If the object is a pre-assembly component for windows and doors, the component must be placed and pushed manually. The edge of the components must touch the top and bottom sliding stoppers, and the top and bottom clamps press down to secure the component. When the dragging jaws move the wall panel to the next component nailing position, the “placement of component” step can be skipped. The nailing gun on each side of the panel is activated based on the motion plan, which indicates the side that requires nailing.

When the nailing gun is activated, it will move up to the first nail position, Z_{jn}, and will move toward the table until it makes contact with the top-plate and bottom-plate. The active nailing gun triggers and then moves back to release the nailing gun from the plate. If there are more nails required at *z*-direction for the current *x*-position, the nailing gun will move up (Z_{jn}) to reach the next nail position. The procedure will repeat until all *z*-direction nails at the current *x*-position are complete.

After the *z*-direction nailing process is complete, if there are no remaining nails in the *x*-direction for *j*-stud (*j*-stud is the vertical stud), or if all the nails on the horizontal stud are finished, the block, which had been raised for top horizontal nailing, will move down and the nailing gun will return to its home position. The clamp and stoppers will release to allow the dragging jaws to move the multi-panel to the next position. If there is a nail at *x*-direction for *j*-stud, the nailing gun will remain at the Z_{jn} position and will only release the clamp and stoppers.

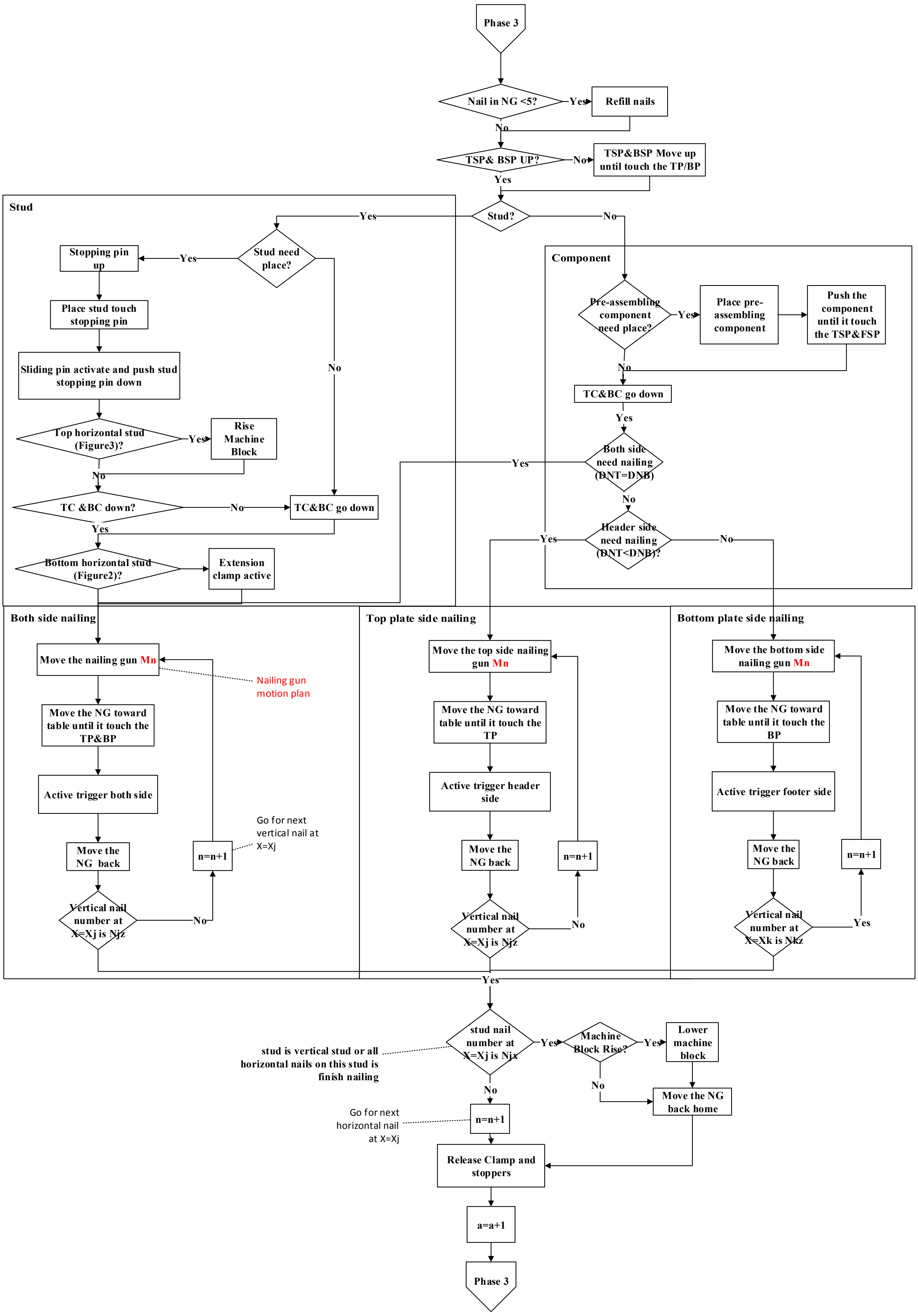
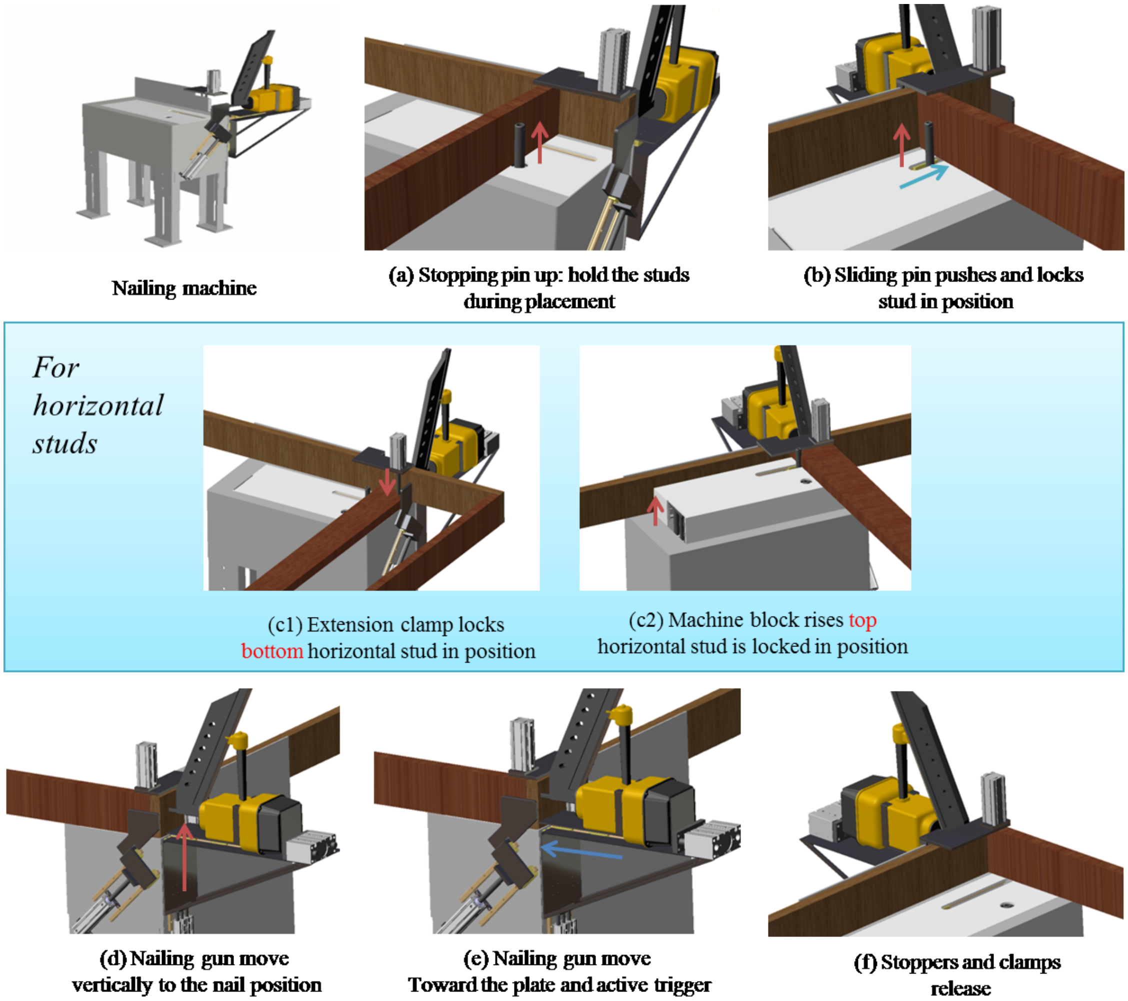


Figure 3.22: Nailing operation logic


Nailing machine

(a) Stopping pin up: hold the studs during placement

(b) Sliding pin pushes and locks stud in position

For horizontal studs

(c1) Extension clamp locks bottom horizontal stud in position

(c2) Machine block rises top horizontal stud is locked in position

(d) Nailing gun move vertically to the nail position

(e) Nailing gun move Toward the plate and active trigger

(f) Stoppers and clamps release

Figure 3.23: Nailing operation schematic

3.3.4.2 Drilling operation

The drill station is designed to drill holes on the multi-panel. The position of the drill holes will be generated from motion planning. The logic and schematic for the drilling machine is shown as Figure 3.24 and Figure 3.25. When drill operation is required, the drill clamp will rotate down and move in the *y*-direction in order to hold the top- and bottom-plates in place. The drill mechanism will then drill holes into both the top- and bottom-plates. After the drilling is complete, the drill mechanism parts retract back to their resting position.

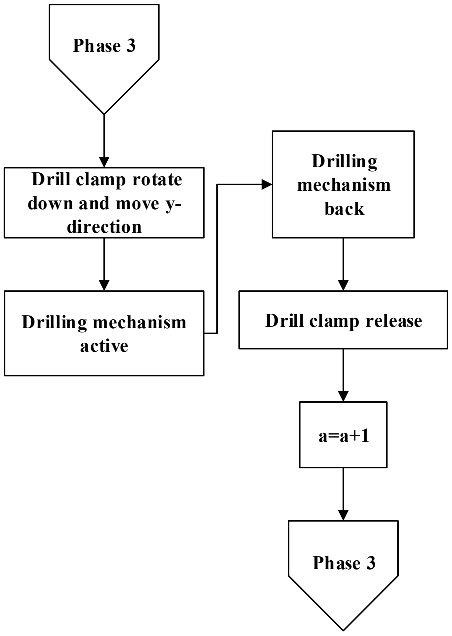
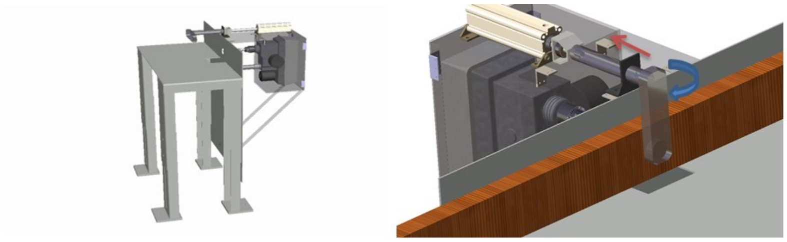
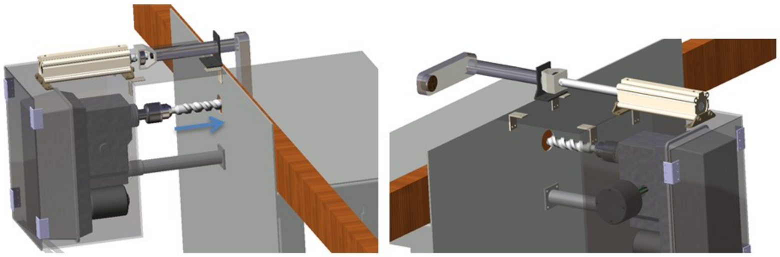


Figure 3.24: Drilling operation logic



Drilling machine

(a) Drill clamp holds wooden plates



(b)Drilling mechanism active

(c) Parts retract back to original positions

Figure 3.25: Drilling operation schematic

3.4.4.3 Cutting operation

To fulfill the multi-panel wall concept involved in wood wall-framing machine design, the wood top- and bottom-plates are pre-cut during factory manufacturing. At the end-point of each sub-wall contained within the multi-panel, the cutting machine will make a partial cut, leave an uncut section, and then make one more partial cut. Also, if the multi-panel is finished and there is an extra top- or bottom-plate, the extra parts will be separated from the multi-panel completely. The logic and schematic for cutting operation is shown as Figure 3.26 and Figure 3.27. When the cutting operation is required, the cutter clamp will move down and the cutter blade will move up Z_m distance. The vertical cutting distance for each cutting point is dependent on user requirements. Upon completion of the cutting task, the cutter blade will return to its resting position. The cutter clamp will move up, and then the machine is ready for the next operation.

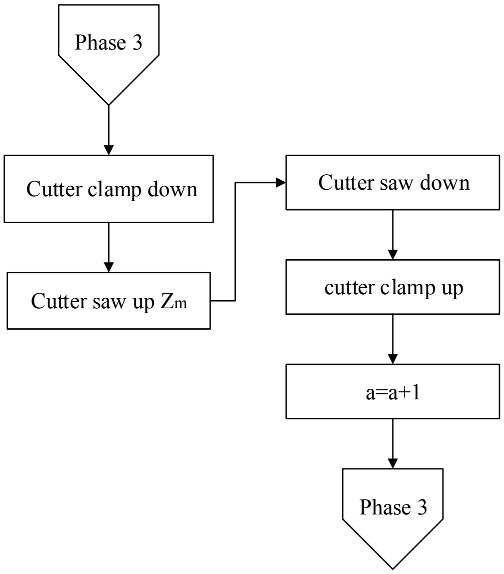
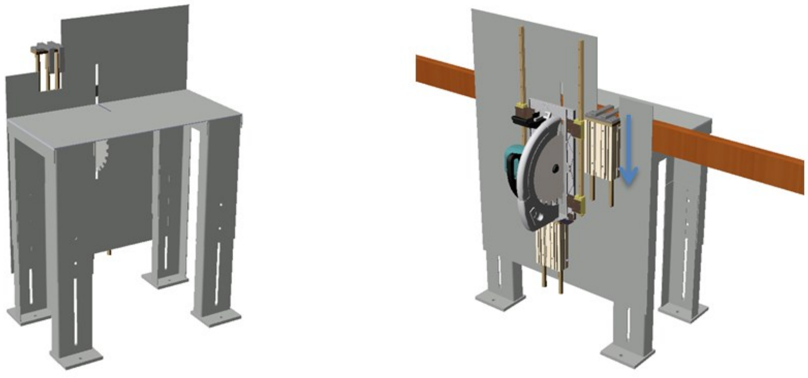
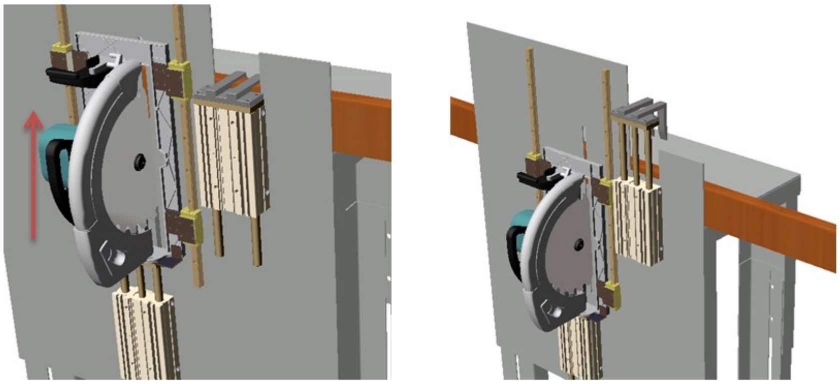


Figure 3.26: Cutting operation logic



Cutting machine **(a) Cutter clamp holds wooden plates**



(b) Cutter blade actives **(c) Parts retract back to original positions**

Figure 3.27: Cutting operation logic and schematic

3.3.5 Panel completion

After the multi-panel assembly is complete, the belt located on table B will activate and move the panel until the first stud edge of the panel reaches the end of table B. In the meantime, the dragging jaws will release the panel and will move back to their resting position. If more panels require assembly, the operation will loop back to the machinery pre-set configuration. Otherwise, the machine will become idle.

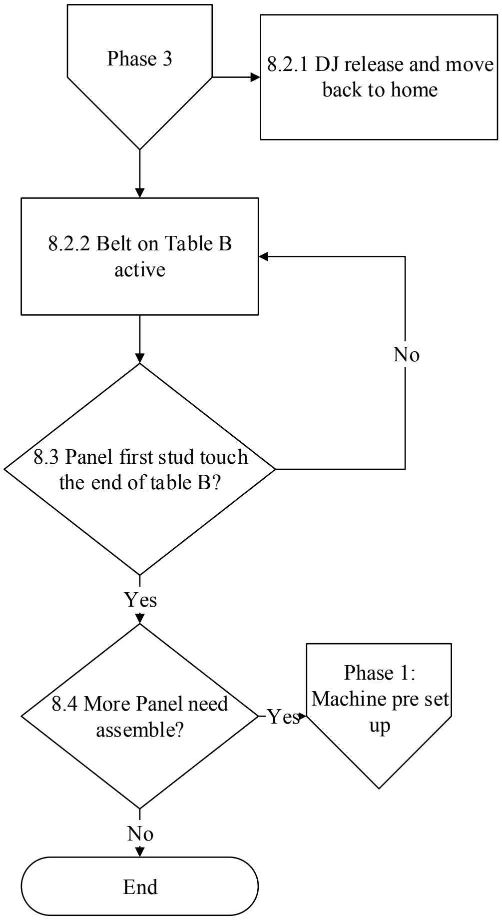


Figure 3.28: Logic for panel completion

3.4 Wood-framing machine motion planning

The multi-panel layouts vary since they contain different sub-walls from the residential building plan. In order to achieve successful operation of the wood wall-framing machine, the nailing, drilling, and cutting operation sequences must be determined based on the multi-panel layout that has been generated from the BIM model. Since only the nailing gun, which belongs to the nailing station, necessitates *z*-direction movement, the proposed assembly procedures and nailing gun motion plan should be generated based on the BIM model. The nailing gun movement can be calculated based on the nailing gun home position and nail locations. The methodology of the nailing gun motion plan is described in Figure 3.3.

After generating and sorting the manufacturing operations based on the equipment locations, the dragging jaw movements (multi-panel moving distance from pervious task point to next task point) are confirmed in order to avoid the omission of any necessary steps or any other conflicts. Therefore, the entire manufacturing plan can be determined. In this regard, the manufacturing operation procedure analyses are implemented interactively to design successful motions of the wood wall-framing table.

3.4.1 Panel manufacturing operation procedures and dragging jaw movement

Dragging jaws are designed to move the multi-panel to the machine location for each operation. The operation coordinate generation, which is explained in section 3.2, is measured from each operation location to multi-panel home positon. Each machine location to multi-panel home position possesses a certain distance. Therefore, operations reaching their corresponding machine distances are the operation locations related to their machine locations (operation locations minus machine locations). Sorting the operation locations related to their machines will obtain the relative distance and sequence for each multi-panel manufacturing procedure. The difference value between each relative distance is the movement distance of the dragging jaws.

$$Dw_a = X_i - X_{i-1} \qquad (3.39)$$

where:

$i = 1,2,3\ldots$total number of machine operations

Dw_a: a^{th} movement of dragging jaws

X: operation (nailing, drilling, and cutting) location relative to their machine

3.4.1.1 Calculation of operation locations relative to corresponding machinery

Since the nailing, cutting, and drilling machinery is positioned as shown in Figure 3.1, the *x*-coordinates of the nailing, drilling, and cutting stations that comprise the wood wall-framing machine will be D_n, D_d, and D_c, respectively. The *x*-coordinates of each operation should be larger than their operation machine *x*-coordinates; any exception should be performed manually. The operation locations related to their corresponding machine location can be calculated as per the following equations. The results will show the relative distance for the operation points reaching their operation machine. Sorting the results from smallest to largest will provide the wood wall-framing machine manipulation sequences.

$$D_i = XD_i - D_d \tag{3.40}$$

$$C_c = X_c - D_c \tag{3.41}$$

$$NT_n = XTj_n - D_n \tag{3.42}$$

$$NB_n = XBj_n - D_n \tag{3.43}$$

where:

D_i: ith drilling coordinates

C_c: c th cutting coordinates

NT_n: n th top side nailing coordinates

NB_n: n th bottom side nailing coordinates

D_n: distance from nailing station machine to home position

D_d: distance from drilling station machine to home position

D_c: distance from cutting station machine to home position

3.4.2 Nailing gun motion planning

The nailing gun is a horizontal nail device that only moves in the vertical direction. The nailing gun home position (Y_0) for *y*-direction is set at a ¾″ from the relative axis, as shown in Figure 3.29, is the midpoint of the bottom horizontal stud. Since the absolute *x*-axis of the multi-panel is set at the top- or bottom-plate vertical orientation stud midpoint, the relative *y*-coordinate for the multi-panel should be determined by adding half the stud width (d) to the absolute multi-panel *y*-coordinate.

The nailing gun movement for the first nail (M_n) is from the home position to the relative *z*-coordinate ($ZRj_1 - Z_0$) of the stud's first nail. In order to trigger the remaining nails on the same stud, the nailing gun will move from the current nail location to the next nail location ($ZRj_n - ZRj_{n-1}$). $M_n = 0$ when the nailing gun does not need to move in order to trigger the nails.

Switch absolute coordinates to relative coordinates:

$$ZTR_{jn} = ZTj_n + \frac{1}{2}d \quad (3.44)$$

First nail:

$$M_n = ZTRj_1 - Z_o \quad (3.45)$$

Remaining nails:

$$M_n = ZTRj_n - ZTRj_{n-1} \tag{3.46}$$

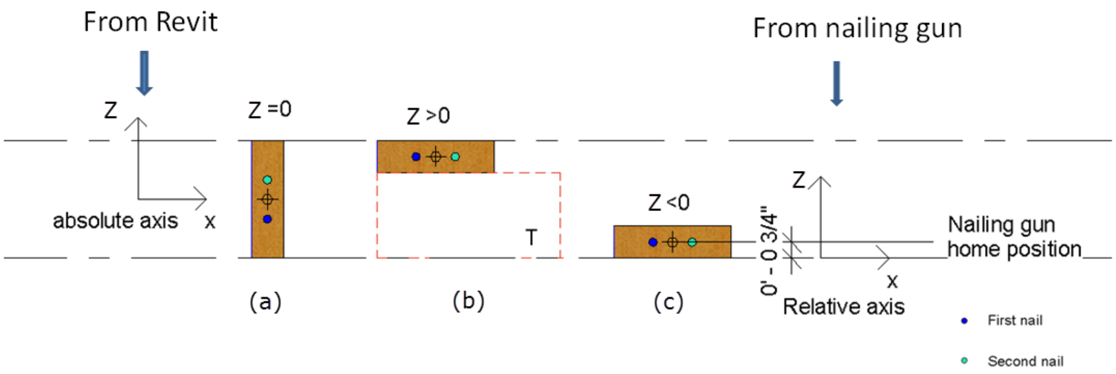


Figure 3.29: Nailing gun home position

3.5 Simulation model

A simulation model for wood framing machine improvement decision support system is built in this research. The purpose for this simulation model is to help the company make decision about improving their production line to automatic wood wall framing machine. By comparing the same housing structural panel production times between automatic wood wall framing machine and their current status, company can determine the feasibility of purchasing the automatic machinery.

3.5.1 Simulation input

The input data is from research and development work being carried out at an industry partner's manufacturing facility. The researcher utilized an RFID system to obtain production data from the industry partner's prefabrication plant. Station operation duration for each panel is collected through the system and stored in the central database. The panel framing machines that have been introduced in this research are similar to those in use at this plant. The machine manufacturing time for the industry partner's prefabrication process can be used as a reference for the machine time study in this research. The information is analyzed in @Risk for distribution fitting. Figure 3.30 shows the probability density function of drill operation processing time at the drilling station, which follows a triangular distribution. Therefore, the remaining data from each station is summarized as the duration distribution and is listed in Table 3.3.

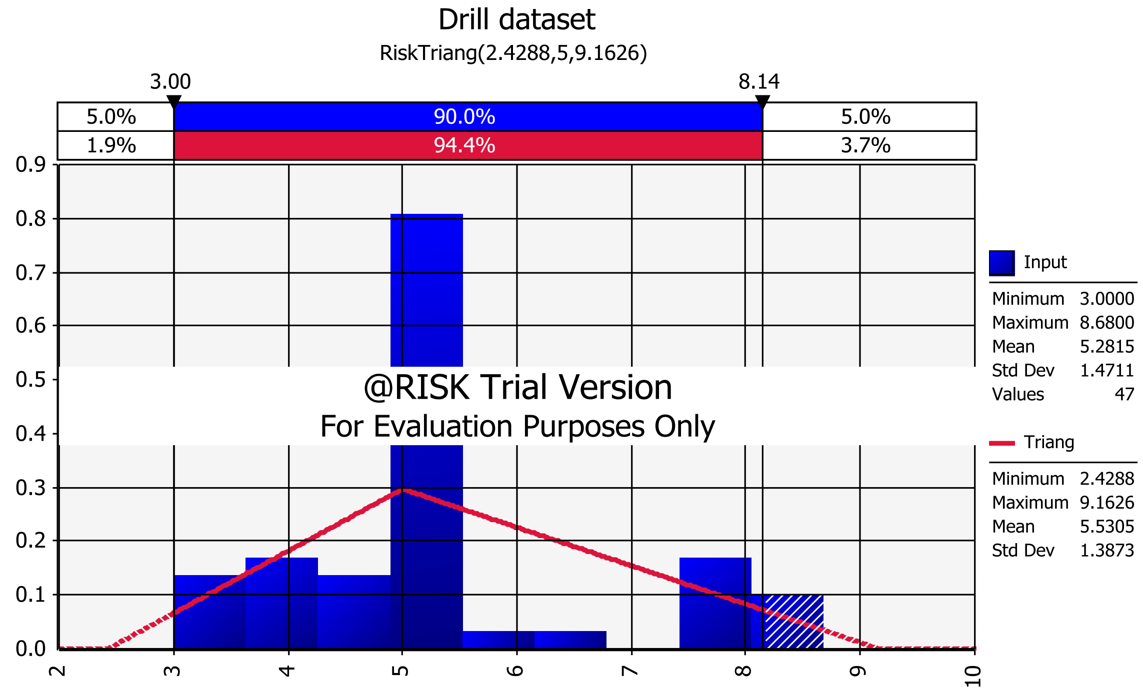


Figure 3.30: Probability density function of drill operation processing time at drilling station

Table 3.3 Duration distribution

	Activity		Sample size	Distribution type and parameter
Machine	Nail		532	Triangular (7.0000, 16.0137, 7.0000)
	Drill		714	Triangular (2.4288, 9.1626, 5.0000)
	Cutting		536	Triangular (4.1013, 10.2267, 8.0000)
	Variation		546	Triangular (0, 1302.7000, 0)
Manual	Feeding	stud	532	Triangular (1.2543, 31.1350, 5.0000)
		window	308	Triangular (50.0000, 142.8790 50.0000)
		door	280	Triangular (35.0000, 98.2860, 35.0000)
	Plate placement		294	Gamma (1.0008, 53.0190)
	Nail refill		532	Triangular (7.4210, 20.3320, 17.0000)

3.5.2 Simulation model development

The simulation models are built in Simphony.NET with the special purpose simulation template, which has been developed by Liu et al. (2015). Panel components from the BIM model as simulation entities will be processed in the simulation model. From that template, the preparations between station operations are represented by a “task” element. Each work station belonging to the panel framing table is represented by a “station” element, which will delay the simulation entities with corresponding fabrication operation durations. The simulation model is demonstrated in Figure 3.31.

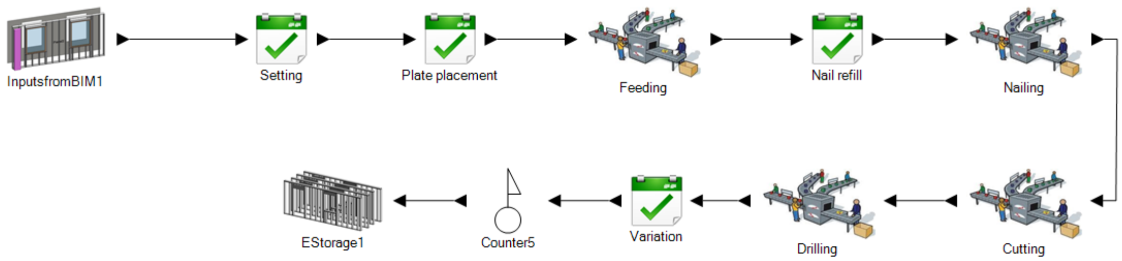


Figure 3.31 Simulation model for panel manufacturing

The panel assembly operation process time is calculated using the following equation:

$$T_A = T_{BP} \times N_{BP} + T_{TP} \times N_{TP} + T_{ST} \times N_{ST} + T_W \times N_W + T_D \times N_D + T_s \times N_s + T_{cut} \times N_{cut} + T_{Drill} \times N_{Drill} + T_N + V \quad (3.47)$$

where T_A is the station assembly time; T_{BP} and T_{TP} are the times, in seconds (s), necessary to place each top- and bottom-plate, respectively; T_{ST} is the time needed to place a single stud; T_W is the amount of time necessary to place each window; T_D is the time necessary to place each door; Ts is the time necessary to assemble a stud (single stud and stud in components); T_{cut} and T_{Drill} are the times necessary to finish the cut and drill, respectively. T_N is the time necessary to refill the nailing gun. N_{BP}, $N_{TP,}$ $N_{ST,}$ N_W, and N_D are the component numbers in the framework, N_s is the single stud and stud in components total number, N_{cut} and N_{Drill} are the cut and drill operations number in the framework. V represents the variation for the assembly process and is assumed in this research to be a triangular distribution. The simulation model determines the total time of the wood wall-framing table assembly process based on BIM model information and each station operation (nailing, drilling and cutting) total cycle time. Comparing the above results with current framing performance will help a given company to determine whether or not replacing manual work with automated processes is feasible.

Chapter 4 Case Study

4.1 Introduction

This chapter describes a case project which demonstrates the proposed methodology. One Revit model from a home building company is involved for this implementation. First, the multi-panel combination is optimized. Second, sample multi-panel information is extracted from the BIM model and validates the wood wall-framing machine design and motion logic. Finally, a simulation model is built.

4.1.2 Background

To verify the benefits of the proposed methodology, a case study is presented in order to demonstrate how the single walls are optimized to form multi-panels, and how the machine implements the manufacturing of these multi-panels. The 3D BIM model that has been selected to verify the proposed methodology is from a manufacturing plant operated by Star Prebuilt Homes (an Edmonton-based modular construction company). The case study object is a two-storey detached house with 1,840 ft^2 living area. This detached house comprises three bedrooms, two and a half bathrooms, one living room, and one dining room. There are also eight windows, one front door, and one patio door distributed throughout the house. The case study house is pictured in detail in Figure 4.1, Figure 4.2, Figure 4.3, and Figure 4.4.

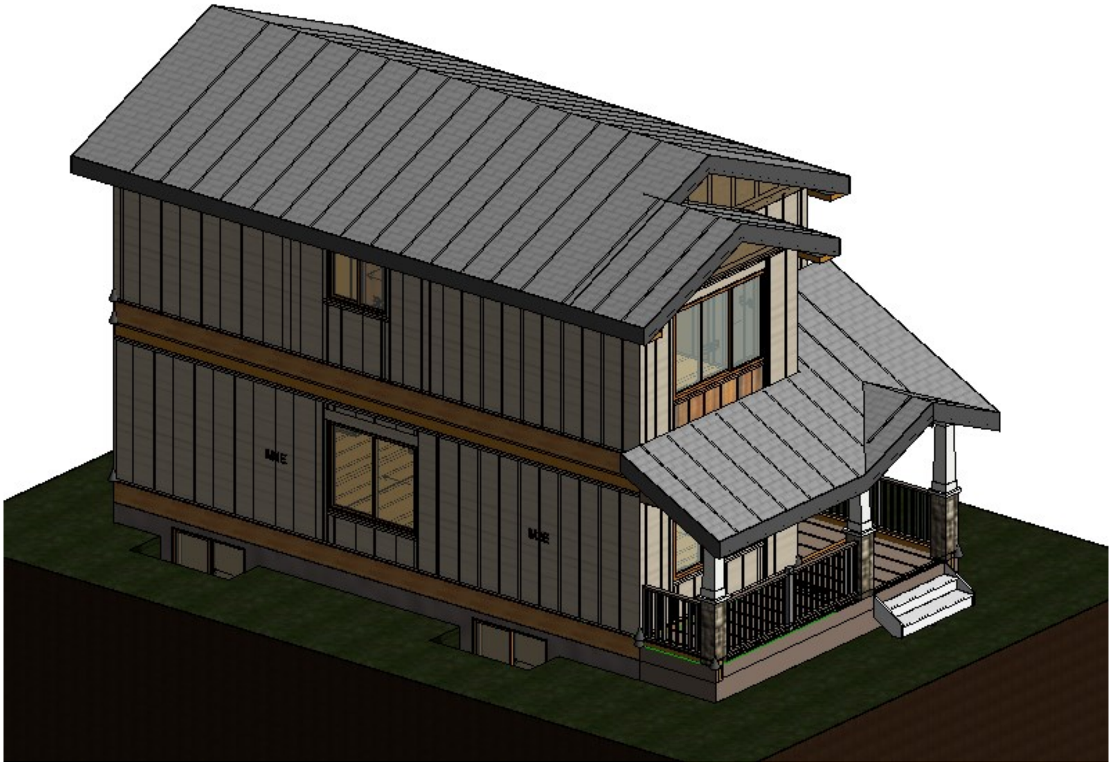


Figure 4.1: 3D view of case study model

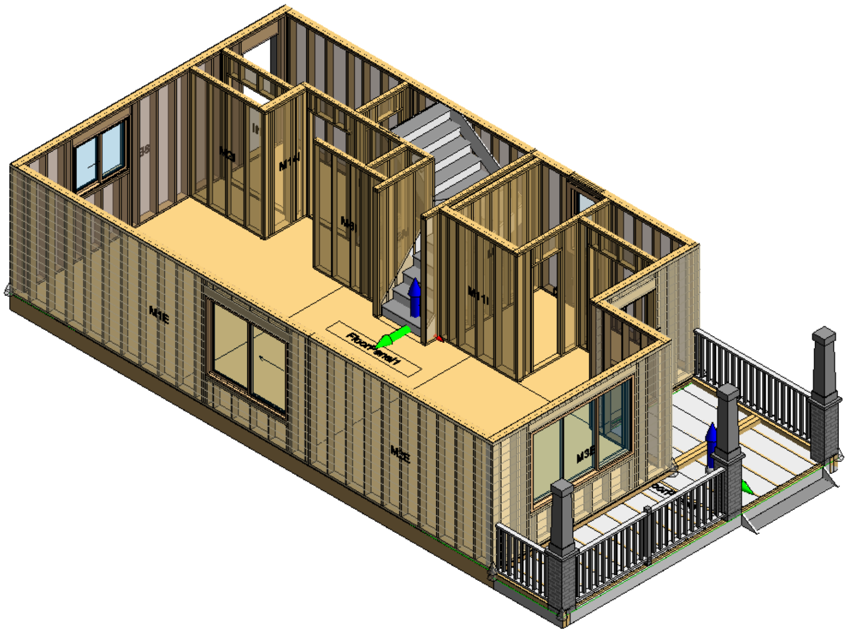


Figure 4.2: Sample model main floor wall panel layout

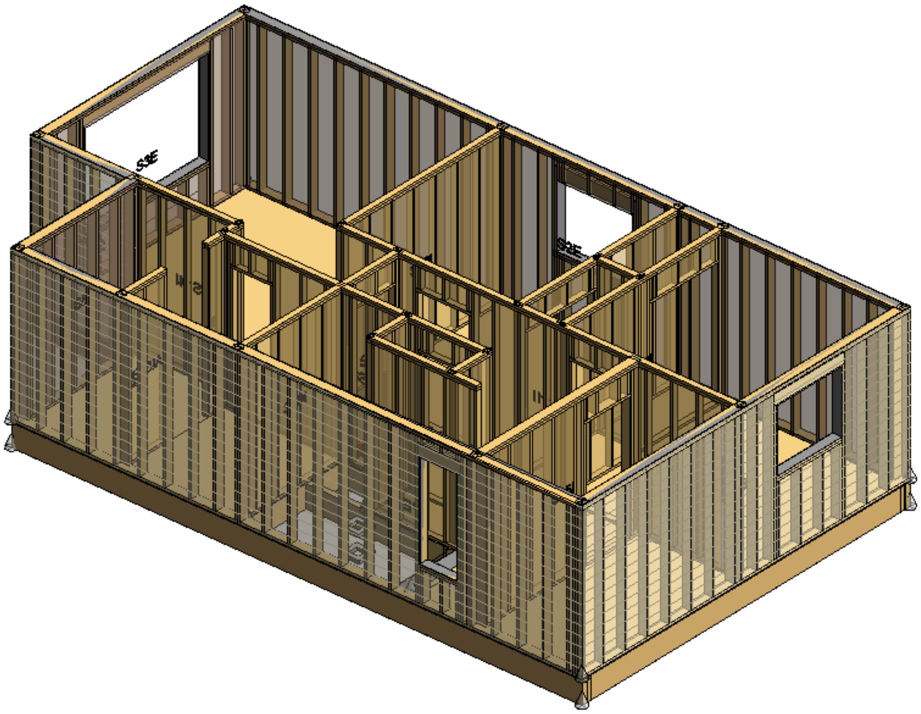


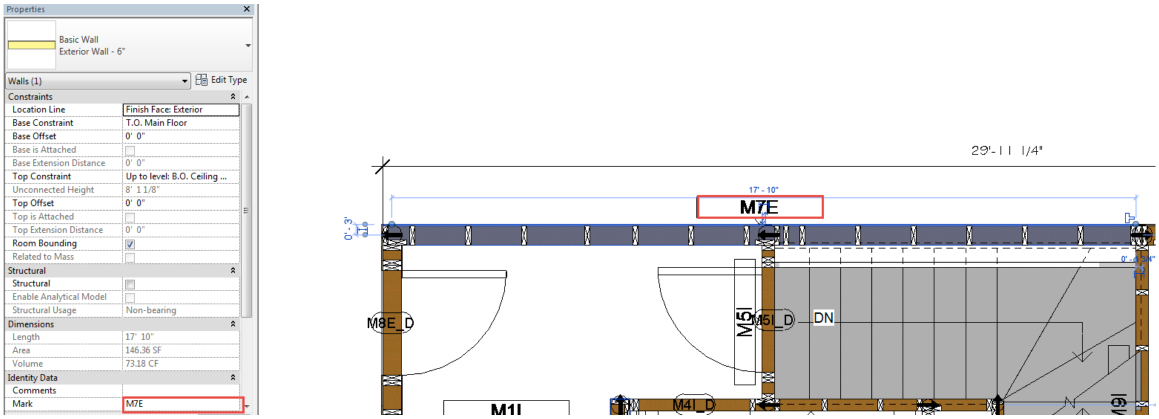
Figure 4.3: Sample model second floor wall panel layout

Figure 4.4: Sample model front elevation view

4.1.3 Revit model preparation

The preliminary task in order to implement the methodology is completing the wall framing for the BIM model. Since Revit software is currently unable to provide the complete structure framing, a Revit add-on is incorporated in order to aid in the framing of the model. This Revit add-on is able to automatically create wood-framing for construction project in Revit. The main floor of the sample BIM model consists of 21 wall panels (Figure 4.2), and the second floor consists of 23 wall panels (Figure 4.3). Once the framing process is complete, a BIMSF_Container label is automatically assigned to each unique panel, and each piece of lumber is assigned a BIMSF_*Description.*

Each wall panel framing is defined by the BIMSF_Container label it was assigned. The first letter represents the level the panel belongs to, either main floor "M" or second floor "S". The rest of the letters represent the panel orientation and sequence. For example, the BIMSF_Container label M7E, listed in Table 4.1, represents the seventh horizontal panel on the main floor. The architectural walls, which contain a property called "identity data mark" (Figure 4.5), are congruent to their corresponding framing panel BIMSF_Container (Figure 4.6). Therefore, the BIMSF_Container will build the bridge between the "wall schedule" and the "structural framing schedule" which are both generated from BIM model. Since the bottom-plate ("TBOT") is the edge of the panel, its length could represent the length of the wall framing.



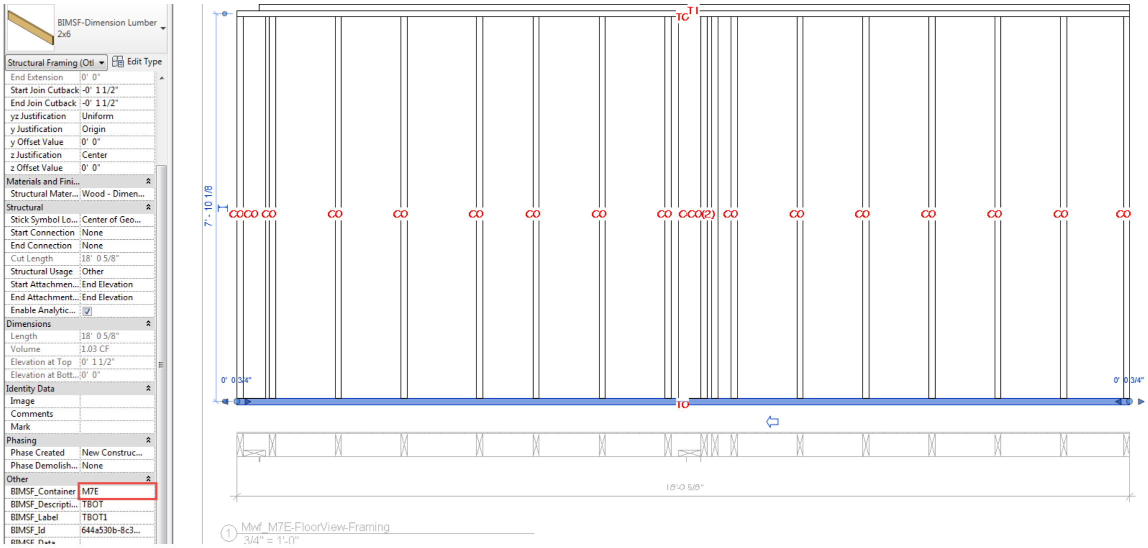
Properties

Basic Wall
Exterior Wall - 6"

Walls (1)

Constraints	
Location Line	Finish Face: Exterior
Base Constraint	T.O. Main Floor
Base Offset	0' 0"
Base is Attached	☐
Base Extension Distance	0' 0"
Top Constraint	Up to level: B.O. Ceiling ...
Unconnected Height	8' 1 1/8"
Top Offset	0' 0"
Top is Attached	☐
Top Extension Distance	0' 0"
Room Bounding	☑
Related to Mass	☐
Structural	
Structural	☐
Enable Analytical Model	☐
Structural Usage	Non-bearing
Dimensions	
Length	17' 10"
Area	146.36 SF
Volume	73.18 CF
Identity Data	
Comments	
Mark	M7E

Figure 4.5: Architectural wall properties



BIMSF-Dimension Lumber
2x6

Structural Framing (Otl

End Extension	0' 0"
Start Join Cutback	-0' 1 1/2"
End Join Cutback	-0' 1 1/2"
yz Justification	Uniform
y Justification	Origin
y Offset Value	0' 0"
z Justification	Center
z Offset Value	0' 0"
Materials and Fini...	
Structural Mater...	Wood - Dimen...
Structural	
Stick Symbol Lo...	Center of Geo...
Start Connection	None
End Connection	None
Cut Length	18' 0 5/8"
Structural Usage	Other
Start Attachmen...	End Elevation
End Attachment...	End Elevation
Enable Analytic...	☑
Dimensions	
Length	18' 0 5/8"
Volume	1.03 CF
Elevation at Top	0' 1 1/2"
Elevation at Bott...	0' 0"
Identity Data	
Image	
Comments	
Mark	
Phasing	
Phase Created	New Construc...
Phase Demolish...	None
Other	
BIMSF_Container	M7E
BIMSF_Descripti...	TBOT
BIMSF_Label	TBOT1
BIMSF_Id	644a530b-8c3...

Figure 4.6: Framing properties

4.2 Multi-panel optimization

The multi-panel optimization is implemented by Greedy algorithm and investigated based on the sample model. As the wall framing shop drawings have been generated, the information pertaining to the walls is accessible such as the wall framing length, wall type, and the wall level. All the wall framing panels in the Revit model are collected and separated into different groups. The walls in each group are ranked based on length and are stored in a corresponding multi-panel pool. In this case study, three types of walls are extracted: exterior 6″, interior 3 ½″, and interior 5 ½″. The wall and structure faming schedules created in Revit can be extracted as .txt files and can be combined based on BIMSF_Container in Microsoft Excel (Table 4.1). The maximum panel length is determined by the machine type; for the machinery introduced in this research, the maximum length is 40 ft. Any wall lengths exceeding 40 ft will be filtered out and reported to the user. The eligible panels will continue on to undergo the process of optimization by means of Greedy algorithm.

Table 4.1 Sample wall information

Structural Framing Schedule				Wall Schedule	
BIMSF_Container	BIMSF_Description	Length (ft)	Type	Wall type	Mark
M1E	TBOT	21.604	2×6	Exterior Wall - 6″	M1E
M1I	TBOT	5.010	2×4	Interior Wall - 3½″	M1I
M2E	TBOT	13.333	2×6	Exterior Wall - 6″	M2E
M2I	TBOT	5.469	2×4	Interior Wall - 3½″	M2I
M3E	TBOT	12.479	2×6	Exterior Wall - 6″	M3E
M4E	TBOT	5.000	2×6	Exterior Wall - 6″	M4E
M4I	TBOT	8.667	2×4	Interior Wall - 3½″	M4I
M5E	TBOT	7.000	2×6	Exterior Wall - 6″	M5E
M5I	TBOT	3.677	2×4	Interior Wall - 3½″	M5I
M6E	TBOT	11.521	2×6	Exterior Wall - 6″	M6E
M6I	TBOT	5.167	2×4	Interior Wall - 3½″	M6I
M7E	TBOT	18.052	2×6	Exterior Wall - 6″	M7E
M7I	TBOT	2.708	2×4	Interior Wall - 3½″	M7I
M8E	TBOT	19.021	2×6	Exterior Wall - 6″	M8E
M8I	TBOT	4.125	2×4	Interior Wall - 3½″	M8I
M9I	TBOT	7.802	2×4	Interior Wall - 3½″	M9I
M10I	TBOT	6.302	2×4	Interior Wall - 3½″	M10I
M11I	TBOT	5.625	2×6	Interior Wall - 5½″	M11I
M12I	TBOT	6.302	2×4	Interior Wall - 3½″	M12I
M13I	TBOT	5.510	2×4	Interior Wall - 3½″	M13I
M14I	TBOT	3.000	2×6	Interior Wall - 5½″	M14I
S1E	TBOT	13.885	2×6	Exterior Wall - 6″	S1E
S1I	TBOT	20.594	2×4	Interior Wall - 3½″	S1I
S2E	TBOT	20.594	2×6	Exterior Wall - 6″	S2E
S3E	TBOT	12.252	2×6	Exterior Wall - 6″	S3E

S3I	TBOT	9.427	2×4	Interior Wall - 3½″	S3I
S4E	TBOT	4.760	2×6	Exterior Wall - 6″	S4E
S4I	TBOT	2.000	2×4	Interior Wall - 3½″	S4I
S5E	TBOT	6.552	2×6	Exterior Wall - 6″	S5E
S5I	TBOT	9.427	2×4	Interior Wall - 3½″	S5I
S6E	TBOT	11.885	2×6	Exterior Wall - 6″	S6E
S6I	TBOT	5.498	2×4	Interior Wall - 3½″	S6I
S7E	TBOT	17.833	2×6	Exterior Wall - 6″	S7E
S7I	TBOT	2.167	2×4	Interior Wall - 3½″	S7I
S8E	TBOT	19.938	2×6	Exterior Wall - 6″	S8E
S8I	TBOT	13.500	2×4	Interior Wall - 3½″	S8I
S9I	TBOT	2.167	2×4	Interior Wall - 3½″	S9I
S10I	TBOT	5.990	2×4	Interior Wall - 3½″	S10I
S11I	TBOT	3.313	2×4	Interior Wall - 3½″	S11I
S12I	TBOT	9.719	2×4	Interior Wall - 3½″	S12I
S13IA	TBOT	2.344	2×4	Interior Wall - 3½″	S13IA
S13IB	TBOT	2.167	2×4	Interior Wall - 3½″	S13IB
S14I	TBOT	4.896	2×4	Interior Wall - 3½″	S14I
S15I	TBOT	9.448	2×6	Interior Wall - 5½″	S15I

4.2.1 Scenario 1: Entire house wall grouping for optimization

For scenario 1, the walls for the entire house will be separated into three pools: exterior 6″, interior 3 ½″, and interior 5 ½″ (see Appendices A, B, and C). The exterior 6″ wall is used as a sample to demonstrate the procedure and the equations which have been formulated in the previous chapter. Since no wall is more than 40 ft, all of the exterior walls should be optimized.

As shown in Table 4.2, the “M1E” has the greatest length among the exterior panels, which will be the first wall added into the multi-panel array 1. There will be at least a 1″ gap between all single panels to account for cutting purposes. Therefore, due to the 1″ gap, the remaining portion of the multi-panel is 18.313 ft. The longest wall panel that is less than the remaining multi-panel available length is “M7E”. Once “M7E” fills in the multi-panel array 1, the remaining portion of the multi-panel is 0.261 ft. The remaining portion is considered as waste and multi-panel array 1 is complete, as shown in Figure 4.7. “S1E”, which is 20.591 ft in length, is the longest wall among the remaining walls in the pool. It will be recorded in the multi-panel array 2. The remaining portion is 19.326 ft and fits the “S8E” wall. There will be 0.305 ft considers as waste for multi-panel array 2. After the above methods are repeated for exterior 6″ walls, there will be a total of 6 multi-panels and 23.458 ft of top- and bottom-plate waste and leftover, as shown in Table 4.3.

Table 4.2 Sample exterior wall information

Structural Framing Schedule				Wall Schedule	
BIMSF_Container	BIMSF_Description	Length (ft)	Type	Wall type	Mark
M1E	TBOT	21.604	2×6	Exterior Wall - 6″	M1E
S2E	TBOT	20.594	2×6	Exterior Wall - 6″	S2E
S8E	TBOT	19.938	2×6	Exterior Wall - 6″	S8E
M8E	TBOT	19.021	2×6	Exterior Wall - 6″	M8E
M7E	TBOT	18.052	2×6	Exterior Wall - 6″	M7E
S7E	TBOT	17.833	2×6	Exterior Wall - 6″	S7E
S1E	TBOT	13.885	2×6	Exterior Wall - 6″	S1E
M2E	TBOT	13.333	2×6	Exterior Wall - 6″	M2E
M3E	TBOT	12.479	2×6	Exterior Wall - 6″	M3E
S3E	TBOT	12.252	2×6	Exterior Wall - 6″	S3E
S6E	TBOT	11.885	2×6	Exterior Wall - 6″	S6E
M6E	TBOT	11.521	2×6	Exterior Wall - 6″	M6E
M5E	TBOT	7.000	2×6	Exterior Wall - 6″	M5E
S5E	TBOT	6.552	2×6	Exterior Wall - 6″	S5E
M4E	TBOT	5.000	2×6	Exterior Wall - 6″	M4E
S4E	TBOT	4.760	2×6	Exterior Wall - 6″	S4E

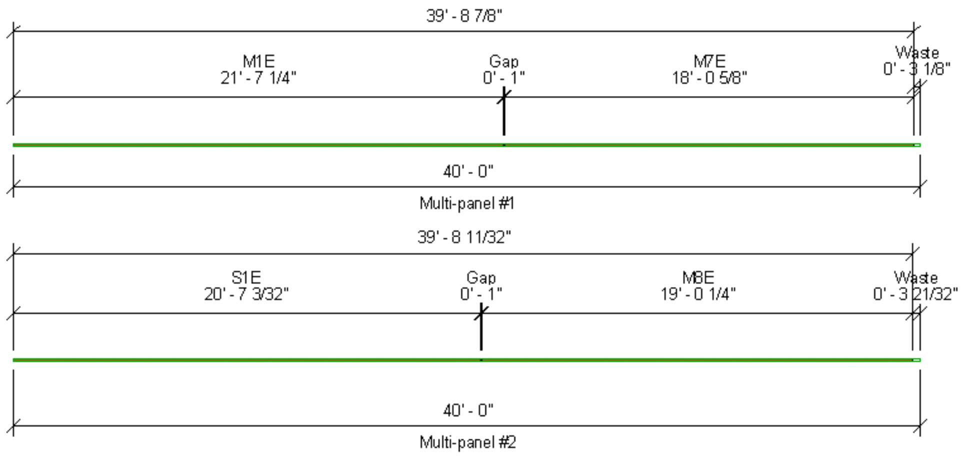


Figure 4.7: Multi-panel #1 and #2 optimization

Table 4.3 Exterior wall multi-panel combination

Multi-panel	Type	Mark	Length (ft)	Remaining
1	Exterior Wall - 6″	M1E	21.604	18.313
	Exterior Wall - 6″	M7E	18.052	0.261
2	Exterior Wall - 6″	S2E	20.594	19.323
	Exterior Wall - 6″	M8E	19.021	0.302
3	Exterior Wall - 6″	S8E	19.938	19.979
	Exterior Wall - 6″	S7E	17.833	2.146
4	Exterior Wall - 6″	S1E	13.885	26.032
	Exterior Wall - 6″	M2E	13.333	12.615
	Exterior Wall - 6″	M3E	12.479	0.136
5	Exterior Wall - 6″	S3E	12.252	27.665
	Exterior Wall - 6″	S6E	11.885	15.696
	Exterior Wall - 6″	M6E	11.521	4.175
6	Exterior Wall - 6″	M5E	7.000	32.917
	Exterior Wall - 6″	S5E	6.552	26.281
	Exterior Wall - 6″	M4E	5.000	21.198
	Exterior Wall - 6″	S4E	4.760	16.438
Waste and leftover				23.458

4.2.2 Scenario 2: Optimization of wall groupings for each floor

For scenario 2, the walls for the entire house will be separated into six pools: main floor exterior 6″, interior 3 ½″, and interior 5 ½″, as well as second floor exterior 6″, interior 3 ½″, and interior 5 ½″ (see Appendices A1, A2, B1, B2, C1, and C2). The exterior 6″ wall is used as an example to illustrate this scenario. The main floor pool (A1) will form a multi-panel first. After applying Greedy algorithm to analyze the multi-panel optimization, the main floor consists of 3 multi-panels. The last multi-panel will have 10.75 ft remaining. The second floor pool (A2) fills in the main floor pool (A1) as shown in Table 4.4, and "S5E" will be recorded into the multi-panel array 3. The remaining second-floor walls form three multi-panels. The total waste and leftover of top- and bottom-plates is found to be 23.458 ft.

Table 4.4 Second floor pool A2 fills into A1

Structural Framing Schedule				Wall Schedule	
BIMSF_Container	BIMSF_Description	Length (ft)	Type	Wall type	Mark
M1E	TBOT	21.604	2×6	Exterior Wall - 6″	M1E
M8E	TBOT	19.021	2×6	Exterior Wall - 6″	M8E
M7E	TBOT	18.052	2×6	Exterior Wall - 6″	M7E
M2E	TBOT	13.333	2×6	Exterior Wall - 6″	M2E
M3E	TBOT	12.479	2×6	Exterior Wall - 6″	M3E
M6E	TBOT	11.521	2×6	Exterior Wall - 6″	M6E
M5E	TBOT	7.000	2×6	Exterior Wall - 6″	M5E
M4E	TBOT	5.000	2×6	Exterior Wall - 6″	M4E
S2E	TBOT	20.594	2×6	Exterior Wall - 6″	S2E
S8E	TBOT	19.938	2×6	Exterior Wall - 6″	S8E
S7E	TBOT	17.833	2×6	Exterior Wall - 6″	S7E
S1E	TBOT	13.885	2×6	Exterior Wall - 6″	S1E
S3E	TBOT	12.252	2×6	Exterior Wall - 6″	S3E
S6E	TBOT	11.885	2×6	Exterior Wall - 6″	S6E
S5E	TBOT	6.552	2×6	Exterior Wall - 6″	S5E
S4E	TBOT	4.760	2×6	Exterior Wall - 6″	S4E

Table 4.5 Multi-panel optimization for six exterior walls (main floor and second floor)

Multi-panel	Type	Mark	Length (ft)	Remaining (ft)
1	Exterior Wall - 6″	M1E	21.604	18.313
	Exterior Wall - 6″	M7E	18.052	0.261
2	Exterior Wall - 6″	M8E	19.021	20.896
	Exterior Wall - 6″	M2E	13.333	7.479
	Exterior Wall - 6″	M5E	7.000	0.479
3	Exterior Wall - 6″	M3E	12.479	27.438
	Exterior Wall - 6″	M6E	11.521	15.833
	Exterior Wall - 6″	M4E	5.000	10.750
	Exterior Wall - 6″	S5E	6.552	4.198
4	Exterior Wall - 6″	S2E	20.594	19.323
	Exterior Wall - 6″	S7E	17.833	1.490
5	Exterior Wall - 6″	S8E	19.938	19.979
	Exterior Wall - 6″	S1E	13.885	6.010
	Exterior Wall - 6″	S4E	4.760	1.250
6	Exterior Wall - 6″	S3E	12.252	27.665
	Exterior Wall - 6″	S6E	11.885	15.780
Waste and leftover				23.458

Interestingly, these two scenarios generate the same total multi-panel numbers, waste and leftover for exterior walls. The only difference is the sequences of the walls in the multi-panel. For scenario 2, the multi-panels belonging to each floor can be transferred to the site as a group. Therefore, the implementation of scenario 2 eliminates uncertainty and additional effort by onsite workers in identifying and classifying each panel, which will increase the onsite productivity. This research uses multi-panel information from the second scenario in order to carry out further analysis.

4.3 Generation of operation locations

Based on the above optimized multi-panel generation information, multi-panel #1, as shown in Figure 4.8, is selected from Table 4.5 as a sample in order to generate operation locations.

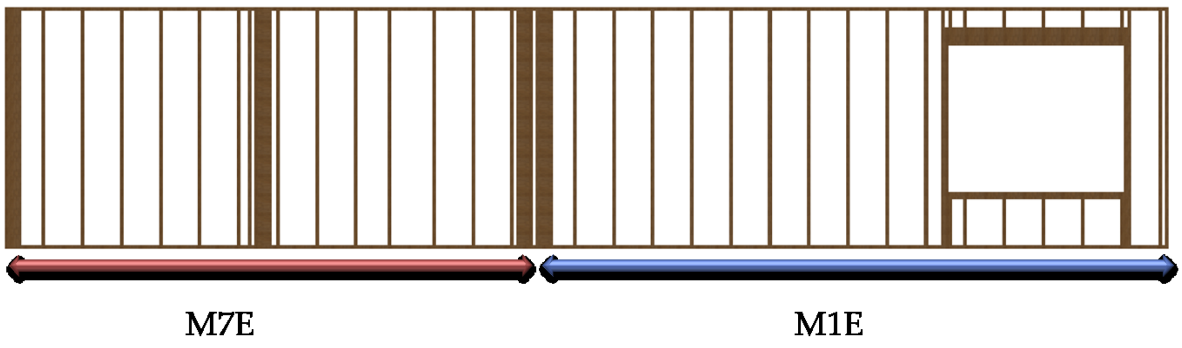


Figure 4.8: Sample multi-panel #1

4.3.1 Cut locations

The information extracted from multi-panel #1 for cut location calculation is presented in Table 4.6.

Table 4.6 Sample multi-panel information (1)

Multi-panel length	39.739	Total number of sub-wall (SW)	2
Sub-wall ID ($_m$)	Sub-wall length (Lsw_m)	Sub-wall start-point *x*-coordinate ($XSWS_m$)	Sub-wall end-point *x*-coordinate ($XSWF_m$)
1	21.604	0.000	21.604
2	18.052	21.687	39.739

Cut locations for a multi-panel are located at the end of the first sub-wall, as well as at the start- and end-points of the remaining sub-walls consecutively; all will be partially cut other than the last point, which is located at the end of the entire panel and will thus be completely cut. The saw thickness for the cutting station is 0.07 ft. The cut location (X_a), which is calculated according to the methodology, is shown in Table 4.7 and Figure 4.9.

Table 4.7 Cut location coordinates

Cut type	Cut ID (a)	Cut distance from home position (XC_a)
Partially cut	1	21.604
	2	21.680
Completely cut	3	39.739

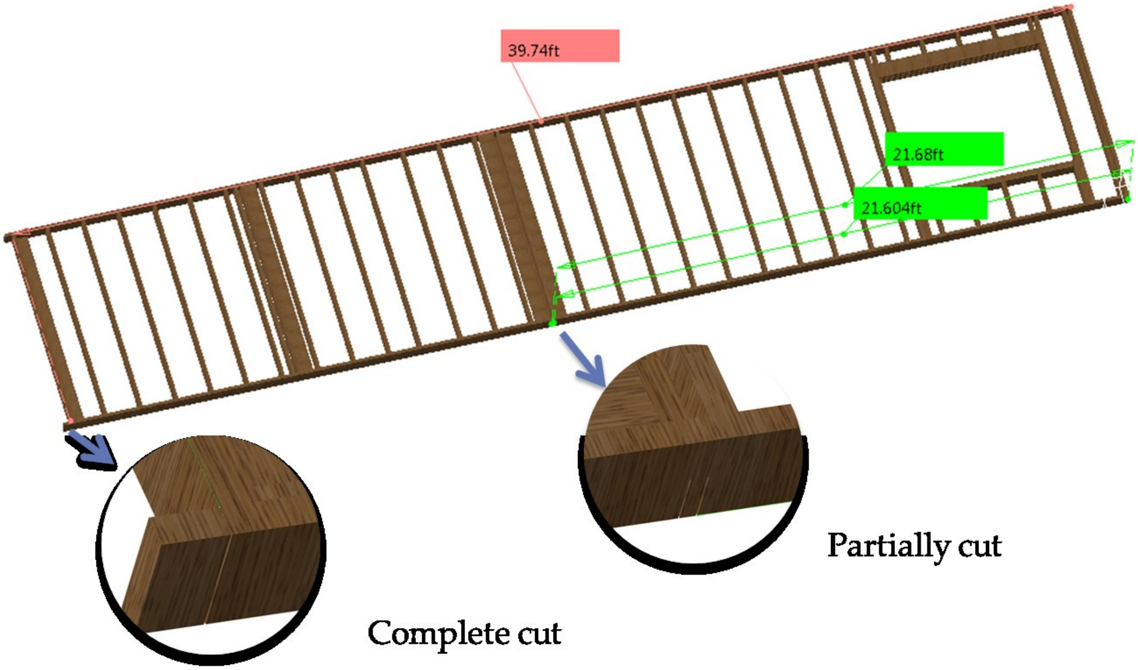


Figure 4.9: Cut locations for sample multi-panel #1

4.3.2 Nailing locations

The nail locations are determined by the coordinates (*x*,*y*,*z*) and the type of object, which can be extracted from Revit and regarded as known values. The number of nails on each object is set to 2. The information extracted from multi-panel #1 for nail location calculation is listed in Table 4.8. Stud 1 is used as the example to show the nail location generation.

Table 4.8 Sample multi-panel information (2)

Name	Type	IsTop	IsBottom	X	Z	Y	Multi-panel *x*-coordinate	b1	d1
M1E	L2×6	TRUE	TRUE	0.063	0.000	0.125	0.063	0.125	0.458
M1E	L2×6	TRUE	TRUE	0.271	0.000	0.125	0.271	0.125	0.458
M1E	L2×6	TRUE	TRUE	1.318	0.000	0.125	1.318	0.125	0.458
M1E	L2×6	FALSE	TRUE	1.443	0.000	0.125	1.443	0.125	0.458
…									
M1E	L2×6	TRUE	TRUE	21.250	–0.167	0.125	21.250	0.125	0.458
M1E	L2×6	TRUE	TRUE	21.542	0.000	0.125	21.542	0.125	0.458

For stud j = k = 1 (Vertical stud)

Known values:

Stud j = 1, k = 1

Stud dimensions (2×6 type) b = 0.125, d = 0.4583

Midpoint coordinates $(XT_1, ZT_1) = (XB_1, ZB_1) = (0.0625, 0)$

User-defined values:

Number of nails on stud NTj = NBk = 2

After substituting the known values in the following equations, the results for nail location $(XT_{jn}, YT_{jn}, ZT_{jn})$ and $(XB_{kn}, YB_{kn}, ZB_{kn})$ can be found.

Nail locations for vertical studs on the top-plate side ($YT_j = 0$) can be determined as follows:

$$XT_{jn} = XT_j \tag{4.1}$$

$$YT_{jn} = H \tag{4.2}$$

$$ZTj_n = [Z_j - (d/2)] + n \times [d/ (NT_j + 1)] \tag{4.3}$$

Nail locations for vertical studs at bottom-plate side ($YB_k = 0$):

$$XBk_n = XB_k \tag{4.4}$$

$$YBk_n = 0 \tag{4.5}$$

$$ZBk_n = [ZB_k - (d/2)] + n \times [d / (NB_k + 1)] \tag{4.6}$$

$XB1_1 = XT1_1 = 0.0625$

$ZB1_1 = ZT1_1 = [0 - (0.4583/2)] + [0.4583 / (2 + 1)] = -0.07638$

$XB1_2 = XT1_2 = 0.0625$

$ZB1_2 = ZT1_2 = [0 - (0.4583 / 2)] + 2 \times [0.4583/(2 + 1)] = 0.07638$

$YT1_1 = YT1_2 = 8.03125$

$YB1_1 = YB1_2 = 0$

Nailing point for stud 1: (0.0625, 8.03125, −0.07638), (0.0625, 0, −0.07638), (0.0625, 8.03125, 0.07638), (0.0625, 0, 0.07638)

For the 21st stud on the top side and the 23rd on the bottom side (horizontal stud):

Known values:

Stud $j = 21$, $k = 23$

Stud dimensions (2×6 type) $b1 = 0.125$, $d1 = 0.4583$

Midpoint coordinates $(XT_{21}, ZT_{21}) = (XB_{23}, ZB_{23}) = (21.25, -0.167)$

User-defined values:

Number of nails on stud $NT_j = NB_k = 2$

Substituting the known values for the following equations:

Nail locations for horizontal studs at top-plate side ($YTj \neq 0$):

$$XTj_n = [XT_j - (d/2)] + n \times [d / (NT_j + 1)] \quad (4.7)$$

$$YTj_n = H \quad (4.8)$$

$$ZTj_n = ZT_j \quad (4.9)$$

Nail locations for horizontal studs at bottom-plate side ($YB_k \neq 0$):

$$XBk_n = [X_k - (d/2)] + n \times [d / (NB_k + 1)] \quad (4.10)$$

$$YBk_n = 0 \quad (4.11)$$

$$ZBk_n = ZB_k \quad (4.12)$$

$XT21_1 = XB23_1 = [21.25 - 0.4583/2] + \{1 \times [0.4583 / (2 + 1)]\} = 21.174$

$ZT21_1 = ZB23_1 = -0.167$

$XT21_2 = XB23_2 = [21.25 - 0.4583/2] + \{2 \times [0.4583 / (2 + 1)]\} = 21.326$

$ZT21_2 = ZB23_2 = -0.167$

$YT21_1 = YT21_2 = 8.03125$

$YB23_1 = YB23_2 = 0$

Nailing point for studs 21 and 23: (21.174, 8.03125, −0.167), (21.174, 0, −0.167), (21.326, 8.03125, −0.167), (21.326, 0, −0.167)

Utilizing the methodology to generate the nail locations, the nail locations for the entire multi-panel are determined. The nail locations are sorted based on the *x*-coordinates of each nail, as shown in Table 4.9.

Table 4.9 Sample nail location coordinates

Top-plate						Bottom-plate					
j	**Nail number**	**No.**	**X**	**Z**	**Y**	**k**	**Nail number**	**No.**	**X**	**Z**	**Y**
1	2	1	0.0625	−0.0760	8.0313	1	2	1	0.0625	−0.0764	0
		2	0.0625	0.0764	8.0313			2	0.0625	0.0764	0
2	2	1	0.2708	−0.0760	8.0313	2	2	1	0.2708	−0.0764	0
		2	0.2708	0.0764	8.0313			2	0.2708	0.0764	0
3	2	1	1.3177	−0.0760	8.0313	3	2	1	1.3177	−0.0764	0
		2	1.3177	0.0764	8.0313			2	1.3177	0.0764	0
						4	2	1	1.4427	−0.0764	0
								2	1.4427	0.0764	0
…						…					
21	2	1	21.1740	−0.1670	8.0313	23	2	1	21.1740	−0.1670	0
		2	21.3260	−0.1670	8.0313			2	21.3260	−0.1670	0
22	2	1	21.5420	−0.0760	8.0313	24	2	1	21.5420	−0.0764	0
		2	21.5420	0.0764	8.0313			2	21.5420	0.0764	0

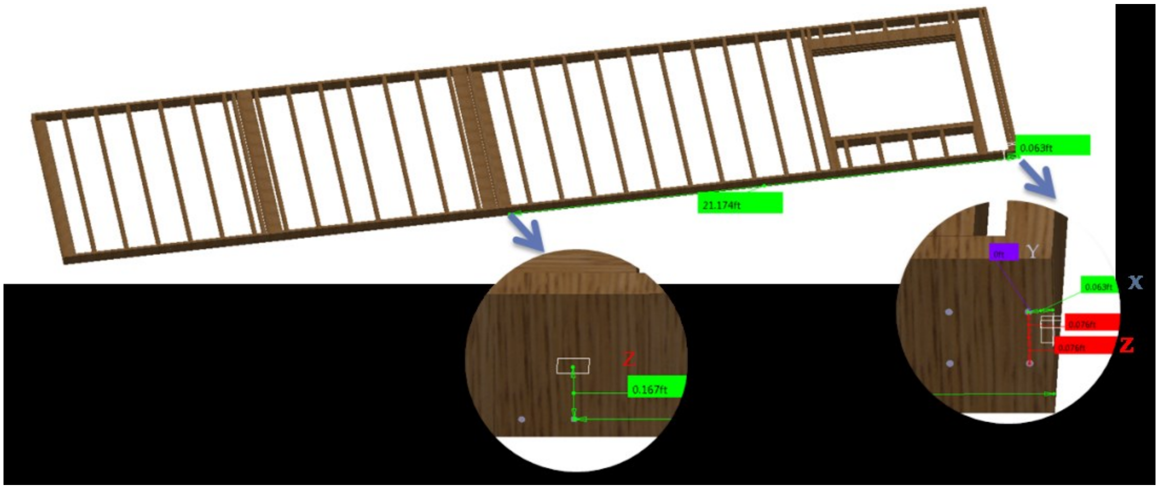


Figure 4.10: Nail locations for sample multi-panel #1

4.3.3 Drilling locations

The COG location calculations for each single panel are as follows:

COG for M1E

Known values:

All member weights and *x*-coordinates as per Appendix E

Center of gravity (COG) location:

$\mathrm{COG}_m = \sum(m_i \times l_i) / \sum m_i$ (3.21)

where i = 1, 2, 3…. total number of members (studs, plates, headers, etc.) in the m^{th} panel

$\sum (m_j \times \text{member } x\text{-coordinate } l_i) = 1{,}201.495$ lb•ft

$\sum m_i = 119.252$ lb

$\mathrm{COG}_1 = 10.075$ ft

The information from multi-panel #1 for drill location calculation is listed in Table 4.10.

Table 4.10 Sample multi-panel information (3)

Sub-wall ID ($_m$)	Sub-wall start-point x-coordinate (XSWS_m)	COG	Drill Number	Spreader Beam length
1	0.000	10.075	2	10
2	21.687	8.612	2	10

The drill location (XD_i), which is calculated according to the methodology, is shown as follows:

Drills #1 and #2

Known values:

Sub-wall ID = 1

$\mathrm{COG}_1 = 10.075$ ft

After substituting the known values for the following equations, the result for the optimized drill location x-coordinate is accessible.

Optimized drill hole location:

$$\mathrm{XD}_i = XSWS_m + COG_m + (-1)^i \times Spreader\ Beam\ length/2 \quad (4.22)$$

$XD_1 = 0 + 10.075 - (-1)^1 \times 10/2 = 5.075$ ft.

$XD_2 = 0 + 10.075 - (-1)^2 \times 10/2 = 15.075$ ft.

The *x*-coordinates for drill holes in multi-panel #1 are listed in Table 4.11 and Figure 4.11.

Table 4.11 Drill location coordinates

Drill ID (i)	Drill distance from home position (XDi)
1	5.075
2	15.075
3	25.299
4	35.299

**Since there is no drill distance from home position falling within the "no drill" range, all the above drill tasks can be done by machine.*

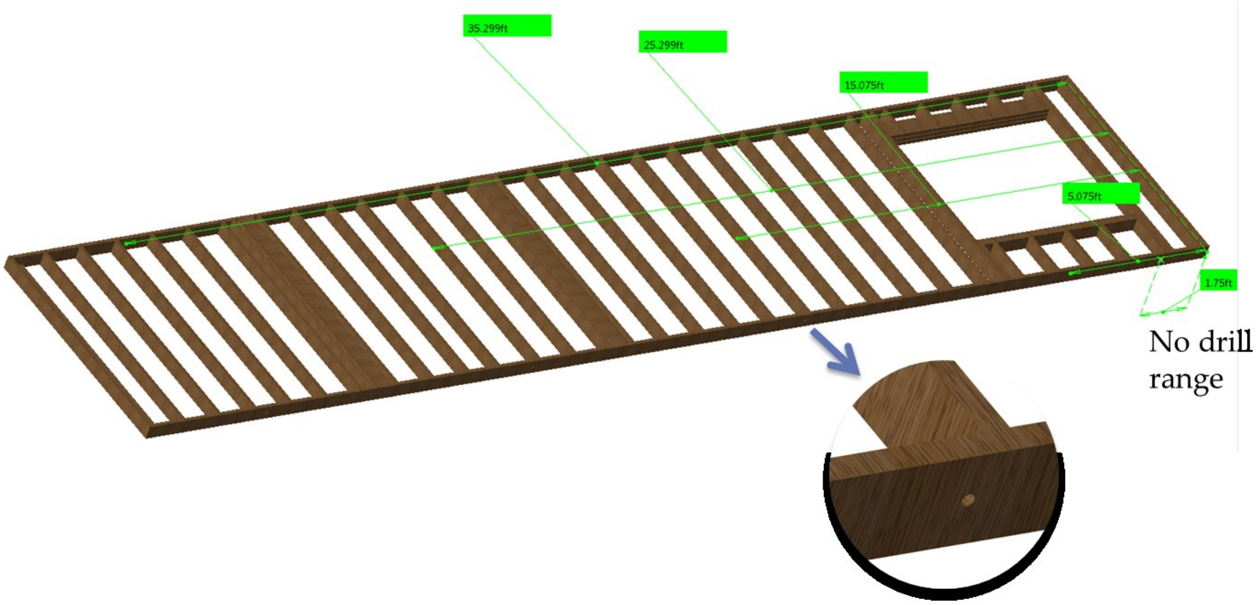


Figure 4.11: Drill locations for sample multi-panel #1

4.3.3.1 Checking for drill hole and stud location interference

For checking the drill and stud location interference, the range can be calculated as follows:

stud #1

Known values:

$j = k = 1$

Stud dimension (2×6 type) $b = 0.125$, $d = 0.4583$

$X_1 = 0.0625$ ft

Maximum drill radius = 1″ = 0.08333 ft

Substituting the known value to the following equations:

$$VSLBT_j = X_j - \tfrac{1}{2}b \tag{3.25}$$

$$VSRBT_j = X_j + \tfrac{1}{2}b \tag{3.26}$$

$$VSLBT_j - R \le XD_i \le VSRBT_j + R \tag{3.28}$$

If drill hole *x*-coordinate < the single-panel COG *x*-coordinate:

$$XD_i = XD_i + 1'' \tag{3.29}$$

Otherwise:

$$XD_i = XD_i - 1'' \tag{3.30}$$

$$VSLBT_1 = VSLBB_1 = 0.0625 - \tfrac{1}{2} \times 0.125 = 0$$

$$VSRBT_1 = VSRBB_1 = 0.0625 + \tfrac{1}{2} \times 0.125 = 0.125$$

$$0 - 0.083333 \le XD_i \le 0.125 + 0.083333$$

Since no drill hole is within these stud ranges, the drill hole location does not need to be adjusted for stud 1. The remaining stud location ranges are calculated and used to check whether or not any drill locations fall within the range specified in Appendix G. Since in the sample multi-panel there is no drill hole location falling within the defined stud range, the drill hole location can remain the same. If a drill location is located within the defined stud range, the drill hole location must move by a distance of 1″ in a direction based on the location of the hole on the multi-panel until it is outside the stud range.

4.4 Wood wall-framing machine motion planning

Based on the operation locations, the sequences of motion for four stations and the nailing gun moving plan can be determined for the purpose of ensuring that the multi-panel will be manufactured completely and smoothly by the wood wall-framing machine.

4.4.1 Calculation of operation locations

Since all the operation locations are calculated based on the home position of multi-panel #1 from section 4.3, the operation locations must be subtracted from the wood wall-framing machine location in order to obtain the actual distance from the operation point to the machine location. The first top-plate nail, first drill, and first cut are used as examples to show the operation locations related to their machine location.

Constant values:

Nailing machine location D_n = ¾″ = 0.0625 ft

Drilling machine location D_d = 21″ = 1.7500 ft

Cutting machine location D_c = 37″ = 3.0833 ft

Known values:

$XT1_1$ = 0.0625 ft, $XB1_1$ = 0.0625 ft, XC_1 = 21.6040 ft, XD_1 = 5.0375 ft

Substituting the known value to the following equations:

$D_i = XD_i - D_d$ (3.40)

$C_c = X_c - D_c$ (3.41)

$NT_n = XTj_n - D_n$ (3.42)

$$NB_n = XBj_n - D_n \qquad (3.43)$$

$$D_1 = 5.0375 - 1.75 = 3.2875 \text{ ft}$$

$$C_1 = 21.604 - 3.0833 = 18.5210 \text{ ft}$$

$$NT_n = 0.0625 - 0.0625 = 0 \text{ ft}$$

$$NB_n = 0.0625 - 0.0625 = 0 \text{ ft}$$

All the multi-panel operation distances are generated and sorted from smallest to largest, and are listed in Table 4.12.

Table 4.12 Multi-panel operation in relation to machine location distance and manufacturing sequences

Operation	*x*-coordinate	Relative to machine location distance
Nail Both 1	0.063	0.000
Nail Both 2	0.271	0.208
Nail Both 3	1.318	1.255
Nail Bottom 1	1.443	1.380
Nail Both 4	1.568	1.505
Nail Both 5	2.938	2.875
Drilling 1	5.075	3.325
Nail Both 6	4.271	4.208
Nail Both 7	5.604	5.542
Nail Both 8	6.938	6.875
Nail Both 9	7.432	7.370
Nail Bottom 2	7.557	7.495
Nail Both 10	7.682	7.620
Nail Both 11	8.271	8.208
Nail Both 12	9.604	9.542
Nail Both 13	10.938	10.875
Nail Both 14	12.271	12.208
Drilling 2	15.075	13.325
Nail Both 15	13.604	13.542
Nail Both 16	14.938	14.875
Nail Both 17	16.271	16.208
Nail Both 22	21.326	21.264
Nail Both 23	21.542	21.479
Nail Both 24	21.750	21.688
Nail Both 25	21.965	21.903
Nail Both 26	22.118	22.056
Nail Both 27	22.406	22.344
Drilling 3	25.299	23.549
Nail Both 28	23.740	23.677
Nail Both 29	25.073	25.010
Nail Both 30	26.594	26.531
Nail Both 31	27.740	27.677
Nail Both 32	29.073	29.010
Nail Both 33	30.406	30.344
Nail Both 34	30.767	30.705
Nail Both 35	30.920	30.858
Nail Both 36	31.135	31.073
Nail Both 37	31.354	31.292
Nail Both 38	31.740	31.677
Nail Both 39	33.073	33.010
Drilling 4	35.299	33.549
Nail Both 40	34.406	34.344

Nail Both 18	17.604	17.542	Nail Both 41	35.740	35.677
Cut 1	21.604	18.521	Cut 3	39.739	36.656
Cut 2	21.687	18.604	Nail Both 42	37.073	37.010
Nail Both 19	18.938	18.875	Nail Both 43	38.406	38.344
Nail Both 20	20.271	20.208	Nail Both 44	39.677	39.615
Nail Both 21	21.174	21.111			

4.4.2 Movement of dragging jaws

Dragging jaws are employed with moving the multi-panel from one operation to the next. The results generated from section 4.4.1 are the multi-panel assembly sequence and relative distances for machine operations. The difference value between each relative distance is the movement distance of the dragging jaws. Since the first movement distance of dragging jaws is zero, the second distance in the sequence is used as an example as follows.

Second dragging jaw movement distance:

Known values:

$X_1 = 0$ ft, $X_2 = 0.208$ ft

Substituting the known value to the following equation:

$$Dw_a = X_i - X_{i-1} \qquad (3.39)$$

where:

$i = 1, 2, 3 \ldots$ total number of machine operations

$Dw_2 = 0.208 - 0 = 0.208$ ft

All whole multi-panel dragging jaw movement distances are generated as expressed in Table 4.13.

Table 4.13 Multi-panel dragging jaw movement

Operation	Relative to machine location distance	Dragging jaw movement distance	Operation	Relative to machine location distance	Dragging jaw movement distance
Nail Both 1	0.000	0.000	Nail Both 22	21.264	0.153
Nail Both 2	0.208	0.208	Nail Both 23	21.479	0.215
Nail Both 3	1.255	1.047	Nail Both 24	21.688	0.209
Nail Bottom 1	1.380	0.125	Nail Both 25	21.903	0.215
Nail Both 4	1.505	0.125	Nail Both 26	22.056	0.153
Nail Both 5	2.875	1.370	Nail Both 27	22.344	0.288
Drilling 1	3.325	0.450	Drilling 3	23.549	1.205
Nail Both 6	4.208	0.883	Nail Both 28	23.677	0.128
Nail Both 7	5.542	1.334	Nail Both 29	25.010	1.333
Nail Both 8	6.875	1.333	Nail Both 30	26.531	1.521
Nail Both 9	7.370	0.495	Nail Both 31	27.677	1.146
Nail Bottom 2	7.495	0.125	Nail Both 32	29.010	1.333
Nail Both 10	7.620	0.125	Nail Both 33	30.344	1.334
Nail Both 11	8.208	0.588	Nail Both 34	30.705	0.361
Nail Both 12	9.542	1.334	Nail Both 35	30.858	0.153
Nail Both 13	10.875	1.333	Nail Both 36	31.073	0.215
Nail Both 14	12.208	1.333	Nail Both 37	31.292	0.219
Drilling 2	13.325	1.117	Nail Both 38	31.677	0.385
Nail Both 15	13.542	0.217	Nail Both 39	33.010	1.333
Nail Both 16	14.875	1.333	Drilling 4	33.549	0.539
Nail Both 17	16.208	1.333	Nail Both 40	34.344	0.795
Nail Both 18	17.542	1.334	Nail Both 41	35.677	1.333
Cut 1	18.521	0.979	Cut 3	36.656	0.979
Cut 2	18.604	0.083	Nail Both 42	37.010	0.354
Nail Both 19	18.875	0.271	Nail Both 43	38.344	1.334
Nail Both 20	20.208	1.333	Nail Both 44	39.615	1.271
Nail Both 21	21.111	0.903			

4.4.3 Nailing gun motion planning

The nailing gun *y*-coordinate (Z_0) is ¾″. As described in section 3.4.2, the relative nail location will be calculated to match the nailing gun coordinate axis. The axis difference between the relative *y*-coordinate and the absolute coordinate of the multi-panel is half the stud width. Using the first top-plate nail as an example, the nailing gun motion can be demonstrated as follows:

Constant values:

Stud $j = 1$

Nailing gun location $Z_0 = 3/4'' = 0.0625$ ft

2×6 vertical Stud width $d = 0.4583$ ft

Known values:

Number of nails on stud $NTj = NBk = 2$

$ZT1_1 = -0.076$ ft

$ZT1_2 = 0.076$ ft

Substituting the known value to the following equations:

$$ZTRj_n = ZTj_n + 1/2d \tag{3.44}$$

For vertical stud:

First nail:

$$M_n = ZTRj_1 - Z_o \tag{3.45}$$

Remaining nail:

$$M_n = ZTRj_n - ZTRj_{n-1} \tag{3.46}$$

$ZTR1_1 = -0.076 + ½ \times 0.4583 = 0.1532$ ft

$ZTR1_2 = 0.076 + ½ \times 0.4583 = 0.3052$ ft

First nail:

$M_1 = 0.1532 - 0.0625 = 0.0907$ ft

Remaining nail:

$M_2 = 0.3052 - 0.1532 = 0.152$ ft

The nailing gun *y*-direction motion for each nail is shown in Table 4.14.

Table 4.14 Sample nailing gun motion plan

Top-plate							Bottom-plate						
j	**Number of nails**	**No.**	**X**	**Y**	**Relative Z**	**Nailing gun motion**	**k**	**Number of nails**	**No.**	**X**	**Y**	**Relative Z**	**Nailing gun motion**
1	2	1	0.0625	−0.0764	0.152750	0.09025	1	2	1	0.0625	−0.0764	0.152750	0.09025
		2	0.0625	0.0764	0.305550	0.15280			2	0.0625	0.0764	0.305550	0.15280
2	2	1	0.2708	−0.0764	0.152750	0.09025	2	2	1	0.2708	−0.0764	0.152750	0.09025
		2	0.2708	0.0764	0.305550	0.15280			2	0.2708	0.0764	0.305550	0.15280
3	2	1	1.3177	−0.0764	0.152750	0.09025	3	2	1	1.3177	−0.0764	0.152750	0.09025
		2	1.3177	0.0764	0.305550	0.15280			2	1.3177	0.0764	0.305550	0.15280
							4	2	1	1.4427	−0.0764	0.152750	−0.15280
									2	1.4427	0.0764	0.305550	0.15280
…							…						
21	2	1	21.1740	−0.1667	0.062483	0.00000	23	2	1	21.1740	−0.1667	0.062483	0.00000
		2	21.3260	−0.1667	0.062483	0.00000			2	21.3260	−0.1667	0.062483	0.00000
22	2	1	21.5420	−0.0760	0.153150	0.09065	24	2	1	21.5420	−0.0764	0.152750	0.09025
		2	21.5420	0.0764	0.305550	0.15240			2	21.5420	0.0764	0.305550	0.15280

4.5 Simulation model

Exterior wall multi-panels from section 4.2.2 are used as examples to analyze the cycle time of the multi-panel manufacturing process. Table 4.15 is extracted from the BIM model, which indicates details of the multi-panels such as the number of doors and windows.

Table 4.15 Exterior multi-panel information for simulation model

Multi-Panel	Type	Length	Window	Door	Cut	Drill hole	Stud	Wall	Nails	Header nail
1	EXT	39.656	1	0	2	4	33	2	118	0
2	EXT	39.354	1	2	3	6	40	3	112	3

3	EXT	35.552	2	0	4	8	50	4	120	10
4	EXT	38.510	2	0	2	4	47	2	94	0
5	EXT	38.750	1	0	3	6	42	3	92	4
6	EXT	24.220	1	0	2	4	31	2	78	8

The simulation model is run one hundred times, and Figure 4.12 shows the cumulative density function of the total duration for the manufacturing of external panels. The duration to produce all 6 multi-panels ranges from 58.04 to 111.54 minutes, with a mean value of 81.91 minutes. The cycle time of the nail station is shown in Figure 4.13. The cycle time ranges from 4.61 to 15.37 minutes with a mean value of 8.58 minutes. The simulation result for average cycle time for each station is presented in Table 4.15.

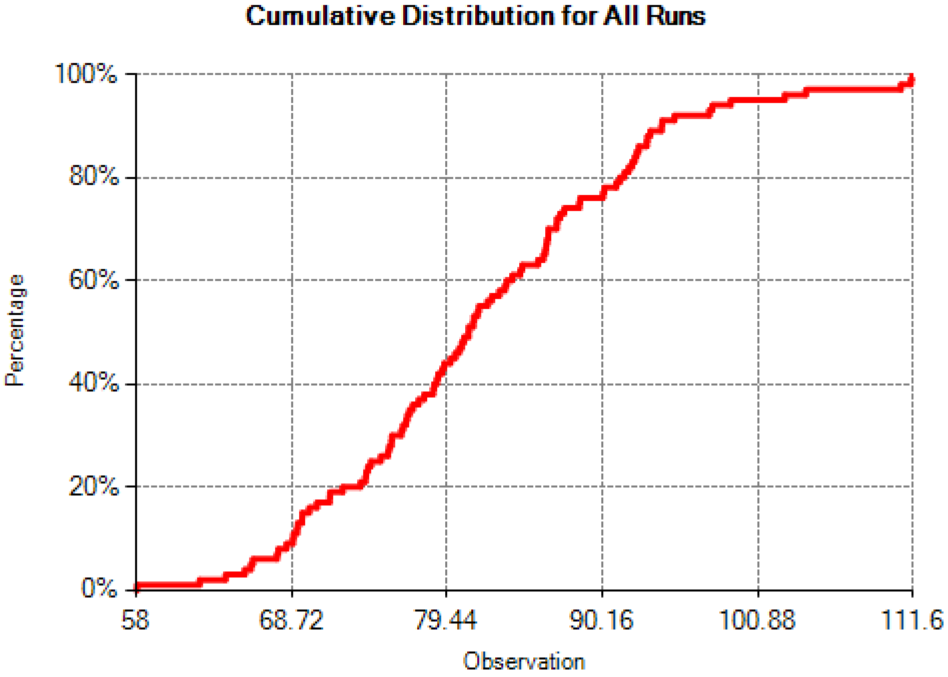


Figure 4.12: Cumulative distribution function of the manufacturing of external multi-panels

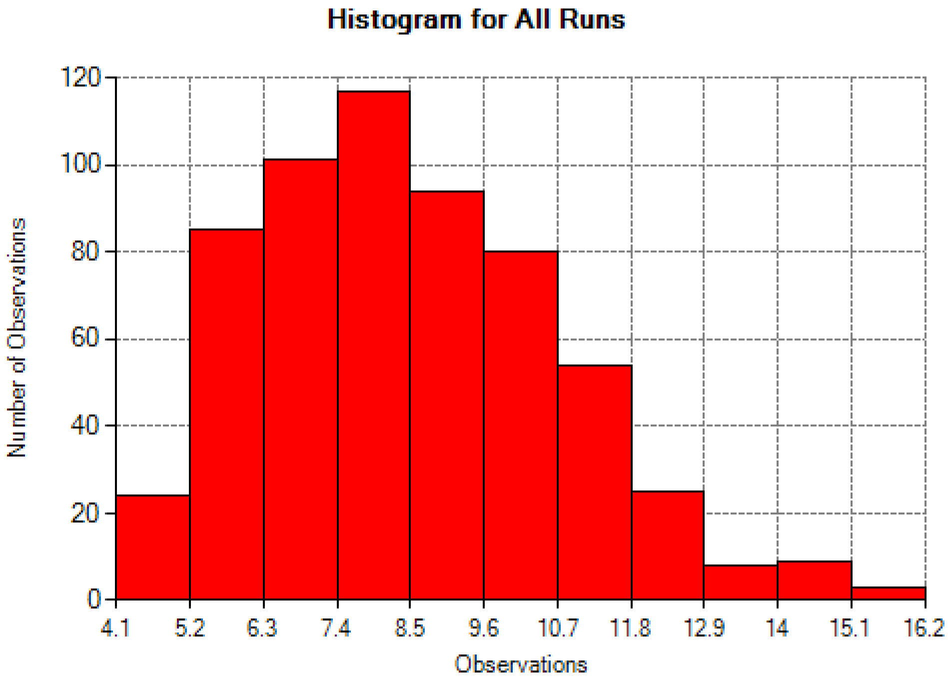


Figure 4.13: Cycle time for nail station

Table 4.16 Simulation results

Station	Mean cycle time (minutes)
Nail	8.4900
Drill	0.5091
Cutting	0.3288

The simulation model can be modified to analyze different production scenarios and estimate the production duration of the panel (Altaf et al. 2015). By evaluating and comparing the performance with company current status, the company can determine the feasibility of purchasing the automatic machinery.

Chapter 5 Conclusion

5.1 General conclusion

This research has been motivated by the necessity to improve the current panel manufacturing process, which is time-consuming, costly, and error-prone. This thesis provides proper panel assembly guideline information and wood-framing machinery to implement the process of industrialized manufacturing of wood panels. The challenge in improving the home building panel manufacturing system is the high customization level in home models and styles. Therefore, the panel manufacturing process should be broken down into the operation of each station (feeding, nailing, cutting, and drilling) in order to facilitate a higher level of customizability. The next step is analyzing operation location information from the BIM model using an algorithm to generate a database for automated operation locations, a process which will solve the problem of high dependency on skilled carpenters to assemble the panels, and thus will save time and increase accuracy. The wood-framing machine is developed to implement automatic panel assembly. The logic describing the steps of operation for each station is defined. The evaluation of the system is discussed by way of a simulation model. The task times of each station are used to develop a task time regression model, integrated with each operation number extracted from the BIM model, and a simulation model is developed to present the process time of automated panel manufacturing. A home building company can utilize the simulation model as a reference to decide whether or not to implement automation on their production line. Therefore, the final outputs are (1) improved multi-panel combination plans; (2) an extension of BIM-integrated panel information such as nail, cut, and drill locations; (3) wood wall-framing machine manufacturing logic; and (4) a decision-making support system that integrates panel information with simulation.

5.2 Research contributions

The contributions of this research can be summarized as follows:

- Optimizing panel combinations gives a clear-cut location for machinery; it not only decreases the material waste but also increases the downstream process productivity.
- Identifying panel design properties, formulating each operation location generation, and developing a guideline for panel assembly all facilitate the reduction in dependency on experience of the carpenter and reduce the risk of human error by enabling efficient information exchange between Revit and Microsoft Excel.
- Bridging the gap between manufacturing and drafting, providing a complete solution from the BIM model to manufacturing.
- Developing a discrete-event simulation model in order to enhance the decision-making process by analyzing the panel manufacturing cycle time; thus aiding industrial companies in determining the feasibility of replacing their manual assembly tools for an automatic manufacturing production line.

5.3 Research limitations

This research is subject to the following limitations:

- Machine models, based on factories with facility assembly lines similar to the machine in this research, have been used as the time study to develop the production simulation models for the multi-panel framing capabilities of this machine. Due to dynamic changes of production lines, the times for task processing also change accordingly; therefore, the regression model for predicting task times may be affected.

- The wood wall framing machine is designed based on rectangular panels, any special angle wall panels cannot be assembled.

5.4 Future research

The research methodology serves as a foundation of automated panel manufacturing. The following areas may require further research:

- After a wood wall-framing machine prototype is developed, the task times can be estimated based on the prototype. The comparison between estimating task times based on the existing factory and those based on the wood wall-framing machine prototype can be investigated.
- Based on the logic of the operation locations and procedures, a program will be developed in the .NET API in order to generate computer numerical control (CNC) code in Revit which can be readily input into the machinery.

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Appendices

A. Exterior wall pool

Structural Framing Schedule				Wall Schedule	
BIMSF_Container	BIMSF_Description	Length (ft)	Type	Wall type	Mark
M1E	TBOT	21.604	2×6	Exterior Wall - 6″	M1E
M2E	TBOT	13.333	2×6	Exterior Wall - 6″	M2E
M3E	TBOT	12.479	2×6	Exterior Wall - 6″	M3E
M4E	TBOT	5.000	2×6	Exterior Wall - 6″	M4E
M5E	TBOT	7.000	2×6	Exterior Wall - 6″	M5E
M6E	TBOT	11.521	2×6	Exterior Wall - 6″	M6E
M7E	TBOT	18.052	2×6	Exterior Wall - 6″	M7E
M8E	TBOT	19.021	2×6	Exterior Wall - 6″	M8E
S1E	TBOT	13.885	2×6	Exterior Wall - 6″	S1E
S2E	TBOT	20.594	2×6	Exterior Wall - 6″	S2E
S3E	TBOT	12.252	2×6	Exterior Wall - 6″	S3E
S4E	TBOT	4.760	2×6	Exterior Wall - 6″	S4E
S5E	TBOT	6.552	2×6	Exterior Wall - 6″	S5E
S6E	TBOT	11.885	2×6	Exterior Wall - 6″	S6E
S7E	TBOT	17.833	2×6	Exterior Wall - 6″	S7E
S8E	TBOT	19.938	2×6	Exterior Wall - 6″	S8E

A1. Exterior main floor wall pool

Structural Framing Schedule				Wall Schedule	
BIMSF_Container	BIMSF_Description	Length (ft)	Type	Wall type	Mark
M1E	TBOT	21.604	2×6	Exterior Wall - 6″	M1E
M2E	TBOT	13.333	2×6	Exterior Wall - 6″	M2E
M3E	TBOT	12.479	2×6	Exterior Wall - 6″	M3E
M4E	TBOT	5.000	2×6	Exterior Wall - 6″	M4E
M5E	TBOT	7.000	2×6	Exterior Wall - 6″	M5E
M6E	TBOT	11.521	2×6	Exterior Wall - 6″	M6E
M7E	TBOT	18.052	2×6	Exterior Wall - 6″	M7E
M8E	TBOT	19.021	2×6	Exterior Wall - 6″	M8E

A2. Exterior second floor wall pool

Structural Framing Schedule				Wall Schedule	
BIMSF_Container	BIMSF_Description	Length (ft)	Type	Wall type	Mark
S1E	TBOT	13.885	2×6	Exterior Wall - 6″	S1E

S2E	TBOT	20.594	2×6	Exterior Wall - 6″	S2E
S3E	TBOT	12.252	2×6	Exterior Wall - 6″	S3E
S4E	TBOT	4.760	2×6	Exterior Wall - 6″	S4E
S5E	TBOT	6.552	2×6	Exterior Wall - 6″	S5E
S6E	TBOT	11.885	2×6	Exterior Wall - 6″	S6E
S7E	TBOT	17.833	2×6	Exterior Wall - 6″	S7E
S8E	TBOT	19.938	2×6	Exterior Wall - 6″	S8E

B. Interior 3 ½″ wall pool

Structural Framing Schedule				Wall Schedule	
BIMSF_Container	BIMSF_Description	Length (ft)	Type	Wall type	Mark
M1I	TBOT	5.010	2×4	Interior Wall - 3 ½″	M1I
M2I	TBOT	5.469	2×4	Interior Wall - 3 ½″	M2I
M4I	TBOT	8.667	2×4	Interior Wall - 3 ½″	M4I
M5I	TBOT	3.677	2×4	Interior Wall - 3 ½″	M5I
M6I	TBOT	5.167	2×4	Interior Wall - 3 ½″	M6I
M7I	TBOT	2.708	2×4	Interior Wall - 3 ½″	M7I
M8I	TBOT	4.125	2×4	Interior Wall - 3 ½″	M8I
M9I	TBOT	7.802	2×4	Interior Wall - 3 ½″	M9I
M10I	TBOT	6.302	2×4	Interior Wall - 3 ½″	M10I
M12I	TBOT	6.302	2×4	Interior Wall - 3 ½″	M12I
M13I	TBOT	5.510	2×4	Interior Wall - 3 ½″	M13I
S1I	TBOT	20.594	2×4	Interior Wall - 3 ½″	S1I
S3I	TBOT	9.427	2×4	Interior Wall - 3 ½″	S3I
S4I	TBOT	2.000	2×4	Interior Wall - 3 ½″	S4I
S5I	TBOT	9.427	2×4	Interior Wall - 3 ½″	S5I
S6I	TBOT	5.498	2×4	Interior Wall - 3 ½″	S6I
S7I	TBOT	2.167	2×4	Interior Wall - 3 ½″	S7I
S8I	TBOT	13.500	2×4	Interior Wall - 3 ½″	S8I
S9I	TBOT	2.167	2×4	Interior Wall - 3 ½″	S9I
S10I	TBOT	5.990	2×4	Interior Wall - 3 ½″	S10I
S11I	TBOT	3.313	2×4	Interior Wall - 3 ½″	S11I
S12I	TBOT	9.719	2×4	Interior Wall - 3 ½″	S12I
S13IA	TBOT	2.344	2×4	Interior Wall - 3 ½″	S13IA
S13IB	TBOT	2.167	2×4	Interior Wall - 3 ½″	S13IB
S14I	TBOT	4.896	2×4	Interior Wall - 3 ½″	S14I

B1. Interior 3 ½″ main floor wall pool

Structural Framing Schedule				Wall Schedule	
BIMSF_Container	BIMSF_Description	Length	Type	Wall type	Mark

		(ft)			
M1I	TBOT	5.010	2×4	Interior Wall - 3½″	M1I
M2I	TBOT	5.469	2×4	Interior Wall - 3½″	M2I
M4I	TBOT	8.667	2×4	Interior Wall - 3½″	M4I
M5I	TBOT	3.677	2×4	Interior Wall - 3½″	M5I
M6I	TBOT	5.167	2×4	Interior Wall - 3½″	M6I
M7I	TBOT	2.708	2×4	Interior Wall - 3½″	M7I
M8I	TBOT	4.125	2×4	Interior Wall - 3½″	M8I
M9I	TBOT	7.802	2×4	Interior Wall - 3½″	M9I
M10I	TBOT	6.302	2×4	Interior Wall - 3½″	M10I
M12I	TBOT	6.302	2×4	Interior Wall - 3½″	M12I
M13I	TBOT	5.510	2×4	Interior Wall - 3½″	M13I

B2. Interior 3 ½″ second floor wall pool

Structural Framing Schedule				Wall Schedule	
BIMSF_Container	BIMSF_Description	Length (ft)	Type	Wall type	Mark
S1I	TBOT	20.594	2×4	Interior Wall - 3½″	S1I
S3I	TBOT	9.427	2×4	Interior Wall - 3½″	S3I
S4I	TBOT	2.000	2×4	Interior Wall - 3½″	S4I
S5I	TBOT	9.427	2×4	Interior Wall - 3½″	S5I
S6I	TBOT	5.498	2×4	Interior Wall - 3½″	S6I
S7I	TBOT	2.167	2×4	Interior Wall - 3½″	S7I
S8I	TBOT	13.500	2×4	Interior Wall - 3½″	S8I
S9I	TBOT	2.167	2×4	Interior Wall - 3½″	S9I
S10I	TBOT	5.990	2×4	Interior Wall - 3½″	S10I
S11I	TBOT	3.313	2×4	Interior Wall - 3½″	S11I
S12I	TBOT	9.719	2×4	Interior Wall - 3½″	S12I
S13IA	TBOT	2.344	2×4	Interior Wall - 3½″	S13IA
S13IB	TBOT	2.167	2×4	Interior Wall - 3½″	S13IB
S14I	TBOT	4.896	2×4	Interior Wall - 3½″	S14I

C. Interior 5 ½″ wall pool

Structural Framing Schedule				Wall Schedule	
BIMSF_Container	BIMSF_Description	Length (ft)	Type	Wall type	Mark
M11I	TBOT	5.625	2×6	Interior Wall - 5½″	M11I
M14I	TBOT	3.000	2×6	Interior Wall - 5½″	M14I
S15I	TBOT	9.448	2×6	Interior Wall - 5½″	S15I

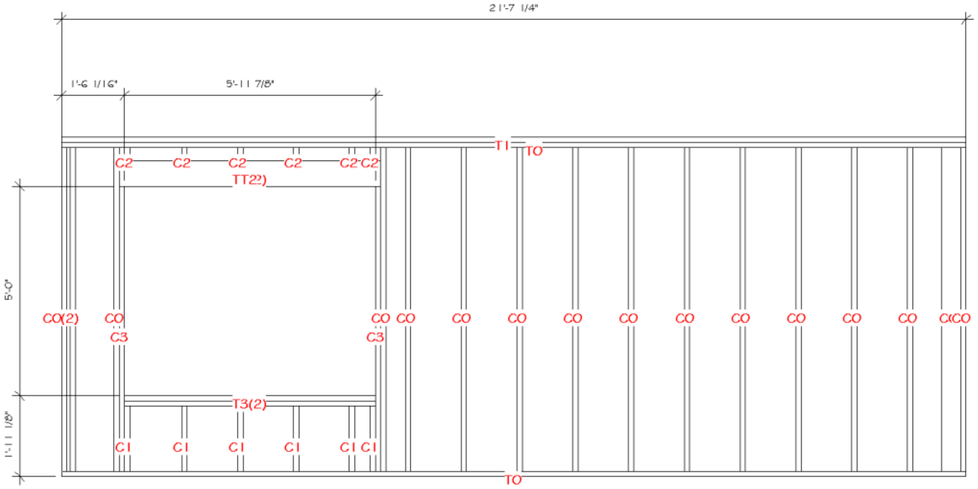
C1. Interior 5 ½″ main floor wall pool

Structural Framing Schedule				Wall Schedule	
BIMSF_Container	BIMSF_Description	Length (ft)	Type	Wall type	Mark
M11I	TBOT	5.625	2×6	Interior Wall - 5½″	M11I
M14I	TBOT	3.000	2×6	Interior Wall - 5½″	M14I

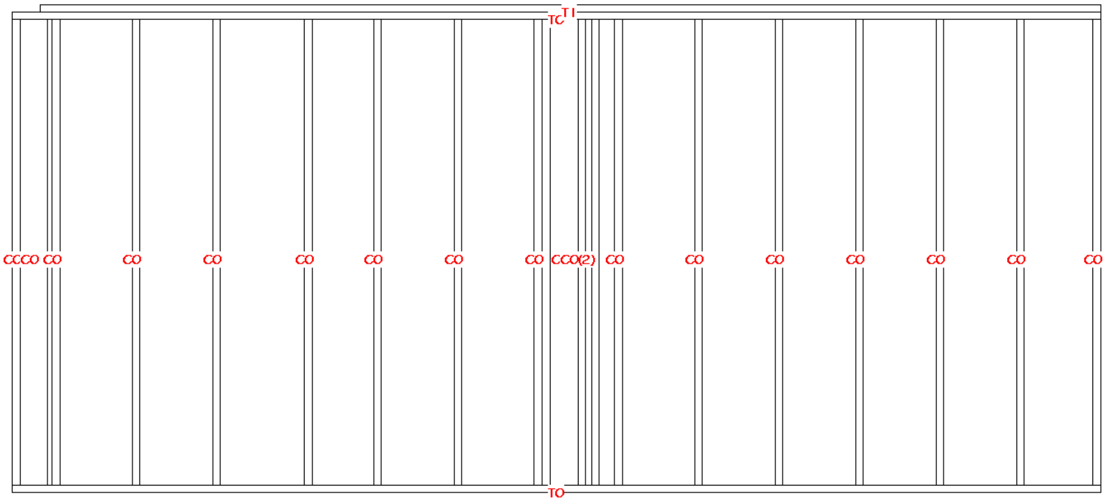
C2. Interior 5 ½″ second floor wall pool

Structural Framing Schedule				Wall Schedule	
BIMSF_Container	BIMSF_Description	Length (ft)	Type	Wall type	Mark
S15I	TBOT	9.448	2×6	Interior Wall - 5½″	S15I

D. M1E framing



E. M7E framing



F. COG calculation for M1E

Name	Function	Multi-panel *x*-coordinate	Weight (lb)
M1E	OC	0.063	3.790
M1E	OC	0.271	3.790
M1E	King	1.318	3.790
M1E	Jack	1.443	3.340
M1E	Cripple	1.568	0.153
M1E	Cripple	1.568	0.762
M1E	Cripple	2.938	0.153
M1E	Cripple	2.938	0.762
M1E	Cripple	4.271	0.762
M1E	Cripple	4.271	0.153
M1E	Cripple	5.604	0.153
M1E	Cripple	5.604	0.762
M1E	Cripple	6.938	0.762
M1E	Cripple	6.938	0.153
M1E	Cripple	7.432	0.153
M1E	Cripple	7.432	0.762
M1E	Jack	7.557	3.340
M1E	King	7.682	3.790
M1E	OC	8.271	3.790
M1E	OC	9.604	3.790
M1E	OC	10.938	3.790
M1E	OC	12.271	3.790

Name	Function	Multi-panel *x*-coordinate	Weight (lb)
M1E	OC	13.604	3.790
M1E	OC	14.938	3.790
M1E	OC	16.271	3.790
M1E	OC	17.604	3.790
M1E	OC	18.938	3.790
M1E	OC	20.271	3.790
M1E	SJoin	21.250	3.790
M1E	OC	21.542	3.790
M1E	Bottom-plate	10.802	10.608
M1E	Top-plate	10.802	10.383
M1E	Top-plate	10.802	10.383
M1E	T2	4.500	3.062
M1E	T2	4.500	3.062
M1E	T2	4.500	3.062
M1E	T3	4.500	2.941
M1E	T3	4.500	2.941
		Total weight	119.252
		member weight *x* member *x*-coordinate	1,201.50
		COG *x*-coordinate	10.075

G. Drill and stud location interference checking

Multi-panel *x*-coordinate	j	HSLB+T	HSLBT-R	HSRBT	HSRBT+R	k	HSLBB	HSLBB–R	HSRBB	HSRBB+R	Check for drill 1	Check for drill 2	Check for drill 3	Check for drill 4
0.06250	1	0.00	–0.08	0.13	0.04	1	0.00	–0.08	0.13	0.04	FALSE	FALSE	FALSE	FALSE
0.27083	2	0.21	0.13	0.33	0.25	2	0.21	0.13	0.33	0.25	FALSE	FALSE	FALSE	FALSE
1.31771	3	1.26	1.17	1.38	1.30	3	1.26	1.17	1.38	1.30	FALSE	FALSE	FALSE	FALSE
1.44271	4	1.38	1.30	1.51	1.42	4	1.38	1.30	1.51	1.42	FALSE	FALSE	FALSE	FALSE
1.56771		1.51	1.42	1.63	1.55						FALSE	FALSE	FALSE	FALSE
1.56771						5	1.51	1.42	1.63	1.55	FALSE	FALSE	FALSE	FALSE
2.93750	5	2.88	2.79	3.00	2.92						FALSE	FALSE	FALSE	FALSE
2.93750						6	2.88	2.79	3.00	2.92	FALSE	FALSE	FALSE	FALSE
4.27083						7	4.21	4.13	4.33	4.25	FALSE	FALSE	FALSE	FALSE
4.27083	6	4.21	4.13	4.33	4.25						FALSE	FALSE	FALSE	FALSE
5.60417	7	5.54	5.46	5.67	5.58						FALSE	FALSE	FALSE	FALSE
5.60417						8	5.54	5.46	5.67	5.58	FALSE	FALSE	FALSE	FALSE
6.93750						9	6.88	6.79	7.00	6.92	FALSE	FALSE	FALSE	FALSE
6.93750	8	6.88	6.79	7.00	6.92						FALSE	FALSE	FALSE	FALSE
7.43229	9	7.37	7.29	7.49	7.41						FALSE	FALSE	FALSE	FALSE
7.43229						10	7.37	7.29	7.49	7.41	FALSE	FALSE	FALSE	FALSE
7.55729						11	7.49	7.41	7.62	7.54	FALSE	FALSE	FALSE	FALSE
7.68229	10	7.62	7.54	7.74	7.66	12	7.62	7.54	7.74	7.66	FALSE	FALSE	FALSE	FALSE
8.27083	11	8.21	8.13	8.33	8.25	13	8.21	8.13	8.33	8.25	FALSE	FALSE	FALSE	FALSE
9.60417	12	9.54	9.46	9.67	9.58	14	9.54	9.46	9.67	9.58	FALSE	FALSE	FALSE	FALSE
10.93750	13	10.88	10.79	11.00	10.92	15	10.88	10.79	11.00	10.92	FALSE	FALSE	FALSE	FALSE
12.27083	14	12.21	12.13	12.33	12.25	16	12.21	12.13	12.33	12.25	FALSE	FALSE	FALSE	FALSE

13.60417	15	13.54	13.46	13.67	13.58	17	13.54	13.46	13.67	13.58	FALSE	FALSE	FALSE	FALSE
14.93750	16	14.88	14.79	15.00	14.92	18	14.88	14.79	15.00	14.92	FALSE	FALSE	FALSE	FALSE
16.27083	17	16.21	16.13	16.33	16.25	19	16.21	16.13	16.33	16.25	FALSE	FALSE	FALSE	FALSE
17.60417	18	17.54	17.46	17.67	17.58	20	17.54	17.46	17.67	17.58	FALSE	FALSE	FALSE	FALSE
18.93750	19	18.88	18.79	19.00	18.92	21	18.88	18.79	19.00	18.92	FALSE	FALSE	FALSE	FALSE
20.27083	20	20.21	20.13	20.33	20.25	22	20.21	20.13	20.33	20.25	FALSE	FALSE	FALSE	FALSE
21.25000	21	21.02	20.94	21.48	21.40	23	21.02	20.94	21.48	21.40	FALSE	FALSE	FALSE	FALSE
21.54167	22	21.48	21.40	21.60	21.52	24	21.48	21.40	21.60	21.52	FALSE	FALSE	FALSE	FALSE
21.75000	23	21.69	21.60	21.81	21.73	25	21.69	21.60	21.81	21.73	FALSE	FALSE	FALSE	FALSE
22.04167	24	21.81	21.73	22.27	22.19	26	21.81	21.73	22.27	22.19	FALSE	FALSE	FALSE	FALSE
22.40625	25	22.34	22.26	22.47	22.39	27	22.34	22.26	22.47	22.39	FALSE	FALSE	FALSE	FALSE
23.73959	26	23.68	23.59	23.80	23.72	28	23.68	23.59	23.80	23.72	FALSE	FALSE	FALSE	FALSE
25.07292	27	25.01	24.93	25.14	25.05	29	25.01	24.93	25.14	25.05	FALSE	FALSE	FALSE	FALSE
26.59375	28	26.53	26.45	26.66	26.57	30	26.53	26.45	26.66	26.57	FALSE	FALSE	FALSE	FALSE
27.73959	29	27.68	27.59	27.80	27.72	31	27.68	27.59	27.80	27.72	FALSE	FALSE	FALSE	FALSE
29.07292	30	29.01	28.93	29.14	29.05	32	29.01	28.93	29.14	29.05	FALSE	FALSE	FALSE	FALSE
30.40625	31	30.34	30.26	30.47	30.39	33	30.34	30.26	30.47	30.39	FALSE	FALSE	FALSE	FALSE
30.84375	32	30.61	30.53	31.07	30.99	34	30.61	30.53	31.07	30.99	FALSE	FALSE	FALSE	FALSE
31.13542	33	31.07	30.99	31.20	31.11	35	31.07	30.99	31.20	31.11	FALSE	FALSE	FALSE	FALSE
31.35420	34	31.29	31.21	31.42	31.33	36	31.29	31.21	31.42	31.33	FALSE	FALSE	FALSE	FALSE
31.73959	35	31.68	31.59	31.80	31.72	37	31.68	31.59	31.80	31.72	FALSE	FALSE	FALSE	FALSE
33.07292	36	33.01	32.93	33.14	33.05	38	33.01	32.93	33.14	33.05	FALSE	FALSE	FALSE	FALSE
34.40625	37	34.34	34.26	34.47	34.39	39	34.34	34.26	34.47	34.39	FALSE	FALSE	FALSE	FALSE
35.73959	38	35.68	35.59	35.80	35.72	40	35.68	35.59	35.80	35.72	FALSE	FALSE	FALSE	FALSE
37.07292	39	37.01	36.93	37.14	37.05	41	37.01	36.93	37.14	37.05	FALSE	FALSE	FALSE	FALSE
38.40625	40	38.34	38.26	38.47	38.39	42	38.34	38.26	38.47	38.39	FALSE	FALSE	FALSE	FALSE
39.67709	41	39.61	39.53	39.74	39.66	43	39.61	39.53	39.74	39.66	FALSE	FALSE	FALSE	FALSE