Residential construction manufacturing estimating framework: the case of lightweight timber framing

By

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Abstract

The term industrialized construction was adopted by the offsite construction industry where the building components are prefabricated in factories and then transported to the construction site for on-site assembly. With this shift towards industrialized construction, new challenges were encountered, especially in terms of accommodating the constraints of the machinery and verifying the manufacturability of a project. Despite these challenges, as the buildings are completed by the automated machines in the production lines, it is now feasible to estimate the production time and the associated cost with a higher level of accuracy. Additionally, as applications of building information modelling (BIM) are being increasingly employed in industrialized construction, a significant benefit is gained in terms of data sharing and transformation between the phases of a project. In this research, a framework for a BIM-based automated system is developed with the aim of linking the 3D BIM models with the automated machines used on the production lines to check the manufacturability of the building components depending on the machines' limitations. Additionally, the proposed automated system generates the computer numerical control (CNC) codes, which are required to manufacture these components, directly from the BIM environment, which eliminates the need for third-party tools to generate the CNC codes. To generate accurate and detailed production duration estimates, the physical and geometric information of the building, such as the dimensions of the structural elements, is used along with the motion of the moving parts of a machine in order to calculate the speed and distance each part travels in each cycle to complete the production tasks required to manufacture the building. The developed production estimation system can also calculate the life-usage of each part in the machine in order to support the maintenance scheduling process. The developed framework is implemented within the

Autodesk Revit environment. A case study of a residential building is used to implement the proposed approach and demonstrate its features.

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Chapter 1 : Introduction

1.1 Background and motivation

Offsite construction has been proven to be an effective construction method to produce affordable housing as it minimizes the effect of weather conditions while providing a safer working environment to produce higher-quality housing. The term industrialized construction refers to implementing mechanization and manufacturing techniques in the field of offsite construction to produce highly efficient and affordable buildings by producing modular building components in a controlled offsite manufacturing facility and shipping them to the site for assembly. Modular construction can speed up construction time by 50% and reduce the associated costs by 20%, and, by 2030, it is estimated modular construction will represent $130 billion of the construction market in the US and Europe with a $22 billion annual cost saving (Nick et al. 2019). Automation systems have been widely used in the industrialized construction sector to pursue productivity improvements, which accomplishes time savings and labour savings as well as increases to the efficiency of the produced units. Industrialized construction is recognized as the future practice with significant potential associated with it. Nevertheless, the growth of modular construction around the world still encounters multiple barriers and challenges. Various of these factors were addressed by a questionnaire conducted by Salama et al. (2018): The questionnaire was addressed to modular construction professionals, and the results show that 63.6% of the respondents indicated that one of the barriers to increasing the market share of modular construction is the lack of academic research that highlights the benefits of modular construction. Additionally, 45.5% of respondents thought that there is a lack of available data to support the decision-making process and encouraged modular and academic institutions to publish more studies regarding the advantages of modular construction.

In the present research regarding the utilization of building information modelling (BIM) to support automation systems used in industrialized construction, a BIM-based estimation and control system is developed to serve as a direct connection between the design phase and the production phase of modular projects. The developed system uses the information extracted from the BIM models, the automated machine's characteristics, the logic of operations of the machines, and the machine's limitations to check the ability of the automated machines to manufacture a project and then it is possible to make changes to the project's design accordingly. The developed system also delivers accurate production time estimation based on the machine's motion and the geometric information of the project. Furthermore, the developed system generates the required computer numerical control (CNC) codes for the automated machines directly from the BIM environment. The research deliverables including the CNC codes generation and the production time estimation, are crucial in the decision-making process, as they provide a clear understanding of the project's requirements, such as the ability to manufacture the project using the available resources, and the duration it would take to be produced. The developed system is implemented in the Autodesk Revit environment for the case of an automated wood-framing machine. A construction project that consists of a set of modular shaped townhouses in a residential complex is utilized as a case study to test the implementation of the developed system and illustrate its potential.

1.2 Research objectives

This research focuses on the fabrication phase of the automated industrialized construction sector. The main scope of the research emphasizes the connection between the design and the production stages by establishing an integrated environment that comprises the physical and geometric information of a project and the production line configurations and limitation. This connection can provide essential decision-making information related to the manufacturability and compatibility check of the project and accurately estimate the production time. The objectives of this research are outlined as follows:

a) Developing a BIM-based system for the industrialized residential construction industry to serve as a direct connection method between the design and production phases of a project and the production lines.
b) Developing a detailed automated production estimation system that is able to forecast the fabrication time of the model's components with a high level of accuracy based on the logic analysis of the automated machines and on the type and purpose of each of its components.
c) Checking the manufacturability of a product promptly in the design phase based on the machine's specifications and the sequence of operation along with the product's geometric information.
d) Generating the readable computer numerical control (CNC) files to be used by the machines directly from the BIM environment without any dependence on third-party computer-aided manufacturing (CAM) software.
e) Developing a maintenance prediction and scheduling system for the automated machines based on the life expectancy of the machines' parts.

1.3 Thesis organization

This thesis is organized into five chapters starting with the introduction in Chapter 1, which introduces the topic and research objective and provides an overview of the study. Chapter 2 provides a literature review covering the related studies and applications involving the history of manufacturing, BIM applications in offsite construction, productivity measurements and improvements using simulation, automation, and computer-aided design (CAD) applications in industrialized construction, production scheduling, and cost estimation in manufacturing. Chapter 3 comprises an overview of the proposed research methodology with a detailed explanation of each proposed objective and the procedures used to achieve it. Chapter 4 includes an implementation of the proposed system in a case study of an automated machine and a residential construction project. Finally, Chapter 5 covers the general conclusion of the proposed research, along with research contributions and limitations.

Chapter 2 : Literature review

2.1 Overview

This chapter reviews the previous research studies related to the following areas. Presented first is the history of industrialization in construction, including literature on the most common techniques of construction industrialization, and a comparison between traditional and industrialized construction methods. The second area of focus emphasizes the use of building information modelling (BIM) technology in industrialized manufacturing. The third area explores the previous studies on production process improvement using discrete-event simulation (DES), where simulation models are used to predict and improve performance along with improving the process flow and the resource allocation of the production lines. Next, the fourth area explored in the literature is the use of automation and computer-aided design (CAD) in manufacturing. Finally, the literature regarding cost estimation and scheduling techniques in manufacturing and regarding the integration of CAD and computer-aided manufacturing (CAM) with BIM is explored.

2.2 History of manufacturing in construction

The idea of mechanization and industrialization of construction was inspired by engineers from the car manufacturing industry that depended on the standard production line developed by Henry Ford after the first industrial revolution in the 20th century (Giles 2008). The main goal was to produce affordable housing and increase the efficiency of the construction process by applying the concept of standardization of components and by applying the prefabrication approach by working in factory conditions that are not affected by weather fluctuations (Generalova et al. 2016). Another primary goal was to encourage manufacturing since it accounts for 30% or more of the total economy in many countries (Steenhuis 2017). As the automotive industry continued to improve throughout the 20th century, industrialized construction adopted many techniques from it. The main and most important effect came from adopting the concept of lean production, which combined the advantages from the previous production methods, while also reducing the cost and the rigidity of these methods (Crowley 1998). All the prior improvements of manufacturing opened the gate to the field of construction manufacturing and increased the popularity of offsite factory-based housing around the world, especially in order to increase the efficiency of work in countries where weather conditions have a significant effect on the construction productivity, such as Canada and the United States (BC Housing 2014; Howes 2002; Siggner, Rebecca & Yamashita 2006).

2.2.1 Offsite manufacturing and on-site construction

Around the world, offsite manufacturing has garnered an increasing amount of interest for being a more efficient method compared to traditional construction and for representing an increasing proportion of the construction industry (Pan et al. 2008). However, some home builders still find it difficult to take up the idea since there are some barriers along with the manufacturing advantages, including their incorrect belief that offsite manufacturing is more expensive than the regular on-site method, which is the main reason behind the slow increase in adopting offsite construction and leads to a negative stigma associated with this approach (Concordia University and the Modular Building Institute 2015; Goodier and Gibb 2005). Some of these misconceptions are simply built on construction organizations' inaccurate comparisons between the two methods; for example, according to a survey conducted by Goodier and Gibb (2005) of 75 UK construction organizations including clients, designers, contractors, and offsite suppliers and manufacturers, 77% of contractor respondents and 67% of client/designer respondents thought that offsite manufacturing is more expensive than traditional construction because they are not taking into account the advantages due to the reduction of on-site construction time. Comparative research was conducted by Pan and Sidwell (2011) between four different construction methods, including a pre-cast concrete panel fabrication, in-situ reinforced concrete frame, steel frame, and temper frame. The authors' objective was to address and demystify the cost barriers to offsite construction in the UK, and their research revealed multiple findings that should encourage construction builders to adopt the offsite construction approach as the most effective way of building by making a comparison between the traditional methods and offsite construction in term of capital and life cost. However, many other comparison studies between conventional construction and offsite manufacturing have stated that manufacturing is actually ahead of traditional construction when it comes to the cost of housing, sustainability, energy consumption, waste reduction, environmental effect and work environment (Altaf et al. 2018; Goodier and Gibb 2007; NAHB Research Center 2002; Siggner et al. 2006).

2.2.2 Modular and panelized construction

The prefabrication construction industry is divided into two main types: modular and panelized construction (Lopez and Froese 2016). Modular housing (Figure 2-1) is defined by Siggner et al. (2006) as "housing that is partially built in a plant, shipped to a development site, and placed on a foundation, where the roof structure and exterior finishes are completed." Panelized housing (Figure 2-2), on the other hand, can be defined as "a method where the building is subdivided into basic planar elements that are typically constructed under some form of mass production then shipped directly to the construction site and assembled into the finished structure" (NAHB Research Center 2002). Each prefabrication method has its own characteristics, but the advantages of both methods are similar: time-efficient, high quality, more sustainable, and cost-efficient (Siggner, Rebecca & Yamashita 2006). In Canada, 15.6% of all single-family homes built in 2015 were prefabricated homes, with a total number of 15,734 prefabricated units in that year (CMHI

2016). In 2011, almost two-thirds of prefabricated single-detached homes were small-sized units with an average square footage of 1,225 (BC Housing 2014).

Figure 2-1 Modular housing

Figure 2-2 Panelized housing

2.3 BIM technology in offsite construction

The use of BIM in the construction field has been gradually increasing since the first development of the technology, making it one of the most promising computer tools in the construction, engineering, and manufacturing fields because of its vast abilities and various usages as a modelling and planning tool (Azhar et al. 2008). The advantages that can be gained from the use of BIM in construction are a mixture of performance enhancement, productivity improvement, waste reduction, and manufacturing cost reduction (Diaz 2016). Ho et al. (2013) proposed a BIM-based knowledge sharing management (BIMKSM) system to be used by managers and project engineers to improve the communication and feedback processes between them and the job site engineers. The system was applied in a case study and was proven to be a visual BIM-based knowledge sharing management platform, which is considered an application of BIM technology in the construction market. From another perspective, Kerosuo et al. (2015) investigated the challenges associated with the expansive use of BIM in construction projects, and according to the authors, the use of BIM can lead to many difficulties and problems between the client, designers, construction site managers, and the operations managers. For example, the integration of the models using BIM can lead to some difficulty in solving design errors, changes during construction and maintenance may not be updated in the BIM model, and the BIM technology may be accessible to the construction site manager only but not to the workers. Rojas et al. (2019) developed a BIM use assessment (BUS) tool to evaluate the level of implementation of the existing uses of BIM in the planning and design phases of construction projects. The tool helps to realize higher benefits from BIM technologies when they are applied in the earliest stages of the projects. Abdelhameed (2017) used BIM to evaluate the sustainability of the architectural designs by analyzing the performance of the model after the design is completed, along with all the components and material details. BIM technology has also been widely used in industrialized construction. Bu Hamdan et al. (2017) developed a BIM-based simulation model to facilitate inventory management and planning in panelized construction. BIM was primarily used to build a model that serves as the source of accurate information and also provides information about the non-panelized elements (concrete elements, earthwork quantities, etc.); this information is then used to feed the simulation model. Bonenberg et al. (2019) discussed the applications of BIM technology in prefabrication and modular buildings and proposed a case study of a prefabricated building that showed BIM technology can be a valuable tool to use in the prefabrication and modular industry through most of a project's phases, in particular by using the technology in terms of component visualization, optimizing the site layout, managing the progress of the project, and improving the design efficiency. A BIM platform for on-site assembly services in prefabricated construction was proposed by Li et al. (2018) that employed BIM in concert with radio-frequency identification (RFID) and global positioning system (GPS) to develop the internet of things (IoT) platform to integrate the information delivered from the various stages of manufacturing and to synchronize the location information of prefabricated components.

2.4 Production productivity measurement and improvement

2.4.1 Definition of productivity

With the rapid increase in the rate of adoption of offsite construction methods as an efficient method of construction, manufacturing organizations were forced to continuously seek improvements in their production processes in order to reduce operational costs and increase productivity (Dozzi and AbouRizk 1993), which was defined by Dozzi and AbouRizk (1993) in their book as the ratio of input/output. Productivity can be translated in the construction field as labour productivity, which is the physical progress the labour achieves per unit of time, often called the person-hour (p-h). Hill (2017), on the other hand, defined productivity as the ratio of what is produced to what is required to produce it. Jan van Ree (2003) refers to productivity as the ratio of the actual result of the process to the actual resources used for it.

2.4.2 Productivity improvement using simulation

As manufacturing organizations started to seek improvements in their production processes, researchers started to put a significant amount of effort towards monitoring and improving the production plants, along with investigating the ideal resource allocation for each type of manufacturing, and the simulation approach was adopted by the researchers as one of the best tools to achieve these goals (AbouRizk 2010). Using the simulation approach facilitates an examination of the suggested production solutions to find their potential benefits before implementing them in the real world, and simulation is capable of predicting and evaluating different scenarios (Vern and Gunal 1998). There are many simulation-based tools, one of which is Simphony.NET that was developed by AbouRizk et al. (2016), which is a complete computer system environment that offers the ability to model the simulation and analyze the results in both discrete events and continuous simulation approaches. AbouRizk and Hajjar (2011) discussed the application of simulation in construction by developing a framework to model a special purpose simulation (SPS), which they defined as "a computer-based environment built to enable a practitioner who is knowledgeable in given domain, but necessarily in simulation, to model a project within that domain in a manner where symbolic representations, navigation schemes within the framework, creation of model specifications, and reporting are completed in a format native to the domain itself". Vern and Gunal (1998) proposed a new construction environment for which simulation could be used, construction element manufacturing: the authors recommended simulation as a tool to re-examine the existing process and resource allocation in order to find better solutions and increase the productivity. Shi (1997) used activity cycle diagrams (ACD) to model the construction processes, considering the activities of the processes as the basic elements of the simulation, because each construction process is a collection of activities and it would be more accurate to consider the activities as the modelling elements instead of the process itself. Lu (2003) presented a new simplified discrete-event simulation approach (SDESA) with the hopes of simplifying construction simulation. Ritter et al. (2017) developed a DES model to investigate the practicality of multiple proposed methodologies in a wall panel fabrication line in a modular home manufacturing facility in order to provide potential production improvements. Garza-Reyes et al. (2012) used DES in their research to improve the production plan of a mobile home production line and balance the workload between the stations of the production line and improve the processes flow. Moghadam et al. (2014) proposed a post-simulation visualization (PSV) that gives the ability to investigate problems that the simulation model is not able to detect in order to improve the production of modular construction manufacturing. Mohsen et al. (2018) used DES to model the floor operations at a cabinet manufacturing facility where different scenarios have been investigated for potential improvements. Altaf et al. (2016) presented an online simulation model of a prefabricated wall panel production line that uses an RFID system with the aim of providing real-time simulation results of the proposed workload to the production control system. An integrated production plan and control system for panelized home prefabrication facility using simulation and RFID was presented by Altaf (2016) in their research in which they used the RFID system to collect real-time production data and used this data as a starting point to build a clean database for the simulation model afterwards. The data is collected using RFID readers that read the codes on the RFID tags on each panel as it flows through the production line and collects the production durations on each station along the line. Liu et al. (2015) developed a special purpose simulation template integrated with BIM with the aim of improving productivity and balancing the production line by suggesting the proper production sequencing.

2.5 Automation and computer-aided applications in industrialized construction

2.5.1 Automation of design and planning

In the prefabricated buildings industry, Retik and Warszawski (1994) developed the first automated design system in the modular and prefabricated structures field. The system proposed a fabrication plan by dividing the building structure into prefabricated parts based on a modular grid. Ostrowska-Wawryniuk and Krzysztof (2018) developed a BIM-based automation tool that can analyze an input BIM model along with the prefabrication constraints and the design parameters in order to convert the design of the building from the traditional technology into a prefabricated one, the process' workflow is shown in Figure 2-3 (Ostrowska-Wawryniuk and Krzysztof 2018):

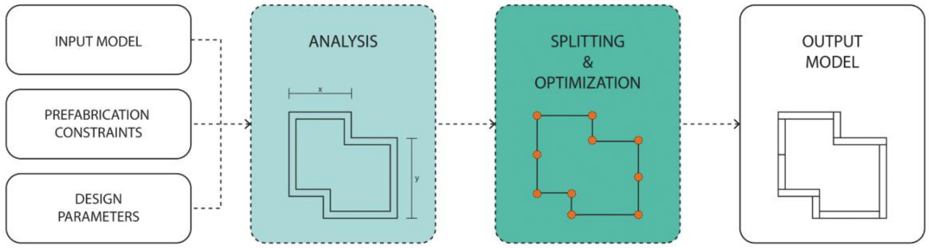


Figure 2-3 Model conversion process workflow.

Controlling the production flow by introducing new automated machines can help minimize the cost of fabrication and reduce the generated waste and increase the efficiency and utilization of the machine (Boucher 1996). With the aim of reaching this goal, Liu et al. (2018) proposed an automated BIM-based tool that generates designs and planning solutions that minimize waste based on the design rules integrated with mathematical algorithms. The main objective of the tool is to automate the boarding design and minimize the cutting material waste by running a cutting-stock optimizer that will propose the cutting plan for the boarding. Alwisy et al. (2019) introduced a systematic methodology that automates the process of design and drafting for the manufacturing of wood-framed panels for modular residential buildings by utilizing the 2D CAD designs to automatically generate a BIM model. The proposed tool was developed using VBA in a CAD environment and depended on specific criteria to produce the design model, including the model dimensions, available equipment, walls priority rules, and constructability. Another automation planning approach in the industrialized construction industry was presented by Iturralde and Bock (2018), who investigated the integration of automated and robotic processes for building upgrading with prefabricated modules. The authors developed a process that automates the customization, the manufacturing, and the installation processes of the modules. The main objective was to reduce the overall project time as the current on-site installation phase generates excessive re-work after the modules are placed and fixed onto the existing building façade. The proposed solution relies on parametric software based on a visual programming language (VPL).

2.5.2 Automation of prefabrication in offsite construction

The adoption of industrialized construction as a new advanced factory production method aims to fulfill the demands of construction projects such as reducing the construction period, reducing the cost, along with increasing the accuracy and building quality (Zhang et al. 2016). The initial implementation of this new construction approach reflected many aspects of the auto manufacturing industry, especially the reliance on automated systems, and was able to satisfy the demand of housing in multiple regions worldwide in an affordable, efficient manner (Howes 2002). The implementation of the automation and robotics techniques in all the construction type sectors—masonry, pre-cast concrete, timber, and steel prefabrication—started to grow and expanded from the use of small machines into fully automated CNC machines that are able to handle most of the operations required and eliminate as much as possible of the manual work (Bock 2007). This transformation led to a high productivity increase and labour cost reduction of up to 40%, along with providing a continuous working time through the year in spite of what would be negative working conditions outdoors (Bock 2007). The main structure of a building is comprised of different components related to each other geometrically, and the prefabrication of these components using the automated approach starts by planning for assembly where the sequence of fabrication of these components should be investigated. The production sequence should take into consideration the constraints and properties of each component, and also the relationships between these components (Neelamkavil 2009). Bock (2015) explored the previous and current applications of automation in construction and proposed future opportunities for automation in the construction sector and indicated that the conventional construction methods had reached their peak, and the future of construction relies on automation technology as the most effective and convenient method. The author used an S-curves to illustrate the relation between conventional construction and the growth of automated strategies and technologies through time. The S-curve proposed by the author is shown in Figure 2-4, where BCM = building component manufacturing, LSP = large-scale prefabrication, STCRs = single-task construction robots, ROD = robot-oriented design, A/ROFs = automated robotic on-site factories, AD = automated deconstruction.

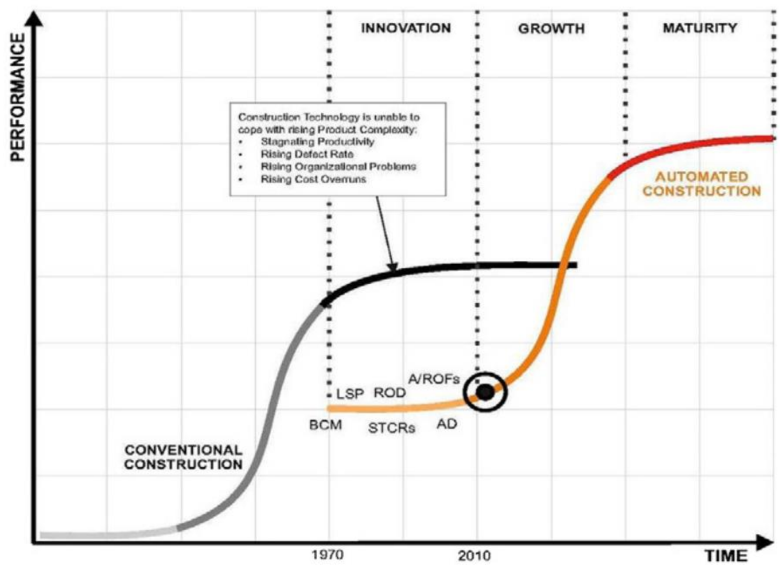


Figure 2-4 S-curves of construction methods performance. (Bock 2015)

2.5.3 CAD/CAM and computer numerical control (CNC)

With the development of numerical control (NC) and programmable automation, the applications of computers in manufacturing started to grow through the development of new computer-aided manufacturing (CAM) technologies that were highly dependent on computer-aided design (CAD) and computer numerical control (CNC) technologies. All of these technologies were primarily used by the operators to control, maintenance, and management of the fabrication process (Kumar et al. 2005). To achieve highly interconnected manufacturing systems, manufacturing companies constantly seek to develop new technologies to integrate their production facilities with their design and drafting systems. This is where the concept of integrated automation systems in manufacturing came from (Kumar et al. 2005). In their research, Wang et al. (2004) developed an intelligent web-based framework named Wise-ShopFloor. The framework is developed in an integrated sensor-driven collaborative environment where the machine operators and production engineers can distribute up-to-date production information through it. The main objective of this framework was to create a proper system with an open architecture for real-time monitoring and control of networked CNC machines. The author's framework aimed to meet both the user requirements for visualization sharing and the production constraints by implementing a list of solutions that included developing Java 3D models for better visualization, building a connection between the Java 3D models and the machines controllers (sensors/actuators), and developing a secure server for the control logic of the machines. The author's methodology was applied in a case study of a milling machine, and the feasibility and the future potential of this approach was proven. CNC programs are typically generated by computer-aided manufacturing (CAM) systems that use information from a computer-aided design (CAD) system. Xu and He (2004) investigated the integration of computer-aided process planning (CAPP), CAD, CAM, and CNC. According to the authors, most machines are programmed using the ISO 6983 "G/ M-code" language. However, this transformation system has many shortcomings that limit its practicality, such as the limited ability to utilize the useful information that is already available in the CAD/ CAM environment. These limitations led to the development of a new more effective standard for transferring data between CAD/CAM systems and CNC machines called "ISO 14649" or "STEP-NC". The STEP-NC data model includes information about the machining tasks (drilling, nailing, cutting, etc.), including "what" and "how" to do. This model can accept data from several sources like a

CAD/CAM system, libraries, or graphic user interface. Marriage and Sutherland (2014) presented a new digitalized construction approach that involves the utilization of CNC cutting machines for cross-laminated timber (CLT) building structures. The authors' research was oriented to providing a new construction method that is able to meet the high demand for rebuilding houses in a cost-effective, high quality, high speed, and affordable way. The substantial potential gain from the use of CNC cutting machines was investigated by the authors and was proven to increase the accuracy and building speed of the construction elements. Li (2016) investigated the development of a modular-based CNC machine for residential building wall framing with the objective of increasing the level of automation and flexibility. The author addressed the challenges facing this approach by studying current offsite construction practices while also gaining an understanding of the practiced wall framing techniques. The first objective of the author's research was to implement the idea of multi-panel optimization as part of the main research goal, the main process for this objective includes the application of a greedy optimization algorithm to rank and combine the wall components of a BIM model in a number of multi-panels that have a specific length in order to increase the utilization of downstream stations to reduced idle time, as was proven by Shafai (2012). The following flowchart in Figure 2-5 demonstrates the multi-panel optimization process.

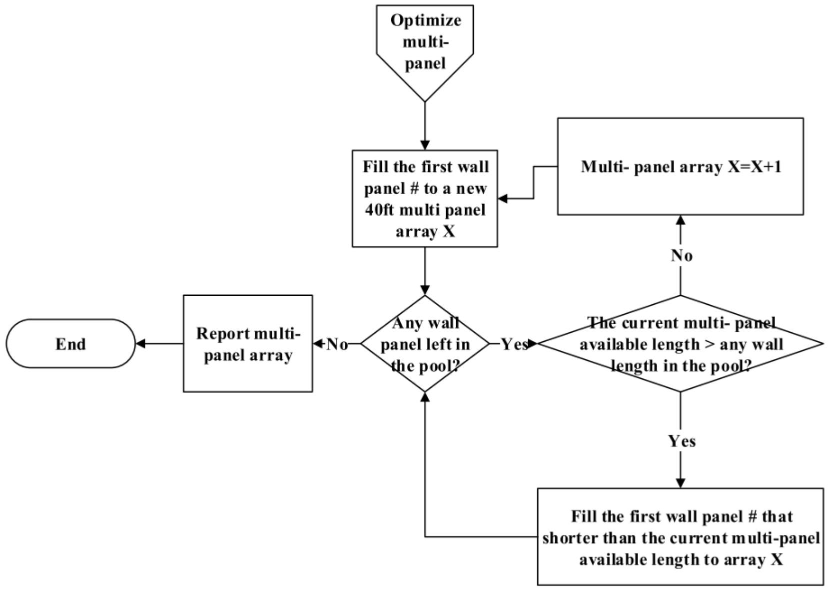


Figure 2-5 Flowchart for multi-panel optimization process (Li 2016).

The second objective of the author's research was to extract the information from the BIM model about the locations of the framing operations required for the multi-panels (nailing, drilling, and cutting). The author developed an algorithm to extract the geometric positions defined by the geometric coordinates of each operation needed on the multi-panel. The next step was to propose the preliminary design of the wood-framing machine and to plan for the machine motion where the machine's operations sequence is defined for each framing operation. The nailing operation schematic is shown in Figure 2-6. The previous research was followed by research on the development of a prototype BIM tool in the .NET API by Liu et al. (2017). The tool supports the same previously mentioned logic to generate the geometric locations of the framing operations after running the multi-panel optimization algorithm, and export the information as a CSV file that services as an input file for the CAM software in order to generate the CNC codes for the framing machine. The graphic user interface (GUI) of the prototyped system is presented in Figure 2-7.

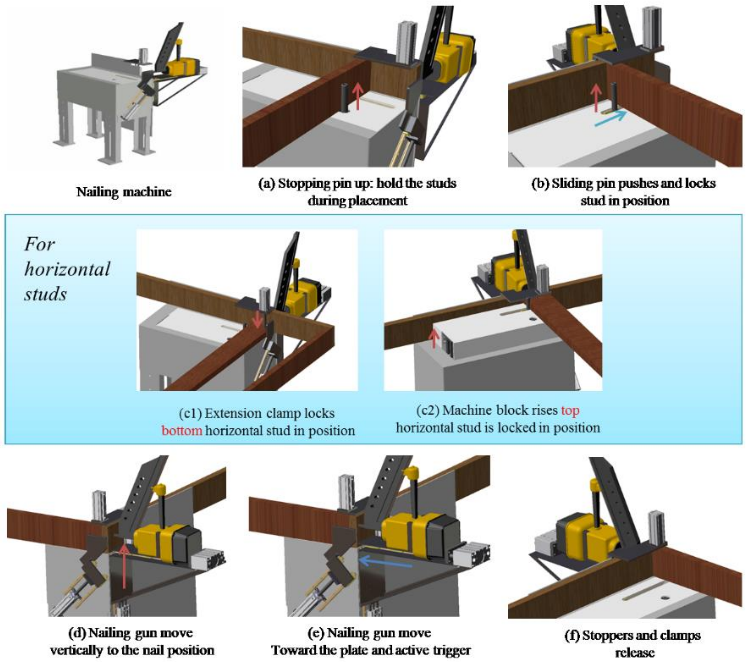


Figure 2-6 Nailing operation schematic (Li 2016)

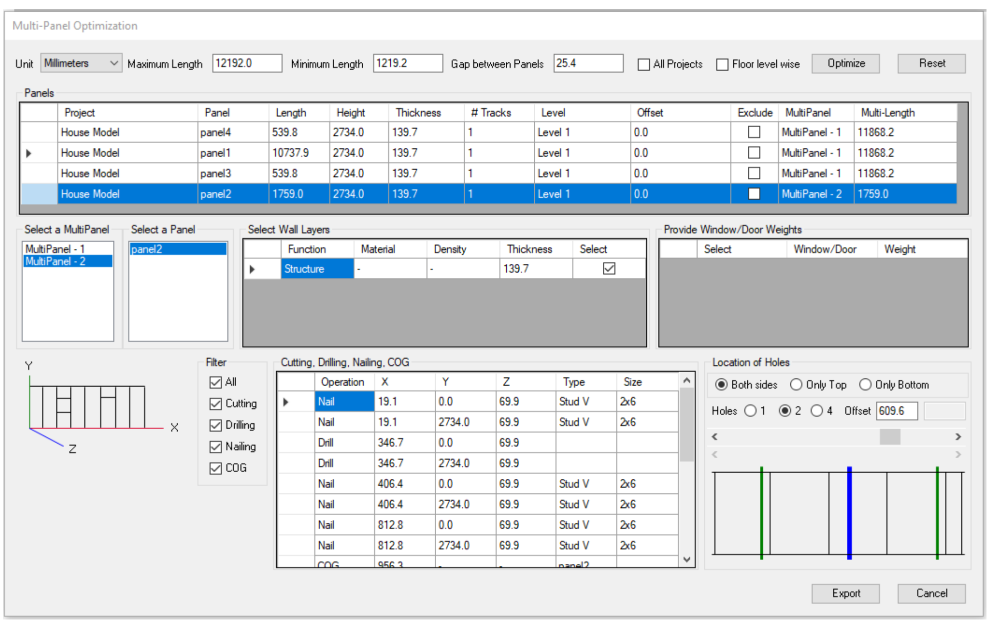


Figure 2-7 Graphic user interface of multi-wall panel designer (Liu et al. 2017)

Kremer (2018) introduced a new framework for mass timber construction (MTC), which is built on a concept called design for mass customized manufacture and assembly (DfMCMA) that aims to increase the efficiency of mass customization in MTC. The proposed framework includes two platforms: digital platforms, and stakeholder platforms. The author suggests that in the future, designers and engineers should have the ability to directly connect their work with the manufacturer who can continue the work by translating the design drawings into machine-readable drawings and CNC codes. Significant efficiency gains can be achieved by developing a new method for CNC operations generation directly from the BIM models. This direct transformation will eliminate the prerequisite of the CNC coding process and the generation of the shop drawing, which used to serve as the connecting element between the designed model and the CNC fabrication (Kremer 2018).

2.5.4 Manufacturability check

Even though the use of BIM brought several significant benefits to the manufacturing industry, multiple shortcomings persist, such as the direct connection between the BIM environment and the manufacturing base, which can serve as a decision support link to check the ability to manufacture a product (Yin et al. 2019). In their research, Martinez et al. (2019) proposed a vision-based system that aims to automate the pre-inspection of steel frame manufacturing. The system collects the required information using a camera installed on the automated framing machine and compares this information with the geometric data extracted from a BIM model of the frame. The implementation of the proposed framework provides real-time information about the manufacturing process and suggests corrections to it whenever needed. An et al. (2019) conducted research exploring the implementation of ontology-based knowledge modelling for frame assemblies manufacturing. The authors' approach aims to link the construction-oriented product assemblies with the manufacturing resources. The authors formed a relationship between the desired product and the manufacturing machines by implementing expert knowledge in defining the intersections between the surfaces of the product's elements in order to determine the location of the required operations to manufacture the product. The proposed framework was implemented in a case study of a wood-frame assembly. Additionally, with an objective to know whether a machine can manufacture a construction product, a BIM-based decision support system for automated manufacturability check of wood assemblies is proposed by An et al. (2020). The inputs of the developed system are the geometric information extracted from the BIM model of the construction project and the automated machine's specifications. The proposed system was developed in Python, and the exported data was used to generate the mating planes between the wooden panel elements in order to identify the positions of the operations, then the positioning of the operations is matched with the region of effect (ROE) of the machine to determine the machine's capability to perform the required job. Several factors can affect the ROE of the machine, which are summarized by the authors as belonging to two main categories: machine configurations, and machine logic, where the machine configurations are defined by the physical components of the machine, and the machine's logic is the sequence of operations the machines follow to perform the required job. However, the authors built their system based only on the machine configurations assuming that a machine's logic can easily be changed based on the operations needed to be performed. Another limitation of the authors' system is that it only accommodates nailing operations since the key factor in determining the positions of the operations is the intersection of two planes in the wooden frame, which excludes the ability to define the additional required framing operations including cutting and drilling.

2.6 Production scheduling in manufacturing

One of the many advantages of implementing manufacturing techniques comes from the ability to plan and schedule for production in a highly efficient way (Pan and Arif 2010). The history of production scheduling was addressed by Herrmann (2006) in his book chapter. Herrmann analyzes previous and current production scheduling systems and addresses the key problem in these systems in order to develop a piece of practical knowledge for researchers about the nature of the production scheduling process. According to the author, by the end of the 19^{th} century, and with the rise of the second industrial revolution, manufacturing companies adopted a method of mass production. This transformation of the production methods produced a new challenge for the production planners regarding the production scheduling process since the foremen could not handle it by themselves anymore. Computer-based production scheduling emerged during the third industrial revolution, where centralized computers were used to create a list that includes the tasks to be assigned to each work station depending on multiple factors including the processing time for each task, the due date, and the number of remaining operations (Herrmann 2006). Automation applications in the context of production schedule started in the early 21^{st} century, and the development of BIM technology played a significant role in adopting this approach of scheduling. Liu et al. (2014) presented an automated scheduling approach for the on-site assembly of prefabricated, panelized walls, and floors along with the panel erection sequence. The proposed method considers the geometric location of each component and the physical and structural connections with the other building structures. The authors implemented their approach in the Autodesk Revit environment using the application programming interface (API). The output generated from the developed API is exported to MS Project through XML in order to perform further modifications and execute the resource leveling required to manage the on-site resources. Another approach was investigated by Ajweh (2014) in his dissertation. The author applied lean principles along with DES to schedule the fabrication of wall panels and examined crew balancing in the production plant. Multiple scenarios were evaluated with the objective of increasing overall performance effectiveness. Altaf et al. (2014) investigated the use of particle swarm optimization (PSO) and DES to plan for the production sequencing of wood-framed wall panels. The authors' approach aimed to reduce the total production time of the wall panels by eliminating the manual work required for panel sequencing. A database was developed to connect a simulation model for the production plan with the wall panels' properties. The PSO is used to initially assign an optimized order for the panels, and then the sequence is updated following the results of the simulation model and using a heuristic tool called the smallest position value (SPV).

2.7 Cost estimation in manufacturing

Cost estimation during the project preparation stage is crucial for adequate cost management of the project, and current practice that depends on 2D documentation of this task is linked with a significant amount of mistakes and usually takes substantial time and effort to prepare (Vitásek and Zak 2018). BIM models are presented as a new more efficient way to accomplish cost estimation, but the existing developed models during the design stage of a project do not usually reflect all the features of the buildings that affect the cost estimation and only represent the components and the relations between them (Staub-French et al. 2003). Typically, the designers during this stage pay the most attention to the resistance of the buildings against applied forces, while they should also consider cost information in the design stage (Heinisuo et al. 2011). From the manufacturing perspective, cost estimation is also a critical process, and it can be done either after the product design or after a detail process plan is built, which requires the machining processes, machines, materials, machining parameters, cutting tools, and operation sequences to be selected in order to set up the processing plan (Jung 2002). Jung (2002) proposed a system for manufacturing cost estimation for repetitive manufacturing, and found that calculations of the cost depends on two main features, machining time and material cost, and is calculated satisfying Equation (1):

$$\text{Manufacturing cost} = (\mathrm{R_o} + \mathrm{R_m})\,(\frac{\mathrm{T}_{su}}{\mathrm{Q}}\ \mathrm{T}_{ot} + \mathrm{T}_{no}) + \text{material cost} + \text{factory expenses} \quad (1)$$

where $\mathrm{R_o}$ is the operator's rate (direct labour), Rm is the machine rate, T_{su} is the setup time, Q is the batch size, T_{ot} is the total operation time, and T_{no} is the total non-operation time. Shehab and Abdalla (2001) proposed a knowledge-based system in their research that is able to estimate the manufacturing cost of a product during the conceptual stage and generate a preliminary processing plan that specifies the machining processes and their parameters.

2.7.1 Automation of cost estimation

The growth of digitization helped significantly in decreasing the amount of the time required to obtain the quantities and the required measurements to be used by the cost estimators, and the availability of cost databases and the development of electronic drawings, which has become a standard in the industry, offer a wealth of information that can be used to help estimate the construction cost (Tong 2005). Ciceri et al. (2010) designed a tool that is able to estimate the material and manufacturing energy for a product based on the bill of material quantities and the processing sequence of the production as an input, but the tool has a low level of accuracy when it comes to estimating energy consumption since it generates a value range instead of an accurate number. Heinisuo et al. (2011) proposed a method for cost estimation, where a feature-based manufacturing cost estimation module is integrated with a commercial BIM program. This method aims to provide a suitable tool for manufacturing phase cost estimation based on a deep knowledge of the manufacturing process of the designed product. The study is limited to the manufacturing cost only without considering the costs of design, transportation, and assembly installation. Akanbi and Zhang (2017) proposed a method and algorithms for fully automated cost estimation in wood construction that can only generate the cost associated with the construction of the wall and without considering a detailed cost estimate breakdown per wall and cannot be used with any building component other than walls. Al-Mashta (2010) proposes a methodology to develop an integrated quantity take-off system with a relational database that has the aim of cost budgeting and cost estimation for building projects. The proposed model's required inputs are divided into two main requirements: the final project design, and the cost data for the unit of work to be performed. The author used Autodesk Revit to read the objects' geometrical information for use in the quantity take-off estimation.

2.7.2 Cost estimation in industrialized construction

The worldwide expansion of industrialized construction has met several major barriers that have not been studied in depth. One of the main barriers is the cost evaluation, which, even though it has been widely reported, has seldom been clearly defined (Goodier and Gibb 2007). Offsite construction has a significant number of variables that should be considered when evaluation or estimation of the product cost is required. These variables include the cost of capital, operation, materials, production, transportation, on-site assembly, and finishing (Smith et al. 2010). A framework for collecting whole life cost (WLC) data for the building industry was developed by El-Haram et al. (2002). The authors proposed a whole lifecycle breakdown data structure consisting of five levels of details, starting with the project level, phase level, category, elements, and tasks. For the first level, the project's whole life cost was broken down into phases along with the cost categories associated with each phase, as demonstrated in Figure 2-8, which is adapted from El-Haram et al. (2002).

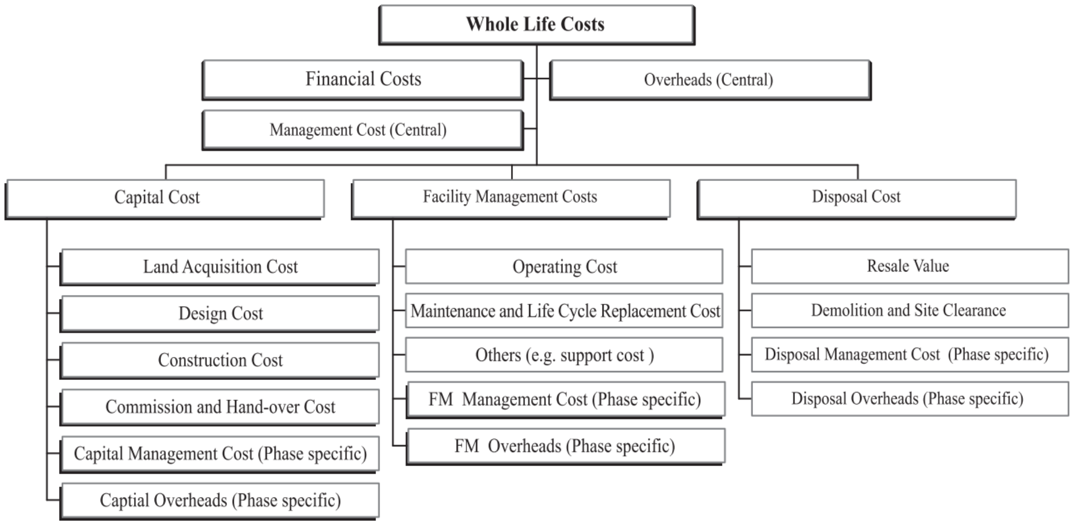


Figure 2-8 Breakdown structure of the cost of each phase of project

The next step proposed by the authors is to break down each cost category into its cost element in order to investigate the related costs in more detail, and then the costs of the elements are also broken down into the tasks and resources cost as the final level of the whole life cost of the project. Mao et al. (2016) adapted the framework formulated by the previous authors and implemented it in the case of offsite construction (OSC) in order to address the significant differences between traditional in-situ construction and OSC in terms of cost categories and elements through in-depth analysis on the OSC industry in China. The authors proposed enhancements to the whole life cost WLC breakdown developed by El-Haram et al. (2002) to include the special categories that differentiate between in-situ construction and OSC. Another approach was presented by Barkokebas et al. (2017) to coordinate cost estimation for wood-framed industrialized residential projects through the use of BIM, and the main objective of the research was to propose areas of improvement in the estimation process for a construction company in Canada using a BIM-based tool called Vico that is able to provide parametric estimation depending on the BIM model. The authors' methodology consists of two main phases. First, the parametric data related to the cost estimate is exported from the BIM model into a spreadsheet format in order to import it into the Vico environment along with the cost database of the company. In the second phase and within the estimation tool, cost estimating is performed, and the cost report is then generated. The authors claim that using this approach can result in a 90% level of automation of the cost estimation process activity. However, the lack of sufficient cost data for all items can affect the accuracy of the estimation as these cost items would be considered as a lump-sum. Another limitation of the research and the estimation tool is that it considers only the cost of materials without considering the labour and overhead costs. Ahn et al. (2017) developed a new method to forecast the logistics cost in panelized construction using the machine learning approach to produce accurate estimates. The authors applied three different support vector machine (SVM) methods—linear, quadratic, and cubic—to come up with an equation to accurately predict the transportation cost part of the total logistics costs. The proposed method calculates the cost satisfying Equation (2) as by Ahn et al. (2017):

$$C_T = \sum(N \times D \times C_{op}) + \sum(T \times C_{id}) \qquad (2)$$

where: (C_T) is the total logistics cost, (N) is the number of site visits, (T) the duration of stay, (D) distance between the factory and the construction site, (C_{op}) unit operation cost, and (C_{id}) unit idling cost. Another problem addressed by the literature is material cost estimation, which was addressed by Wang et al. (2019) who developed an automated system that is able to convert the material data required for the cost estimation from the BIM model into the enterprise resource planning (ERP) system in order to calculate the cost associated with it for the panelized residential construction industry. The authors' proposed system algorithm starts by extracting the required building component information from the BIM software into a (.txt) format. This information then flows into a conversion module that runs cleaning processes and converts them into a readable

ERP format by assigning a unique identification code to each component that matches one of the recorded codes on the ERP tables database. The code assigning process is not always an easy step because infrequent cases, manual work is needed to assign a new unique identification code for the new material that has never been used in the database before and to add this new input into the database for future reference. By comparing the results obtained from the developed system with previous projects' true values that were obtained by manually converting the components information from the BIM model, a higher number of errors associated with the automated system were discovered.

Chapter 3 : Proposed methodologies

3.1 Overview

The focus of this research is on the industrialized residential construction industry, where residential buildings are built in a factory offsite and shipped to the construction site for assembly. Every residential project can be divided into three main structural segments: walls, floors, and roofs. Each of these segments is fabricated in the industrialized factories using different techniques and approaches. However, only the wall fabrication lines are investigated in this research where the proposed system is implemented in the case of offsite wall panels fabrication using automated fabrication machines. As a prerequisite, the modelled wall panels are framed in the BIM environment as per the relevant building codes. A set of external and internal walls can then be generated from the BIM model, as demonstrated in Figure 3-1, in order to initiate the fabrication process. The fabrication of wall panels goes through a set of stations and machines, starting with the framing station where the main structure of the wall panels is formed by fastening the panel elements to each other using nails. This process is performed by an automated wood-framing machine, and this research focuses on the fabrication process at this station only.

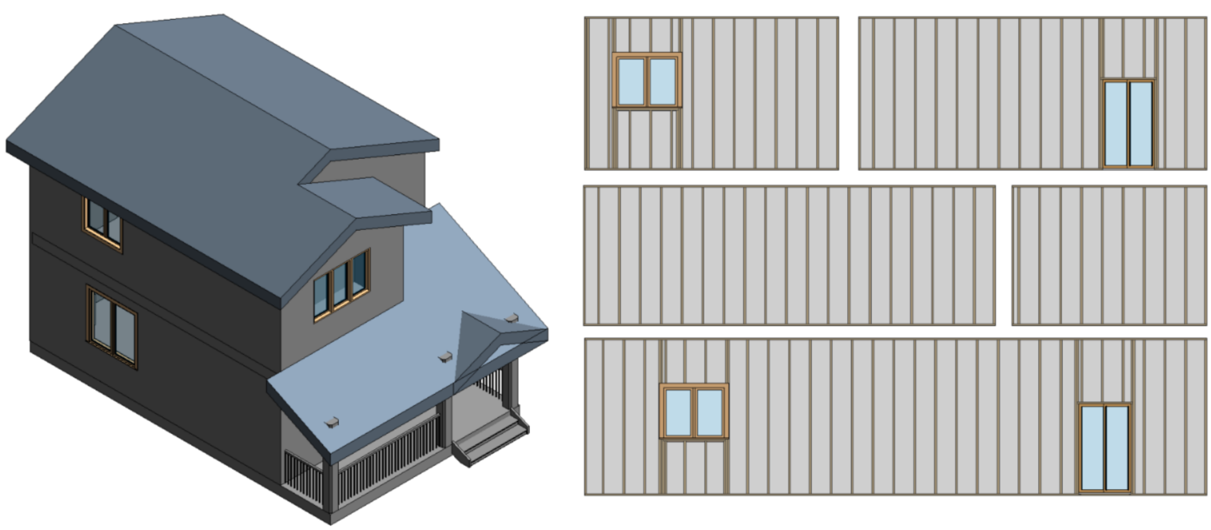


Figure 3-1 Residential project wall panels

Each wall panel consists of multiple different elements as shown in Figure 3-2, including the vertical studs (*VSm,n*), the horizontal studs (*HSm,n*), double stud (*DSm,n*), top & bottom plates (*Pm,n*), window openings (*Wm,n*), and door openings (*Dm,n*).

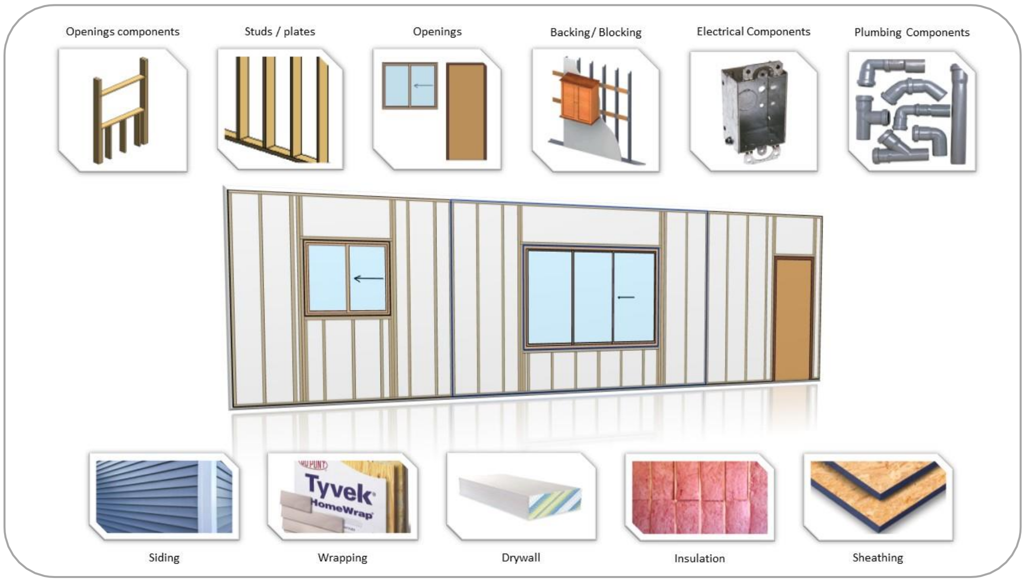


Figure 3-2 Wall panel components

The automated wood-framing machine used in this research is a prototype developed by the University of Alberta to automate the process of wood-framed wall panels fabrication by fastening the wall studs and components to the top and bottom plates of the wall panels. The framing operations executed by the machine are divided into three types: nailing ($N_{i,t}$), drilling ($D_{i,t}$), and cutting operations ($C_{i,t}$) (Figure 3-5). The movement of the machine is powered by a set of linear actuators, pneumatic ($P_{r,i}$), and electrical ($E_{r,i}$) actuators (Figure 3-3 & Figure 3-4).

Figure 3-3 Electrical actuator

Figure 3-4 Pneumatic actuator

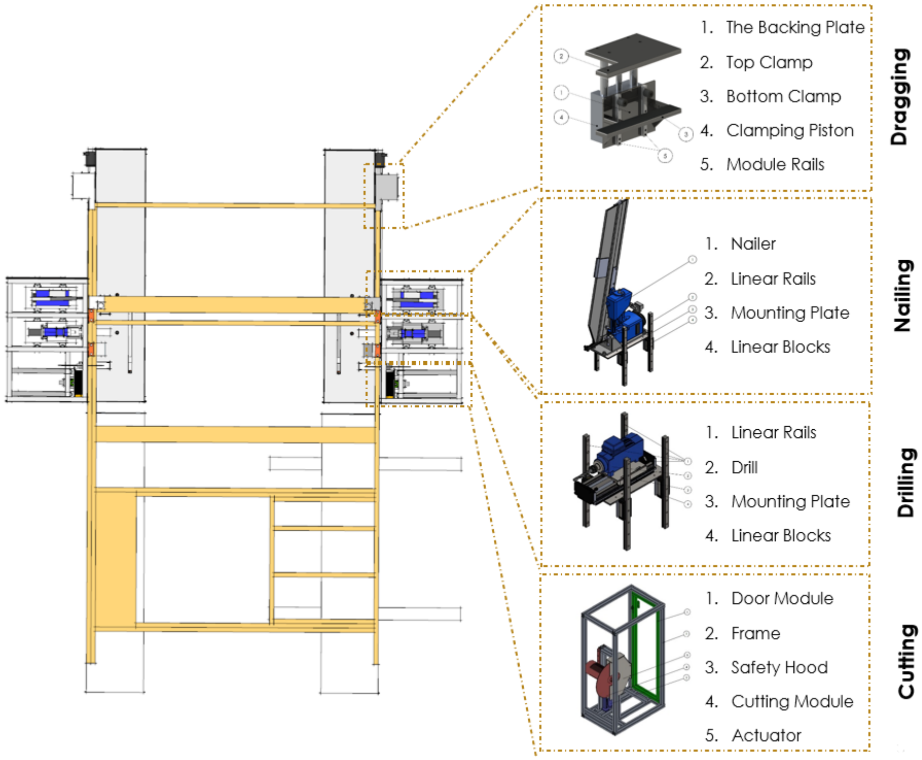


Figure 3-5 Wood-framing machine prototype

The studied machine is equipped with the following configurations (Figure 3-6):

1. Placement system: It consists of a series of linear pneumatic actuators that assist the loading and placing of each element in the wall panel by the machine operator and ensure these elements are placed correctly during the performed operation. The following are the main parts of the placement system:
    a. Stopping pin (*SP*): A pneumatic linear actuator (P_1) that defines the zero position of the machine, the stopping pin aligns the loaded element into the nailing position on the machine where the nailers are located.
    b. Pulling pin (*PP*) and pushing pin (*HP*): Two pneumatic linear actuators (P_2, P_3) are attached together to assist the operator in loading the elements into place. The mechanism is divided

into two movements: the PP moves vertically aligned to the Z-axis while the HP moves horizontally aligned to the -axis and pulls the loaded element to the zero position.

c. Guiding pin (*GP*): A pneumatic linear actuator (P_4) serves as a reference point for the machine's operator to load the element. The use of the GP allows the operator to load the next element while the machine is still working on the previous one, which reduces the waiting time required to load each element separately.

d. Lifting plate (*LP*): A linear electric actuator (E_1) is used only in the case of nailing horizontal studs located on the top (external) side of the wall frame. The LP lifts the loaded studs into its correct position in order for them to be fastened into the plates of the wall frame.

2. Nailing system: Industrial nailers are used on each side of the wall panel to fasten the wall plates into the studs and wall components using nails. The nailers are capable of moving vertically to reach the multiple nailing positions using a linear electric actuator (E_2).
3. Drilling system: Drills are used on each side of the panel to drill holes in the wood plates for crane lifting. The holes allow for the attachment of hooks or run straps through the panel to facilitate it being picked up by a crane for easy transport. The drills can move vertically to reach the vertical drilling position, and horizontally to perform the drilling in the required position. Movements in both directions are powered by two electric linear actuators (E_3, E_4).
4. Cutting system: A cutting saw is placed to perform the partial cuts between the single panels within a multi-panel for marking and assisting the separation, and also to perform full cuts at the endpoint of the multi-panel to size and cut the extra material. An electric linear actuator (E_5) is attached to the cutting saw to control its motion.
5. Dragging system: A dragging jaw is used to clamp the wall frame and drag it to the next operation position after each operation is finished. Two types of linear motion are performed

by the dragging jaw: a pneumatic actuator (P_5) is used on the top and bottom clamps of the dragging jaw to clamp onto the wall frame while an electric linear actuator (E_6) controls the distance the dragging jaw travels to reach the required position.

6. Supporting system: A set of clamps powered by pneumatic linear actuators supports the wall frame while performing the framing operations. The following clamps are used on the machine:
   a. Stopping clamp (*S*) is used as a reference point for the operator to load the top and bottom plates of the wall frame to it (P_6).
   b. Top clamp (*T*), L-clamp (*L*), and inside clamp (*I*) are used to clamp on the wall plates and the loaded studs while performing the operations to ensure the stability of the wall frame (P_7, P_8, P_9).

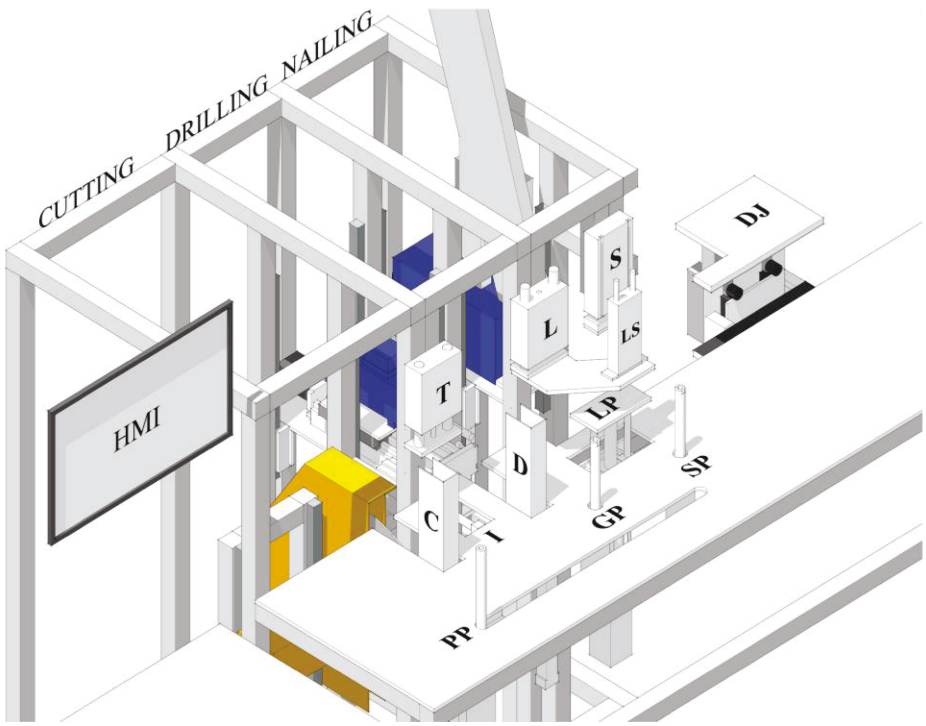


Figure 3-6 Wood-framing machine configurations

3.2 Research main methodology

In this chapter, the methodology of this research is presented in detail. The implementation of this methodology by construction manufacturers leads to the development of a new BIM-based estimating and control system in the industrialized residential construction industry. The proposed methodology is illustrated in Figure 3-7.

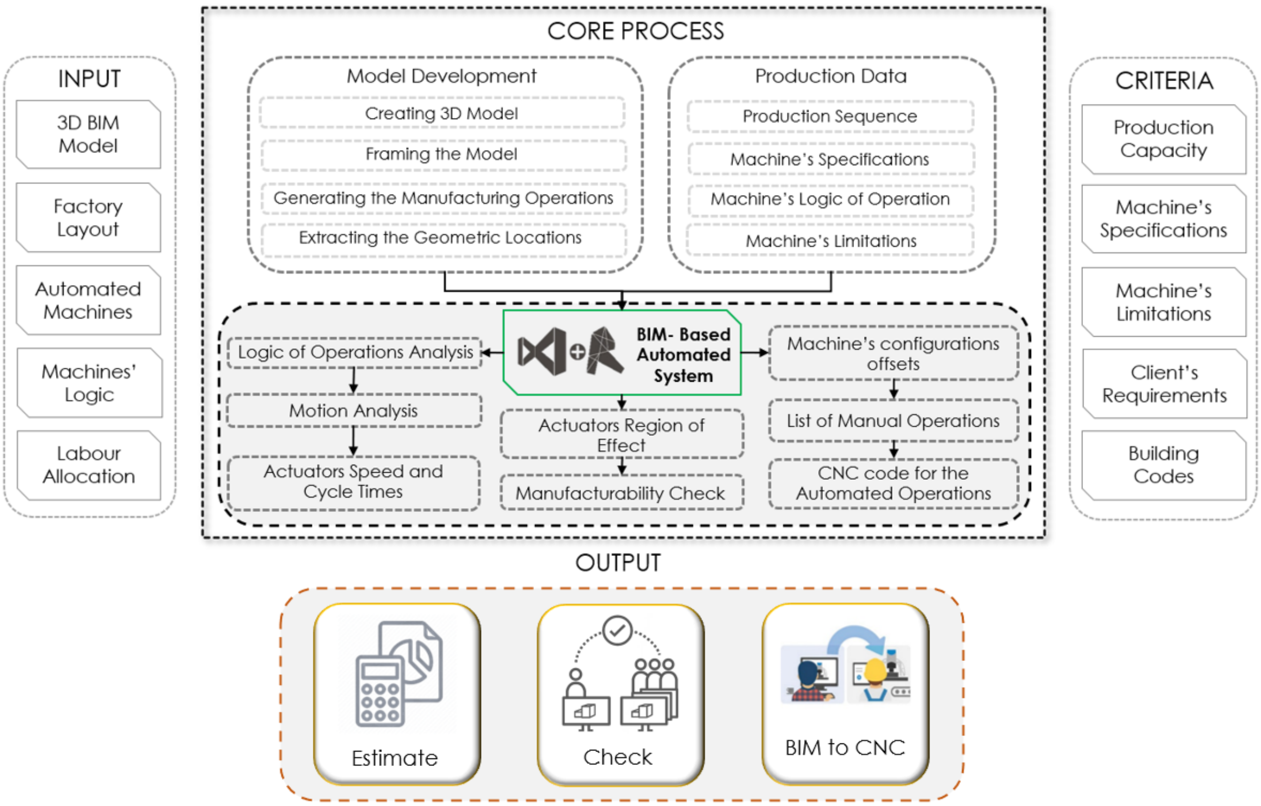


Figure 3-7 Overview of research methodology

❖ The inputs of the framework include:

i. The BIM model that contains essential information about the required job including but not limited to, the geometric parameters, the operations coordinates, and the material types.

ii. The specifications of the automated machines used in the facility also serve as input for the developed framework.

iii. The machine’s logic of operation, which will be followed to calculate the fabrication duration.

- ❖ The criteria employed throughout the framework include the machine’s production capacity, the machine’s configuration specifications, the machine’s limitations, the client’s requirements, and finally, the national building codes.
- ❖ The outputs of the framework include the results and contributions of the proposed research, which fall into four main outputs:

i. Forecasting the fabrication time ($TF_{n,j}$) of the building’s structural components with a high level of accuracy depending on the element properties (Ep_m) of the model’s structural components and the machine’s specifications.

ii. The manufacturability check results for all the operations required to manufacture a project (K_n) depending on the framework criteria.

iii. The generation of the CNC-readable codes ($CNC_{n,i}$) to provide the machines directly from the BIM environment without the dependence on third-party CAM software.

iv. Predict and schedule the maintenance stops for the automated machines based on the life expectancy of the machine’s elements ($PLU_{r,t}$, $ELU_{r,t}$), and mitigate the emergency maintenance stops.

- ❖ The core of the methodology is demonstrated in Figure 3-8, and it will be clarified more in the following section.

The implementation of the framework mainly depends on the steps performed in this stage, and the core process of the proposed methodology starts with the development process of the BIM model for the project including the framing modelling of the structural segments of the model either manually or by using an automated framing tool. Each of the segments has a unique set of elements. For the wall panels, the proprieties of the structural wall elements, along with the machine's configuration specifications, are integrated within the proposed BIM-based tool using a programming language.

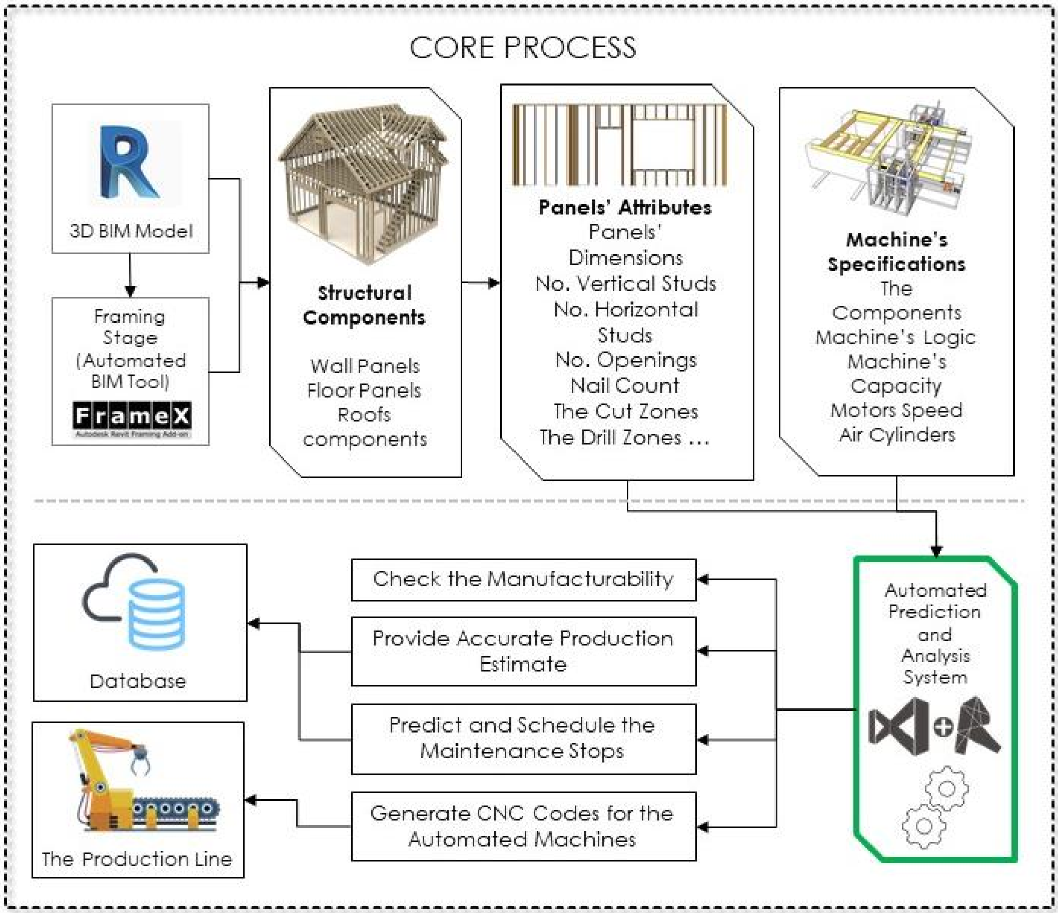


Figure 3-8 Detailed view of the core process

3.3 Production estimation

The implementation of automation in industrialized construction allows for producing accurate and reliable production estimates ($TF_{n,j}$). Given the ability to accurately track the movement of the automated machine's components and calculate the duration associated with each task performed by them. The production time estimates can be developed more accurately and by using automated approaches. As has been elaborated on previously, the machine's movement configurations are powered by the linear actuators connected to them ($P_{r,i}$, $E_{r,i}$). These actuators are of two types;

pneumatic ($P_{r,i}$) and electrical actuators ($E_{r,i}$), each type has multiple factors that influence its movement speed ($CS_{r,t,i}$), which directly affects the duration it takes to perform the associated task ($T_{t,n,i}$). The implementation of this objective of the research starts by analyzing and examining the factors affecting the movement speed of the machine's actuators ($CS_{r,t,i}$) in order to calculate the duration of each movement ($T_{t,n,i}$). The machine's logic of operations is also examined to define the movements required for each operation type ($N_{i,t}$, $D_{i,t}$, $C_{i,t}$) and the sequence of these movements. This results in developing an estimation system based on the machine's specifications, the logic of operation, and the physical properties of the structural wall elements manufactured using the automated machine. This system is integrated with the BIM environment where the geometric information ($G_{t,n,i}$) of the required operations are extracted from the BIM model into the estimation system. Figure 3-9 demonstrates the methodology followed to achieve this objective.

Pneumatic actuators ($P_{r,i}$) typically consist of three elements: the external cylinder, the piston, and the actuator rod (Figure 3-10). Following the flow of air into the cylinder ($Q_{r,i}$), the rod length ($PL_{r,i,t}$) extends in the same direction to reach a full stroke of the actuator ($PS_{r,i,t}$). The same operation occurs in the other direction as the rod retracts. Since the movements follow only one of the previously mentioned states, where the actuator can only be fully extracted or fully retracted, the distance the piston of the actuator travels in each movement is known as it is equal to the stroke of the piston which is defined as part of the actuator specifications.

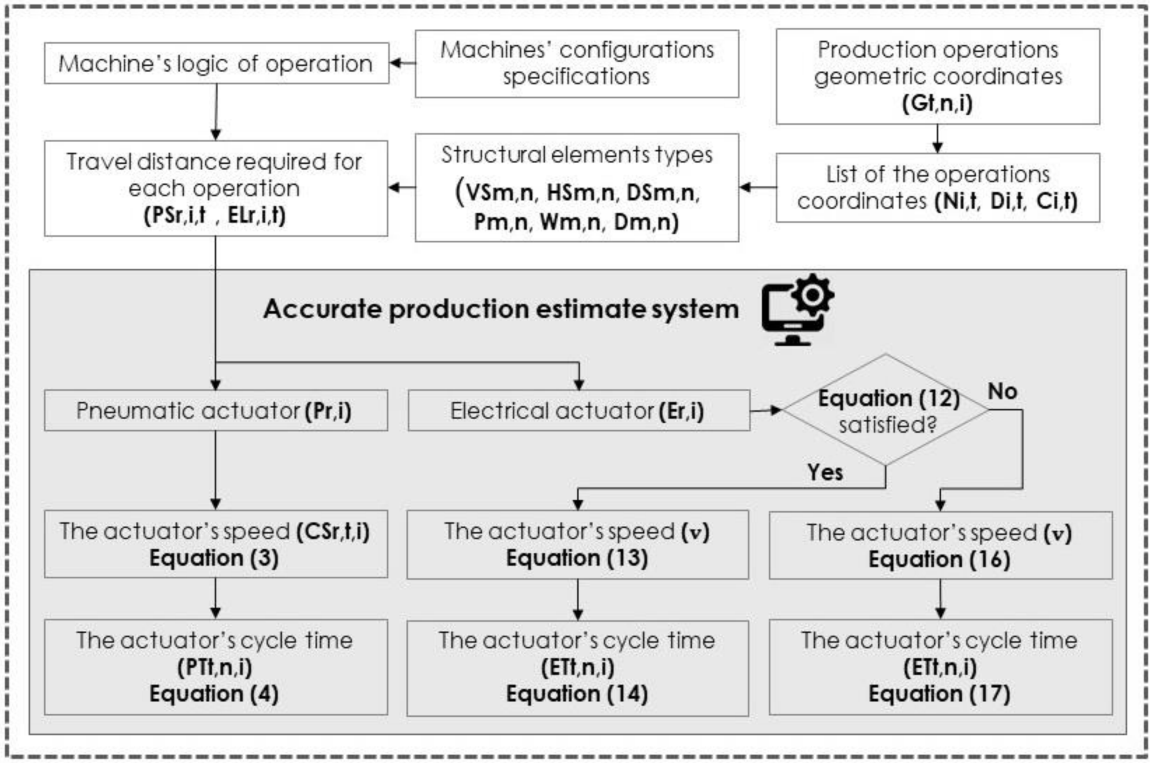


Figure 3-9 Production estimation methodology

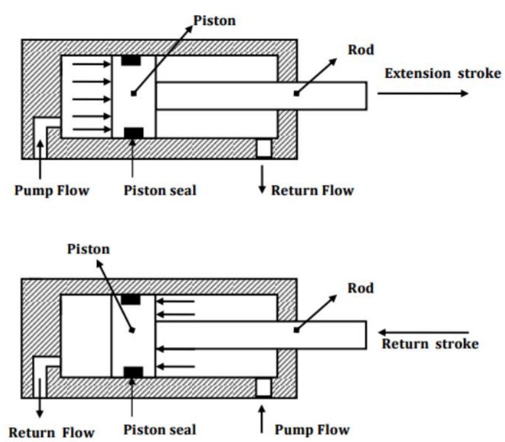


Figure 3-10 Pneumatic actuator elements (Palani et al. 2018)

However, to calculate the duration of each movement ($PT_{t,n,i}$), the speed of the rod ($CS_{r,t,i}$) is investigated. The speed of the actuator differs between the two states, where it can be calculated as a function of the following variables in Equation (3) and satisfying Equations (4–6):

$$CS_{r,t,i} = F(Q_{r,i}, Pmin_{r,i}, Pmax_{r,i}, PA_{r,i}, F_{r,i}, PS_{r,i,t}, Py_{r,I}, Pt_{r,I}, Pr_{r,i}) \quad (3)$$

$$CS_{r,t,i} = Q_{r,i} / PA_{r,i} = PS_{r,i,t} / PT_{t,n,\mathrm{i}} \quad (4)$$

$$PA_{r,i} = F_{r,i} / Pp_{r,i} \quad (5)$$

$$Pmin_{\,r,i} < Pp_{r,i} < Pmax_{r,i} \quad (6)$$

where:

$CS_{r,t,i}$: the speed of the pneumatic actuator (*r*) in the automated machine (*i*) while performing the task (*t*) (mm/s);

$Q_{r,i}$: the applied airflow for the actuator (*r*) in the machine (*i*) (l/min);

$Pmin_{\,r,i}$: the minimum operating pressure of the actuator (*r*) in the automated machine (*i*) (psi);

$Pmax_{r,i}$: the maximum operating pressure of the actuator (*r*) in the automated machine (*i*) (psi);

$Pp_{r,i}$: the applied operating pressure on the actuator (*r*) in the automated machine (*i*) (psi);

$Py_{r,i}$: the external cylinder diameter of the actuator (*r*) in the automated machine (*i*) (mm);

$Pt_{r,i}$: the piston length of the actuator (*r*) in the automated machine (*i*) (mm);

$Pr_{r,i}$: the rod diameter of the actuator (*r*) in the automated machine (*i*) (mm);

$PA_{r,i}$: the effective area of the actuator's piston (*r*) in the automated machine (*i*) (mm^2);

$F_{r,i}$: the applied force on the actuator (*r*) in the automated machine (*i*) (kg);

$PS_{r,i,t}$: the travel distance while performing the operation (*t*) which represented as the stroke of the piston of the actuator (*r*) in the automated machine (*i*) (mm).

$PT_{r,n,\mathrm{i}}$: the travel time the actuator (*r*) needs to complete a movement in the wall panel (*n*) (s).

Electric actuators ($E_{r,i}$), are powered by an attached electrical motor (Figure 3-11), which gives the actuator the ability to reach any point within its stroke range. The traveled distance required for each movement ($EL_{r,i,t}$) is programmed into the logic of the machine, and the speed of the piston movement ($CS_{r,t,i}$) is affected by multiple factors that differ from the factors listed for the pneumatic actuators ($P_{r,i}$). The cycle time of the electric actuator ($ET_{r,n,i}$) for each task is calculated satisfying Equation (7) (Figure 3-11, Figure 3-12).

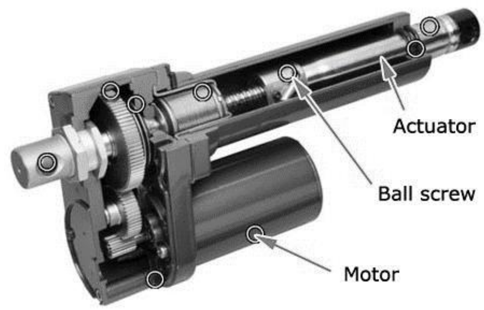


Figure 3-11 Electrical actuator elements

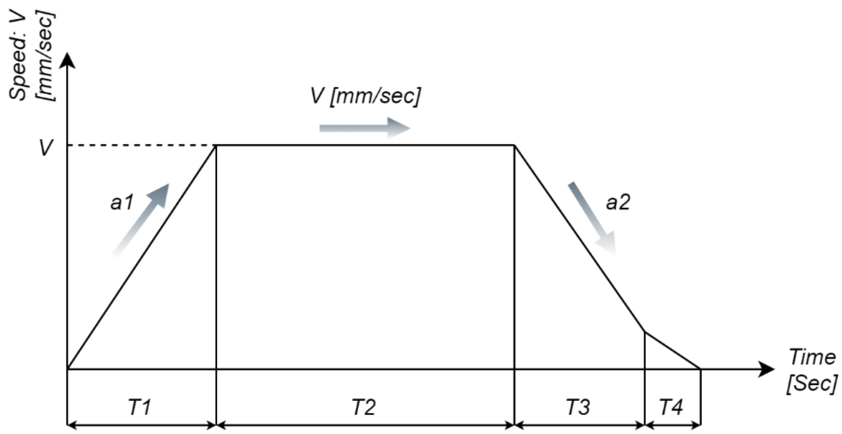


Figure 3-12 Electric motors speed chart

The cycle time [seconds]:

$$ET_{r,n,i} = \sum T_{y\,(r,n,i)} \quad : \quad y = (1, 2, 3, 4) \tag{7}$$

The acceleration time [seconds]:

$$T_{1(r,n,i)} = V_{r,i}/a_{1r,i} \tag{8}$$

The deceleration time [seconds]:

$$T_{3(r,n,i)} = V_{r,i}/a_{2r,i} \tag{9}$$

The constant speed travel time [seconds]:

$$T_{2(r,n,i)} = \frac{EL_{r,i,t} - 0.5V_{r,i}(T_{1(t,n,i)} + T_{3(t,n,i)})}{V_{r,i}} \tag{10}$$

$T_{4(r,n,i)}$: Settling time varies depending on the conditions such as motor types, load, and in the positioning of the step data [seconds].

where:

$a_{1r,i}$: the acceleration of the motor ($Em_{r,i}$) of the actuator (r) in the automated machine (i) (m/s^2);

$a_{2r,i}$: the deceleration of the motor ($Em_{r,i}$) of the actuator (r) in the automated machine (i) (m/s^2);

$EL_{r,i,t}$: the traveled distance required to complete the task (t) by the actuator (r) in the automated machine (i) (m);

$V_{r,i}$: the steady speed of the motor ($Em_{r,i}$) of the actuator (r) in the automated machine (i) (m/s^2).

Using the previous factors, the distance the motor travels during the acceleration phase (d_1) can be calculated satisfying Equation (11). A comparison between the distance required to complete the movement ($EL_{r,i,t}$), and the previously calculated distance (d_1) is performed in order to calculate the speed of the motor depending on which stage the motor is at as per Equation (12, 17):

$$d_1 = \frac{V_{r,i}}{2a_{1r,i}} + \frac{V_{r,i}}{2a_{2r,i}} \tag{11}$$

1. $\boldsymbol{EL_{r,i,t} \leq d_1}$: (12)

$$\rightarrow v = \sqrt{\frac{2EL_{r,i,t} * a_{1r,i} * a_{2r,i}}{a_{1r,i} + a_{2r,i}}} \tag{13}$$

$$\rightarrow ET_{r,n,i} = T_{1(t,n,i)} + T_{3(t,n,i)} = \frac{v}{a_{1r,i}} + \frac{v}{a_{2r,i}} \tag{14}$$

2. $\boldsymbol{EL_{r,i,t} > d_1}$: (15)

$$\rightarrow v = V_{r,i} \tag{16}$$

$$\rightarrow\ ET_{r,n,i} = T_{1(r,n,i)} + T_{2(r,n,i)} + T_{3(r,n,i)} + T_{4(r,n,i)} = \frac{V_{r,i}}{a_{1r,i}} + \frac{EL_{r,i,t} - d_1}{V_{r,i}} + \frac{V_{r,i}}{a_{2r,i}} + T_{4(r,n,i)} \quad (17)$$

Following the previous approach, an accurate production estimate ($TF_{n,j}$) can be obtained by analyzing each movement of the machine components ($EL_{r,i,t}$) depending on its logic of operation and the list of operations required to be achieved ($N_{i,t}$, $D_{i,t}$, $C_{i,t}$).

3.4 Manufacturability check

Several automated BIM tools have the capability to export the geometric locations of the required machinery operations ($G_{t,n}$) from the 3D BIM models. Thus, this task is out of the scope of this research. However, one of the challenges from the manufacturing perspective is to determine the capability of the machines to perform the required operations. Multiple factors should be considered to achieve this objective, including:

- the machine's configurations, which represent the physical parts of the machine and any attached systems;
- the machine's logic of operation, which outlines the sequence of movements the machine follows to perform each task; and
- the machine's limitations, which can be identified based on the configurations and the logic of the machine.

In this research, an automated manufacturability check approach is proposed within the Revit application programming interface (API). The proposed system follows the previous work proposed by An et al. (2019, 2020) and expands on it by covering some of the limitations in the former systems, including:

- the effects of the machine's logic of operation on the region of effect (ROE) of the machine;

- defining the ROE of the machine's elements (actuators) based on the type of actuator;
- including all the framing operations types since the previous research focused only on the nailing operations ($N_{i,t}$) without including the other operations such as the drilling ($D_{i,t}$) and cutting ($C_{i,t}$); and
- the BIM integration, since the developed tool is programmed in the Revit API which increases the level of automation of the process since it will be performed directly in the design stage after developing the 3D model of the project.

Furthermore, the implementation within the Revit API has a significant effect on the design and drafting stage since the designers will have the ability to check the manufacturability of the designed structural elements and perform any modifications required directly without the obligation to wait for the feedback from the production department on the manufacturability of the design. Figure 3-13 provides an overview of the followed methodology for this objective. The machine's configurations consist of multiple physical components that control the movement of each part of the machine, depending on the programmed logic.

The linear motion of the pneumatic actuators is limited to two scenarios only, where it could either be fully extended ($XE_{r,i}$) or fully retracted ($XR_{r,i}$). This constraint affects the ROE of the machine since the machine's components that are controlled by the pneumatic actuators would not be able to perform any task ($N_{i,t}$, $Di_{,t}$, $C_{i,t}$) located within the range of the two previous cases ($G_{t,n,i} \neq G(XE_{r,i})$ *or* $G_{t,n,i} \neq G(XR_{r,i})$). However, electrical actuators do not have this limitation since one of their main advantages come from the ability to reach any geometric location ($G_{t,n,i}$) located within its operation range ($\overline{A}$) represented as a vector that connects between the fully extended and fully retracted points, which is restricted only by the length of the full stroke of the actuator ($ST_{r,i}$).

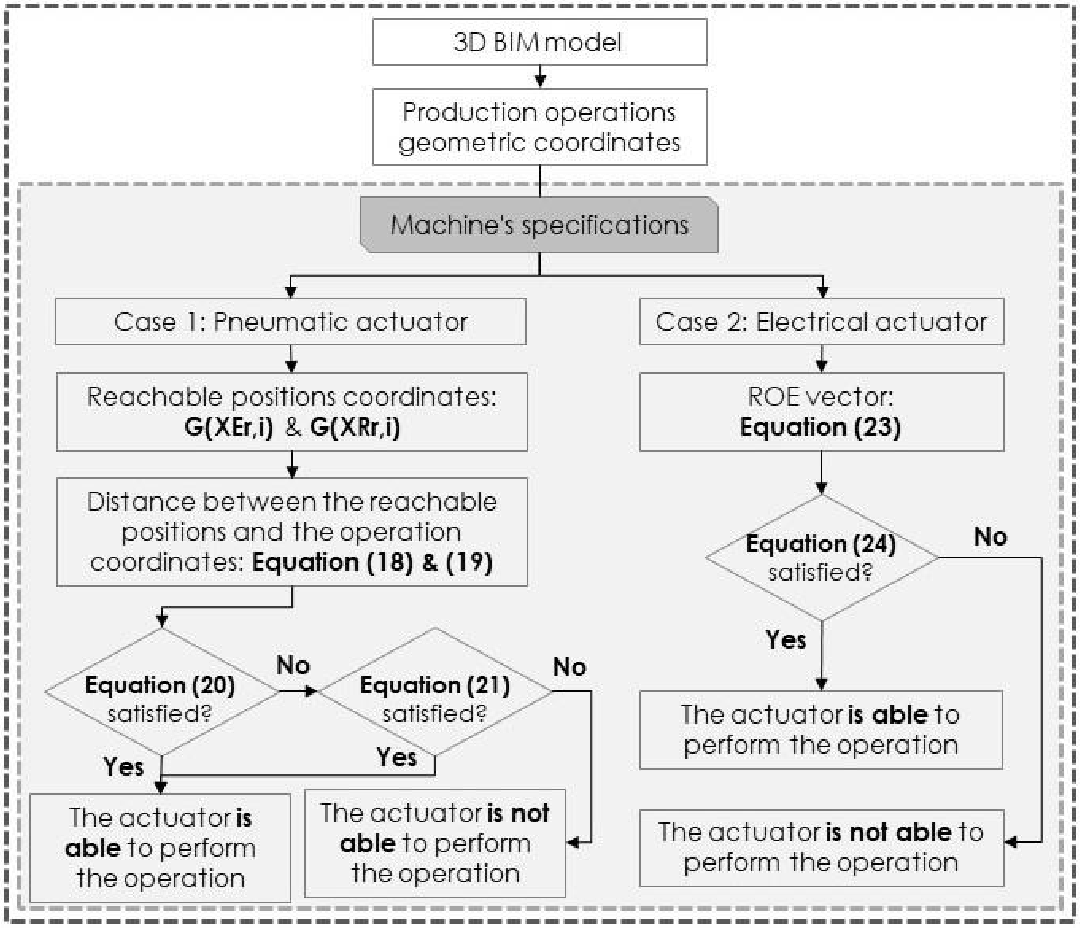


Figure 3-13 Manufacturability check methodology

As previously stated, since the motion of the pneumatic actuator is restricted to two scenarios only (full extraction, full retraction), the ROE for each component controlled by this type of actuator can be expressed using the 3D coordinates as two points (Figure 3 14), while the ROE for the electrical actuators is defined as the linear distance between the previous two positions of the actuator since the actuator, in this case, has the ability to reach any point that falls within this range in order to perform the required job.

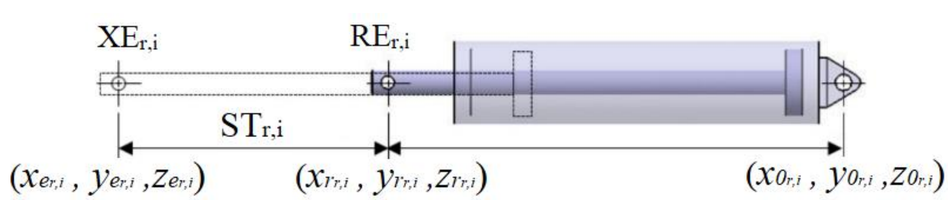


Figure 3-14 Linear actuators ROE

The process can be expressed using the following equations for the pneumatic actuators.

- The distance ($D_{T,XE}$) between the geometric position of the required operation ($G_{t,n,i}$) and the maximum reachable point for the pneumatic actuator on the full extraction state ($G(XE_{r,i})$) is calculated satisfying Equation (18):

$$D_{T,XE} = \mid \mathrm{G_{t,n,i}} - \mathrm{G}(\mathrm{XE_{r,i}}) \mid = ((x_{\mathrm{t,n,i}} - xe_{\mathrm{r,i}})^2 + (y_{\mathrm{t,n,i}} - ye_{\mathrm{r,i}})^2 + (z_{\mathrm{t,n,i}} - ze_{\mathrm{r,i}})^2)^{1/2} \quad (18)$$

- The distance ($D_{T,XR}$) between the geometric position of the required operation ($G_{t,n,i}$) and the settling point for the pneumatic actuator on the full retraction state ($G(XR_{r,i})$) is calculated satisfying Equation (19):

$$D_{T,XR} = \mid \mathrm{G_{t,n,i}} - \mathrm{G}(\mathrm{XR_{r,i}}) \mid = ((x_{\mathrm{t,n,i}} - xr_{\mathrm{r,i}})^2 + (y_{\mathrm{t,n,i}} - yr_{\mathrm{r,i}})^2 + (z_{\mathrm{t,n,i}} - zr_{\mathrm{r,i}})^2)^{1/2} \quad (19)$$

- The condition which indicates that the required operation can be performed by the pneumatic actuator while the actuator at its fully extracted position can be expressed as the state at which the distance between ($G_{t,n,i}$) and ($G(XE_{r,i})$) is satisfying Equation (20):

$$D_{T,XE} = 0 \quad (20)$$

- The condition which indicates that the required operation can be performed by the pneumatic actuator while the actuator at its home position without any additional movement can be expressed as the state at which the distance between ($G_{t,n,i}$) and ($G(XR_{r,i})$) is satisfying Equation (21):

$$D_{T,XR} = 0 \quad (21)$$

- The geometric position of the required operation ($G_{t,n,i}$) is considered out of the pneumatic actuator reach when satisfying Equation (22):

$$D_{T,XE} \neq 0 \ \ or \ \ D_{T,XR} \neq 0 \tag{22}$$

Electrical actuators ROE, on the other hand, can be expressed as a vector that connects between the two positions of the actuator: the full extraction and full retraction positions. The following equations illustrate the process of checking the actuator's ability to reach an operation position.

- The electrical actuator ROE vector, considering that the center of coordinates at the zero position of the actuator where $x_{0\mathrm{r,i}} = 0$, $y_{0\mathrm{r,i}} = 0$, $z_{0\mathrm{r,i}} = 0$ can be calculated satisfying Equation (23) (Figure 3-14).

$$\bar{A} = \left(xe_{\mathrm{r,i}}\right)\hat{\mathrm{X}} + \left(ye_{\mathrm{r,i}}\right)\hat{\mathrm{Y}} + \left(ze_{\mathrm{r,i}}\right)\hat{\mathrm{Z}} \tag{23}$$

- The condition which indicates that the required operation can be performed by the electrical actuator can be expressed as the state at which the coordinates of the required operation ($G_{t,n,i}$) locates on the ROE vector of the electric actuator by satisfying Equation (24):

$$\mathrm{G}_{\mathrm{t,n,i}} \in \bar{A} \tag{24}$$

In addition, the machine's logic defines how the machine configurations would react to each operation assigned ($N_{i,t}$, $D_{i,t}$, $C_{i,t}$) since it outlines the sequence of motion for each configuration based on the type of operation and the types of the structural elements in the wall panel ($VS_{m,n}$, $HS_{m,n}$, $DS_{m,n}$, $P_{m,n}$, $W_{m,n}$, $D_{m,n}$). The production flow in a manufacturing line always flows in one direction, which influences the sequence of operations performed on each station in the line since the order of the operations is affected by the physical position of the machine configuration needed to complete the operation in the machine (Figure 3-15). For example, to frame a wall panel (MW_n) using an automated machine ($M_{i,j}$), different types of operations are required (Figure 3-16), and these operations can be categorized as being one of three main operations: nailing ($N_{i,t}$), drilling ($D_{i,t}$), and cutting ($C_{i,t}$) operations. Each of these three operations is also affected by the properties of the structural elements of the wall panel (Ep_m) (i.e., vertical stud ($VS_{m,n}$), horizontal stud ($HS_{m,n}$), double stud ($DS_{m,n}$), top & bottom plates ($P_{m,n}$), windows openings ($W_{m,n}$), doors openings ($D_{m,n}$)), and each operation is performed by a specific set of configurations in the machine. This variation is considered in the manufacturability decision.

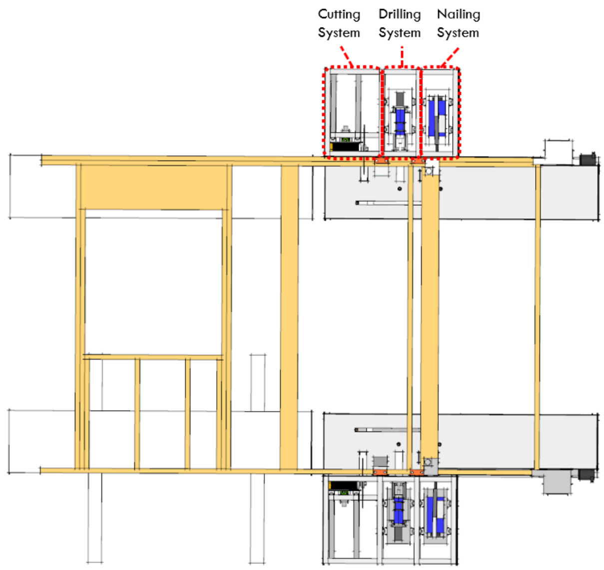


Figure 3-15 Framing machine configuration

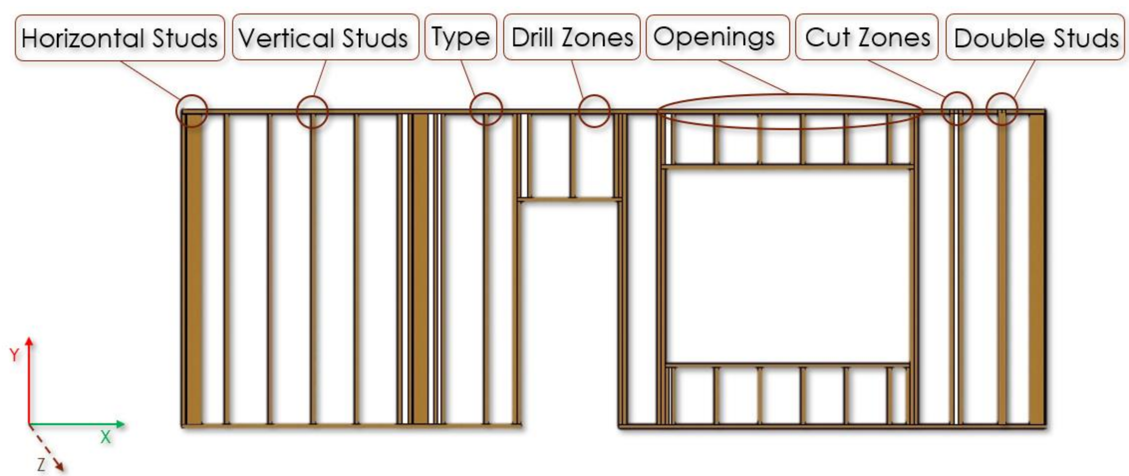


Figure 3-16 Wall framing operations

To summarize, a more accurate ROE can be developed for each configuration of the automated machine to define its limitations and used as the main indicator for the manufacturability determination of the machine. The new ROE is matched with the extracted 3D coordinates of the operations ($G_{t,n,i}$) to check the ability of execution using the specified machine based on the machine's limitations.

3.5 CNC codes generation

As a result of the integration between BIM and the automated machines, and based on the logic of the machines and the locations of the required operations ($G_{t,n,i}$), a system is developed in the Revit API in order to generate the CNC readable codes ($CNC_{n,i}$) from the BIM model directly, which can then be inputted into the machines in the production line. As stated in the literature, most CNC machines are programmed using the ISO 6983 ‘‘G-code’’ language. The programmed codes are readable by the machines and contain detailed information about the machinery operations ($N_{i,t}$, $D_{i,t}$, $C_{i,t}$), which include the 3D coordinates of each operation ($G_{t,n,i}$) along with the manufacturing sequence of these operations. The current practice that results in the generation of these codes involves the generation of the detailed shop drawings from the BIM models; these drawings are imported into a third-party CAD/CAM where the information about the CNC machines including the machine's logic and the sequence of operations as well as the machine's configuration specifications are coded and used to generate the required CNC codes based on the imported shop drawings. However, this process can be improved by generating the codes straight from the BIM model since the required detailed information about the assigned job is available (such as the intersections between the elements indicating the need for a nailing operation to be performed, and the 3D accurate coordinates that can be obtained from the developed model) and can be directly integrated with the machine's specifications to export the readable codes. Figure 3-17 provides an overview of the methodology followed to accomplish the objective of developing CNC readable codes.

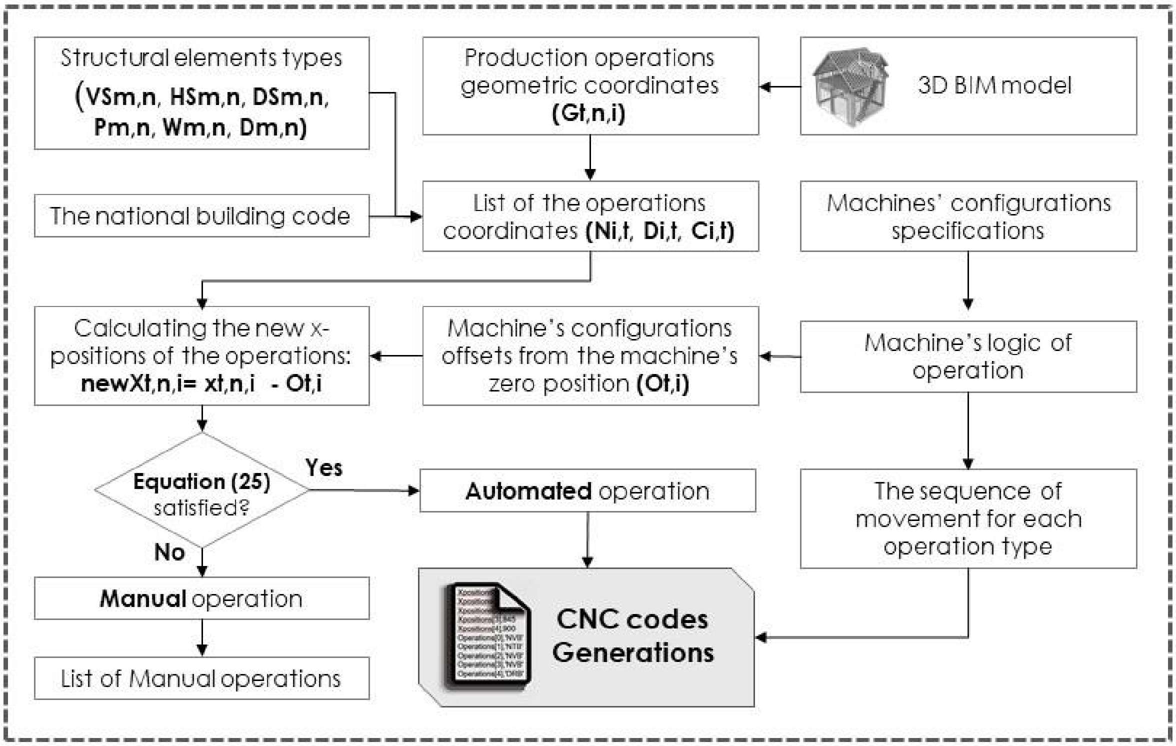


Figure 3-17 CNC codes generation methodology

The proposed methodology can be applied in the case of wooden wall panels manufacturing as per the following logic.

1. The generation of the nailing operation ($N_{i,t}$) 3D coordinates ($G_{n,n,i}$) follows the approaches previously proposed by An et al. (2019, 2020), Li (2016), and Li et al. (2017), where the locations are extracted based on the mating positions between the structural elements of the panel. For instance, the nailing operations between the studs ($VS_{m,n}$, $HS_{m,n}$, $DS_{m,n}$) and the panel's top and bottom plates ($P_{m,n}$) are generated on the mating planes between these elements since they are joined using nails.
2. The number of nails ($NN_{n,m}$) in each nailing position ($G_{n,n,i}$) is determined based on the followed construction codes and the construction practice. The national building code Alberta edition (NRC 2019) indicates that the minimum number of nails required to fasten studs into the wall plates is two nails with a minimum nail length of 82 mm.

3. The drilling operation ($D_{i,t}$) positions ($G_{d,n,i}$) are defined based on the panel's center of gravity (COG) together with user preference since they will be used to lift the panel using the crane available at the facility.
4. The cutting operation ($C_{i,t}$) positions ($G_{d,n,i}$) occur at the endpoint of each single wall panel. These cutting tasks define the start and end of each single wall panel in a multi-panel.
5. Each operation is defined by its 3D coordinates ($G_{t,n,i}$) with respect to the panel's starting point and is sequenced based on the x-position of each operation (Figure 3-18).

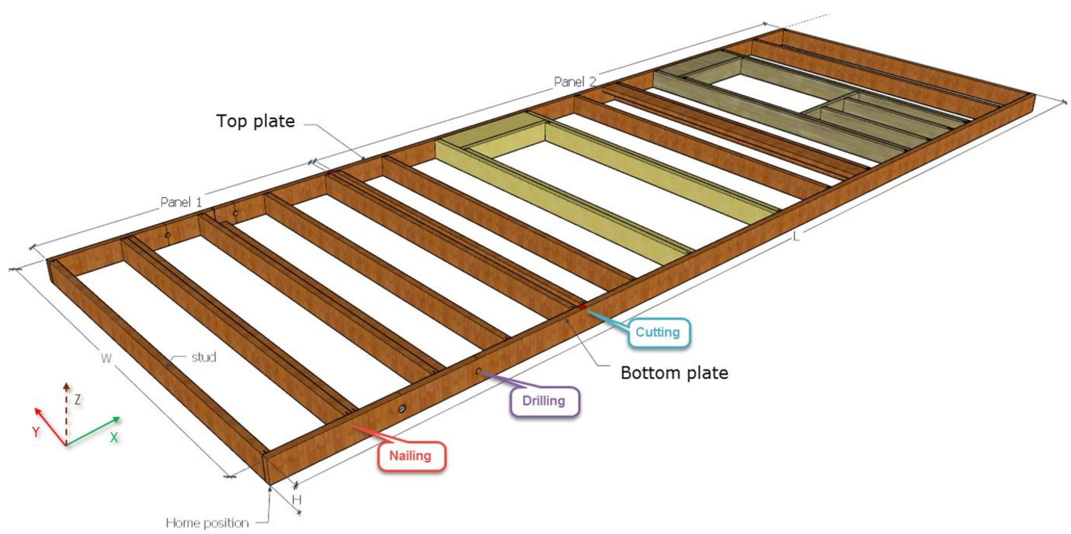


Figure 3-18 Wall panel framing operations (Li 2016)

6. The order and position of each component of the machine configuration are then considered to rearrange the operations, so they follow the order of the machine's configurations (Figure 3-19).

This step is crucial to guarantee the flow of the production in one direction only without having to move in the opposite direction in order to perform an operation, which interferes with the machine's logic of operation. The new order should follow the new x-position of the operations after considering the machine's configurations offsets from the machine's zero position ($X_{ZO\ i,j}$).

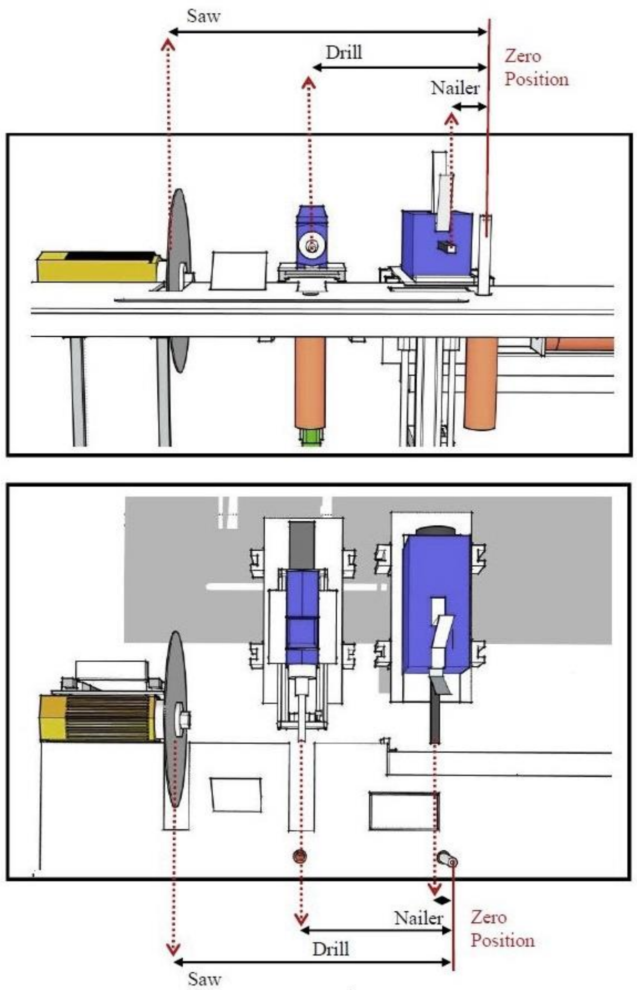


Figure 3-19 Machine configuration order

The new x-position of each operation must meet the minimum requirements by satisfying Equation (25). Any exception must be performed manually.

$$newX_{t,n,i} = x_{t,n,i} - O_{t,i} > X_{ZO\ i,j} \tag{25}$$

where:

$newX_{t,n,i}$ is the new x-position of the operation (*t*) in the wall panel (*n*) and the machine (*i*);

$x_{\mathrm{t,n,i}}$ is the original x-position of the operation (*t*) in the wall panel (*n*) and the machine (*i*);

$O_{t,i}$ is the offset of the machine configuration that responds to the operation (*t*) in the machine (*i*); from the machine's zero position; and

$X_{ZO\ i,j}$ is the x-coordinate of the machine's zero position.

The machine's zero position ($X_{ZO\ i,j}$) is the machine's operational starting point at which the panel's elements are loaded in order to get framed. Each of the machine's components has an offset away from this position ($O_{t,i}$), and the component's offset is reflected in the previous Equation (25) to ensure the correct sequencing of the operations where the zero position is considered as a reference point to calculate the coordinates on which the operations are based ($newX_{t,n,i}$). The coordinates of the operations in the new order ($newX_{t,n,i}$), accompanied by the panel's elements information (Ep_m) such as the elements' type and size, are then extracted into a CNC code format that is readable by the machines. These conversion steps are programmed into one BIM tool that is able to perform the previous tasks within the BIM environment and without the necessity to use CAM software. The machine's configuration specifications must be programmed into the tool, including the machine's logic of operations, in order to be able to generate the required CNC codes.

3.6 Maintenance prediction and scheduling

Since each of the machine's components is powered by either an electric ($E_{r,i}$) or pneumatic ($P_{r,i}$) actuator, planning for the machine's maintenance stops ($MT_{i,j}$) starts by analyzing the movements of these actuators. By knowing the duration during which the actuators are active ($T_{t,n,i}$), and the distance traveled during this duration ($EL_{r,i,t}$, $PS_{r,i,t}$), maintenance stops can be scheduled based on the life expectancy of each part ($PLE_{r,i,t}$, $ELE_{r,i,t}$).

Three types of maintenance stops are applicable to the machines in the production line:

i. Emergency stops ($GMT_{r,i}$) are when an unexpected failure of one component occurs, causing the machine to be unable to perform its assigned tasks. This could cause a production stop until discovering the failed part and providing an alternative, which might not be available right away.

ii. Preventive stops ($VMT_{r,i}$) could be scheduled on a repetitive base in order to inspect the machine's durability and execute any maintenance required for any of the parts. However, this type of maintenance stops is time and cost consuming as it includes the inspection of each part on the machine.

iii. Predictive stops ($PMT_{r,i}$) are based on the analysis and monitoring of the lifecycle of the machine's parts ($PLU_{r,i,t}$, $ELU_{r,i,t}$). It is feasible to predict the failure of each part of the machine and prepare for it by providing the required replacements in advance and scheduling maintenance stops to be performed in order to replace the predicted part only, which takes less time than the preventive stops. In this type of schedule, the chances of having an unexpected or emergency failures are significantly decreased and are mostly limited to unpredictable causes or human errors.

Predictive stops ($PMT_{r,i}$) are proven to be the best option to follow since it is achievable with the help of the currently available automated tools that can potentially monitor and predict the possible failure of each part. In this research, the emergency stops ($GMT_{r,i}$) are mitigated by accurately analyzing the lifecycle of the machine's parts ($PLU_{r,i,t}$, $ELU_{r,i,t}$) and by relating it to the life expectancy ($PLE_{r,i,t}$, $ELE_{r,i,t}$) of each part in order to calculate the usage of each part and plan for the predictive maintenance stops. The life expectancy of a linear actuator is usually measured as a traveled distance. Equations (26) and (27) are used to calculate the usage of each part depending on its type (i.e., electric or pneumatic).

The life-usage of a pneumatic actuator:

$$PLU_{r,i,t} = \frac{CLU_{r,i,t-1} + 2EL_{r,i,t}}{PLE_{r,i}} < 100\% \quad (26)$$

The life-usage of an electrical actuator:

$$ELU_{r,i,t} = \frac{CLU_{r,i,t-1} + 2EL_{r,i,t}}{ELE_{r,i}} < 100\% \quad (27)$$

where:

$PLU_{r,i,t}$: the life-usage percentage of the pneumatic actuator (*r*) in the machine (*i*) after performing the task (*t*) (%);

$ELU_{r,i,t}$: the life-usage percentage of the electric actuator (*r*) in the machine (*i*) after performing the task (*t*) (%);

$CLU_{r,i,t-1}$: the cumulative life-usage of the actuator (r) after performing the task (t-1) (m);

$PLE_{r,i}$: the life expectancy of the pneumatic actuator (*r*) in the machine (*i*) (m); and

$ELE_{r,i}$: the life expectancy of the electric actuator (*r*) in the machine (*i*) (m).

As observed from the previous equations, the life-usage of each part on the machine (linear actuator) can be expressed as the percentage between the cumulative aggregate of the distance traveled by the machine part during each task divided by the life expectancy of the investigated part. Since the pneumatic actuators can only be fully extracted or fully retracted, the stroke of the actuator ($EL_{r,i,t}$) will define the traveled distance for each movement, and this distance is double to count for both of the extraction and retraction movements. On the other hand, for the electrical actuators, the distance required to complete each movement ($EL_{r,i,t}$)—which does not necessarily equal the full stroke of the actuator—is considered in the life-usage calculation. However, the failure of each examined part occurs once the life-usage percentage reaches the 100% limit, and maintenance stops should be scheduled to prevent these cases of emergency stops, as illustrated previously.

Mathematical modelling using deterministic simulation is used to achieve this objective, wherein all of the machine’s parts are modelled as resources in the simulation environment and used to calculate the utilization rates for each part as well as the traveled distance based on the programmed machine’s logic and the operation type required.

Chapter 4 : Implementation and case study

4.1 Introduction

In this chapter, a case study of a residential project and an automated light-wood wall-framing machine is implemented within the developed framework in order to examine the proposed objectives of this research. A 3D model of the described project is developed in Autodesk Revit and framed according to the building code rules using an automated framing add-on. The structure of the project consists of walls, floors, and roof segments. However, only the fabrication of the wall panels is taken into consideration in this research, and the automated machine used is a wall-framing machine. The geometric information of the wall panels is extracted from the model and used to create the CNC codes for the described automated machine and to fulfill the rest of the research objectives, as described in the previous chapters. For the automated machine part of the implementation, the machine configurations and structure are analyzed in detail to achieve a thorough understanding of the machine's movement and logic of operation. The speed and duration of each movement of the machine are assessed with the level of accuracy required to achieve a reliable production estimate and to measure the life-usage of each part of the machine.

4.2 Revit model development

The first step of the case study implementation is to develop the 3D BIM model of the proposed project in the Autodesk Revit environment. The proposed project is a townhouse complex with a total area of 8,000 ft^2, including five two-storey residential units comprised of three bedrooms and an attached garage for each unit. The total unit's area is 1,600 $ft^{2,}$ including the garage and the upper floor. The developed Revit model for the project is shown in detail in the following figures (Figure 4-1, Figure 4-2, Figure 4-3, Figure 4-4, Figure 4-5).

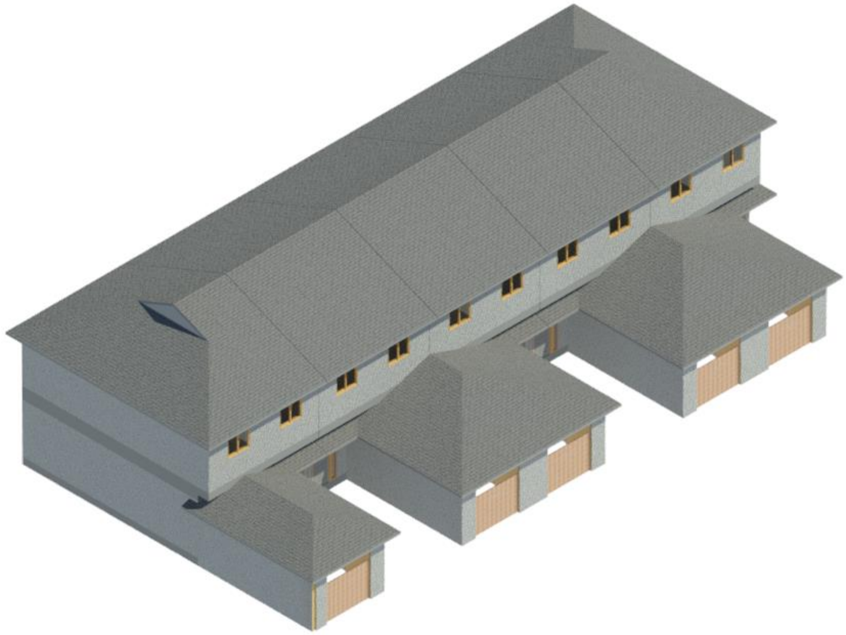


Figure 4-1 3D view of the case study

Figure 4-2 Front view of the case study

Figure 4-3 Back view of the case study

Figure 4-4 First floor layout

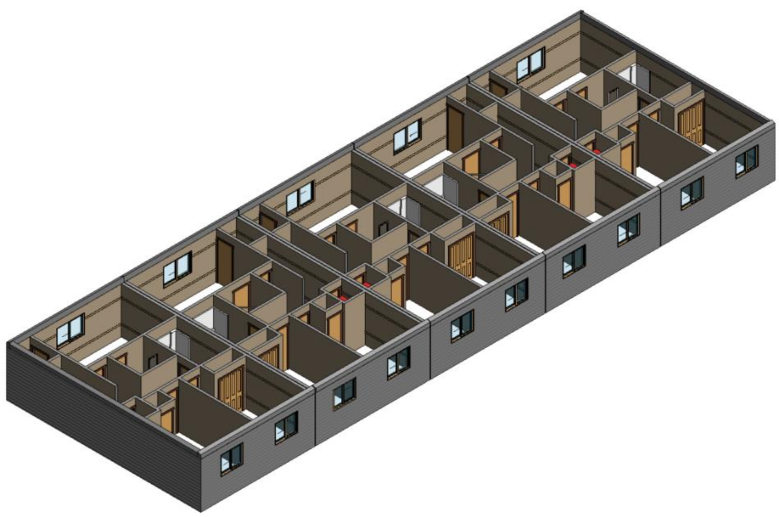


Figure 4-5 Second floor layout

The walls of the project were framed using an automated Revit add-on (Figure 4-6) and fitted into multi-panels by following the greedy algorithm shown in Figure 2-5, as proposed by Li (2016). A total of 51 multi-panels are generated with a maximum length of 40 ft. Two types of multi-panels are generated based on the type of walls fitted within the multi-panel as there are internal (2×4) and external (2×6) wall types. The following Table 1 shows a sample of the exported multi-panels information:

Table 1 Multi-panels information

Multi-Panel Name	Multi-panel Length (mm)	Panel Name	Length (mm)	Weight (kg)	Height (mm)	Thickness (mm)	Type	Nails	Cuts	Drill Holes	Vertical Stud	Horizontal Stud	Windows	Doors
Multi-Panel – 1	9734.6	Panel4	9734.6	330.98	2749.6	139.7	2x6 ext	64	2	4	26	6	0	0
Multi-Panel - 2	9734.6	Panel16	9734.6	287.31	2749.6	139.7	2x6 ext	54	2	4	25	2	0	0
Multi-Panel - 3	12154.3	Panel17	6045.2	201.83	2749.6	139.7	2x6 ext	39	4	4	17	2	0	0
Multi-Panel - 3	12154.3	Panel19	6083.7	191.61	2749.6	139.7	2x6 ext	36	2	4	16	2	0	0
Multi-Panel - 4	12063.8	Panel20	5993.2	191.61	2749.6	139.7	2x6 ext	37	4	4	16	2	0	0
Multi-Panel - 4	12063.8	Panel18	6045.2	191.61	2749.6	139.7	2x6 ext	36	2	4	16	2	0	0
Multi-Panel - 5	11785.6	Panel12	5880.1	329.33	2749.6	139.7	2x6 ext	42	2	4	30	0	1	0
Multi-Panel - 5	11785.6	Panel13	5880.1	329.33	2749.6	139.7	2x6 ext	43	4	4	30	0	1	0
Multi-Panel - 6	11734.4	Panel1	5829.3	300.84	2749.6	139.7	2x6 ext	43	4	4	30	0	1	0
Multi-Panel - 6	11734.4	Panel14	5879.7	329.33	2749.6	139.7	2x6 ext	42	2	4	30	0	1	0
Multi-Panel - 7	11682	Panel3	5829.3	191.61	2749.6	139.7	2x6 ext	36	2	4	16	2	0	0
Multi-Panel - 7	11682	Panel15	5827.3	329.33	2749.6	139.7	2x6 ext	43	4	4	30	0	1	0
Multi-Panel - 8	11985.6	Panel43	2225.7	72.27	2749.6	88.9	2x4 int	21	4	4	8	2	0	0
Multi-Panel - 8	11985.6	Panel10	9734.6	182.84	2749.6	88.9	2x4 int	54	2	4	25	2	0	0
Multi-Panel - 9	11985.6	Panel65	2225.7	72.27	2749.6	88.9	2x4 int	21	4	4	8	2	0	0
Multi-Panel - 9	11985.6	Panel11	9734.6	182.84	2749.6	88.9	2x4 int	54	2	4	25	2	0	0
Multi-Panel - 10	11985.6	Panel2	9734.6	182.84	2749.6	88.9	2x4 int	54	2	4	25	2	0	0
Multi-Panel - 10	11985.6	Panel53	2225.7	72.27	2749.6	88.9	2x4 int	21	4	4	8	2	0	0

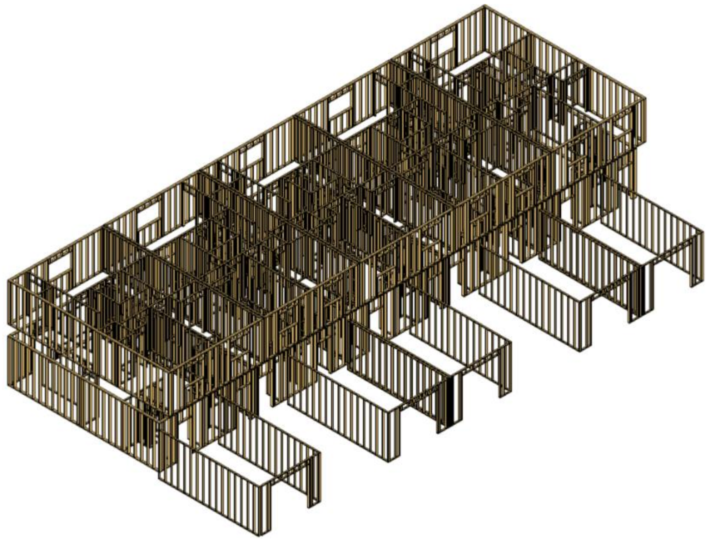


Figure 4-6 3D view of the framed wall panels

4.3 The machine's logic of operation

The machine's logic is investigated to achieve a clear understanding of each executed movement needed to perform the required operations ($N_{i,t}$, $D_{i,t}$, $C_{i,t}$). The machine's logic is a series of micro-operations performed in a defined sequence to serve the final objective required in each operation. Thus, each operation type requires its own set of movements in a unique order. The logic is hardcoded in the machine, and it follows the operations information provided in the CNC codes ($CNC_{n,i}$); therefore, the CNC code is a prerequisite by the machine to operate and perform the required motion as per the coded logic. As described in Section 3.5, CNC codes generation; the CNC code incorporates the information of the required operations in a readable format that the machine can follow. For the wood-framing machine under study, the main operations that the machine can handle are nailing ($N_{i,t}$), drilling ($D_{i,t}$), and cutting ($C_{i,t}$), as has been detailed before. However, for the machine to read this information and run according to the coded logic, it requires the following identification system: each operation should be defined by a three-character code that accommodates the operation information where the first character indicates the type of operation, the second character further specifies the operation, and the last character indicates at which side of the wall panel the operation occurs. The second character of the operation code depends on the definition of the first character; therefore, the character defines the sub-operation type, for example, for the nailing operations ($N_{i,t}$); the second character describes the element type on which the operation is performed (i.e., vertical (*V*), horizontal top (*T*), and horizontal bottom (*B*) studs). The code also identifies the start and end position of the framing components (i.e., window opening, door opening, and special-shaped elements) since they require a special processing technique. The characters used in the machine's code are listed in Table 2, and following this identification system, a list of operation codes can be generated and used in the machine's logic to define the required parameters of the executed operation.

Table 3 summarizes the operation codes that the machine can perform based on the machine's configurations and the coded logic. Figure 4-7 shows the types of wood frame elements used in the CNC codes and the machine's logic of operation.

Table 2 Wood-framing machine operations identification system

First Character	Second Character		Third Character
Nail: ***N***	Vertical: ***V***	Nail Exclusive	Left: ***L***
	Top: ***T***		
	Bottom: ***B***		
Drill: ***D***	Placeholder: ***R***	Drill Exclusive	Right: ***R***
Cut: ***C***	Full Cut: ***F***	Cut Exclusive	
	Partial Cut: ***P***		
Component: ***K***	Start: ***S***	Component Exclusive	Both: ***B***
	End: ***E***		

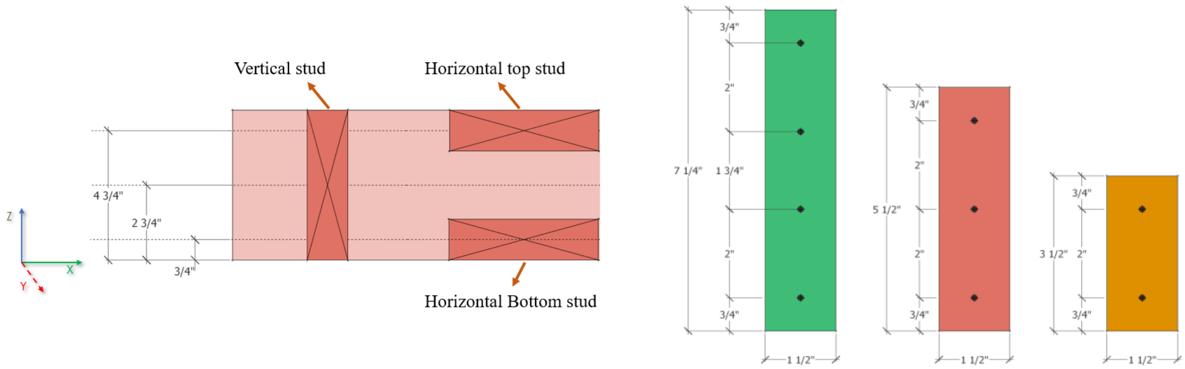


Figure 4-7 Wood frame elements

Table 3 Machine's operations codes

NVB: Nailing Vertical Both sides	NTL: Nailing Top Left side
NVR: Nailing Vertical Right side	DRB: Drilling Both sides
NVL: Nailing Vertical Left sides	DRR: Drilling Right side
NBB: Nailing Bottom Both sides	DRL: Drilling Left side
NBR: Nailing Bottom Right side	CPB: Cutting Partial Both sides
NBL: Nailing Bottom Left side	CFB: Cutting Full Both sides
NTB: Nailing Top Both sides	KSB: Component Start point
NTR: Nailing Top Right side	KEB: Component End point

The machine's logic can be expressed as a flowchart using decision elements to identify the operation type and the micro-operations related to it. Figure 4-8 shows a flowchart for the operation routine that the machine follows at the start of each operation, as well as the vertical nailing operation sequence:

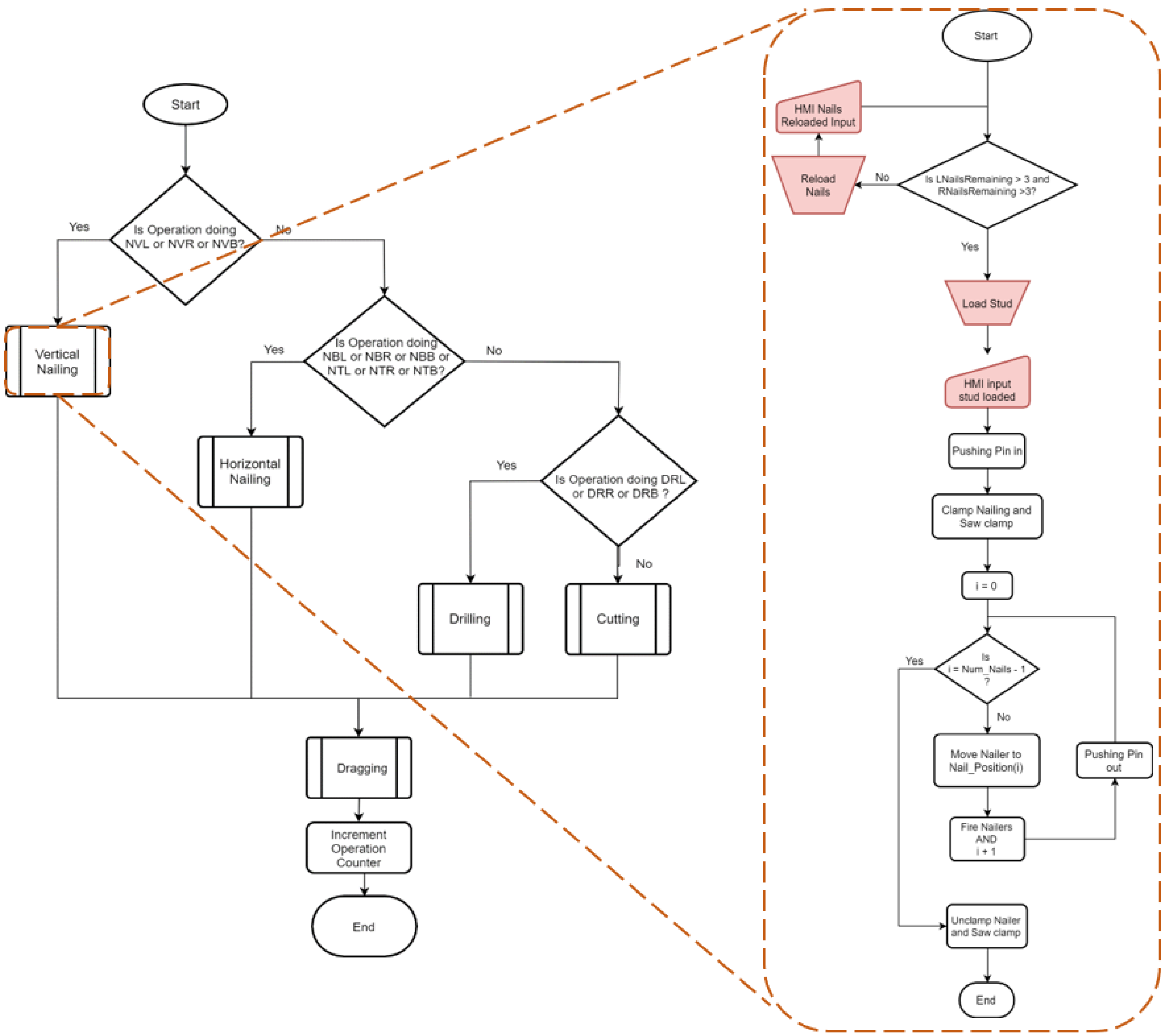


Figure 4-8 Flow chart for the coded nailing logic

For each operation type, the cycle time ($CT_{t,n,\mathrm{i}}$) is calculated based on the machine's logic and satisfying Equation (28):

$$CT_{t,n,\mathrm{i}} = \sum(MT_{t,n,i}) + \sum(m_{t,n,i} * PT_{r,t,n,i} + k * ET_{r,t,n,i}) \tag{28}$$

where:

$CT_{t,n,\mathrm{i}}$ is the cycle time of the task (t) in the wall panel (n) performed by the machine (i) (second);

$MT_{t,n,i}$ is the manual operations performed by the machine operator (second);

m is the number of movements required to be performed by the pneumatic actuator (r) to complete the task (t);

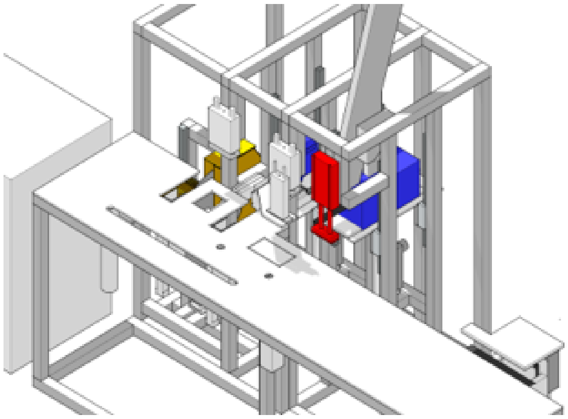
$PT_{r,t,n,i}$ is the cycle time of the pneumatic actuator (r) (second);

k is the number of movements required to be performed by the electric actuator (r) to complete the task (t); and

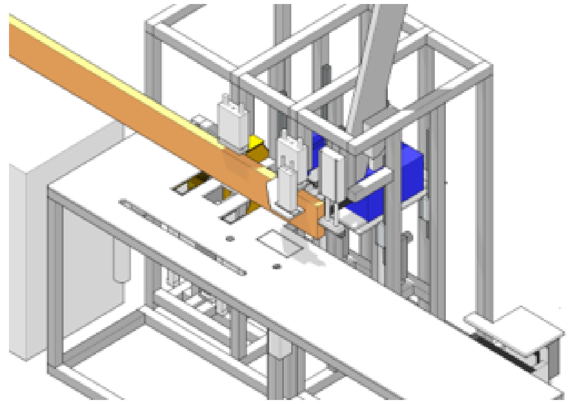
$ET_{r,t,n,i}$ is the cycle time of the eclectic actuator (r) (second).

The human interaction between the operator and the machine is accomplished via a programmed human machine interface (HMI). The operator's tasks are divided between loading the wall panel's plates and the structural elements of the wall frame, and refilling the nail slots for each nailer when required. The following Figure 4-9 shows a detailed view of the sequence of operations that the machine follows in the situation of loading the wall's top and bottom plates.

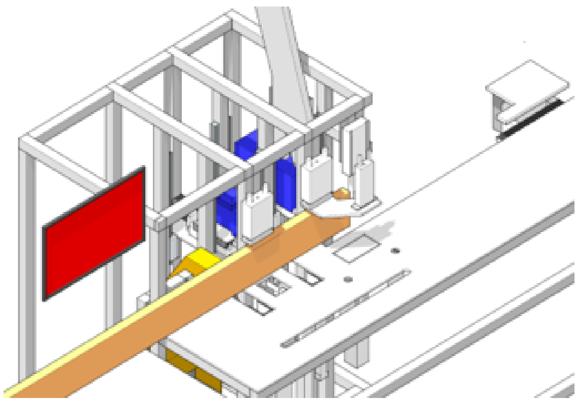
Following the same operation analysis through the entire machine's logic leads to the determination of all the moving parts of the machine during each operation and the distance traveled by each one. This information is beneficial for the estimation part of this research.



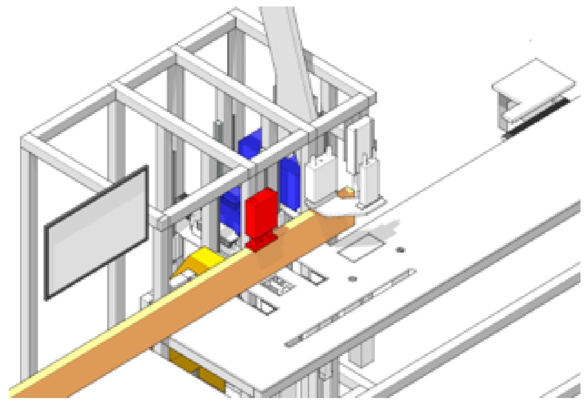
Step #1: Activate stopping clamp (S)



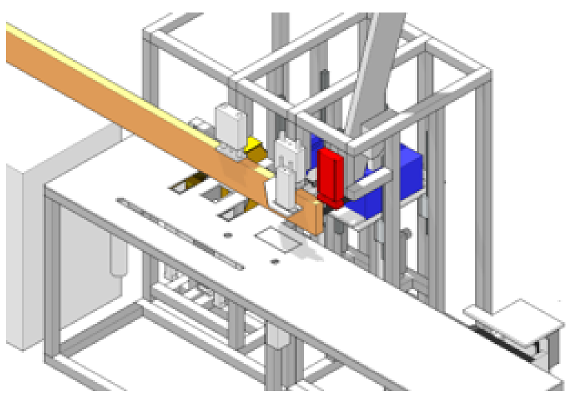
Step #2: Load top and bottom wood plates



Step #3: Press the HMI button to indicate that the plates have been loaded



Step #4: Activate Top clamp (T) so that the plate does not move



Step #5: Deactivate Stopping clamp (S)

Figure 4-9 The sequence of operation of loading the wall's plates

4.4 Machine motion analysis

As per the machine's logic, each movement of the machine is defined based on the operation type. Since each part is powered by a special type of linear actuator, as has been stated in Section 3.3, the machine's configurations are investigated to identify the type and model of each actuator used in the machine's structure. The actuators specifications such as the stroke (*PSr,i,t*), rod (*Prr,i*), applied pressure (*Ppr,i*), the maximum (*Vmax*) and minimum (*Vmin*) speed are also collected to calculate the movement duration (*Tt,n,i*)of each part in each operation. Starting with the pneumatic actuators (*Pr,i*), since the part motion is restricted to two states only, fully extracted and fully retracted, the distance traveled in each motion is predefined and equal to the stroke of the actuator (*PSr,i,t*), as shown in Equations (3-6). Nevertheless, the speed of the actuator differs between the two states as it's a function of the effective area of the air cylinder (*PAr,i*), for the extending state, the effective area is calculated satisfying Equation (29):

$$PA_{r,i} = RA_{r,i} = 0.25\pi(Ar_{r,i})^2 \tag{29}$$

where:

$PA_{r,i}$ is the effective area of the air cylinder in the actuator (r) and the automated machine (i) (mm^2);

$RA_{r,i}$ is the total rod area in the actuator (r) and the automated machine (i) (mm^2); and

$Ar_{r,i}$ is the bore diameter in the actuator (r) and the automated machine (i) (mm^2).

While for the retraction state, the effective area is calculated as per Equation (30):

$$PA_{r,i} = RA_{r,i} = 0.25\pi(Ar_{r,i} - Rr_{r,i})^2 \tag{30}$$

where:

$Rr_{r,i}$ is the rod diameter in the actuator (r) and the automated machine (i) (mm^2).

Investigating the motion of the electric actuators (*Er,i*) requires the examination of multiple influencing factors since the actuators are run by motors, not air pressure. The electric motors used for the remaining machine parts are listed in Table 4 , and the influencing factors are considered as explored in Section 3.3 and collected from the manufacturer specifications based on the motor's model. Since the electric motors are able to reach any point within the range of the actuator's full stroke, the speed of each movement based on the required stroke should be calculated in order to calculate the cycle time for this movement, taking into account the acceleration, deceleration and the settling of the motor in each movement. Table 5 summarizes the results of the calculations for each pneumatic actuator combined with the required information found in the specifications provided by the manufacturer of the parts. The speed of the piston is compared to maximum and minimum speeds, as advised by the manufacturer. The duration is then calculated as per Equations (3-6) based on the preferred value for the speed.

Table 4 The machine's electric motors

	Part name	Model	Type	Full Stroke (mm)
E_1	Lifting plate (LP)	LEY25B-150MG	Electric	150
E_2	Nailer (N)	LEY25B-150MG	Electric	150
E_3, E_4	Drill (D)	LEY25B-150MG	Electric	150
E_5	Cutting Saw (W)	LEY25B-150MG	Electric	150
E_6	Dragging jaw (DG)	LMDCE851	Electric	

Table 5 The machine parts specifications

	Part name	Actuator model	$PS_{r,i,t}$ (mm)	$PA_{r,i}$ (mm^2)	$Pp_{r,i}$ (psi)	V_{min} (mm/s)	V_{max} (mm/s)	$CS_{r,t,i}$ (mm/s)	$T_{,r,n,i}$ (s)
P_1	Stopping pin (SP)	CG1FN50-150FZ	150	1963	90	50	1000	600	0.25
P_2	Pulling pin (PP)	NCGLN50_2400	610	1709	90	50	1000	610	1
P_3	Pushing pin (HP)	CG1BN50_200Z	200	1963	90	50	1000	666	0.3

P_4	Guiding pin (GP)	CG1FN50-100FZ	100	1963	90	50	1000	666	0.15
P_5	Dragging clamp (DC)	MGPM63_100Z	100	3117	90	50	1000	666	0.15
P_6	Stopping clamp (S)	MGPM32_150Z	150	804	90	50	500	375	0.4
P_7	Top clamp (T)	MGPM32_100Z	100	804	90	50	500	370	0.27
P_8	L-Clamp (L)	MGPM32_100Z	100	804	90	50	500	370	0.27
P_9	Inside clamp (I)	MDBD40TN-50N	50	79	90	50	500	333	0.3

The first step towards the motion analysis for the electrical motors starts by analyzing the required travel distance for each movement based on the operation type and the coded logic:

1. For the nailing operations ($N_{i,t}$) and as shown in Figure 4-7, three different nailing patterns and levels are defined based on the element type and size as follows:
   a. For the 2×4 studs where two nails are used for this type.
   b. For the 2×6 studs where three nails are used.
   c. For the 2×8 horizontal studs where four nails are used to fasten the stud into the wall plates (this type is only used in the horizontal state).

   However, the nailing levels are divided into three levels for all the nailing types as follows:
   a. At the 20 mm (3/4 inch) y-position, at this level, the horizontal nailing is performed for all the stud types, and the first nail is placed at this level for both 2×4 and 2×6 vertical studs.
   b. At the 70 mm (2 ¾ inch) y-position, the second and final nail for the vertical 2×4 studs is placed at this level, and also the second nail for the 2×6 vertical studs.
   c. At the 121 mm (4 ¾ inch) y-position, where the last nail for the 2×6 vertical studs is placed. The nailer's stroke for each movement between these levels will follow the distance between them as expressed in the following equations:

   The motor's traveled distance ($EL_{r,i,t}$) for each movement follows Equation (31, 32):

For the extending state:

$$EL_{r,i,t} = NY_{l,n,m} - NY_{l-1,n,m} \quad (31)$$

For the retracting state:

$$EL_{r,i,t} = NY_{l,n,m} - NY_{0,n,m} \quad (32)$$

where:

$EL_{r,i,t}$: the traveled distance required to complete the nailing task (t) by the electric actuator (r) in the automated machine (i);

$NY_{l,n,m}$: the y-coordinate of the nail (l) in element (m) in the wall panel (n);

$NY_{l-1,n,m}$: the y-coordinate of the nail (*l-1*) in element (m) in the wall panel (n); and

$NY_{0,n,m}$: the y-coordinate of the zero position of the nailer's motor (the first nail).

The nailer's zero position in the studied machine is at the first nailing level (y=19 mm), which means that the first nail for each vertical stud is performed without any additional movement. The same is true for the horizontal nailing of all the stud types since all the horizontal nailing positions are located at the first nailing level. By applying the previous method on the other vertical stud types used on the machine, the traveled distances are calculated satisfying Equations (31-32). The results obtained are shown in Table 6:

Table 6 Nailers motors stroke

Required stroke (mm)/ Stud type	Second nail (Extending) (mm)	Third nail (Extending) (mm)	Settling (Retraction) (mm)
2×4 Vertical	51	n/a	51
2×6 Vertical	51	51	102

2. For the drilling operations ($D_{i,t}$), only two drilling levels are used based on the wall's plates size. The drilling operations occur vertically in the center of the wall plates, for the 2×4 plates,

the drilling level is at the 44 mm (1 ¾") y-position, and at the 70 mm (2 ¾") y-position for the 2×6 vertical studs. The zero position for the drills is set at the first drilling level (44 mm), which means that there is no need for any vertical movement in the case of 2×4 studs. However, a vertical movement with a 26 mm (70 - 44 = 26 mm) stroke is required to perform the drilling operations for the 2×6 studs.

3. For the circular cutting saw ($C_{i,t}$) vertical movement, there are two types of operations performed by the saw: the partial cuts, and the full cuts. Each of these operations requires special vertical movement; thus, the stroke value is determined for the electric motor based on the wall plates size. The circular saw's zero position is located at the (0 mm) y-position, and the stroke required for each movement is calculated using Equation (33):

$$EL_{r,i,t} = CY_{r,t,n} - CY0_{r,i} \quad (33)$$

where:

$EL_{r,i,t}$: the traveled distance required to complete the nailing task (t) by the electric actuator (r) in the automated machine (i);

$CY_{r,t,n}$: the y-coordinate of the cutting task (t) in the wall panel (n); and

$CY0_{r,i}$: the y-coordinate of the zero position of the cutting saw motor.

Table 7 summarizes the required travel distance values for the circular saw's motors to complete each type of operation for each stud size based on the machine's logic and satisfying Equation (33).

Table 7 The circular saw's motor's stroke

	Partial cut distance (mm)	Full cut distance (mm)
2×4 Plates	45	89
2×6 Plates	70	140

4. For the dragging jaw movement, in this situation, the motor's traveled distance value is a variable that depends on the dragging distance required between the two sequenced operations ($\Delta x_{t,n,i}$). This value can vary significantly for each wooden panel. The traveled distance can be expressed, as shown in Equation (34):

$$EL_{r,i,t} = \Delta x_{t,n,i} = x_{(t),n,i} - x_{(t-1),n,i} \tag{34}$$

where:

$x_{(t-1),n,i}$: the motor's x-position after completing the operation (*t-1*); and

$x_{t,n,i}$: the x-position of the following operation (*t*).

Based on the machine's logic ($MG_{i,j}$), two arguments are investigated in this case:

i. In the first operation, there is no predecessor operation in this situation to refer to. In this situation only, the dragging jaw moves to the zero position ($dgx0_{r,i}$) to clamp on the wall frame and drag it for a distance equal to ($\Delta x0_{t,n,i}$) as per Equation (35):

$$EL_{r,i,1} = \Delta x0_{t,n,i} = x_{(1),n,i} - dgx0_{r,i} \tag{35}$$

where:

$x_{(1),n,i}$: the x-position of the first operation in the wall panel; and

$dgx0_{r,i}$: the x-position of the dragging jaw zero position.

However, since the motor moves back to the home position ($dgh_{r,i}$) after completing the dragging process, the retraction distance, in this case, is equal to ($\Delta xR_{t,n,i}$), where the dragging jaw home position is the position it moves back to after completing each task (the settling position). This can be expressed, as shown in Equation (36):

$$EL_{r,i,1} = \Delta xR_{t,n,i} = x_{(1),n,i} - dgh_{r,i} \tag{36}$$

where:

$x_{(1),n,i}$: the x-position of the first operation in the wall panel; and

$dgh_{r,i}$: the x-position of the dragging jaw home position.

ii. The regular movement between each operation and the operation that follows it, the traveled distance, in this situation is always equal to ($\Delta x_{t,n,i}$), as expressed in Equation (34). The retraction distance is always the same as the extended distance in this situation.

For the machine under study, the following are the values used for the dragging jaw zero position ($dgx0_{r,i}$), and the motor's home position ($dgh_{r,i}$) with respect to the machine's zero position ($X_{ZO\ i,j}$) and as collected from the machine's specifications:

$$dgx0_{r,i} = -40\ mm$$

$$dgh_{r,i} = 150\ mm$$

Subsequently, and since the motor's traveled distance ($EL_{r,i,1}$) has been defined for each particular task, the speed of the motors is investigated as proposed in Chapter 3 in order to calculate the cycle time ($ET_{r,n,i}$) for each task completed by the electric motors. As was shown in Table 4, the same model of the electric motor is used for the vertical movement of the nailing, drilling, and cutting systems, and the properties of the motor are provided by the manufacturer guide and used to calculate the motor's average speed and cycle time ($ET_{r,n,i}$) using Equations (11–17) as follows:

The cycle time [seconds]:

$Assuming\ that$: $\boldsymbol{EL_{r,i,t} > d_1}$:

$$a_{1(r,i)} = a_{1(r,i)} = 3000\ mm/s^2$$

$$V_{r,i} = 100\ mm/s$$

$$ET_{r,n,i} = \sum T_{(r,n,i)} : \quad y = (1,2,3,4)$$

$$T_{1(r,n,i)} = {V_{(r,i)}}/{a_{1(r,i)}}, \qquad T_{3(r,n,i)} = {V_{(r,i)}}/{a_{3(r,i)}} \rightarrow T_{1(r,n,i)} = T_{3(r,n,i)} = \frac{100}{3000} = 0.03\ s$$

$$T_{2(r,n,i)} = \frac{EL_{r,i,t} - 0.5V_{r,i}\left(T_{1(t,n,i)} + T_{3(t,n,i)}\right)}{V_{r,i}} = \frac{EL_{r,i,t} - 0.5 * 100(0.03 + 0.03)}{100}$$

$$\rightarrow T_{2(r,n,i)} = 0.01EL_{r,i,t} - 0.03\ (\mathrm{s})$$

where $T_{4(r,n,i)}$, the motor's settling time is assumed to be 0.2 s;

$$ET_{r,n,i} = \sum T_{(r,n,i)} = 0.03 + \left(0.01EL_{r,i,t} - 0.03\right) + 0.03 + 0.2 = 0.01EL_{r,i,t} + 0.23\ (\mathrm{s})$$

4.5 CNC tool development

A CNC tool is developed as an add-on to Autodesk Revit via API (Figure 4-10). The main purpose of the developed tool is to implement some of the proposed objectives of this research into a case study of wood-framing machines, where the machine's specifications can be predefined and inputted into the tool using the developed graphical user interface (GUI). The developed tool has the ability to locate the operations' positions ($G_{t,n,i}$) from the BIM model by following the previous methodologies proposed by An et al. (2019, 2020), Li (2016), and Li et al. (2017). The collected information is integrated with the machine's specifications and translated into a CNC code that is readable by the automated wood-framing machine. For the case study implementation, the CNC code is generated as a Recipe file extension. The format of the Recipe file is shown in Figure 4-11. The offsets ($O_{t,i}$) between the machine's configurations and the machine's zero position ($X_{ZO\ i,j}$) are coded as an input parameter for the user to specify based on the machine's structure as well as the number of drills and cutting saws used in the machine, if applicable.

The machine's configurations offset ($O_{t,i}$) are used to rearrange the framing operation in the right order as performed by the machine to keep the production flow in one direction, instead of following only the geometric order based on the wall frame starting point, and are also used to check the manufacturability of the exported tasks.

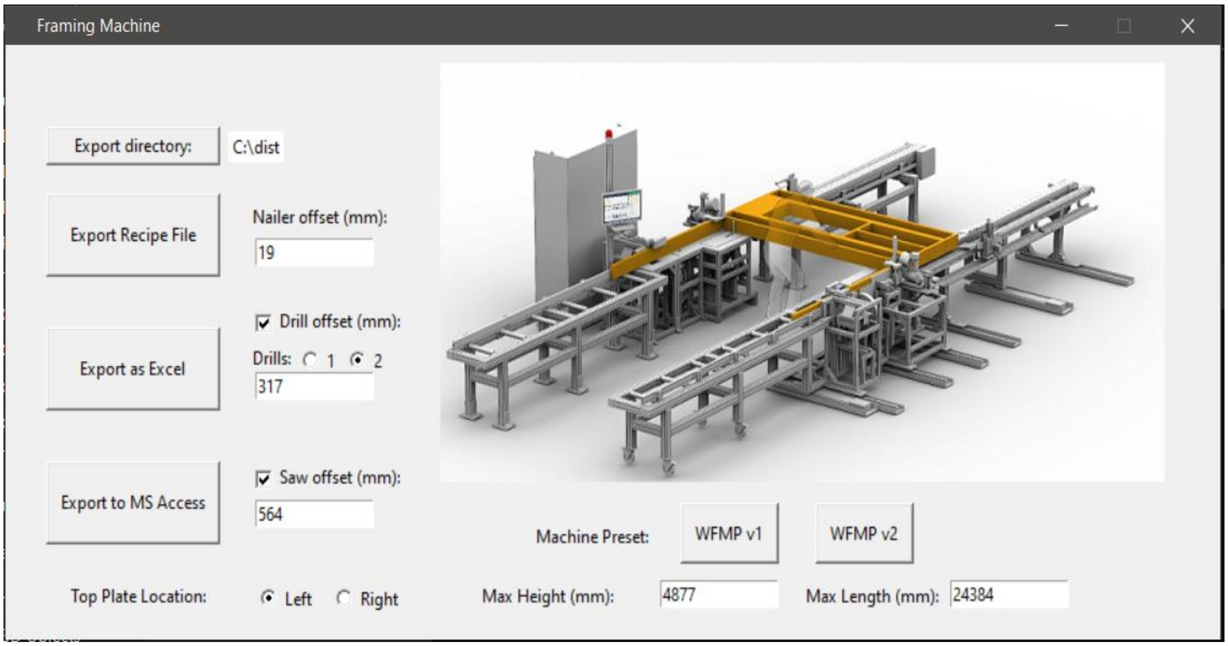


Figure 4-10 CNC tool GUI

Equation (25) is used to achieve this objective, as described in Section 3.5: CNC codes generation:

$$newX_{t,n,i} = x_{t,n,i} - O_{t,i} > X_{ZO\ i,j} \qquad (25)$$

where:

$X_{ZO\ i,j} = 40\ mm$

Nailer's offset:

$O_{t,i} = 19\ mm$

Drill's offset:

$O_{t,i} = 317\ mm$

Saw's offset:

$$O_{t,i} = 564\ mm$$

Additionally, the machine's limitations in regards to the maximum frame height ($maxWH_n$) and maximum frame length ($maxWL_n$) that the machine can handle are inputted into the tool in order to check the manufacturability of the wall frame. The combination of the machine's limitations and the machine's configurations specifications are used to check the multi-panel's measurements (WH_n, WL_n) as well as the positions of operations ($G_{t,n,i}$) on the multi-panel to decide on the manufacturability of each operation. Each multi-panel that has a non-feasible measurement will be skipped without generating the CNC code for it since the machine can not manufacture it based on its limitations. However, if one or more of the operations in a multi-panel is out of the related machine's system reach, it will cause the removal of these operations, and their information will be provided for the operator to perform manually. Figure 4-12 shows examples of the operations manufacturability check results based on the previously mentioned parameters.

Additionally, the detailed information regarding the operations, as well as the multi-panel's measurements, can be exported using the developed tool into Microsoft Excel format and into a Microsoft Access database. The database output is required for use as an information source for the purposes of the machine's production estimation by either following the developed estimation equations or using the developed mathematical simulation model. The exported database structure is shown in Figure 4-13.

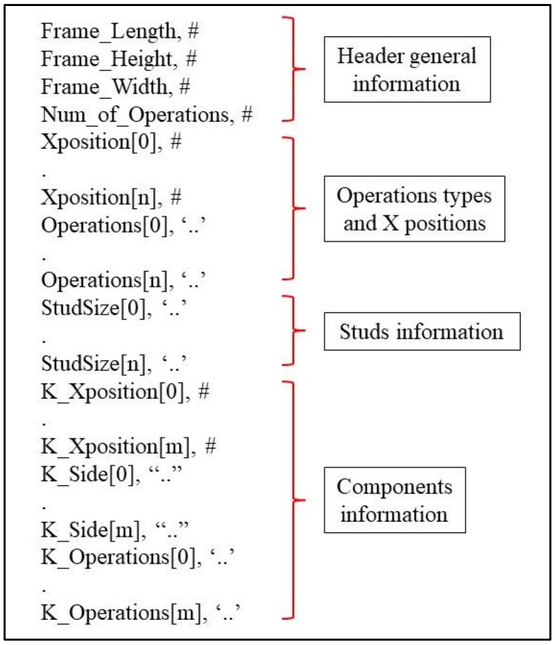


Figure 4-11 Recipe file format

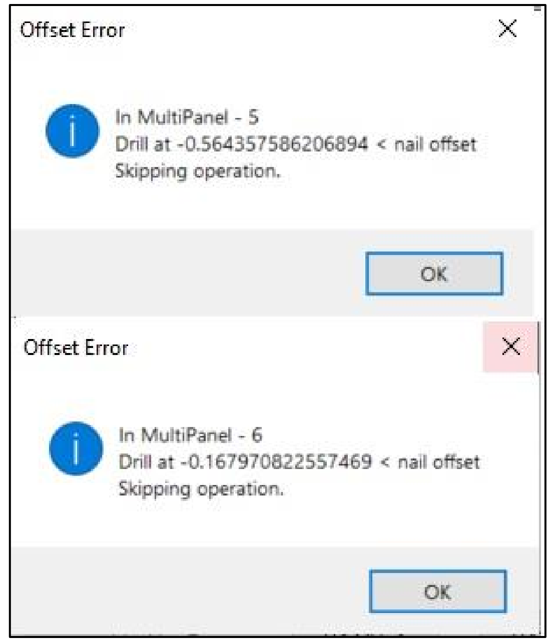


Figure 4-12 Manufacturability check results

ID	MultiPanelName	PanelName	Operation	X	Y	Z	Type	Size	Machine	Comp
204	MultiPanel - 6	Panel14	Nail	19	0	70	Stud V	2x6	NVB	
205			Drill	149	0	70			DRB	
206			Nail	375	0	70	Stud V	2x6	NVB	
207			Nail	413	0	70	Stud V	2x6	NVB	KSB
208			Nail	451	0	70	Jack Stud	2x6	NVB	
209			Nail	489	0	70	Cripple	2x6	NVR	
210			Nail	813	0	70	Cripple	2x6	NVB	
211			Nail	1219	0	70	Cripple	2x6	NVB	
212			Nail	1626	0	70	Cripple	2x6	NVB	
213			Nail	2032	0	70	Cripple	2x6	NVB	
214			Nail	2438	0	70	Cripple	2x6	NVB	
215			Nail	2826	0	70	Cripple	2x6	NVB	
216			Nail	2864	0	70	Cripple	2x6	NVR	
217			Nail	2902	0	70	Jack Stud	2x6	NVB	
218			Nail	2940	0	70	Stud V	2x6	NVB	KEB
219			Nail	3232	0	70	Stud V	2x6	NVB	
220			Nail	3639	0	70	Stud V	2x6	NVB	

Figure 4-13 Exported database format

4.6 Production estimation

Following the logic of the machine, the production estimation is forecasted using the developed Equation (28) based on the operation type.

$$CT_{t,n,\mathrm{i}} = \sum MT_{t,n,i} + \sum(m_{t,n,i} * PT_{t,n,i} + k * ET_{t,n,i}) \quad (28)$$

As an example, the equation is implemented for the vertical nailing operation from both sides of the wall panel (*NVB*) where the required machine movements are performed as per the following sequence:

Step 1. The number of nails in each nailer's slot ($NQ_{l,j}$) is checked for any required refilling (MT_R) by the operator if the remaining nails are less than the number of nails required to complete the task ($NR_{l,j}$). A time study was conducted on the machine to determine the duration of the manual operations, and it was found that the nailer refill process takes 15 s on average. Equations (37) and (38) summarizes the previous description.

$$NQ_{l,j} \leq NRl,j \ \rightarrow \ MT_R = 15\ s \quad (37)$$

$$NQ_{l,j} > NRl,j \ \rightarrow \ MT_R = 0 \quad (38)$$

Step 2. The guiding pin (*GP*) moves up for easy loading of the wood element—the vertical stud—by activating the pneumatic actuators connected to it (P_4).

Step 3. The operator manually loads the wood element (MT_L) against the guiding pin (*GP*). The duration of this manual task is also collected during the conducted time study and is found to be 22 s on average in the case of regular vertical studs.

Step 4. The pushing pin (*HP*) moves up using the pneumatic actuator (P_3). Subsequently, the guiding pin (*GP*) retracts back to its position.

Step 5. The pulling pin (*PP*) moves horizontally—by way of the pneumatic actuator (P_2)—to pull the loaded studs into the machine's loading plates, which represent the machine's zero position ($XZO_{i,j}$).

Step 6. The clamping system (i.e., top clamp (*T*), L-clamp (*L*), and inside clamp (*I*)) gets activated by activating the actuators (P_7, P_8, P_9).

Step 7. The pulling (*PP*) and pushing pins (*HP*) retract back as the nailing process starts.

Step 8. The nailing process starts, assuming the stud size is (2×4 inches), the number of nails ($NN_{n,m}$) required, in this case, is two nails divided between two nailing levels (one nail per level). As was described in Section 4.4 (i.e., Machine motion analysis), the first nailing level doesn't require a vertical movement by the nailer's electric actuator (E_2). However, after firing the first nail, the nailer moves vertically by 51 mm to reach the second nailing level, where the nailer fires the second nail and retracts to the home position by moving 51 mm back.

Step 9. The clamping system gets deactivated, and the clamps move back to their positions.

Step 10. The dragging process starts with the dragging jaw (*DG*).

The previous steps (1 to 9) that describe the vertical nailing operation can be implemented in the developed estimation Equation (28), which results in the following Equation (39) as follows:

$$CT_{NVB,n,\mathrm{i}} = (MT_R + MT_L) + (1 * PT_2 + 1 * PT_3 + 2 * PT_4 + 2 * PT_{(7,8,9)} + 2 * ET_2) \quad (39)$$

Following the same approach on all the other operation types results in the accurate estimation of the duration of these operations, and by considering the sequence of the operations for each wall panel, the production duration estimates are stored in the exported database, and a table can be generated that includes the total framing duration of the single panels in the first 25 multi-panels on the database, including the length of the single panel and the source multi-panel, along with the number of operations that are required to complete the wall frame, as is shown in Table 8.

Table 8 Wall panels framing duration

Multi-Panel Name	Multi-panel Length (mm)	Single Panel Name	Single Panel Length (mm)	Operations Count	Framing Duration (min)
Multi-Panel - 1	9735	Panel4	9735	35	10.35
Multi-Panel - 2	9735	Panel16	9735	30	8.44
Multi-Panel - 3	12154	Panel17	6045	25	6.33
Multi-Panel - 3	12154	Panel19	6084	19	4.98

Multi-Panel - 4	12064	Panel20	5993	24	6.09
Multi-Panel - 4	12064	Panel18	6045	19	4.96
Multi-Panel - 5	11786	Panel12	5880	23	4.73
Multi-Panel - 5	11786	Panel13	5880	28	5.87
Multi-Panel - 6	11734	Panel1	5829	28	6.85
Multi-Panel - 6	11734	Panel14	5880	23	4.73
Multi-Panel - 7	11682	Panel3	5829	19	4.92
Multi-Panel - 7	11682	Panel15	5827	28	5.86
Multi-Panel - 8	11986	Panel43	2226	17	3.54
Multi-Panel - 8	11986	Panel10	9735	27	6.70
Multi-Panel - 9	11986	Panel65	2226	17	3.63
Multi-Panel - 9	11986	Panel11	9735	27	6.75
Multi-Panel - 10	11986	Panel2	9735	27	6.70
Multi-Panel - 10	11986	Panel53	2226	17	3.59
Multi-Panel - 11	11986	Panel8	9735	27	6.75
Multi-Panel - 11	11986	Panel21	2226	17	3.63
Multi-Panel - 12	11915	Panel32	2226	13	2.59
Multi-Panel - 12	11915	Panel9	9664	32	7.98
Multi-Panel - 13	9595	Panel180	9595	34	8.30
Multi-Panel - 14	9595	Panel181	9595	31	7.63
Multi-Panel - 15	9595	Panel179	9595	29	7.20
Multi-Panel - 16	10394	Panel165	6470	19	4.61
Multi-Panel - 16	10394	Panel170	3899	23	4.27
Multi-Panel - 17	10394	Panel174	3899	24	4.62
Multi-Panel - 17	10394	Panel166	6470	18	4.26
Multi-Panel - 18	10301	Panel168	6470	18	4.26
Multi-Panel - 18	10301	Panel172	3806	21	3.69
Multi-Panel – 19	10301	Panel169	6470	18	4.26
Multi-Panel – 19	10301	Panel167	3806	22	3.99
Multi-Panel – 20	10188	Panel171	6470	18	4.26
Multi-Panel – 20	10188	Panel164	3693	22	4.01

4.7 Simulation model development

For the production estimation and maintenance scheduling purposes, a discrete event simulation (DES) model to mimic the motion of the wood-framing machine is developed using Simphony.NET (AbouRizk et al. 2014). The simulation model follows the same estimation approach presented in the previous section, where the duration of the tasks is calculated using Equation (28). The simulation model does, however, provide a higher level of automation for the estimation process. The output of the simulation would include an accurate parts life-usage calculation to use for the purpose of creating a maintenance schedule. The basic entities used in the simulation model are the framing operations in the multi-wall panel. The modelling of operations starts with reading records stored in the local database file that was exported using the CNC tool. Each entity represents a framing operation in a wall panel with all the properties attached to it, such as the operation ID, description, type, 3D coordinates, structural element type, the multi-panel name, and the single panel name. These properties are used for time calculations and to make branching decisions throughout the entity production cycle in the simulation. The simulation structure follows the machine's logic of operation for each operation type, and it starts with the machine calibration process at the beginning of the working shift, after the framing processes for the first operation starts depending on the operation type and the resources required for it. The following are the machine resources as modelled in the simulation: the machine operator, nailers, drills, cutting saws, inside clamp, top clamp, L clamp, guiding pin, pushing pin, pulling pin, pressing pin, and the dragging jaws. Each wall-framing operation, represented by a single entity, goes through a series of tasks based on its type, and the tasks required for each operation type are represented by a 'composite element' in the simulation, which encompasses several operations and activities related to that specific operation type. The simulation model structure is shown in Figure 4-14.

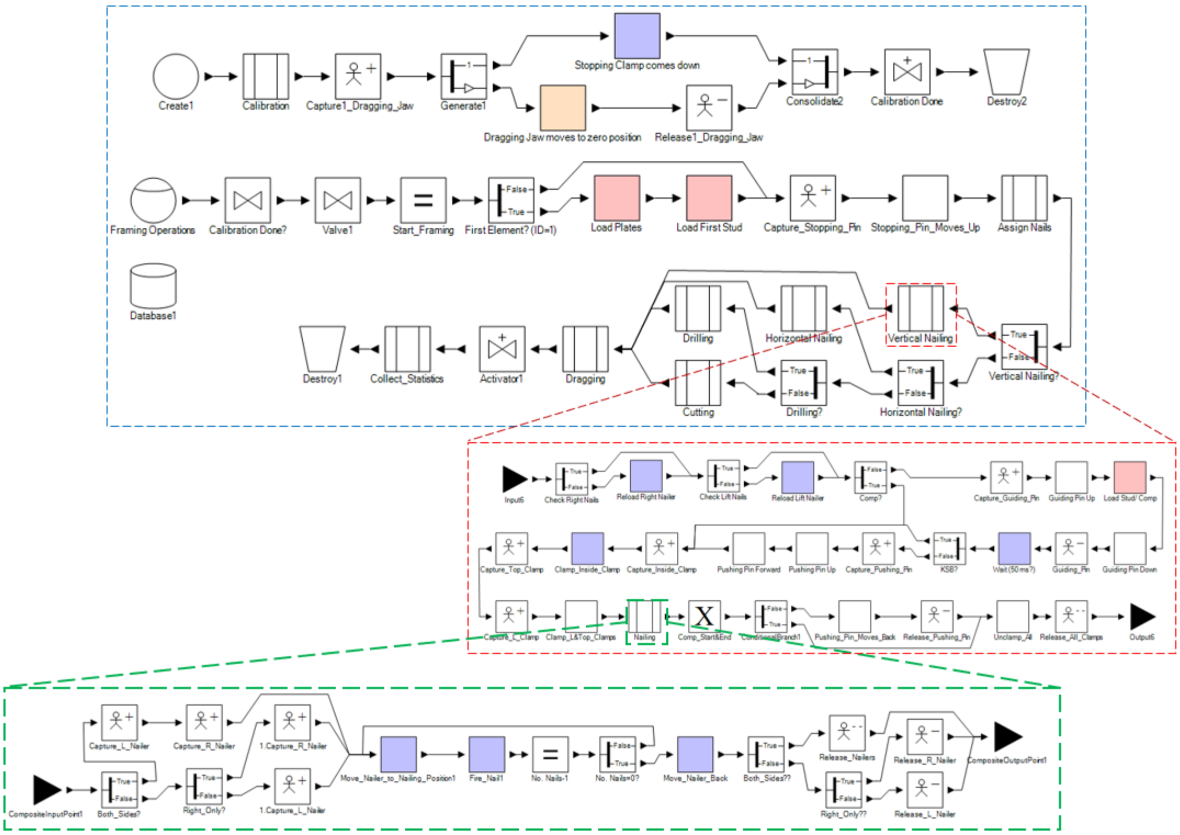


Figure 4-14 Simulation model of the wood-framing machine in Simphony.NET

Time differences between operations are calculated and collected in 'statistics' containers, which are used later to calculate the total production duration, along with resource utilization. A set of local and global variables are used in the simulation model for defining the operation's properties as read from the database and for calculating the production duration for each operation and each multi-wall panel in the project. Table 9 shows the types and descriptions of the variables as used in the simulation model.

Table 9 Local and global variables used in the simulation

Variable	Type	Description	Variable	Type	Description
LX (0)	Local/ Floating point	Operation ID	LS (1)	Local/ Text string	Element type

LX (1)	Local/ Floating point	Operation X-coordinate	LS (2)	Local/ Text string	Element size
LX (2)	Local/ Floating point	Operation Y-coordinate	LS (3)	Local/ Text string	Operation code
LX (3)	Local/ Floating point	Right side nails required	LS (4)	Local/ Text string	Component start/ end
LX (4)	Local/ Floating point	Left side nails required	LX (10)	Local/ Floating point	Operation starting time
LX (5)	Local/ Floating point	Operation Z-coordinate	LX (11)	Local/ Floating point	Operation finish time
LS (0)	Local/ Text string	Operation description	LX (12)	Local/ Text string	Operation duration
G X(0)	Global/ Floating point	No. of nails remaining on the right nailer	GX (1)	Global/ Floating point	No. of nails remaining on the left nailer

The results of the simulation model will be exported into a CSV file for the data analysis. The results indicate the automated machine's total framing duration for every single panel in the investigated multi-panels. The relationship between the framing duration and the panels' parameters is also studied. From the simulation results, the resource utilization can be observed, and based on that, the life-usage of each resource, which represents a machine part, is calculated to eventually compare it to the life expectancy of the specific part to check for any required maintenance that interferes with the production of the loaded panels. The calculation of the parts' life expectancies can follow the previous research conducted by Chang et al. (2013, 2014), Chen et al. (2012a; b), and Seong-woo (2018), and is outside the scope of the present research which only considers the life-usage of the machine parts. The framework presented herein will potentially allow for the scheduling of the predictive maintenance stops since they will be outlined before the start of the production by measuring the life-usage of each part of the machine accurately based on the motion analysis and perform a comparison to the life-expectancy of these parts. However, scheduling for the maintenance stops is highly related to the production scheduling process, which is outside the scope of this research, since the maintenance schedule depends on the cumulative life-usage of the machine parts and the sequence of the production of the wall panels which should be planned in the production scheduling phase, so only the parts' life-usage is being calculated in this framework which is highly significant to the predictive maintenance scheduling process.

4.8 Results and discussion

The production estimation results show that the total required duration to finish the total of 51 multi-panels of the studied project is 516 minutes, which is equal to 8.6 manhours since only one operator is required to operate the framing machine. This result could be used to generate accurate production and cost estimates that will be more efficient than the currently practiced estimation techniques, which only depend on the physical properties of the project, such as the total area or the length of the wall panels. The results indicate a direct relationship between the framing duration and the panel length, as well as the framing duration with the number of operations required to complete the wall frame. Scatter charts were developed to visualize the abovementioned relationships and to investigate these relationships in more detail.

Figure 4-16 and Figure 4-16 illustrate that the proposed estimation technique, where the production time is estimated based on the operation required for each panel and the analysis of the machine motion for each operation, is more reliable and accurate than the currently used technique where the production time is estimated based on the panel length only. The relationship in the first case, as shown in Figure 4-15, can be expressed as a linear trendline based on the calculated durations and the associated panels' length. However, the second case, shown in Figure 4-16, generates a better normally-distributed trendline, which indicates a stronger relationship between the two selected parameters and proves the higher accuracy of the proposed method.

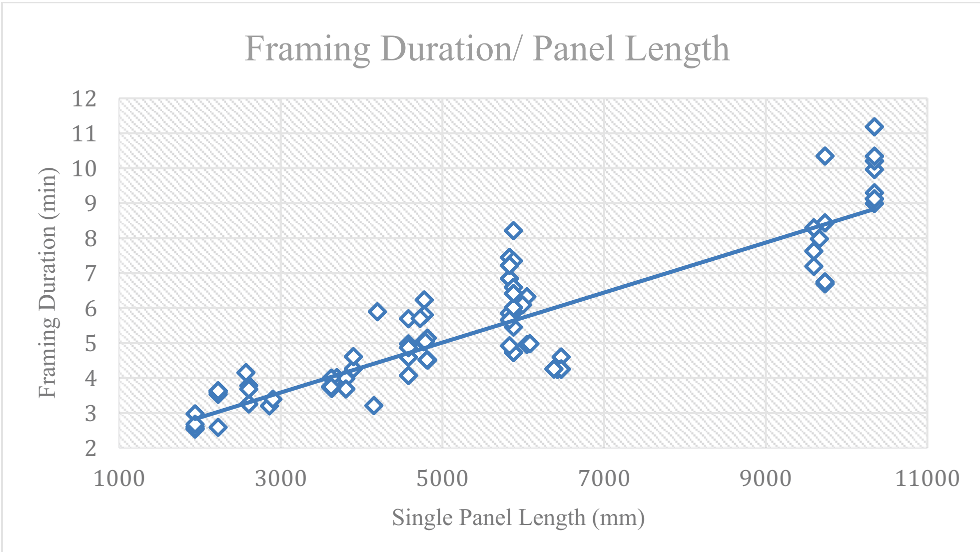


Figure 4-15 Relationship between the panel length and the framing duration

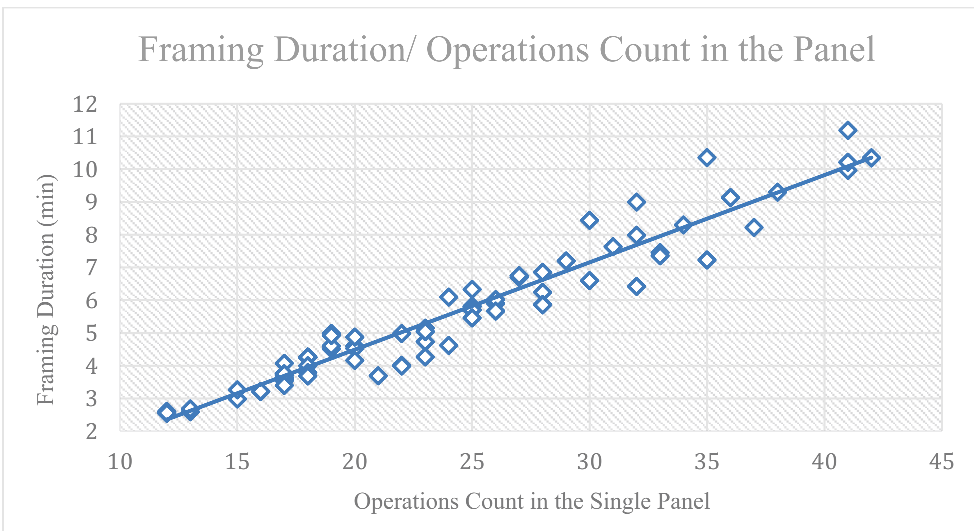


Figure 4-16 Relationship between the operations count in a panel and the framing duration

The utilization rate of the resources used in the simulation model, which includes the machine parts and the operator resources, are also explored in the simulation output. The exported results, as shown in Figure 4-17, illustrate the variation in utilization between the various machine parts and from this it can be observed that the most utilized part is the stopping pin (SP), while the right and left cutting saws have the lowest utilization rates.

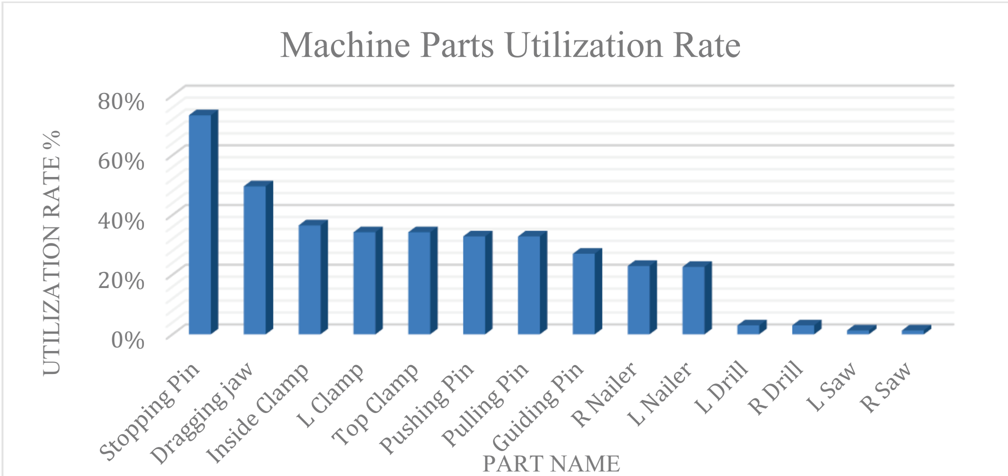


Figure 4-17 Machine parts utilization rates

The utilization rates (UR) of the machine parts are used to calculate the duration for which each part was utilized during the production process. Moreover, the number of cycles performed by each part is also calculated along with the distance travelled by each one, which indicates the life-usage of the investigated parts. Table 10 shows the results which can be correlated to the life expectancy of the machine parts and used to schedule the machine maintenance stops.

Table 10 Machine parts life-usage

Machine Part	UR %	Time Utilized (min)	No. of Cycles	Distance Travelled (M)	Machine Part	UR %	Time Utilized (min)	No. of Cycles	Distance Travelled (M)
SP	73%	379	1911	573.3	GP	27%	139	1911	382.2
DJ	50%	256	2231	1090.6	R N	23%	118	1782	119.1
I	37%	188	2230	223.0	L N	23%	117	1772	116.6
L	34%	176	2230	446.0	L D	3%	15	185	9.4
T	34%	176	2230	446.0	R D	3%	15	186	9.5
HP	33%	169	1911	764.4	L W	1%	7	135	9.4
PP	33%	169	1911	2331.4	R W	1%	7	135	9.4

Chapter 5 : Conclusion

5.1 General conclusion

A framework for a BIM-based automated system is developed to establish a direct connection between the BIM environment and the CNC automated machines on the production line. The developed system has the ability to export the information pertaining to the required manufacturing operations from the BIM model in a machine-readable CNC code format. In addition, the proposed automated system can check the manufacturability of a product based on the machine's configurations and limitations along with the machine's logic and provide a database containing the information for the manufacturable operations and the associated structural elements' properties to use for the purposes of production duration estimation. The moving parts of the machine's structure are investigated in terms of a motion analysis to calculate the speed and distance each part travels in each cycle. This information is used to generate accurate and detailed production estimates that rely on the production operations required to produce the product along with the physical and geometric information of the product, such as the dimensions of the elements in the product. The developed production estimation system is also used to calculate the life-usage of each part in the machine for use in the maintenance scheduling process.

The proposed automated system was developed and implemented in the Revit API environment for a case study of an automated wood-framing machine. A residential construction project was also used as a case study to examine the proposed methodology. A 3D BIM model for the project was modelled in Revit to generate the operations information. A detailed simulation model is developed to mimic the motion of the wood-framing machine under study and to generate accurate production estimates using the operations information exported from the BIM model.

5.2 Research contributions

- Proposing a BIM-based system for the automated manufacturing industry, which serves as a new method of connection between the design phase of the project and the CNC automated machines in the production lines.
- Developing a detailed automated production estimation system that is able to forecast the fabrication duration of the building's components with a high level of accuracy. The estimation is provided based on a detailed motion analysis of the parts of the machines based on the type and purpose of each part.
- Generating the machine-readable CNC codes using the developed system that can be provided to the machines directly from the BIM environment; hence, eliminating the dependency on third-party CAM software that requires preparation works to connect to the BIM model and to the machines afterwards, which is a time-consuming task to complete.
- Providing the ability to check the manufacturability of a project during the design phase based on the geometric information of the project and on the machine's specifications and sequence of operations, which defines the machine's limitations. Adjustments can then be made to the design directly without waiting for feedback from the production crew.
- Proposing a potential maintenance prediction and scheduling method for the automated machines depending on the usage of the machines' parts, where the parts usage can be compared with the life expectancy of the parts to schedule for the maintenance stops.

5.3 Research limitations

- The developed system was applied in a case study of one automated framing machine only. However, the implementation in a case study with a larger scope having multiple stations in sequence should be investigated in the future.

- The developed system does not accommodate for the production scheduling process, i.e., the CNC codes for all the panels in the project are generated at the same time without considering the production schedule.
- The life expectancy of the machine parts was outside the scope of this research since this information is not provided by the manufacturer and requires mechanical field experience to calculate. Thus, the proposed research was limited to the calculation of the parts' life-usage only without having the ability to schedule for the maintenance stops.

5.4 Recommendations and future studies

- The same proposed approach can be used in the future for all the automated machine types used in the offsite manufacturing industry to establish a full conversion to automated construction systems.
- The research methodology proposes the development of a database to be connected to the automated system. However, the database structure was outside the scope of this research, and it is recommended to be developed in the future.
- The applied case study is limited to an automated wood-framing machine that requires a Recipe format as a CNC code, which limits the system's output to one CNC code format only.
- Manual estimation equations and a simulation tool were used to provide the production estimate; these approaches can be replaced with an integrated tool that follows the same methodology but within the BIM environment. This shift to BIM-based tools would limit the number of tools required to achieve the desired objectives.

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