Framework for automated manufacturing-centric BIM for light wood frame buildings

By

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ABSTRACT

Building information modelling (BIM) technology has the potential to improve the collaboration between multiple stakeholders and to streamline construction projects. In order to increase the adoption of BIM within Canadian building industry, and in particular, the modular or prefabricated construction industry, the BIM models must be designed with sufficient fabrication details to facilitate the production phase. However, in current practice, fabrication details require substantial manual modelling efforts limiting the utilization of BIM models in the industry. In this context, the focus of this research is to create a framework that can be implemented in drafting software to automate construction details for modular construction. Therefore, the research objectives are formalized to include the drafting automation of wood framing building components through: a rule-based modelling approach that is capable of analyzing and designing building frames automatically as per the National Building Code (NBC) of Canada; analyzing the transportation regulations for modular components that can affect the design of the building module; creating of a cases collection for industry best practices using a knowledge-based approach. To validate and demonstrate the effectiveness of the proposed framework, various industry real-time case studies were investigated using an in-house developed wood framing tool which works as an add-on within Autodesk REVIT software. The results support the applicability of the proposed framework to optimize the manufacturing of prefabricated buildings and minimize drafting time and material required.

PREFACE

This thesis is the original work by Mahmud Abushwereb who completes the thesis work under the supervision of Dr. Mohamed Al-Hussein. The research-related topics, proposed methodology, and paper writing were finished by Mahmud Abushwereb with guidance from Dr. Al-Hussein. One conference paper related to this thesis has been published and it is listed below.

List of proceedings:

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LIST OF ABBREVIATIONS

BIM:	Building Information Modelling
AEC:	Architecture, Engineering, and Construction
LoD:	Level of Details
CBR:	Case-Based Reasoning
MEP:	Mechanical, Electrical, and Plumbing
KBM:	Knowledge-Based Modelling
IBP:	Industry Best Practice
NBC:	National Building Code of Canada

LIST OF SYMBOLS

TP: Top Plate

BP: Bottom Plates

HP: Header Plate

SP: Sill Plate

TC: Top Cripples above openings

BC: Bottom Cripples below openings

S: Stud

TS: Temporary Stud

S_K: King Stud

S_J: Jack Stud

S_{SO}: Side Opening Stud

W: Wall

TW: Temporary Wall

O: Opening

P_t: Top Points

P_b: Bottom Points

L: Length

L_S: Stud length

L_J: Jack Stud length

L_T: Total Wall length

L_{TW}: Temporary Wall length

L_{TC}: Top Cripple Length

L_{BC}: Bottom Cripple Length

L_{left}: Left side Length from Opening Edge to Wall Edge

L_{right}: Right side Length from Opening Edge to Wall Edge

L_{SP}: Sill Plate Length

L_{HP}: Header Plate Length

L_W: Wall Length

L_{TW}: Temporary Wall Length

S_T: Stud Thickness

H: Height

H_{SP}: Sill Plate Height

H_{HP}: Header Plate Height

H_W: Wall Height

O_H: Opening Height

O_W: Opening Width

Sp: Spacing Between Elements

Sp_{MAX}: Maximum Spacing Allowed

S_N: Number of Studs

TS_N: Number of Temporary Studs

S_{NJ}: Number of Jack Studs

TC_N: Number of Top Cripples

BC_N: Number of Bottom Cripples

G: Gap Between Openings

t: Drafting Time

Chapter 1 : INTRODUCTION

1.1 Background

In recent years, offsite construction has been a trend for industry seeking to decrease labour-intensive tasks and reduce construction time and cost. Companies began looking toward modular construction where the building arrives at the construction site broken down into nearly completed multi-units to be assembled on site. In the factory, most building components, such as walls, floors, roofs, are prefabricated to be shipped to the project location. Manufacturing and modular construction are the potential markets that meet the growth of building developments both of which would create a new competitive market against traditional constructions in terms of time and cost.

Modular construction methods can be applied in a variety of different types of residential and commercial buildings. The size and shape of these buildings are inconsequential given that the buildings are composed of modules to be assembled on site. In order to transport the building modules from the factory to the project site, the buildings are divided into modular units of the appropriate dimensions and weights accounting for jurisdictional regulations for road transportation. However, modular construction itself does not limit the building size or shape. Therefore, a building constructed by means of modular units can achieve the same design features as on-site construction.

Automation of the drafting process using BIM technology has been developed through different applications. However, the existing solutions still require some manual work by the user to finalize the CAD model (Lopez et al., 2010). This manual work could cause an issue with the integration of the components in the BIM model (Alwisy et al., 2018). Current available applications are not sufficient to fulfill the users' expectations (Liu et al., 2017).

Therefore, users must apply manual changes to the application outputs, which consumes time and effort as well as increases the probability of errors in the project drawings.

The main problems in utilizing the automated drafting tools effectively in the light wood frame buildings industry are:

1) Solutions that are available by software which can offer a semi-automated approach are limited (Bosché et al., 2015). These applications must function seamlessly and reliably according to the required specification.
2) Since most of the manufacturers use the conventional method of construction; this eliminates the need for each company to have its specific standards for the representation and formatting of shop drawings, which are illustrations containing the information needed for the various manufacturing processes that take place in the factory. Tasks including mechanical, electrical, and plumbing (MEP) are performed counting on experienced trades mainly.
3) Various manufacturers utilize unique manufacturing processes.
4) Errors and changes in the fabrication drawings are common drawback of automated drafting in BIM. Therefore, foremen must depend on their expertise to resolve these modifications, which are time-consuming, to meet the project's timeline without issuing revised fabrication drawings (Manrique et al., 2015).

1.2 Research Objectives

The objectives of this research are outlined as follows:

1) Enhancement of an existing rule-based modelling approach that is capable of analyzing and designing building frames automatically as per national building code taking into consideration the constructability and manufacturability features.
2) Analyzing the transportation regulations for modular components that can affect the design and drafting automation process of the BIM model.
3) Establishing a collection for industry best practices using a knowledge-based approach and integrating it with an adaptive intelligent feedback system to facilitate the integration of the automation process in design and drafting.

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 modular construction and building information modelling for framing design. Research methodology is presented in Chapter 3 by demonstrating the proposed framework using knowledge-based modelling, case-based reasoning, and the industry best practice cases collection in order to accomplish the objectives of this research. Chapter 4 includes case studies and the discussion of the results of this research in addition to how this research would help to fill the gap between BIM and best practices of the industry. Finally, the conclusion, research limitations, and future work of this research are presented in Chapter 5.

Chapter 2 : LITERATURE REVIEW

2.1 Modular construction

Modular home building has been proven to be beneficial over the traditional construction process by previous studies in this field. Garza-Reyes et al. (2012) conducted a comparison between traditional construction methods and factory method and determined the advantages of manufacturing-based construction, which are better production control, higher usage of labourers, quicker response by maintenance team, controlled workplace, and easy to apply new technology. Accordingly, industrialized construction is becoming increasingly popular lately in the construction industry, which uses a schematic system in the factory to optimize the production process, maximize the benefits of an applied method, and improve the productivity (Sadiq et al., 2018).

Producing efficient buildings in terms of energy, cost, and quality is the primary motivation behind the construction industry's transition to manufactured buildings (Garza-Reyes et al., 2012). Different strategies are being explored in an attempt to reduce production time and to lower the cost of products that satisfy customers' preferences. In manufactories, production and transportation plans affect the performance of designers and labourers, because missing information may cause delays and errors that lead to rework and miscommunication between design staff and production staff. In the construction process, quality, cost-effectiveness, and time schedules play a major role in the performance of design and drafting stage (Liu et al., 2017). A key advantage of modular construction is that eliminating assumption and design errors reduce the redundant design activities and project completion time.

Manufactured building units get built in a factory in a designed process with controlled conditions and then the units are placed on-site (Alwisy, 2010). Modular construction manufacturing is a production plan that involves a sequence of stations starting with panel prefabrication (floor, walls, doors, windows, electrical wires, and mechanical pipes) and ends by shipping the building to the construction site. Several plans need to be considered in the manufacturing process such as the production stations inside the factory, as well as the transportation and installation plan in the construction site (Alwisy, 2010). For example, a production plan layout can be set in order stations for the wall production to be assembled faster (Sadiq et al., 2018). As such, modular construction manufacturing takes place in an efficient manufacturing environment.

Moreover, the transportation regulations for the modular industry will vary depending on the location in Canada, where each province's allowance varies in terms of the maximum dimensions and weight of transported modules. During the transportation of the modules, various sizes in terms of height, length, and width need to be shipped smoothly without problems. Exceeding these requirements requires different legal approvals from regulatory authorities. In addition, to prevent damage due to weather conditions during transportation, each module must be designed as a closed box to prevent any water leakage and wind turbulence. In practice, the current solution to this transportation issue involves manually drafting the temporary shipping walls, which are used only during the transportation of the modules (Abushwereb, 2019). Thus, the case of applying temporary walls is proposed in this research in order to automatically add this function to the current version of the automated drafting tools.

Prefabricated construction provides opportunities to implement factory production strategies to improve efficiency and eliminate waste, and such strategies cannot be replicated at the site. Modular construction manufacturing processes include panel prefabrication, production line in the factory, and on-site unit assembly stages (Alwisy et al., 2018). For example, the building layout gets divided into units to meet the road regulations for allowable dimensional models. For wall connections without special details, onsite construction engineers deal with those by using other software, whereas a BIM model can offer all the details needed to avoid any future conflicts (Alwisy, 2010).

Modular construction manufacturing is a method of breaking the project into small units to be fabricated offsite and shipped to the construction site for installation. When it comes to options to construct the modules differently, Companies usually follow standard specification in the plant for most of the projects. Therefore, changes through the construction phase are reduced which enhances the performance of the construction process.

Additionally, modular construction provides opportunities for employing automation in construction to improve efficiency (Liu et al., 2018) Automation of the drafting process for the structural elements offers a promising solution in construction manufacturing because it has the potential to decrease the project's overall timeframe (Liu et al., 2018). The prerequisites for automation of the construction process are a user-friendly working environment in a factory setting, and precise and well-made construction plans (Sadiq et al., 2018). The information provided by the client could be translated by the designers using automated software to benefit the construction process. Designers' working time can be decreased through the use of automation in the design phase, which ensures the incorporation of sufficient details in the construction drawings (Azhar, 2011). Also, automation must have the ability to deal with continuous design changes during the project with a high level of accuracy and up-to-date information must be easily and readily available. Plans, such as the layout of production stations inside the factory and the installation plan at the construction site, need to be developed for the manufacturing process (Alwisy, 2010). Prefabrication of light-frame buildings is an efficient way to reduce both the cost and time of the building process, reduce the amount of waste material, and improve the quality of the buildings (Alwisy et al., 2018).

In the off-site construction industry, model entities must contain a high level of complex details on the basis of which construction drawings are produced (Alwisy et al., 2018). Currently, modular construction industry best practices are not tailored toward using BIM. For example, typical current practice in drafting frames must be controlled by the user. All these framing specifications add significant details to the BIM model and increase the framing's complexity.

2.2 Building Information Modelling

Building information modelling is a valuable technology that integrates various aspects of construction projects. The use of BIM to integrate the architecture, engineering, and construction (AEC) design is the intelligent system that this research focuses on in order to help the end-user during decision-making process in designing framing based on the framing code and best practices. Projects undergo continuous changes during the lifecycle followed by significant decisions. However, the integration of elements in BIM is a useful approach for early design analysis that leads to a shift in the decision making at an earlier stage of design (Cavieres et al., 2011). Autodesk stated that decision making and performance across the building and infrastructure lifecycle is improved by using BIM technology (Khemlani, 2004).

In the USA, the National BIM Standard has defined BIM as "a digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle from inception onward" (NBIMS-US, 2015). According to Autodesk's description of BIM, AEC professionals are given the tools of building information modelling to efficiently plan, design, construct, and manage buildings and infrastructure using an intelligent 3D model-based process (Autodesk, 2018). The technology of building information modelling (BIM) combines the architectural and structural features, as well as other aspects such as mechanical and electrical. In the building industry, AEC professionals must work collaboratively in order to avoid conflicts. BIM provides an easy technique for transfer of information and facilitates better communication between different parties of the project throughout the construction processes. It improves the coordination and collaboration among team members through the project lifecycle. Since BIM is a platform which generates three-dimensional models for better visualization and information, architectural, structural, mechanical, electrical and plumbing drawings and more, could be the output of a BIM model (Alwisy, 2010). Additionally, this incorporation would raise the quality of the projects where the accuracy of the data increases using this technique. As a matter of fact, the full capacities of BIM have yet to be reached (Manrique et al., 2015).

Human intelligence was solely dependent on the reasonable explanation of projects in previous research (Ibrahim & Krawczyk, 2003). Research has been moving forward toward computer intelligent systems to move away from entity-based computer-aided design (CAD). The construction industry has been assisted by BIM models for smart information collection through geometric relationships. Researchers and practitioners have attracted attention because the AEC industry has been transformed due to BIM. Zhao (2017) provided a scientometric review to explore the status and trends of global BIM research with a total of 614 bibliographic records were used to identify and visualize the status and trends of BIM research (Zhao, 2017). Also, Zhao (2017) stated that construction, system, and model are the most frequent keywords in this research (Zhao, 2017). Researchers have been focusing on the development of BIM from the perspective of architecture, design, and planning in the last years.

The improvement of the information transfer process using building information modelling technology has been proven regarding communication and coordination between construction teams and trades (Salazar et al., 2006). Many factors are combined in the 3D model like architectural, structural, mechanical, electrical and plumbing. Project information transfer process requires easy access for team members for better performance. Communication between members is crucial and can reduce the conflicts throughout the stages of a project.

Furthermore, three-dimensional (3D) information is being actively used by many approaches to develop object detection and recognition algorithms for the point cloud data in the 3D models (Bosché et al., 2015).

The construction industry could be revolutionized by using building information modelling technology (Liu et al., 2018). BIM provides object geometry and attributes elements that are visualized in three-dimensions for design and planning stages of a building's lifecycle (Eastman et al., 2009). Information in BIM is built at a specific level of details (LoD) to be used for dependent tasks (Eastman et al., 2009). The model can be made more efficient by defining the required LoD, which can vary from 100 to 500 for objects generated in BIM. In general, a higher level of details in BIM strengthens the graphics and non-graphic information of the building (Ramaji et al., 2016). These BIM details are crucial during the construction process where it affects decisions related to the quantity takeoff and planning stage in the project coordination (Liu et al.,2016). However, building a model manually increases the process time and the probability of errors in the construction-centric BIM (Hexu Liu et al., 2018). Leite et al. (2011) stated that the modelling time would significantly increase by two to eleven times because of increasing one level of detail. The main challenge faced by users when implementing an efficient BIM in the construction industry is identifying a cost-effective solution (Ding et al., 2014). Construction projects generally follow strict time frames, thus translating the construction data into BIM is a challenge for designers and drafters.

Several types of research focused on the utilization of BIM technology in supporting the wood framing design and drafting process. Basic BIM applications can deal with flexible features, but commercial add-on applications are still unable to automate the drafting work with a high degree of efficiency. Three-dimensional (3D) and parametric modelling supported the development of repetitive drafting activities. Manrique et al. (2015) developed an algorithm for generating automated shop drawings for the manufacturing of wall panels. In addition to shop drawings, a list of the optimum quantity of material for each panel individually is generated. Another application, MCMPro tool, uses a scenario-based analysis for generating the shop drawings needed according to national building codes, city bylaws, and framing methods and concepts (Alwisy, 2010). Alwisy (2010) covered design aspects of construction manufacturing by developing an intelligent design system through BIM model.

A BIM model can provide automatic shop drawings for wall panels using automated add-ons, while it also generates a schedule of the amount of material needed for the project (Alwisy, 2010). The optimum material cutting list minimizes material waste (Alwisy, 2010). A major advantage of using automation to generate the shop drawings is that the drawings are supposed to have zero errors to avoid delays in the production lines (Manrique et al., 2015). Canadian industries have been largely using Autodesk software to meet their needs, but the challenge is in standardizing the rules. Also, BIM can provide detailed design of modular buildings and detailed information about every item in the building. The integration system of BIM enables the effective management of information during several stages such as the planning, design, construction, operation, and maintenance stages of a project’s lifecycle.

FrameX is an Autodesk drafting tool that is used in AutoCAD to draft the structural components of light-frame buildings. It is also able to create quantity takeoff lists and shop drawings for production. Manrique et al., (2015) claim software like FrameX assists construction companies in the drafting phase for wood-framing design. FrameX automatically drafts the structural elements and generates shop drawings for light-frame wood buildings. Also, Manrique et al. (2015) stated that FrameX reduces several working hours during the design and drafting process. The primary objective of software such as FrameX and MCMPro is to minimize the drawing time for faster production. MCMPro tool uses a scenario-based analysis for generating the shop drawings needed (Alwisy et al., 2018). However, using available add-ons such as FrameX at this stage may unreasonably increase the number of working hours because manipulating the output of an add-on to meet the client standards and specifications would take more effort and time due to lack of software flexibility.

Components are incorporated by using parametric modelling for the purpose of generating accurate material quantity take-off lists. Industry professionals have come to realize that creating the BIM model is a time-consuming process, and this has prompted an investigation into ways to automate or semi-automate parts of the process of building an efficient BIM model (Alwisy et al., 2019). Common industry practices that differ from rule-based framing are presented to illustrate how workers can save material, time, and effort in the future. Minimizing material waste is one significant factor in favour of modular construction as it helps to reduce project costs by means of saving material and man-hours. Although many studies have explored minimizing material waste, the optimal quantity target has yet to be reached (Liu et al., 2017). Automating the creation of BIM elements would increase the accuracy of material quantity takeoffs, which would lead to a reduction in material waste because factories continue to waste resources on unnecessary material.

The limitations of previous research are the inability of a software add-on to adapt complex construction details that are required by the construction industry. The detail level increases when mechanical and electrical information is necessary for the particular framing layout. In addition to the framing layout, drywalls and sheathing layouts are still under development to reach full automation process (Liu et al., 2017). It is crucial to automate the detail level required for the job because when more manual changes are required to be added to the drawings, the accuracy level decreases where changes are not tracked. FrameX is a useful tool because it improves the efficiency of the framing material quantity takeoff and the drafting of the 3D modelling, but the industry has been requiring further additional information to meet specifications.

Although drafting technology such as Autodesk Revit assists the drafters with the modelling process, these manual changes take more than two-thirds of the total time required for the modelling task to be completed (Brilakis et al., 2010). The identification of frequently-used objects is fully automated in Brilakis' example after several repetitive processes, a process that would save time for the users. However, all the objects need to undergo a final check for the output of this process to confirm that they match the project specifications (Brilakis et al., 2010).

Automation is a crucial topic for stakeholders in terms of cost-savings. On average, a drafter requires a minimum of 8 hours of work to complete framing drawings such a building with two modules (Abushwereb, 2019). By using FrameX, the number of working hours would decrease to only a few minutes for drafting the structural elements of the light-frame building. However, manual changes would still require some time to modify the FrameX outcomes as well as draw the specific components requested by the customer. FrameX is able to automatically adhere to the standard set for each user in order to create the appropriate drawings for the production line, which involves creating the drawings with a sufficient detail to illustrate the structural framing elements.

There are three main challenges to confront in the integration of modern technologies, which are data level, process level, and application level. Data level is the level of details that represent building item attributes as a feature. The BIM model includes a set of interactive policies, processes, and techniques to develop a methodology for managing the basic project design and project data in a digital format throughout the lifecycle of the facility (Liu et al., 2017). For instance, the existing relationship between architectural, structure layout, and mechanical and electrical design layouts can be identified and clarified by BIM by systematically coupling project components together. As well as additional information regarding cost, scheduling, energy simulation, and more that can be represented through BIM technology. Information describes the physical and functional components through transparent information sharing and management between BIM users. The most comprehensive and popular exchange format for BIM is the building smart industrial class within the industry. It is a common standard for sharing information about BIM and is supported by most BIM tools in the AEC industry.

During the construction process, errors can occur. However, these errors occur in situations that have no rule or knowledge or where there is limited information available about knowledge-based errors. Errors are defined as mistakes that lead to failure or conflict in the project because of incomplete knowledge (Lopez et al., 2010). Using a BIM platform such as Autodesk Revit has benefits regarding clash detection between components and systems. For instance, a warning sign appears when there is a clash in the framing components around openings such as windows and corner connections.

2.3 Framing design and modelling

Previous research such as that by Manrique et al. (2015) has focused on the fundamental framing rules in the NBC pertaining to stud spacing and framing for openings framing. This research concentrates on special framing cases that occur in working on a real construction projects with multiple companies in the field of modular construction. These cases have been proven in the Advanced Framing Construction Guide (APA, 2014). Moreover, modular construction has specific requirements due to the fact that the components are fabricated off-site and must be shipped to site for assembly, in contrast to built off-site which is different than on-site construction. As such, the focus of this research is on only the platform-framing method based on the practical knowledge gained through actual modular construction industry partner projects.

In recent years, various technologies and construction methods have been developed for the purpose of providing new ways to increase the efficiency of the design process throughout the whole project lifecycle (Alwisy et al., 2019). Increasing the capacity to comprehensively represent the capability of the design details is the goal to integrate all the technologies of BIM (Azhar, 2011). One promising aspect of BIM is its ability to be applied to the various areas of the AEC industry. Although many aspects of a project may be developed in different BIM models, there is still an interoperability problem among different software applications (Martínez-Aires et al., 2018). Different analysis tools are required to use the information and data exchange in the BIM system amid multi-disciplinary users. For example, the use of automation of the different processes of construction in modular construction occurs on various platforms. A comparison between the traditional integration comparison and the early integration approach demonstrates the relationship between available knowledge and the levels of design flexibility. Filling the gap between practicality and software performance is a crucial consideration throughout the process of integrating knowledge at the early stages of the construction projects' lifecycle. According to the knowledge of practicality, this research emphasizes the requirement for knowledge, early in the decision process, that affects economics and strongly influences lifecycle-costs. In this regard, it is important to address concurrency and integration at the early design phases stage, since current BIM tools still have limited abilities in modelling (Cavieres et al., 2011).

Autodesk gives engineers the opportunity to develop add-on tools to improve the performance of the drafting and design process. A prototype system called FrameX was developed in Dr. Al-Hussein's lab at the University of Alberta. FrameX automates the structural drafting process where the target is to achieve the stage of analyzing and design the building framework in less time. Designers would still have the job of making sure all the information is included in the drawings. The automation of the design would only make the process faster.

The FrameX add-on has been developed by previous students, and the task of finding the bugs and examining the features to determine if they are sufficient enough for stakeholders formed part of this research. Reporting errors in the programming was one of the tasks in the process of enhancing the performance of this application. The biggest advantage of FrameX is that it works on the of Autodesk Revit platform to improve the technology of BIM. Testing this application involved going through real-time projects that were provided by industry partners.

FrameX improves the wood framing design and drafting process seeking to fully automate the manufactured construction system. FrameX automatically generates the needed shop drawings to start a construction project. Minimizing the number of manual changes is crucial for the process of automating the design and drafting process. A big advantage of using automation in the shop drawings is that the drawings have almost zero errors to avoid delays in the production lines (Manrique et al., 2015). The allowable amount of error in the design is the maximum 1/8 in. (or 3.18 mm), which is needed for cutting techniques (Manrique et al., 2015).

FrameX is designed to draft the framing of a model using the information provided such as length, width of a wall, size, and location of an opening. As well as the stud spacing and wall connections according to the building model following the National Building Code of Canada (NBC). The structural draft fulfills the requirement of national building guidelines. Walls are identified as interior or exterior walls by the developed algorithm of FrameX using the provided information in the model. It deals with all the elements that are fundamental to the framing process. For instance, it recognizes the wall boundaries and location and dimensions of all the openings in walls and floors. The framing direction gets defined by the users depending on the location of the original point of the building. FrameX was created following the framing design rules in the building code, but lacked the flexibility to accommodate various framing scenarios encountered in the offsite industry specifically. FrameX was tested by modular construction companies and it was discovered, in some cases related to framing, that best practices need to be developed.

FrameX is an application created with the intent to automate the process of drafting the structural members in light-frame wood construction. The prototype application performs the wood design on the platform construction method and generates shop drawings with quantity take-off automatically according to the BIM model. This reduces the design and drafting time and increases the productivity of the designer, with fewer errors (Liu et al., 2017). Using this method minimizes the wasted material and enhances the efficiency of labourers during the construction process, which is part of the advantage of using BIM technology (Liu et al., 2017). As illustrated in Figure 2.1, BIM supports the construction project's lifecycle by integrating different project phases and BIM attributes (Lu et al., 2017).

Figure 2.1: BIM attributes and project phases (Lu et al., 2017)

Eastman et al. (2009) stated that BIM tools are used to build a model using a state-of-the-art approach by collecting and organizing data, and integrating the as-built data of a constructed facility into a single data-based model. Parametric modelling is generated by creating parametric relationships for producing logical building objects following the current approach (Brilakis et al., 2010). A significant amount of information can be produced using parametric modelling (Manrique et al., 2015). BIM can be built through different approaches and technologies, where attributes are able to modify the parametric model to be used in a different location and with different dimensions. The building components are represented using parametric volumetric primitives in BIM (Tang et al. 2010). Revit software is a powerful tool for BIM that allows engineers to use parametric model-based processes to plan, design, construct, and manage buildings. Revit supports a multidisciplinary design process for collaborative design, which is the motivation for using this technology.

Wood-frame construction is currently the most common building method in Canada. Manrique et al. (2015) explored mathematical algorithms to solve complex problems in the construction design process using the AutoCAD platform. Wood-framing design's basic rules follow the Alberta Building Code. FrameX, the proposed BIM-based software application, is an add-on to Autodesk Revit that is used to draft the structural elements using light wood and light-gauge steel according to input specifications. FrameX, at this stage, serves the industry to automatically generate the framing and shop drawings of the Revit model for manufactured construction. Shop drawings provide the LoD and quantity takeoff for each panel to be constructed. The FrameX application is time-saving, reducing the number of hours required during the construction drawings phase. The use of parametric modelling represents the component coordination to be framed through the model functions, and establishes relationships between components such as the connection between two walls at a specific location (Tang et al., 2010). Panelization of walls in offsite construction is one of the methods used to increase the production rate. However, Ajweh (2014) proposed a multi-panels method to optimize one long multi-panel that groups panels together, which reduces the overall production time and improves the efficiency and material savings. Panels are grouped according to their similarities in frame wall type, for example, exterior and interior as shown in Figure 2.2.

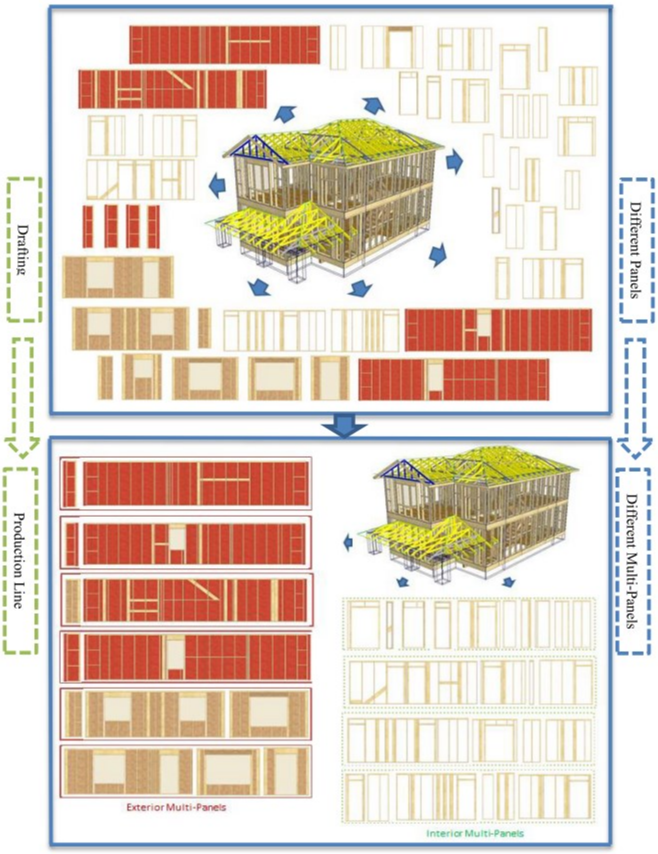


Figure 2.2: Multi-wall panel approach toward manufacturing-centric BIM model (adapted from Ajweh, 2014)

2.4 Constructability

Constructability issues will occur in a project in the case of not having a construction expert who applies the applicable knowledge to review and detect problems in the design. The experts would apply their knowledge for the sake of providing opportunities to save cost and keep the project on schedule. This knowledge is not documented properly by construction experts and not shared with the project team (Jiang & Leicht, 2014). Construction information is categorized as follows: design rules, performance, resource constraints, lessons-learned, and external impacts (Hanlon & Sanvido, 2002). Structural design is one of the main concerns in construction projects where it has a valuable impact on project performance.

Constructability is characterized as the ideal utilization of construction knowledge and experience in planning, design, procurement, and field operations to accomplish generally the project objectives (Gibson et, al., 1996). Constructability features get affected by project elements such as mechanical, electrical and plumbing (MEP) components that are supported by BIM. Mechanical elements have an impact on the structural design that needs to be modified through the integration between elements in BIM. Previous research has targeted the minimization of design errors during the project early stages (Cavieres et al., 2011). In the architecture, engineering, and construction (AEC) industry, unresolved structural framing drafting issues are caused because of a lack of tools to support effective knowledge integration at the early design stages (Cavieres et al., 2011). Current BIM tools are not sufficient due to their limited ability to provide the integration between project elements at early design phases as illustrated in Figure 2.3 (Cavieres et al., 2011).

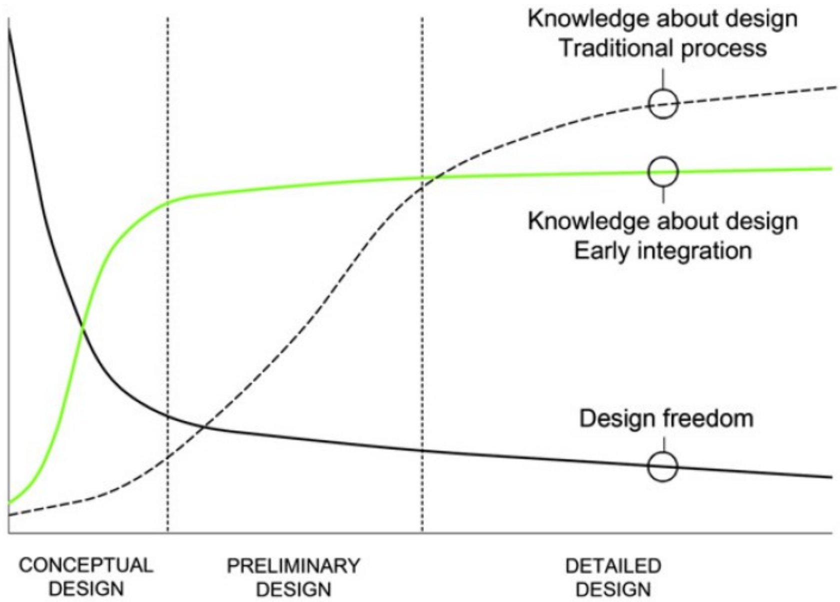


Figure 2.3: Early stage integration based on knowledge (Cavieres et al., 2011)

Users who are inexperienced and unfamiliar with the various practices of the construction process can contribute to the increased probability of errors. However, users who are very familiar with the software can usually detect these errors and mistakes. The most common errors can be converted to a knowledge-based model, which would be beneficial for updating the features of the FrameX add-on in the future. Documenting new errors would be very helpful for future projects of a similar kind and for a specific builder where the improvement rate of drafting process would continually increase through a feedback process. The knowledge gained from exploring the cause of errors should be documented in the database and implemented in the continual development process to make the software more functional. Automation of the drafting process allows users to learn from their mistakes and further promote the creation of a template for ultimately fewer errors and a faster design and drafting process. BIM technology promotes better coupling between functions and geometry of design to create an expert system under the parametric modelling improvements (Liu et al., 2017). The FrameX add-on could create a history of stored solutions for different framing cases that are reusable in future work and will increase the level of user interaction. It represents the framing layout and associated assemblies of various cases. Using this add-on, users can create reports with all the constraints and fabrication requirements to be stored in the practical knowledge and expert system databases for the purpose of improving the design and drafting process.

2.5 Process map of offsite construction

The process map of a typical offsite construction project illustrated in Figure 2.4. Building the architecture model is the first stage, followed by adding the components of mechanical, electrical, plumbing, and furniture. This information is required to design a structural framing plan. In the case of any modifications in the model, the design must be checked if any updates to the model are required. Shop drawings are generated to get the building permit from the city, depending on the specifications of the project. Once the building permit is issued, fabrication drawings will be sent to the plant to start the production and assembling the project components. During the production process, experienced trades might notice some mistakes or missing information in the drawings; trades fix the issues according to their experience, without sending feedback to the design team to avoid similar errors in the future projects. This type of feedback is necessary to avoid similar mistakes in future projects, and the feedback process must be efficient to find the best method to prevent any errors and modifications in the drawings. Once the modules are assembled and ready for shipping, the modules will be loaded on trucks to be shipped for onsite assembly. Shipping regulations are different for every province in Canada where regulations apply to govern the length, width, height, and weight of the module.

Revised shop drawings could be regenerated when there is flexible time for the project's deadline. The missing feedback from the production stage is critical for current and future construction projects. This link is crucial to improve the performance with more accurate shop drawings. Additionally, Errors in the shop drawings such as missing dimensions, framing members, and overlapping elements could be passed on from the production to the drafting team in report forms.

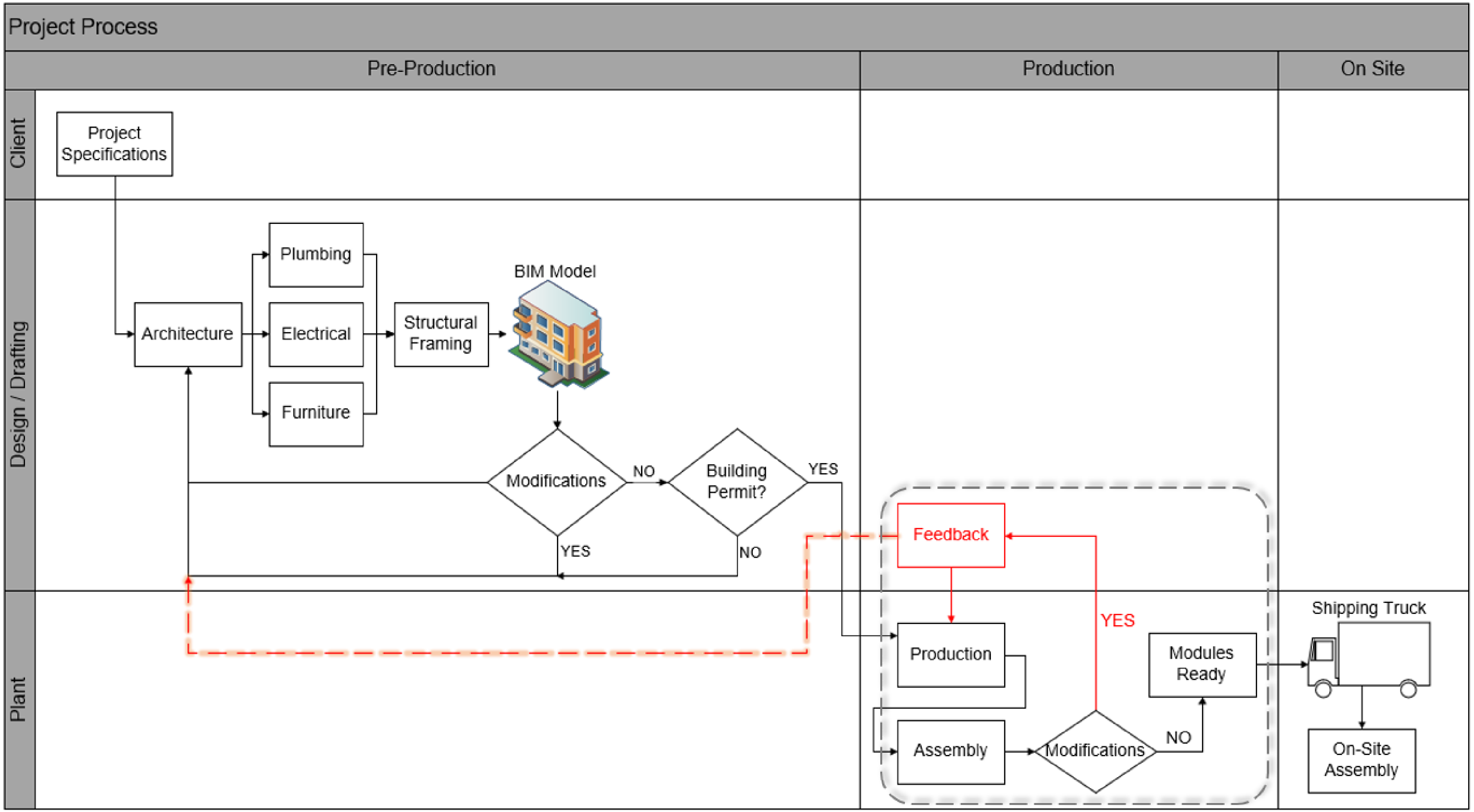


Figure 2.4: Modular construction process map

The production stages of creating a module to be assembled for shipping are presented in Figure 2.5. The production process starts with providing the trades on the floor of the manufacturing facility with the project shop drawings as shown in the previous process map. The next step is to assemble the panels with the temporary walls and opening framing, then to add the sheathing layers and finishing layers down the production line. Electrical wiring and insulation material are installed before the panel is finished by closing in the drywall layer. Walls are installed on the floor panel according to the project layouts. Finally, the roof panel is installed in the last stage to finish assembling the module. The final products would also include mechanical, electrical, and plumbing elements attached to the module.

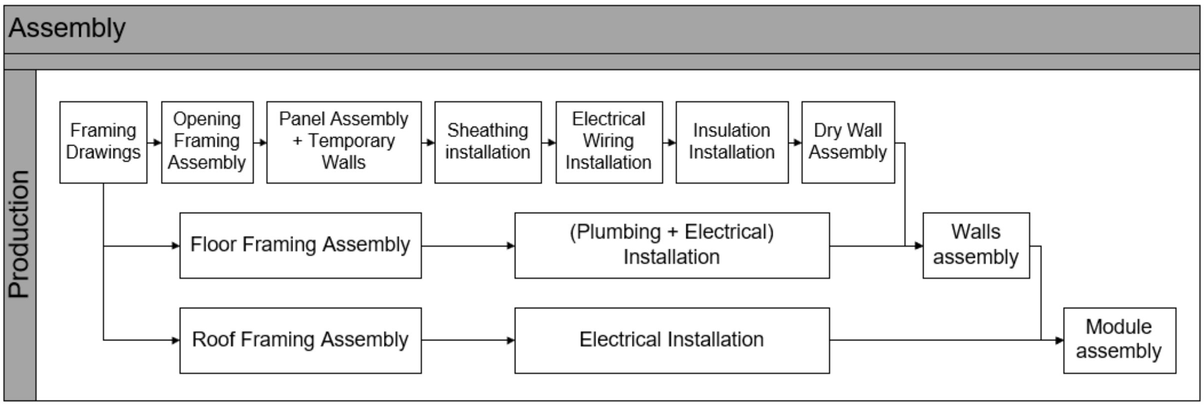


Figure 2.5: Module Assembly

Chapter 3 : METHODOLOGY

3.1 Overview

As illustrated in Figure 3.1; A knowledge-based approach was utilized to achieve the objective of analyzing and designing building structure frames automatically as per Canada's National Building Code (NBC), taking into consideration the constructability and manufacturability features with a focus on light-weight wood buildings. After that, the transportation regulations for modular components that can affect the design and drafting automation process in Alberta were analyzed using a case-based reasoning (CBR) approach. Finally, the cases collection for the industry best practices was established using a knowledge-based approach, and was integrated with an adaptive intelligent feedback system to facilitate the integration of the automation process in design and drafting. The adaptive intelligent feedback process is the link between the application of the drafting tool and the industry best practice database. The collected feedback is then processed in the knowledge based model to implement it as a new feature or upgrade to the current drafting tool. The proposed framework was tested and validated using the customized REVIT Add-on "FrameX" in multiple actual prefabricated construction case studies such as residential buildings.

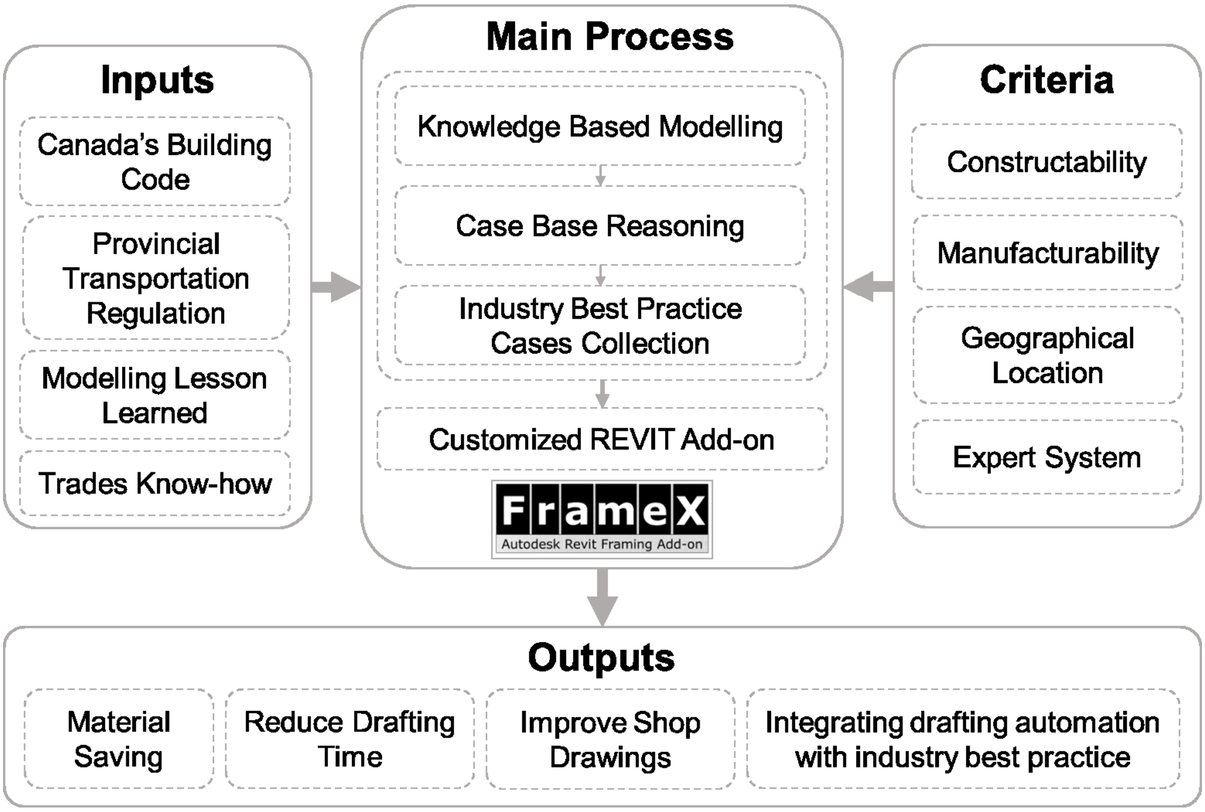


Figure 3.1: Research Methodology

There are four inputs for the research methodology: Canada's National Building Code (NBC), provincial transportation regulations, modelling lessoned learned, and trades know-how. The NBC dictates the design guidelines for light weight structural design that must be followed by designers, such as the spacing between structural components, connections, and framing around openings. In addition, the provincial transportation regulations limit the modules' sizes in terms of height, length, and width that can be transported on roads within the provincial jurisdiction. Also, the modelling lessons learned and the industry best practice (IBP) come from trades' know-how based on previous projects and experience from different construction methods and can be an asset for the framework.

In designing the framework, the following criteria for the methodology are taken into consideration: constructability, manufacturability, geographical location, and expert system. With respect to constructability, the structural elements in modular projects may need to be different from the original BIM design, which can lead to contradictions. In terms of manufacturability, detailed structural component drawings can improve effectiveness in the manufacturing facility. The geographical location of the manufacturing facility and the job site is important because it limits and constrains the transportation of the modules on provincial highways and roads. The system of expert knowledge that is formed based on the experience of trades and stakeholders can play an important role in the automation of the drafting process.

The framework's main process is represented in Figure 3.1 and consists of knowledge-based modelling, case-based reasoning, an industry best practice database, and the customized Revit add-on "FrameX". The details of the framework's main process are illustrated in Figure 3.2 and will be explained in the next sections.

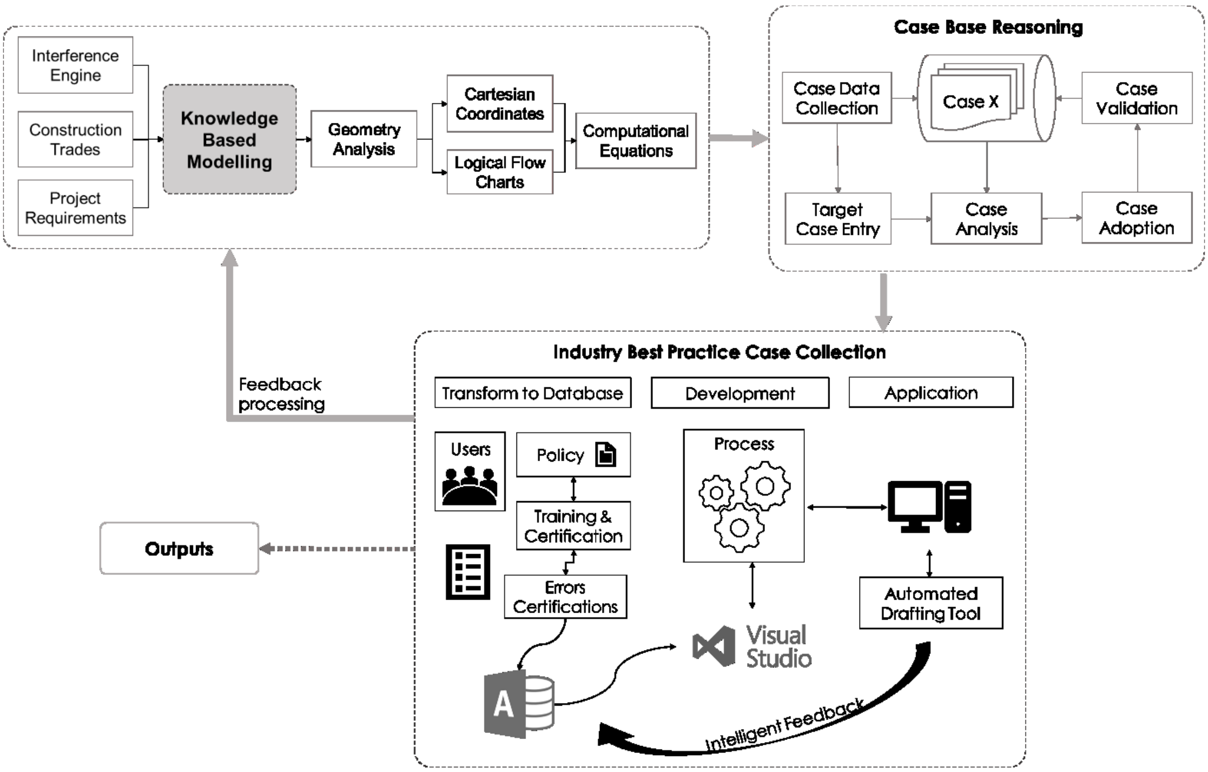


Figure 3.2: Research framework

The outputs from this framework are reducing material required and drafting time, improving shop drawings, and integrating drafting automation with industry best practice.

3.2 Rule-based framing design

The rule-based framing design approach depends on the analysis and understanding of the architectural BIM model to execute the structural design and drafting process. The engineering data extracted from the NBC are translated into structural design guidelines as shown in Table 3.1. FrameX analyzes all structural components in the BIM model and automatically generates the lightweight structural design and drafting for the exterior and interior walls, floors, and roof. If there are any changes made in the architectural BIM model, then the FrameX application will automatically run the analysis again to implement these new changes in the BIM model. FrameX will take into consideration the building code guidelines and industry best practices to generate the structural design for the BIM model. Subsequently, this will lead to the creation of the fabrication drawings that contain all the required information with a high detail level to facilitate the assembly process.

Table 3.1 represents an extracted collection of the framing rules that apply to framing design adopted from the National Building Code (NBC). Additionally, wall framing elements and components around openings in load-bearing walls are illustrated in Figure 3.3. Figure 3.4 shows openings in non-load-bearing walls adapted from the Advanced Framing Construction Guide (APA, 2014).

Table 3.1: Adopted from Alberta Building Code (ABC, 2014) and advanced framing construction guide (APA, 2014).

	Description	Framing Rule
Interior and Exterior Walls	Interior and Exterior Wall studs spacing depends on the loads carried by the wall	12”
		16” (commonly used)
		24”
	Shipping walls studs spacing	24” (to be removed after shipping)
	Minimum thickness of a wall	1 1/2”
	Bottom wall plate	Single
	Top wall plate	Single or double for loadbearing and non-loadbearing walls
Windows and Doors Openings	Opening width with more than 9’ 10”	Tripled studs on the side (2 Jack studs, 1 King stud)
	Opening width with less than 9’ 10”	Double studs on the side (1 Jack, 1 King)
	Opening in non-loadbearing interior wall	1 King stud, 1 head plate, no Jack,
	Opening in loadbearing interior and exterior walls	1 King stud, 1 head plate (lintel), 1 Jack, 2 Headers
	Minimum Cripples	Zero, If length of cripples < 24 inches (required for attaching wall finish material)
	Lintel = Head plate + headers	Headers < 32 feet in single-story construction

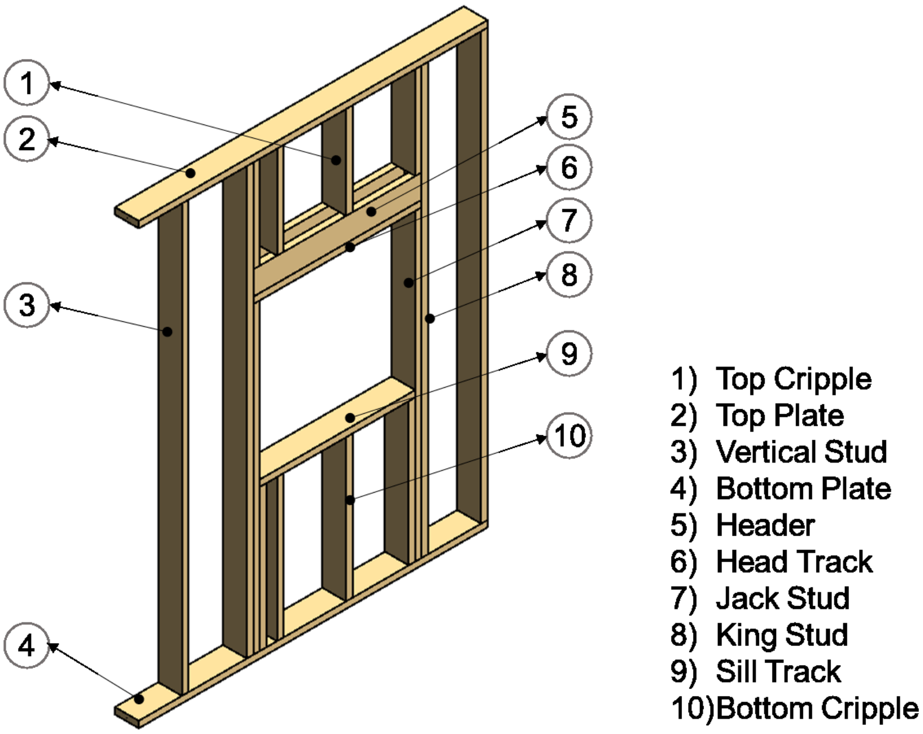


Figure 3.3: Framing Elements

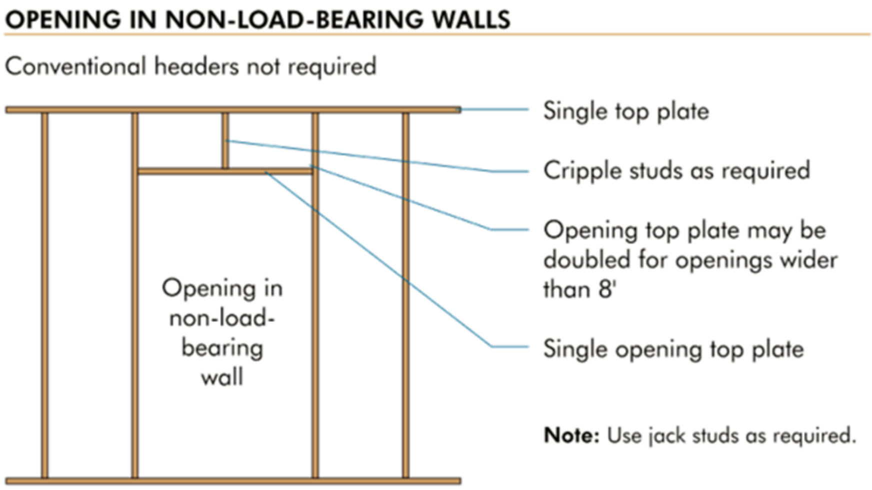


Figure 3.4: Framing around openings in non-load-bearing walls (adapted from Advanced framing construction guide, 2014)

3.3 Knowledge-based modelling (KBM)

The first stage of the methodology's main process is knowledge-based modelling. Panel attributes are determined through analyzing the BIM model according to the building code and construction trades. The logic of this application design follows the lightweight wood building code design guidelines for the spacing between structural components, connections, and framing around openings. The attributes that need to be considered when framing a panel in offsite construction are represented in Figure 3.5 and are programmed as one function of classes that applies the design rules of the NBC. The proposed interface engine is the platform that can be used to automate the design and drafting process.

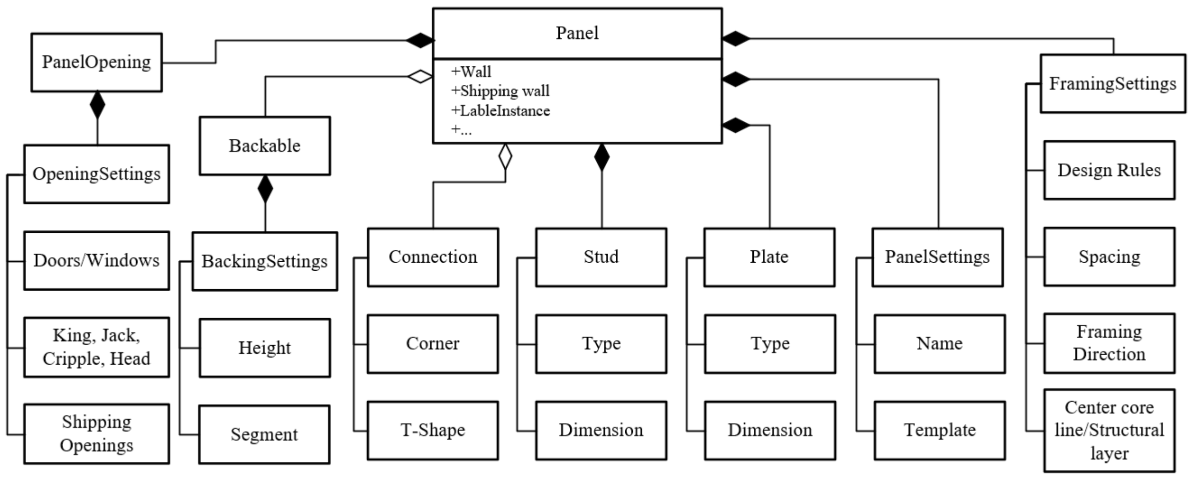


Figure 3.5: Structural framing design parameters and attributes for panel

Lopez et al. (2010) suggested further research to determine strategies and methods to reduce design errors in construction projects. A characteristic feature of the knowledge-based expert system is that it is easy to add new information and new rules according to the knowledge base of experts to illustrate the effectiveness of the system. A knowledge-based expert system is implemented to support future decisions to ease and improve the structural design for construction projects. Collecting the date of each framing case is the first step where the inputs are interference engine, construction trades and project requirements. The knowledge-based model can be presented in cartesian coordinates extracted from the analysis of the BIM model geometric data and represented in flow charts. After that, these coordinates and flow charts are represented in mathematical formulas. The knowledge-based model is a dynamic model featuring an intelligent feedback system from the industry best practice (IBP) cases collection framework as illustrated in Figure 3.6.

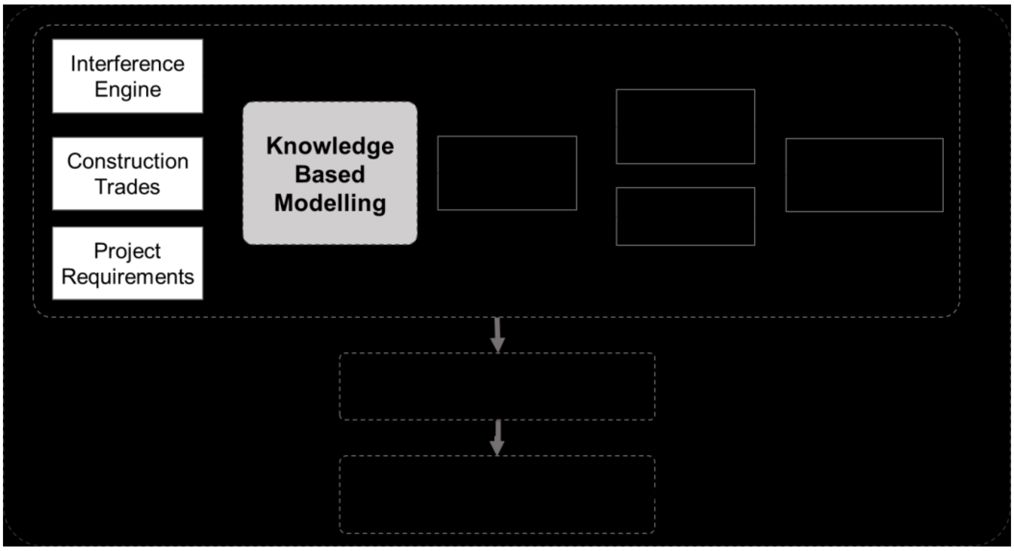


Figure 3.6: Knowledge-based approach model

3.4 Case-based reasoning (CBR)

The case-based reasoning approach is the second stage of methodology's main process where the input for this model is provided by the knowledge based as shown in Figure 3.7. Cases that might occur during the design and drafting process that are common in practice can be documented. Each case dataset is collected for future development based on the NBC and industry best practices. These cases are analyzed to be validated according to the construction method's standards such as in the case of framing around openings. The validation of these cases follows the industry best practices such that it satisfies the building code requirements in order to optimize the design and drafting process. Finally, the collection of all the new cases are compiled in a collection system for future development of the drafting tools and to improve the performance of FrameX.

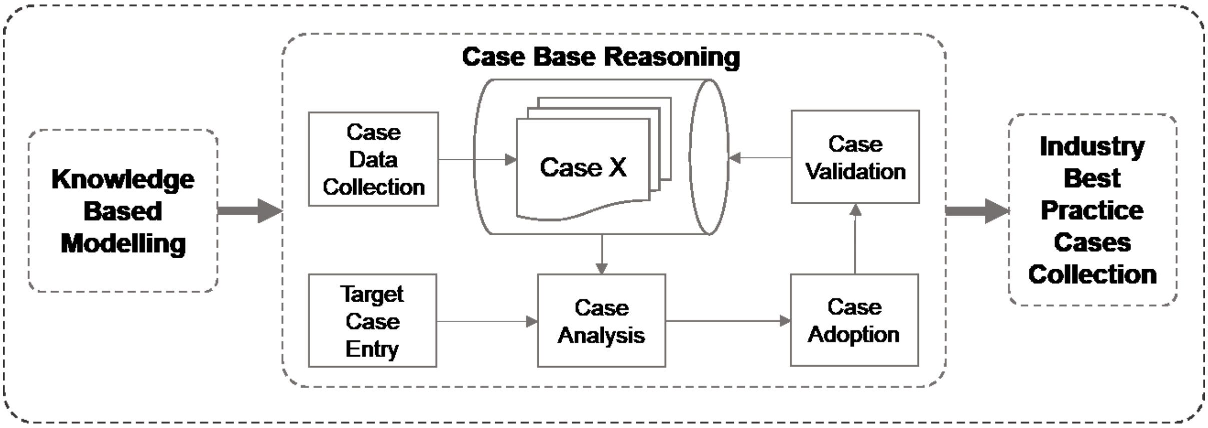


Figure 3.7: Case-based reasoning approach

3.5 Industry best practice (IBP) cases collection

The industry best practice database is the last stage in the main process of the methodology. It begins with transforming the outputs of the case-based reasoning to a functional database as shown in Figure 3.8. Data is collected from skilled drafters based on the project's policy and certifications. Errors in design drawings are classified into categories for data collection. Next, the data is sent to the development phase to be processed case by case. The implementation of these new features in the development of FrameX is accomplished through a visual basic platform coded in C#. The improved version of FrameX will consider the intelligent feedback feature from the application performance depending on the complexity of future projects.

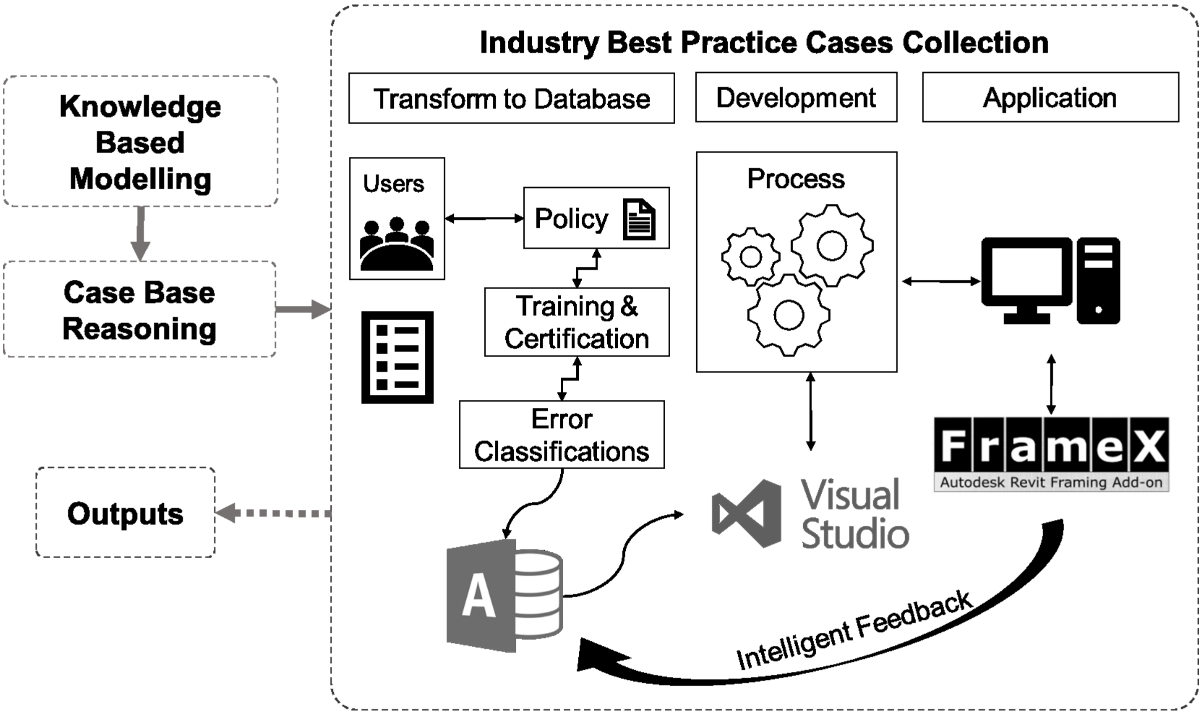


Figure 3.8: Industry best practices database

There are many types of errors that can occur during the design and drafting process of the BIM model. These framing errors are shown in Figure 3.9 and could be classified into categories as follows:

1) Connections: errors that might occur in corner and T-shape connections. Connections must satisfy the stability of the structure and area to fasten the drywall and sheathing without changing the main wall stud spacing.
2) Openings: framing around openings such as windows or doors might be missing members that will lead to an error in the framing. For example, cripples to fasten the drywalls and sheathings are missing as shown in the coming case study section.
3) Kitchen and washrooms: backing for elements hosted on the wall might be missing, which is an error in the drawing. Despite their vast experience in the field, trades sometimes do not notice this mistake until later, which also leads to delays in the completion of the task. Removing some of the material to fix the problem increases the wasted material and total time of the project. Applying backing framing members is crucial in areas like kitchens and washrooms where cabinets, mirrors, urinals, and mobility aid bars must have the backing to support the heavy load.

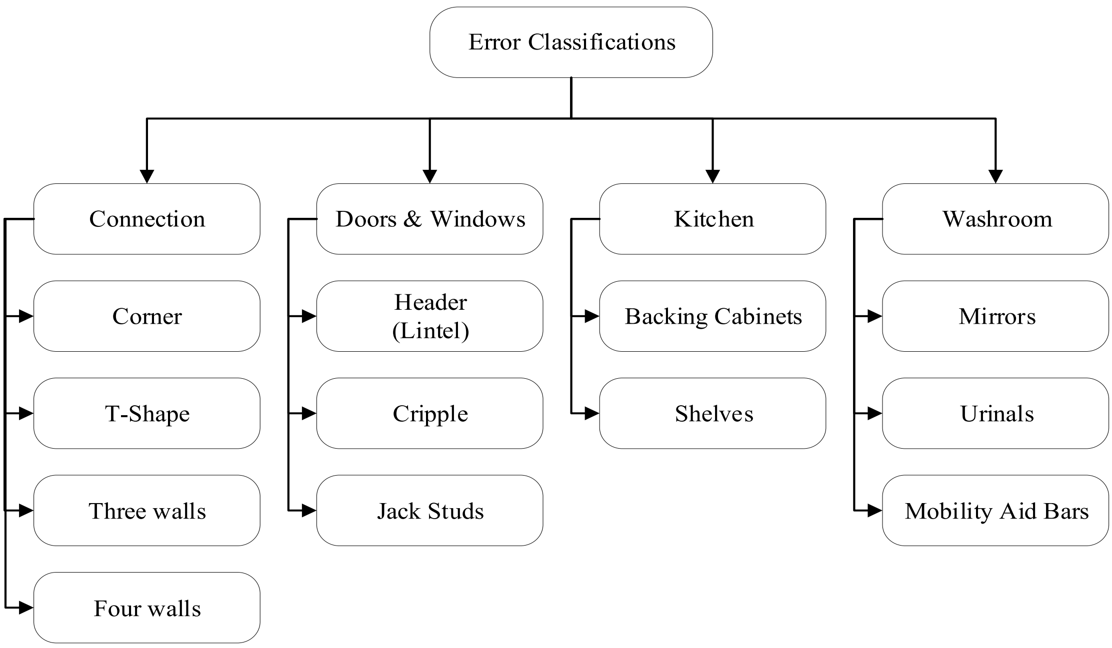


Figure 3.9: Error classifications

Chapter 4 : CASE STUDY

This chapter presents framing cases that were investigated during this study where the FrameX add-on was tested on construction projects provided by industry partners for example in collaboration with Canadian modular builders, ATCO Structures & Logistics, C&V Smart Structures, and Kent Homes. These projects were constructed in Alberta, Saskatchewan, and British Colombia. These cases support the objective of this research, which is to improve productivity in the design and drafting stage of construction projects via the BIM models, thereby making the utilization of this add-on more efficient by improving its features related to constructability and flexibility.

Figure 4.1 represents a common type construction project in Canada which is a two-storey residential building. In modular construction, these types of buildings are assembled into four modules, as illustrated in Figure 4.2, that can be shipped to site for assembly. The case studies described below focus on the wall components framing and their respective shop drawings.

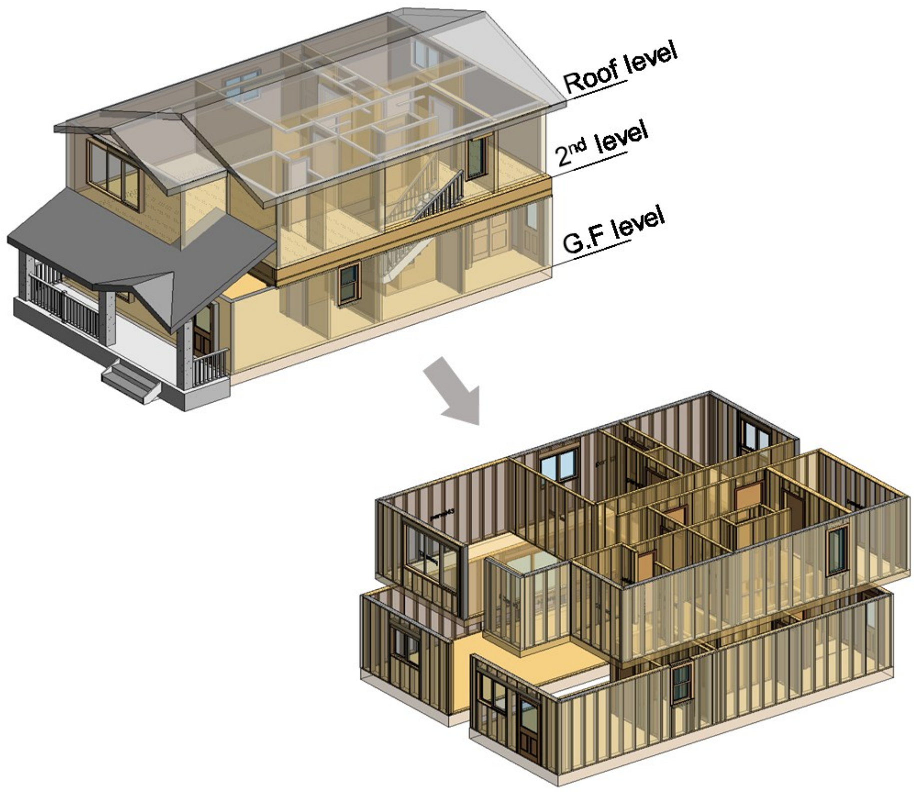


Figure 4.1: A sample two-storey single family residential building

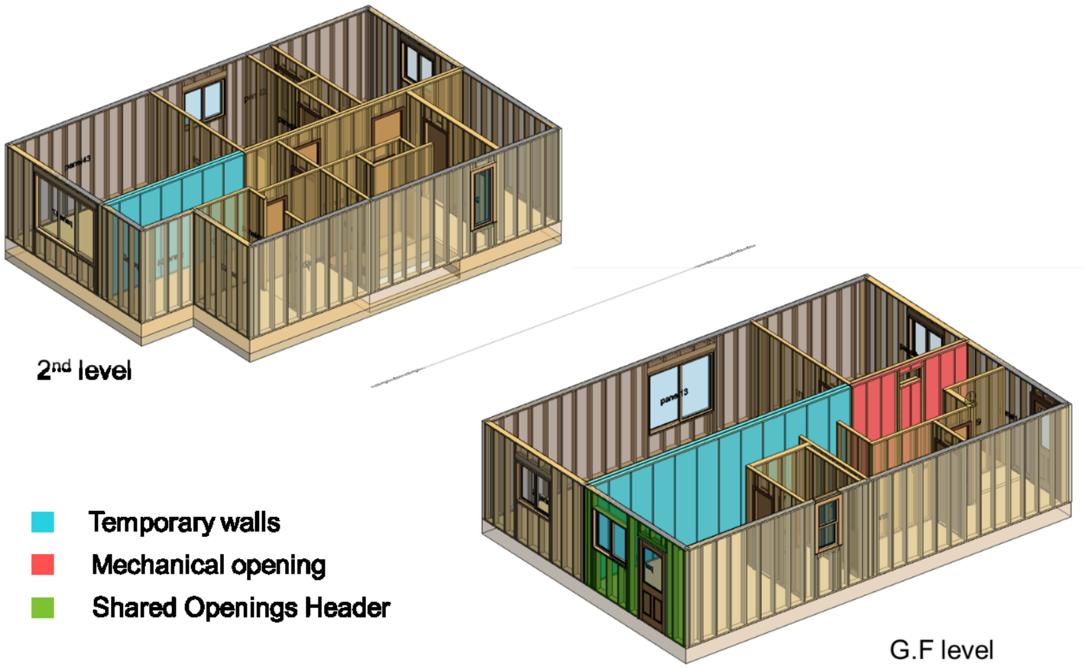


Figure 4.2: Framing cases in the 3D view of a Ground floor and Second level

During the FrameX validation process with the industry partners, multiple cases emerged from the testing phase. These cases would occur in special situations or scenarios such as mechanical openings, shared headers, or temporary walls for shipping purposes. Temporary walls that are placed to cover the open area between two modules are shown in blue color in Figure 4.3.

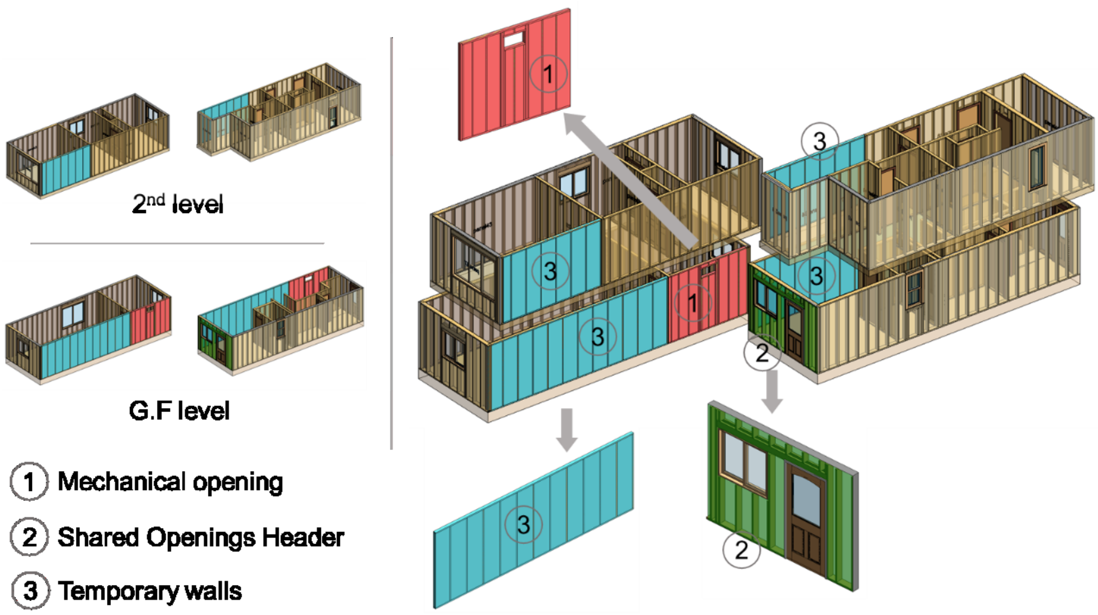


Figure 4.3: Exploded building model divided into four modules

4.1 Development of mathematic model

Wall framing includes a number of elements depending on the wall attributes, such as height and thickness, in addition to the components within the wall, such as openings. Height of the wall (H_W) is determined by its top and bottom coordinates. A stud (*S*) is defined as a structural column member that transfers the vertical load from the upper level floor joists to the lower level. Top (*TP*) and bottom (*BP*) plates are the horizontal elements that distribute the load to the vertical elements and connect the wall elements together. The length of TP and BP are equal to total wall length (L_T) according to the BIM model. Most structural lumber members in light wood framing buildings are 1.5 in. (or 38 mm) thick. Stud length (L_S) is determined by substituting the total thickness of the top (*TP*) and bottom plate (*BP*) from the wall height (H_W).

Openings (*O*), such as doors and windows, can require different elements to frame the wall (*W*). These additional framing elements can include a header and sill plate, and king and jack studs. The header plate (*HP*) is a horizontal structural member that is placed on top on an opening to transfer the vertical load to king (S_K) and jack studs (S_J) surrounding the openings. King Studs (S_K) are equal to the length of a regular stud (L_S), whereas jack studs (S_J) are equal to the height of the header plate (*HP*) minus the bottom plate (*BP*) thickness. The sill plate (*SP*) is a horizontal plate underneath the window opening that supports the window. In addition, cripple studs are short lengths of studs that are placed on top (*TC*) and below (*BC*) the openings following the standard spacing (*Sp*) in the wall framing.

4.1.1 Mechanical opening at non-loadbearing wall

Description:

In this section, non-loadbearing walls with mechanical openings to run ducts through the walls will be analysed. Ducts are light weight and attached to the roof, so all its load is supported by the roof. Therefore, the number of supporting framing members can be decreased.

The current performance of FrameX for example generates the framing members as shown in Figure 4.4. Highlighted elements are either required to be removed or modified for example, the king studs (*S_K*), which are the studs placed on each side of the opening (*Duct*), could be removed as well as couple of cripples above (*TC*) and below (*BC*) the opening. On the other hand, header plate (*HP*) and sill plate (*SP*) have to be modified by increasing their length (*L*) to fit in between the nearest standard studs (*S*) from each side as shown in Figure 4.5. These manual modifications are time-consuming which has to be reported through the feedback of the framework proposed in the previous chapter.

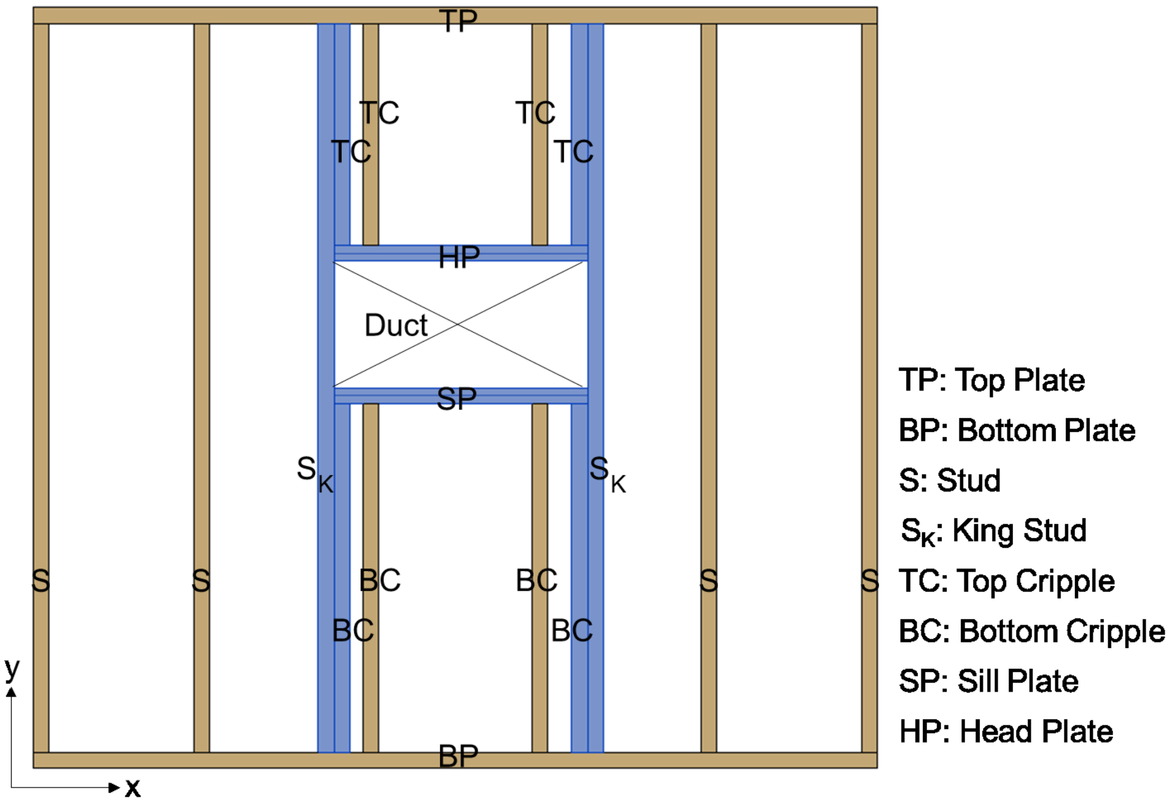


Figure 4.4: Standard wall framing around mechanical opening

In common practice, the proposed plan reduces the number of studs (*S*) required around the opening (from four to two elements) which saves an amount of wood material. The new set of structural elements required around the mechanical opening after applying the proposed method could be as follows: two studs (*S*), two top cripples (*TC*) and two bottom cripple (*BC*), longer sill plate (*SP*) and header plate (*HP*) + adding two lumbers pieces to the two sides of an opening (*SO*), which can be observed in Figure 4.5.

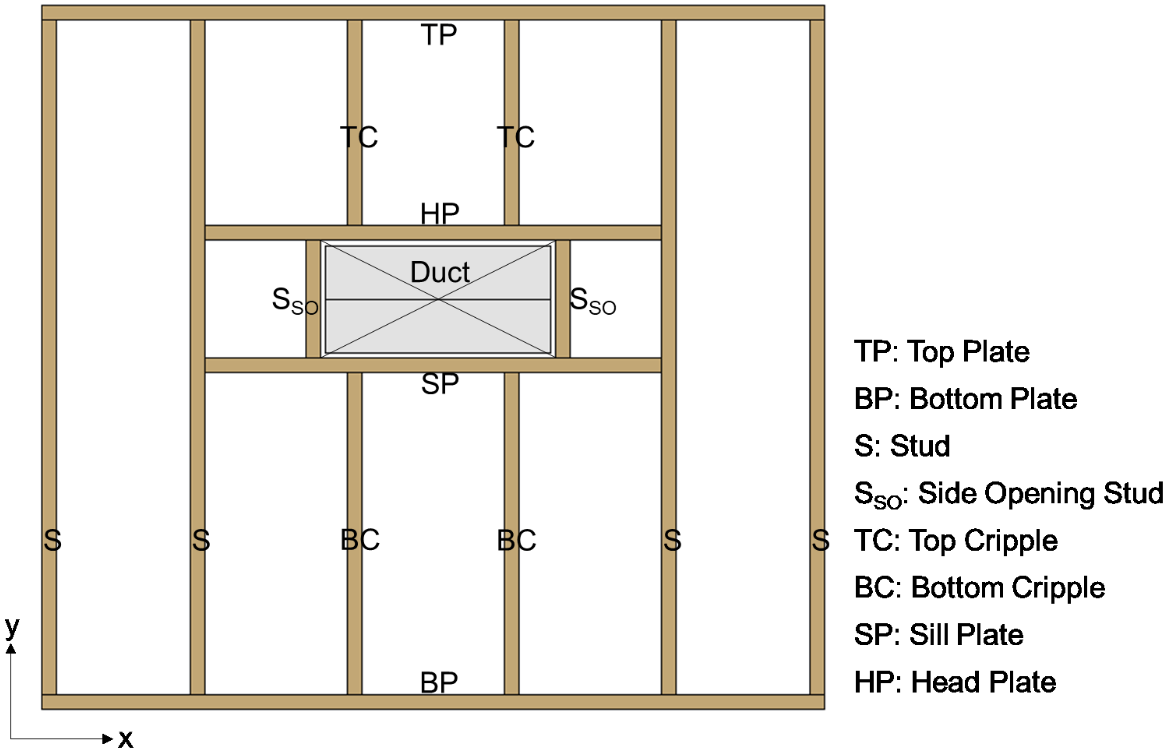


Figure 4.5: Advanced wall framing around mechanical opening

State (Condition):

In the case of an opening in a non-loadbearing wall following the flowchart in Figure 4.6 reduces the number of framing members used around the mechanical openings. When facing a situation with a duct type opening that's not taking any load; sill plate (*SP*) and header plate (*HP*) will be extended to the next regular studs from both sides which causes a decrease in the number of cripples (*TC)* and *(BC*) and studs (*S*) required.

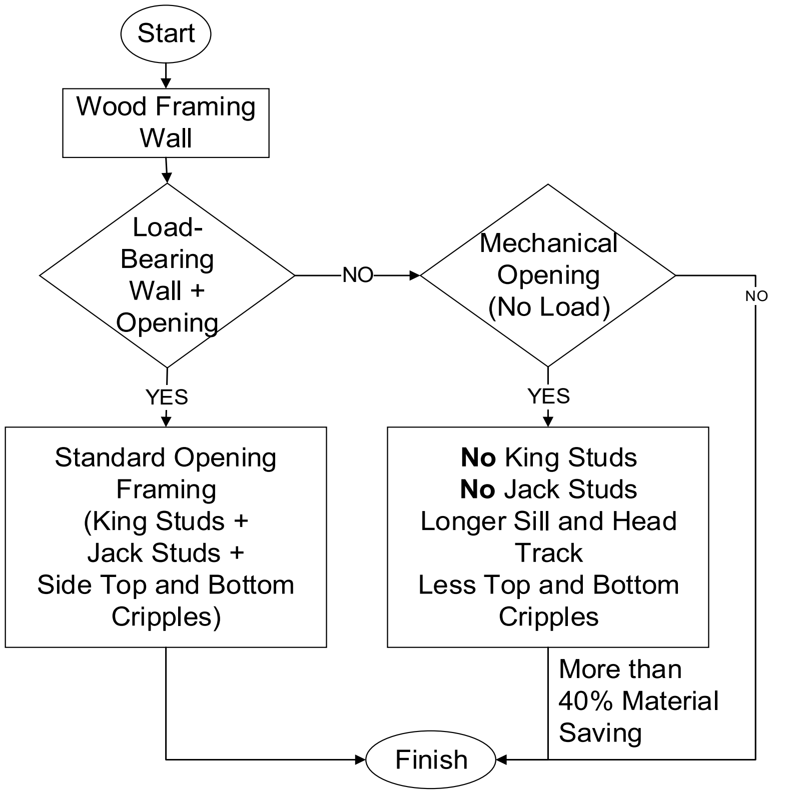


Figure 4.6: Flowchart for wall framing around mechanical openings

Mechanical openings in non-loadbearing walls cause major conflict in framing around openings. These are openings that need to be placed in partition walls to run the heating, ventilation and air conditioning systems (HVAC). Due to the case of a non-loadbearing wall, a minimum number of framing elements around these openings should be used. Table 4.1 and Figure 4.7 represent material quantity comparison between current and automated method of framing and the results show that more than 40% of the wood material can be saved in this case. The total amount of the material saved is determined by analyzing this case and measure the length of all the wall structural components.

Table 4.1: Material quantity comparison between current and automated method

2X6 size	Current Method			Automated Method		
	Quantity	Unit Length /m	Total Length /m	Quantity	Unit Length /m	Total Length /m
Top cripples	4	0.53	2.13	2	0.53	1.07
Bottom cripples	4	2.06	8.23	2	2.06	4.11
Studs	4	2.97	11.89	2	2.97	5.94
Side opening	-	-	-	2	0.31	0.61
Sill plate	1	0.91	0.91	1	1.18	1.18
Header plate	1	0.91	0.91	1	1.18	1.18
Total			**24.08**			**14.10**
Variance = **41% Material saving**						

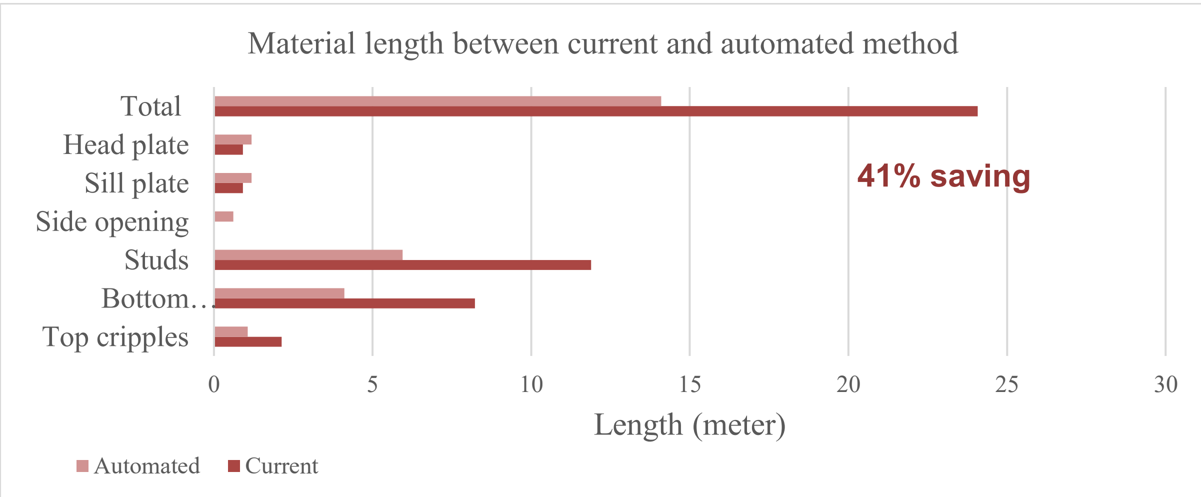


Figure 4.7: Comparison of material used between current and automated wall framing around mechanical opening

Based on the analysis of the framing cases, these equations represent the logic for automating the BIM modelling. Figure 4.8 illustrates the variables of the mathematical equations for the framing case of mechanical opening. These equations are generic to be used for each side of a wall. First, the model determines the coordinates (x, y) of the wall opening (O). Equation 1 determines the height of the sill plate (*H*$_{SP}$) which is equal to the coordinates of the opening's height used in the model that is defined by the user. Equation 2 calculates the height of the header plate (*H*$_{HP}$) by adding the opening's height (*O*$_{H}$) to the sill plate height (*H*$_{SP}$) and determining the opening's coordinates through Equation 3 for each opening in the wall.

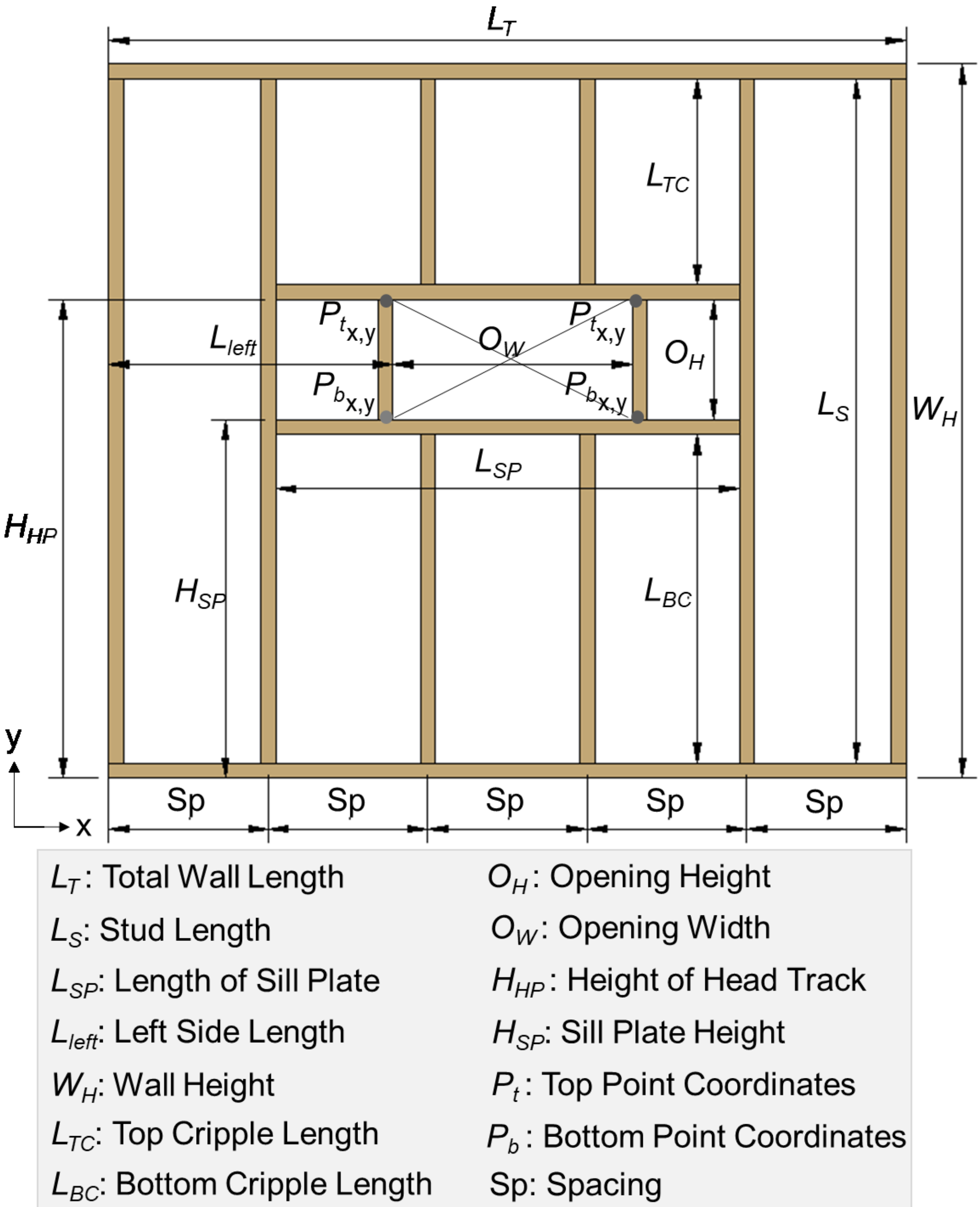


Figure 4.8: Defined variables in the case of wall framing around mechanical opening

$$H_{SP} = \left[P_{x,y}, \ldots, P_{x,y_n} \right]_b \qquad \text{Equation (1)}$$

$$H_{HP} = H_{SP} + O_H \qquad \text{Equation (2)}$$

$$O = \begin{bmatrix} Pt_{x,y} & Pt_{x,y} \\ Pb_{x,y} & Pb_{x,y} \end{bmatrix}_i \qquad i = 0,1,2,\ldots,n \quad (i\text{= each opening}) \qquad \text{Equation (3)}$$

where:

H_{SP}: Sill Plate Height (ft)
H_{HP}: Header Plate Height (ft)
O_H: Opening Height (ft)
O: Opening
P_t: Top Points coordinates (x, y)
P_b: Bottom Points coordinates (x, y)

As the opening's coordinates are known using Equation 3, Equation 4 calculates the distance (L_{left}) between the opening side and the wall edge (L_T) from the same side in order to estimate the number of studs (S_N) by using Equation 5 and depending on the typical framing spacing (Sp). Equations 6 is used to calculate the coordinates (x, y) of each stud (S) in the wall, while the length of the sill plate (L_{SP}) and the header plate (L_{HP}) can be determined using Equation 7:

$$(L_{left})_n = P(b)_x - S_0 \qquad \text{on the } x\text{-axis} \qquad \text{Equation (4)}$$

$$S_N = \left({}^{L_T}\!/_{Sp} \right) \qquad S_N \rightarrow Roundup \qquad \text{Equation (5)}$$

$$S_N = \begin{bmatrix} S_{0,0} & S_{0,y_n} & \ldots & S_0 \\ S_{x,y} & S_{x,y} & \ldots & S_1 \\ \ldots & \ldots & \ldots & \ldots \\ S_{x_n}, _{y_n} & Sx_n, y_n & \ldots & S_N \end{bmatrix} \qquad \text{Equation (6)}$$

where:

L_T: Total Wall length (ft)
L_{left}: Left side Length before opening (ft)
S: Stud coordinates (x, y)
S_N: Number of Studs
Sp: Spacing Between Elements (ft)

$$L_{SP} = S_{n(right)x} - S_{n(left)x} \qquad \text{Equation (7)}$$

$$L_{SP} = L_{HP}$$

where:

L_{SP}: Sill Plate Length (ft)

L_{HP}: Header Plate Length (ft)

S: Stud coordinates (x, y)

Wall framing could be done in BIM model either by applying manual work using the built-in tools in Revit manually or by using automated tool. Table 4.2 illustrates the drafting steps that Revit users take to frame a wall with mechanical opening manually. It starts with designing the case to determine the wall thickness, material type and spacing between framing elements. Then, drafting process starts with placing top (*TP*) and bottom plate (*BP*). It continues with adding studs according to the wall height (H_W) and total wall length (L_T), along with the cripples below (*BC*) and above (*TC*) the opening in the BIM model. Adding side openings (*SO*) and modify the sill plate (*SP*) and header plate (*HP*) is the last step in the manual drafting process. The user has recorded the drafting time (*t*) taken with each step to define the total time that can be saved by using the automated drafting tool. According to Table 4.4 and Figure 4.9, total drafting time (*t*) is 150 seconds to manually frame one single wall with mechanical opening. However, utilizing an automated drafting tool such as FrameX can minimize the total drafting time to 30 seconds where only small manual changes to the framing steps and FrameX settings are needed as shown in Table 4.3. FrameX interface allows the user to define all the design settings for all the elements to be generated faster according to the wall (*W*) and opening (*O*) properties. Applying manual changes is required to adapt the industry specifications. The results show the automated software application, FrameX, can save up to 80% of drafting time compared to manual work on BIM.

Table 4.2: Wall framing steps around mechanical openings manually in Revit

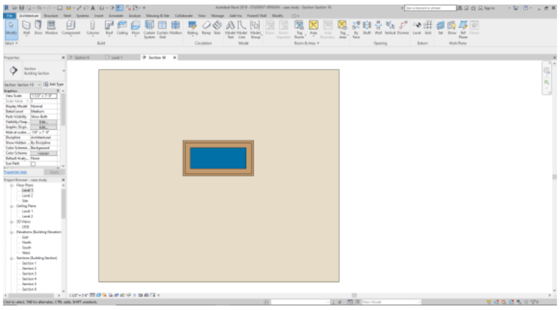
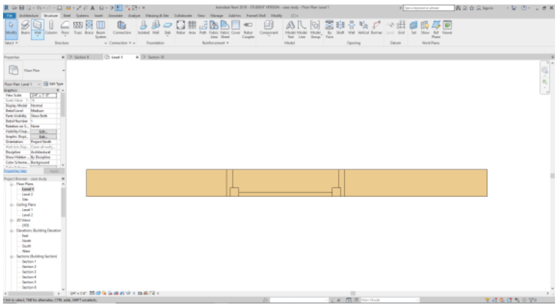
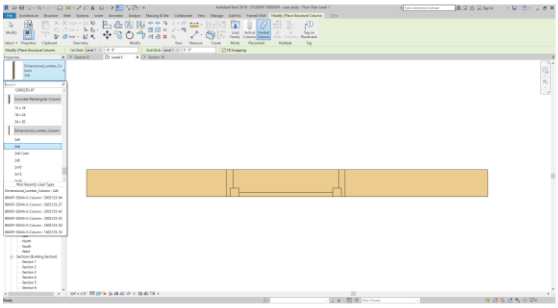
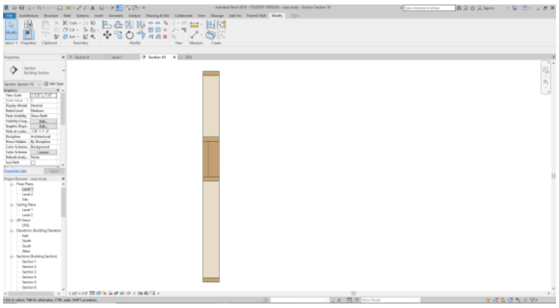
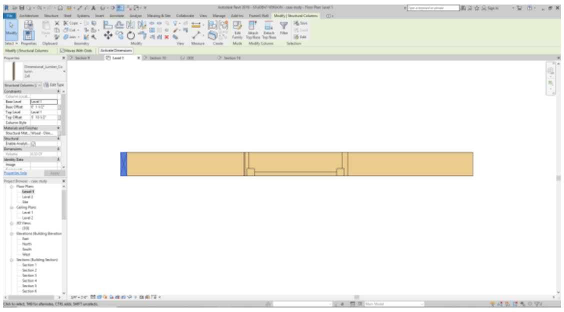
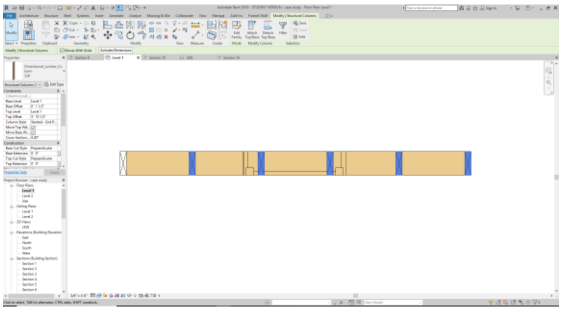
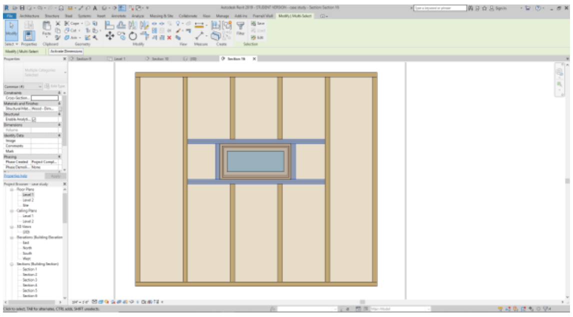
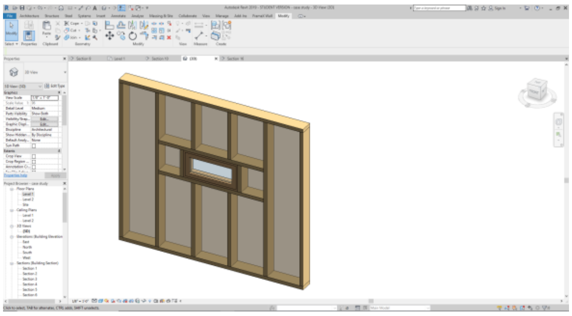
Step 1: Designing the wall (t = 15 sec) 	Step 2: Start the drafting (t = 20 sec) 
Step 3: Choose the top and bottom plate (t = 15 sec) 	Step 4: Define the properties of elements (t = 26 sec) 
Step 5: Adding Stud and defining its properties (t = 10 sec) 	Step 6: Copy and add new studs according to the wall length (t = 30 sec) 
Step 7: adding side openings and modify the header and sill plate (t = 34 sec) 	3D view of the final result 

Table 4.3: Wall framing steps around mechanical openings using FrameX add-on tool

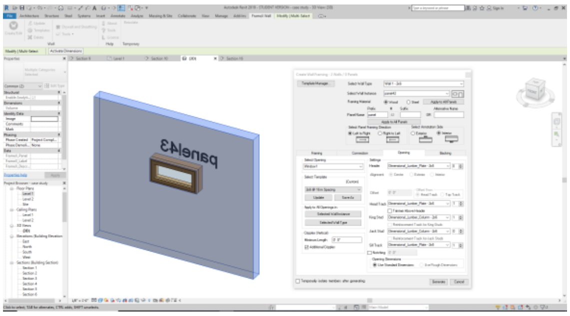
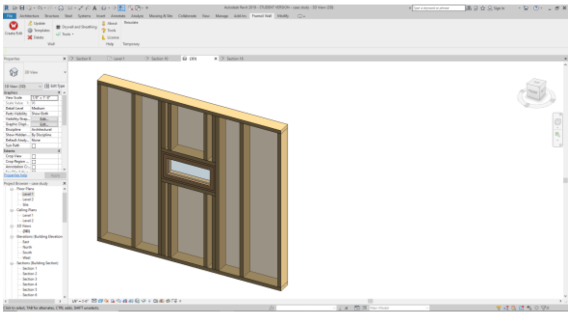
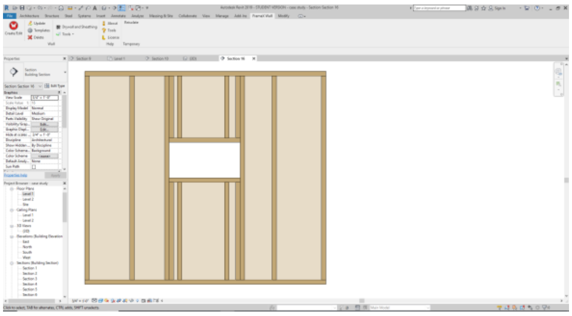
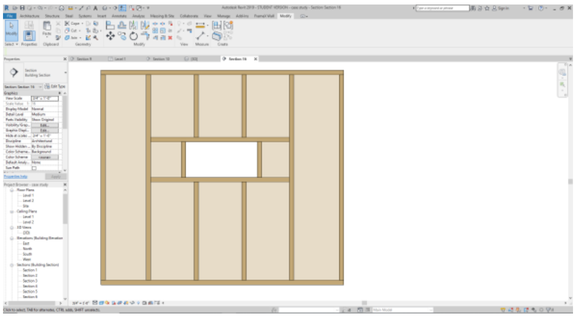
Step 1: FrameX interface for design settings (t = 13 sec)	Step 2: FrameX outputs (t = 3 sec)
	
Step 3: FrameX generation (t = 1 sec)	Step 4: applying few manual changes (t = 11 sec)
	

Table 4.4: Drafting time for manual and FrameX performance for the mechanical opening case in a non-loadbearing wall

Mechanical Opening	Drafting Time
Manual	150 sec
FrameX	30 sec
Savings	80 %

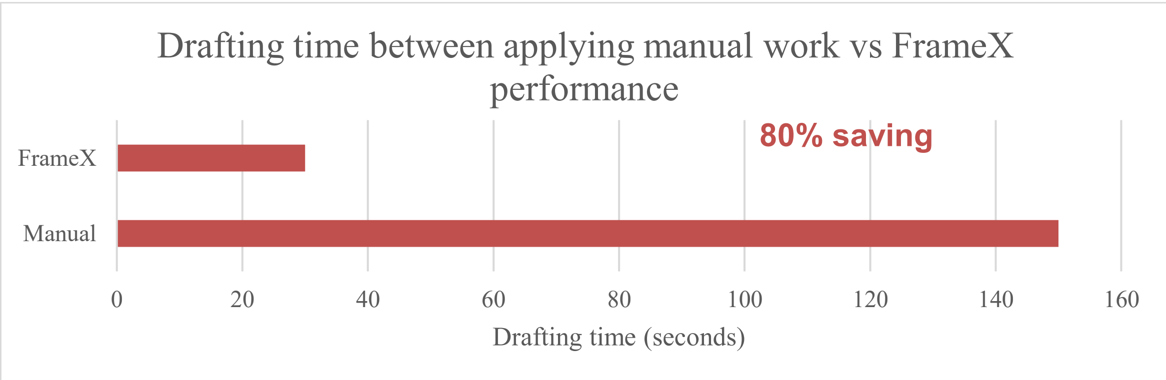


Figure 4.9: Drafting time for framing around mechanical opening

4.1.2 Shared header between multiple openings

Description:

In the case of wall framing with multiple windows and doors, which are at the same top height as the header Plate (*HP*), can be joined together for better performance and saving lengths of lumber. The current performance of FrameX is generating the framing members as shown in Figure 4.10. Highlighted elements are framed correctly but the constructability of this case can be improved by either removing or modifying the case with the use of shared header for the multiple openings with the aim of material saving. For example, some of the king studs (S_K) which are on each side of the door and window openings can be removed and replaced with jack studs (S_J) taking in consideration the regular stud spacing (*Sp*) as well as couple of the top cripples (*TC*). These openings are placed with a gap in between as shown in Figure 4.10. On the other hand, header plates (*HP*) have to be modified by increasing their length (*L*) to cover the total distance from far edge of the first opening to the far edge of the last opening as shown in Figure 4.11. These manual modifications are time-consuming which has to be reported through the feedback of the framework proposed in the previous chapter.

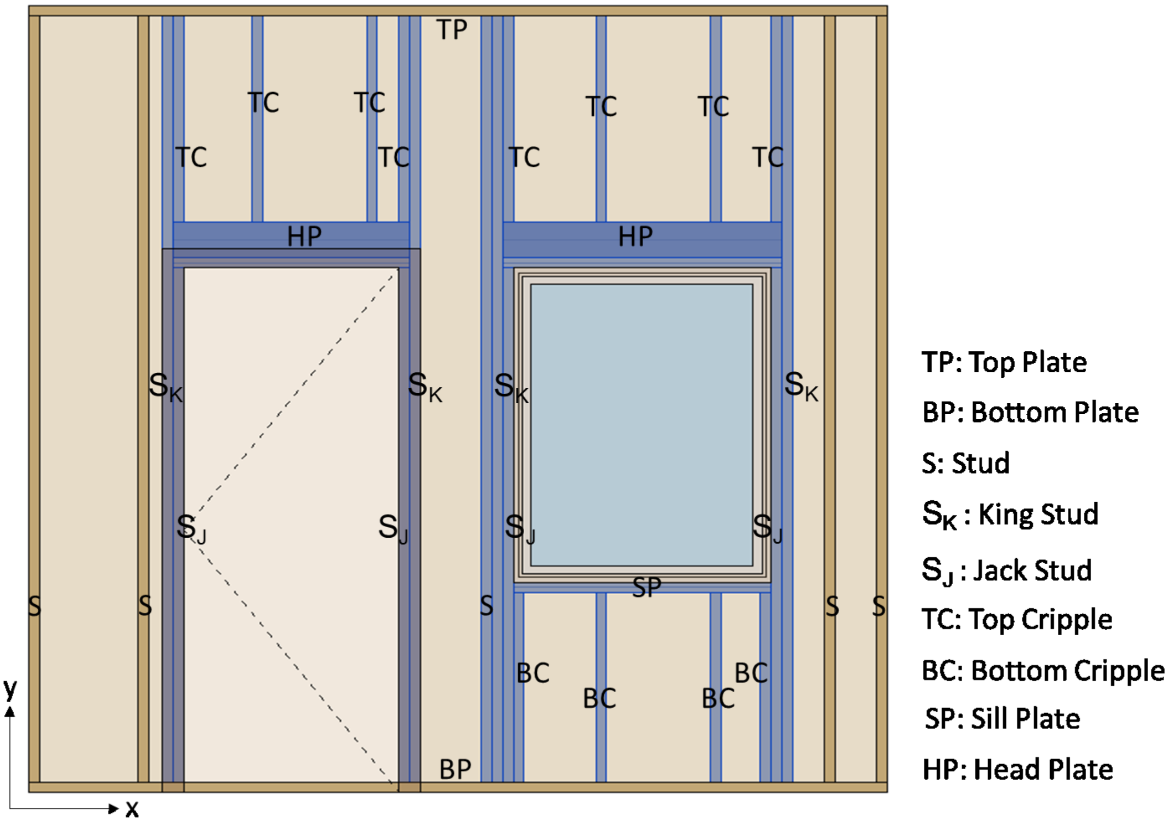


Figure 4.10: Standard wall framing for multiple openings

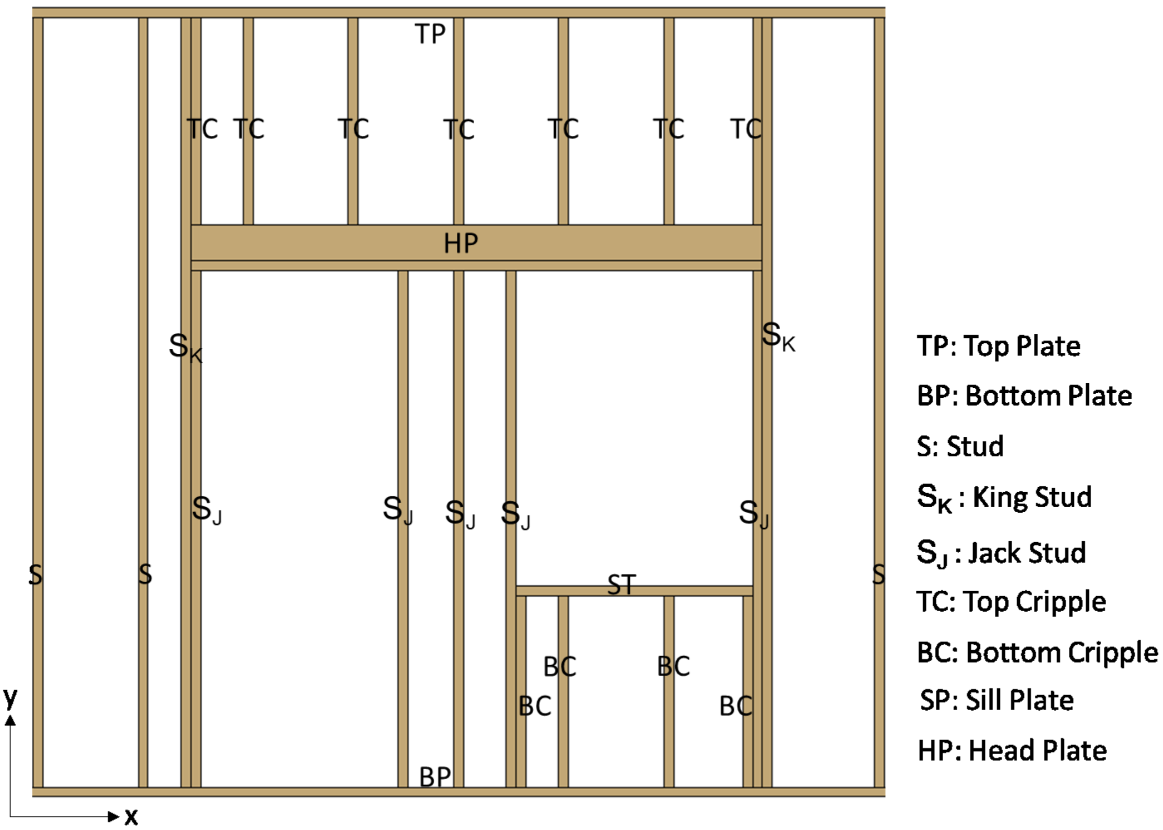


Figure 4.11: Advanced wall framing for multiple openings

State (Condition)

In the case of multiple openings (*O*) that are at the same top-level height, using shared headers (*HP*) between these openings can be achieved following the flowchart shown in Figure 4.12.

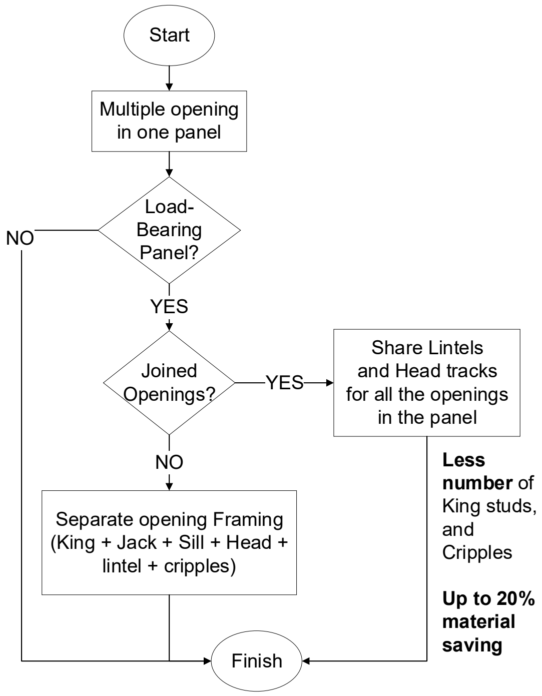


Figure 4.12: Flowchart for wall framing in the case of shared openings header

The case of loadbearing wall with multiple openings was handled by the users manually, which takes a great amount of effort and time. The total quantity of the material saved was measured by analyzing the structural components' length in the presented case. Figure 4.13 and Table 4.5: Material quantity comparison between current and automated framing in the case of shared header framing and the results show that more than 20% of the material can be saved in this case.

Table 4.5: Material quantity comparison between current and automated framing in the case of shared header

2X6 size	Current Method			Automated Method		
	Quantity	Unit Length /m	Total Length /m	Quantity	Unit Length /m	Total Length /m
Top cripples	12	0.70	8.39	10	0.70	6.70
Jack	6	2.10	12.58	8	2.10	16.77
Studs	10	2.97	29.72	4	2.97	11.89
Lintel plate	3	0.10	-	1	0.36	3.43
Header plate	3	0.10	2.97	1	1.18	3.43
Total			**53.66**			**42.50**
Variance = **20% material saving**						

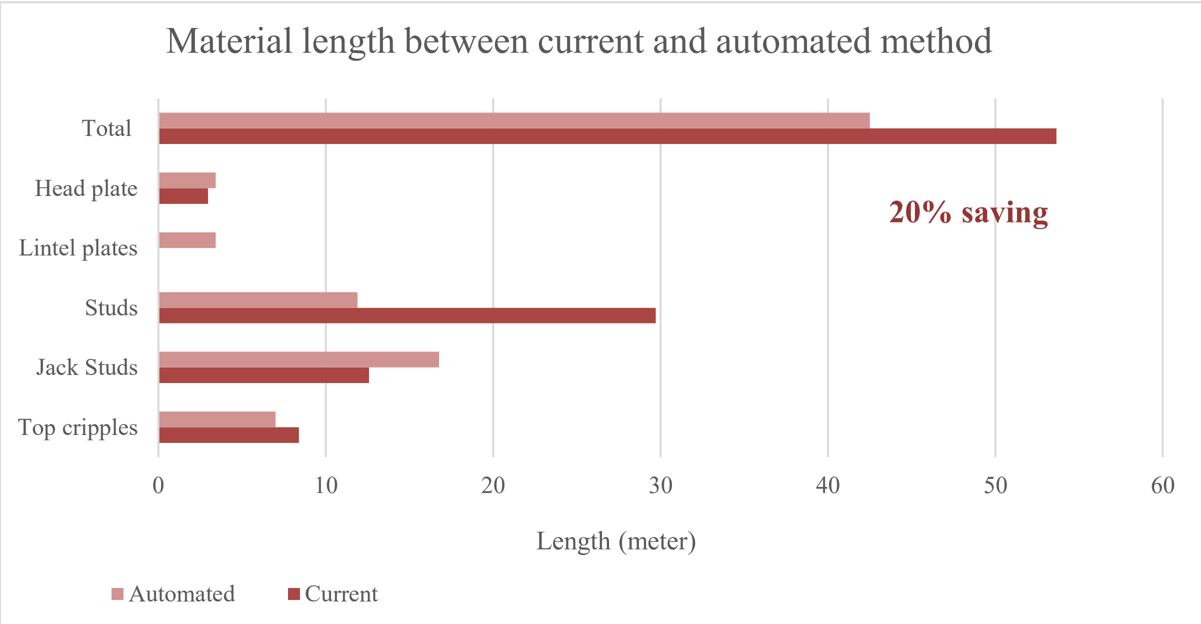
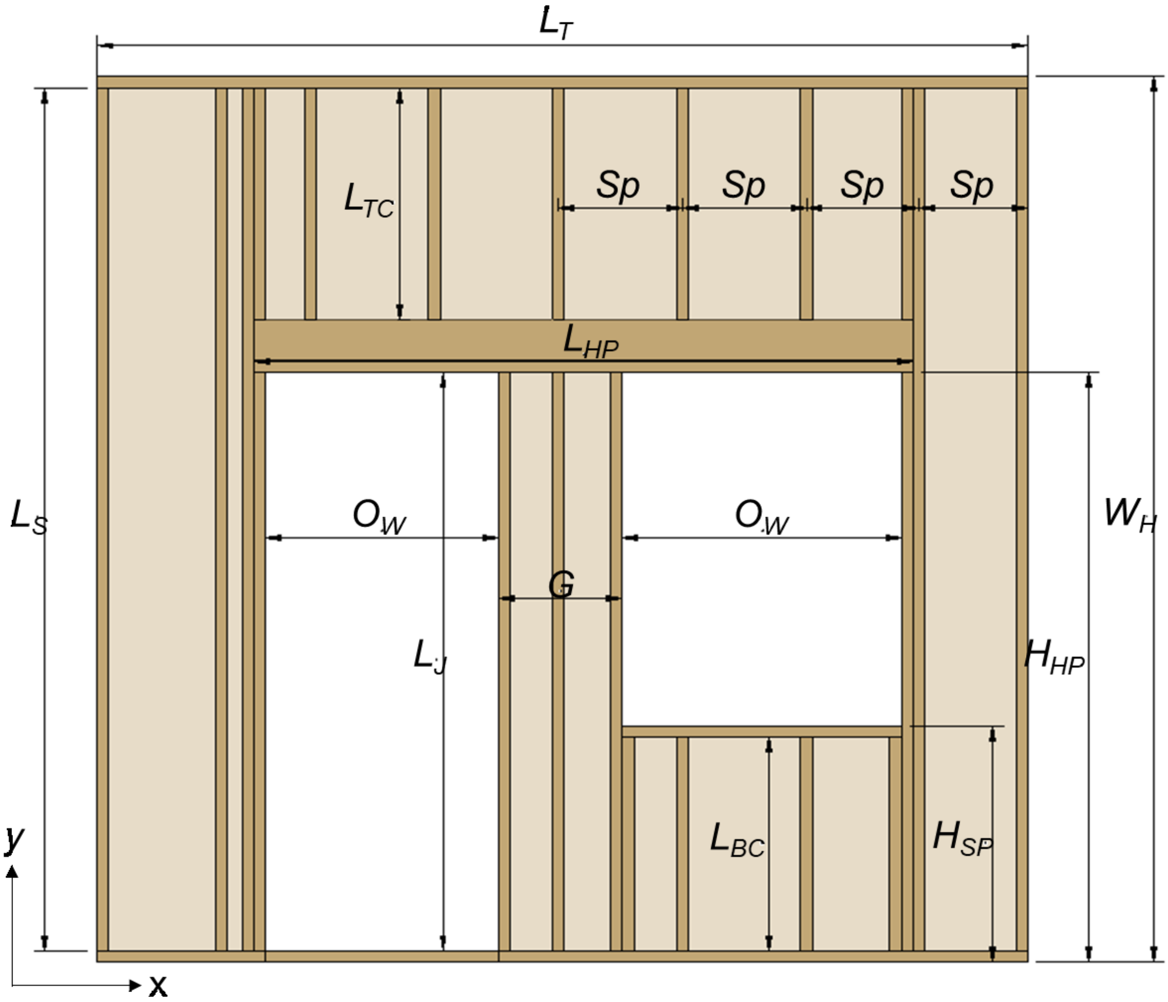


Figure 4.13: Comparison of materials used between current and automated wall framing for multiple openings

Based on the analysis of the framing cases, these equations represent the logic for automating the BIM modelling. Figure 4.14 illustrates the variables of the mathematical equation for the framing case of multiple opening with the same header height. First, the user would define the coordinates (x, y) of the wall openings and the height of the sill plate (H_{SP}) for the windows opening. Equation 8 is used to check if the condition for the gap between openings (G) is satisfied. Length of header plate (L_{HP}) is determined using Equation 9 to determine the total length of the shared header (L_{HP}) above the openings and the gap between them.



L_T: Total Wall Length
L_S: Stud Length
L_J: Jack Stud length
L_{TC}: Top Cripple Length
L_{BC}: Bottom Cripple Length
Sp: Spacing
G: Gap Between Openings
O_W: Opening Width
H_{HP}: Height of Head Track
H_{SP}: Sill Plate Height
W_H: Wall Height

Figure 4.14: Defined variables in the case of wall framing with multiple openings

These equations represent the logic for automating the BIM modelling for the shared header.

$$G \leq Sp$$ Equation (8)

$$L_{HP} = \sum O_W + \sum G + (2\bullet$$ Equation (9)

Length of Top Cripples (L_{TC}) is calculated using Equation 10 depending on the length of studs (L_S), Header Height (H_{HP}), and stud thickness (T_S). Equation 11 determines the Length of Bottom cripples (L_{BC}) through the sill plate height (H_{SP}) and stud thickness (T_S). Number of Jack Studs (S_{NJ}) around openings is calculated by Equation 12 while Equation 13 determines the number of top cripples (TC_N) above the multiple openings.

$$L_{TC} = L_S - H_{HP} - \sum T_S$$ Equation (10)

$$L_{BC} = H_{SP} - (2\bullet$$ Equation (11)

$$S_{NJ} = (2\bullet \qquad ((\sum G) / Sp)$$ Equation (12)

$$TC_N = \left[\left(\sum O_W + \sum G \right) / Sp \right] + 1$$ Equation (13)

+1 … in the case of Horizontal Sheathing

+3 … in the case of Vertical Sheathing

where:

L_{TC}: Top Cripple Length (ft)	L_{HP}: Header Plate Length
L_S: Stud length (ft)	L_{BC}: Bottom Cripple Length (ft)
H_{HP}: Header Plate Height (ft)	H_{SP}: Sill Plate Height (ft)
T_S: Stud Thickness (ft)	S_{NJ}: Number of Jack Studs
O_W: Opening Width (ft)	TC_N: Number of Top Cripples
Sp: Spacing Between Elements (ft)	G: Gap Between Openings (ft)

The shared header framing case can be drafted in Revit through manual work or by utilizing an automated drafting tool such as FrameX. The drafting steps that Revit users take to frame a wall with multiple openings with shared header manually are illustrated in Table 4.6. It starts with designing the case to determine the wall thickness, material type and spacing between framing elements. Then, drafting process starts with placing top (*TP*) and bottom plate (*BP*) with total length equal to total wall length (L_T). It continues with adding studs according to the wall height (H_W), along with the cripples below (*BC*) and above (*TC*) the openings in the BIM model. Adding the sill plate (*SP*) and modify header Plate (*HP*) to be covering the distance (L_{HP}) above the door and window openings (*O*) is the last step in the drafting process. The drafting time (*t*) that the user spent has been recorded for each step to compare with the total time that can be saved by using the automated drafting tool. According to Table 4.8 and Figure 4.15, total drafting time is 140 seconds to manually frame one single wall with multiple openings. However, utilizing an automated drafting tool such as FrameX can minimize the total drafting time to 25 seconds where only small manual changes to the framing steps and FrameX settings are needed as shown in Table 4.7. FrameX interface allows the user to define all the design setting for all the elements to be generated faster according to the wall (*W*) and openings (*O*) properties. Applying few manual changes is required to adapt the industry specifications. Figure 4.15 and Table 4.8 represent the drafting time between manual vs FrameX performance in the case of shared header. The results show that the automated software application, FrameX, can save up to 82% of drafting time compared to manual work on BIM.

Table 4.6: Wall framing steps to frame a wall with multiple openings manually in Revit

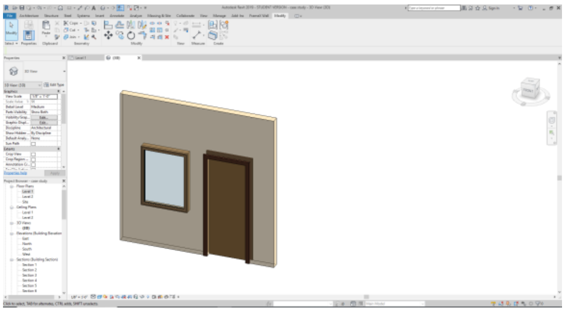
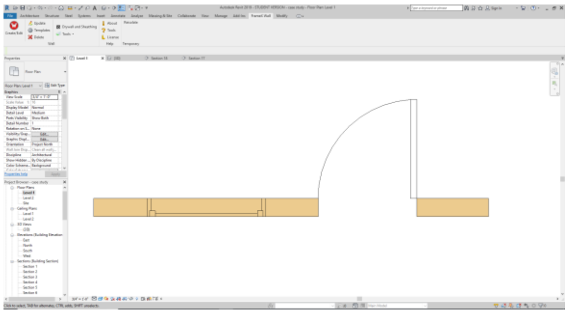
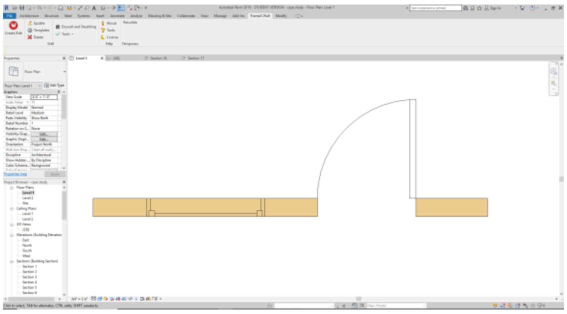
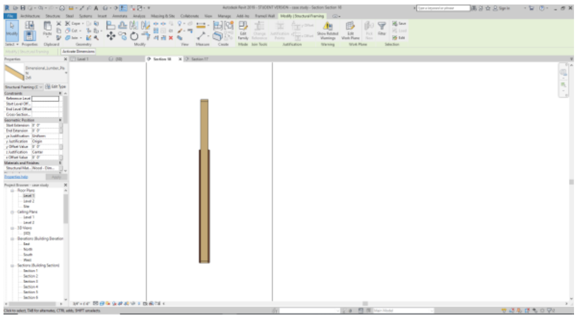
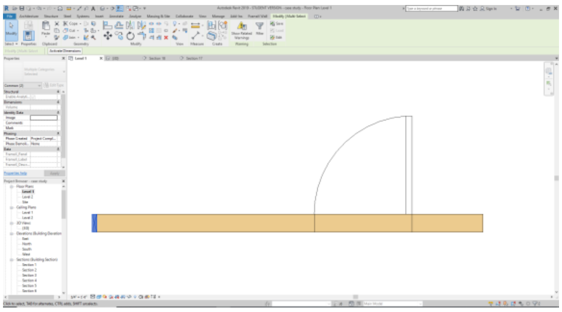
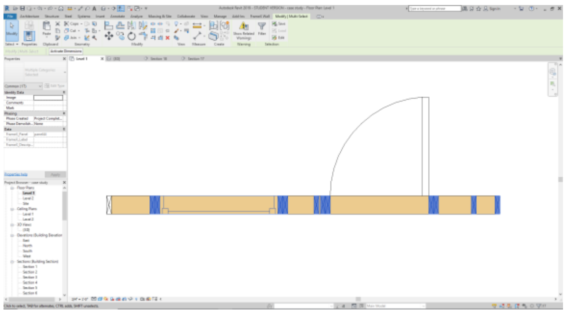
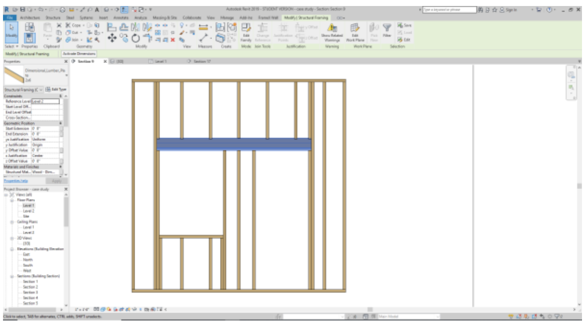
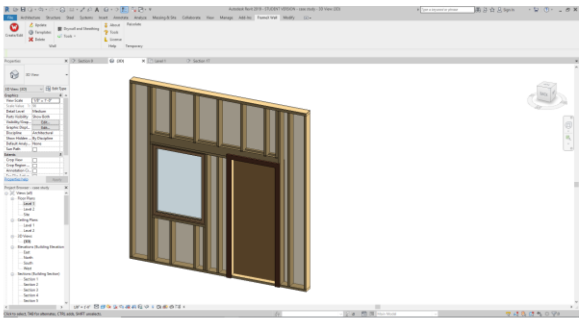
Step 1: Designing the wall (t = 10 sec) 	Step 2: Start the drafting (t = 20 sec) 
Step 3: Choose the top and bottom plate (t = 15 sec) 	Step 4: Define the properties of elements (t = 21 sec) 
Step 5: Adding Stud and defining its properties (t = 10 sec) 	Step 6: Copy and adding new studs according to the wall length (t = 25 sec) 
Step 7: adding the sill plate and header plates (t = 39 sec) 	3D view of the final result 

Table 4.7: Wall framing steps to frame a wall with multiple openings using FrameX add-on tool

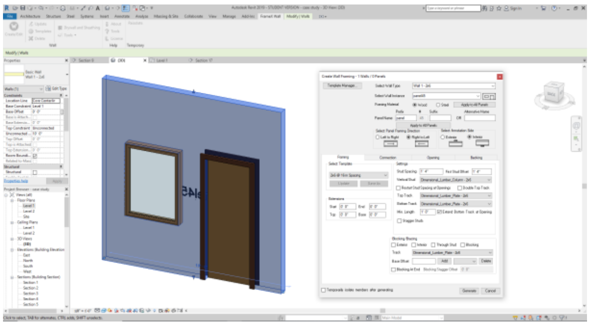
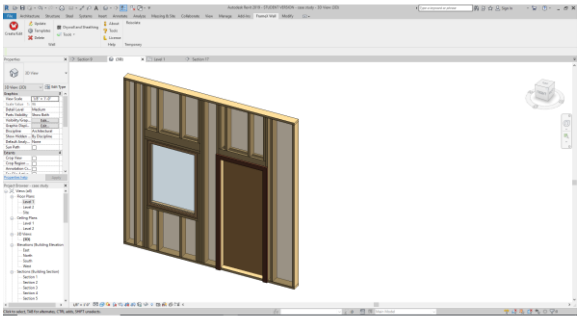
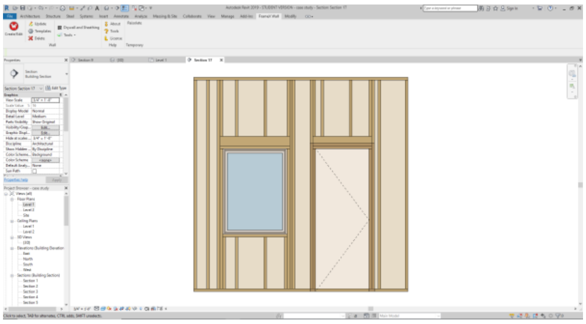
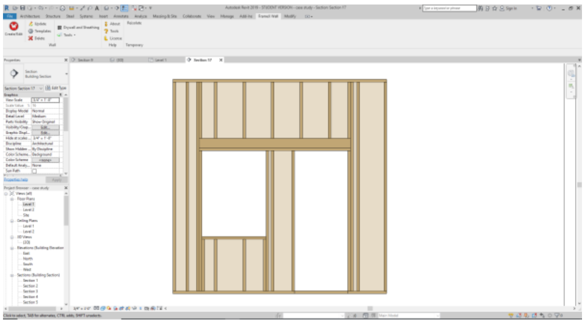
Step 1: FrameX interface for design settings (t = 11 sec) 	Step 2: FrameX outputs (t = 3 sec) 
Step 3: FrameX generation (t = 1 sec) 	Step 4: applying few manual changes (t = 10 sec) 

Table 4.8: Drafting time between manual vs FrameX performance in the case of shared header

Shared header	Drafting Time
Manual	140 sec
FrameX	25 sec
Saving	82%

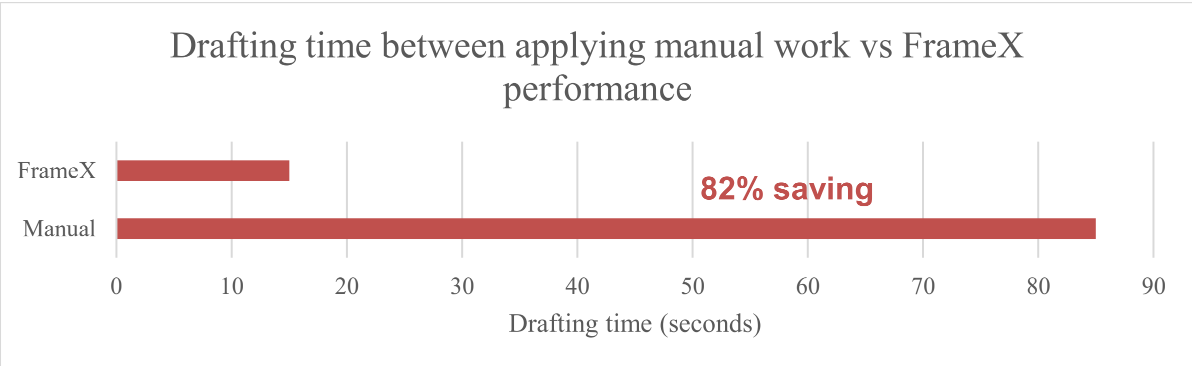


Figure 4.15: Drafting time for shared header

4.1.3 Temporary walls for shipping

Description:

Shipping walls are temporary walls (*TW*) that need to be installed for the purpose of transporting the modules to its destination. Two walls aligned on one straight line are built together as one assembly joined by a temporary wall (*TW*). Because temporary walls do not support a load they can be constructed with 24 in. stud spacing (O.C.) rather than the required 16 in. stud spacing in standard walls (*W)* as shown in Figure 4.16. Additionally, temporary walls can be constructed with low-grade lumber studs (*TS*) to minimize the material waste and costs. The temporary studs (*TS*) are only used during the shipping process and they will be removed on the project site.

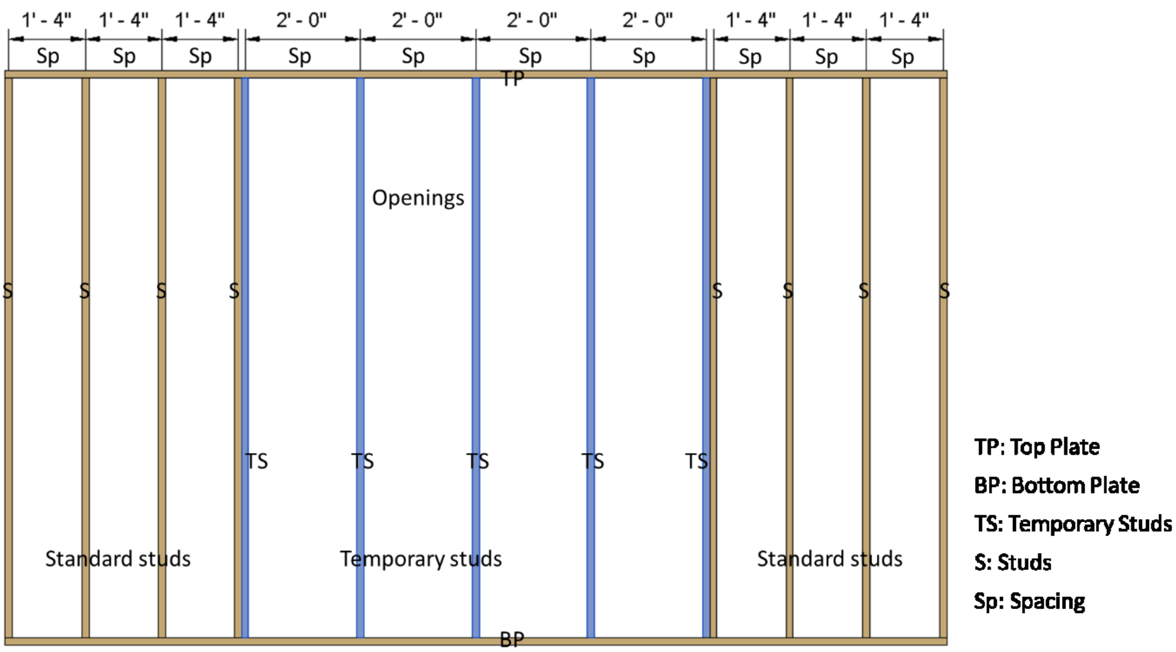


Figure 4.16: Front view of multiple walls with temporary wall in between

One of the major cases in this research is the BIM modelling of temporary walls (*TW*) which are common in the industry of modular construction. These temporary walls (*TW*) are required for transportation purposes to avoid damaging to the module throughout the transportation process and protect the module from weather conditions.

Framing the exterior walls must be done in accordance with design rules and with no gap (*G*) openings to comply with transportation regulations, for this reason, extra framing elements are added solely for transportation purposes. These extra framing components would be wasted and need to be considered as part of the total project cost; for example, large openings (*O*) in between modular units would require a temporary wall (*TW*) to be added. Framing these temporary walls (*TW*) may have a significant effect on the drafting time. Drafting all these details is time-consuming for the users, therefore, a comparison between the time required to frame a 60-foot wall (*W*) with shipping openings (*TW*) manually and using FrameX is presented in Table 4.9, and Table 4.10. It is expected to save 69% of the drafting time for the structural model.

Table 4.9: Time required to frame one 60-foot wall manually and by FrameX

60 ft wall	Drafting Time
Manual	4:33
FrameX	0:45

Table 4.10: Time required to frame 60-foot wall with temporary openings manually and by FrameX

60 ft wall with Temporary wall	Drafting Time
Manual	12:44
FrameX	4:00

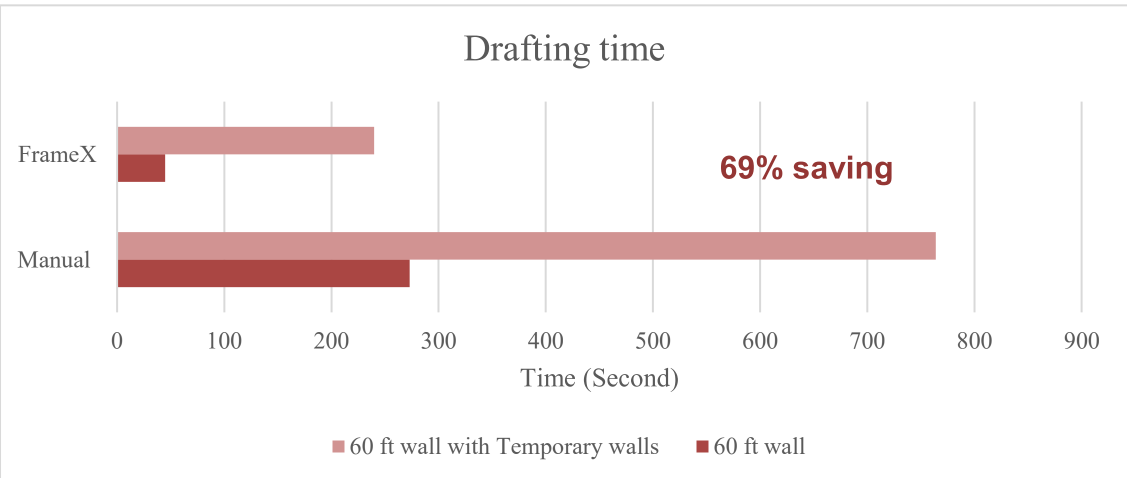


Figure 4.17: Drafting time for 60-foot wall

State (Condition)

If two walls (*W*) are on the same line with an opening (*O*) in between, one drawing with one schedule must be used for the frames on the same line. The two walls (*W*) with regular studs (*S*) + shipping opening framing (*TW*) with temporary studs (*TS*) are shown in Figure 4.18.

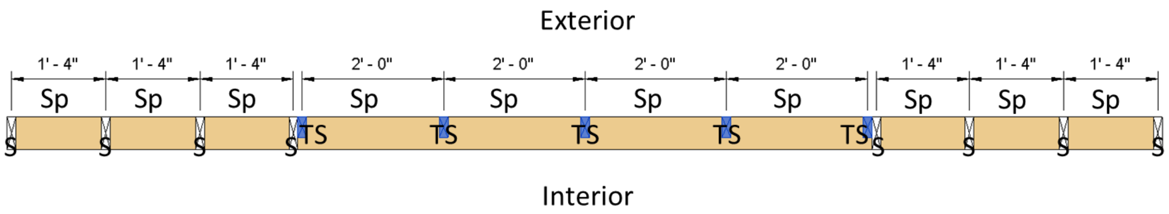


Figure 4.18: Top view of multiple walls with temporary wall in between

Based on the analysis of the framing cases, these equations represent the logic for automating the BIM modelling for the temporary walls. If *z*-coordinates are matching for the multiple walls, Equation 14 and 15 determines the coordinates of all the studs in regular walls (*W*) and temporary wall (*TW*) respectively. Therefore, the multi-panel total length is calculated by Equation 16 which lead to determine the number of regular studs (*S*) in Equation 17 and the temporary studs (*TS*) in by Equation 18.

$$(W)i = \begin{pmatrix} S_{11} & \cdots & \\ \vdots & \ddots & \vdots \\ S_{m1} & \cdots & \end{pmatrix} \qquad \text{Equation (14)}$$

$$(TW)j = \begin{pmatrix} TS_{11} & \cdots & \\ \vdots & \ddots & \vdots \\ TS_{m1} & \cdots & \end{pmatrix} \qquad \text{Equation (15)}$$

where:

S: Stud

m: x Coordinates for Stud Sequence

i: Number of Walls

TS: Temporary Stud

n: y Coordinates for Stud Sequence

j: Number of Temporary Walls

$$L_T = \sum L_{W\,i} + \sum L_{TW\ j}$$ Equation (16)

$$S_N = \left(L_T \big/ Sp \right) + 1 \big| \text{each wall}$$ Equation (17)

where:

S_N: Number of Studs

L_T: Total Wall length

L_W: Wall Length

W: Wall

TW: Temporary Wall

L_{TW}: Temporary Wall Length

$$TS_N = \left(L_{TW} \big/ Sp_{Max} \right) + 1$$ Equation (18)

where:

TS_N: Number of Temporary Studs

L_{TW}: Temporary Wall length

Sp_{MAX}: Maximum Spacing Allowed

The flowchart in Figure 4.19 illustrates that it is possible to use the multi-panel concept to create longer walls. It aims to achieve the creation of multiple walls (*W*) together with the temporary walls (*TW*) with different wall types as shown in Figure 4.20. The limitation of this methodology is with the top (*TP*) and bottom plate (*BP*) length and type. Long wall (L_T) can be grouped with the same dimensional lumber along the multi-panels for efficient manufacturing. However, there is no foreseeable problem with using different size of studs (*S*) with different spacing (*Sp*). Even in the case of different stud sizes, they will be aligned with the exterior core edge to fasten the sheathing layer as shown in Figure 4.21.

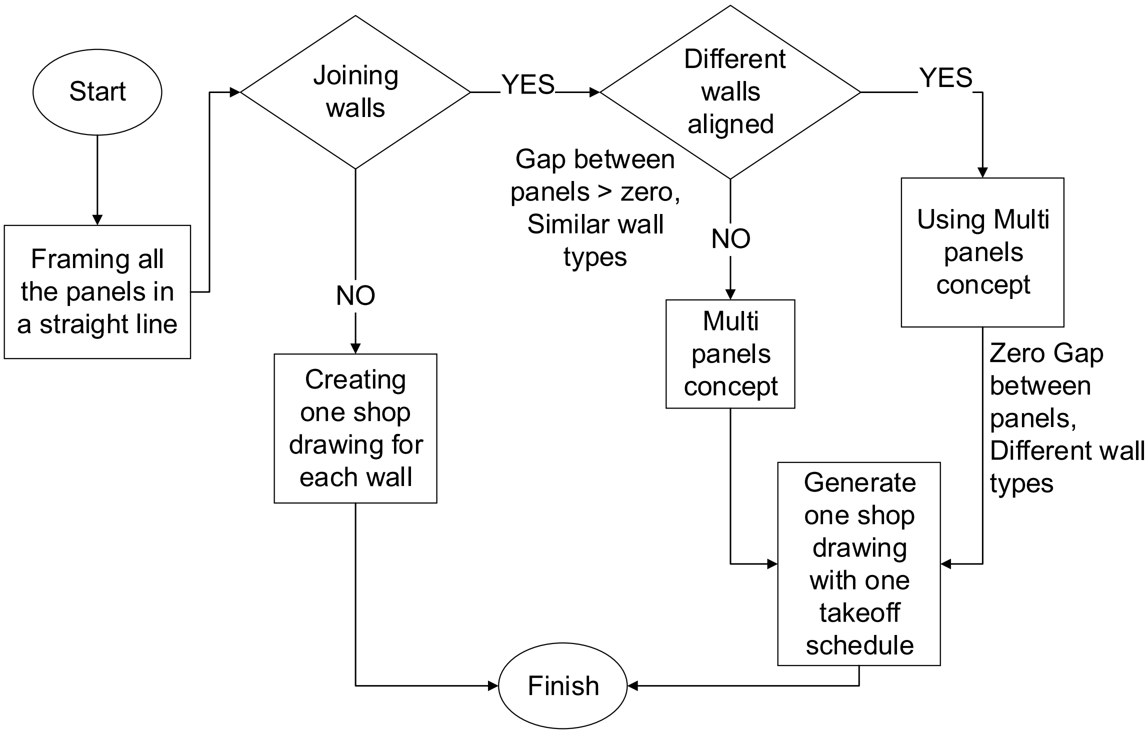


Figure 4.19: Flow chart the logic of multiple walls and temporary walls

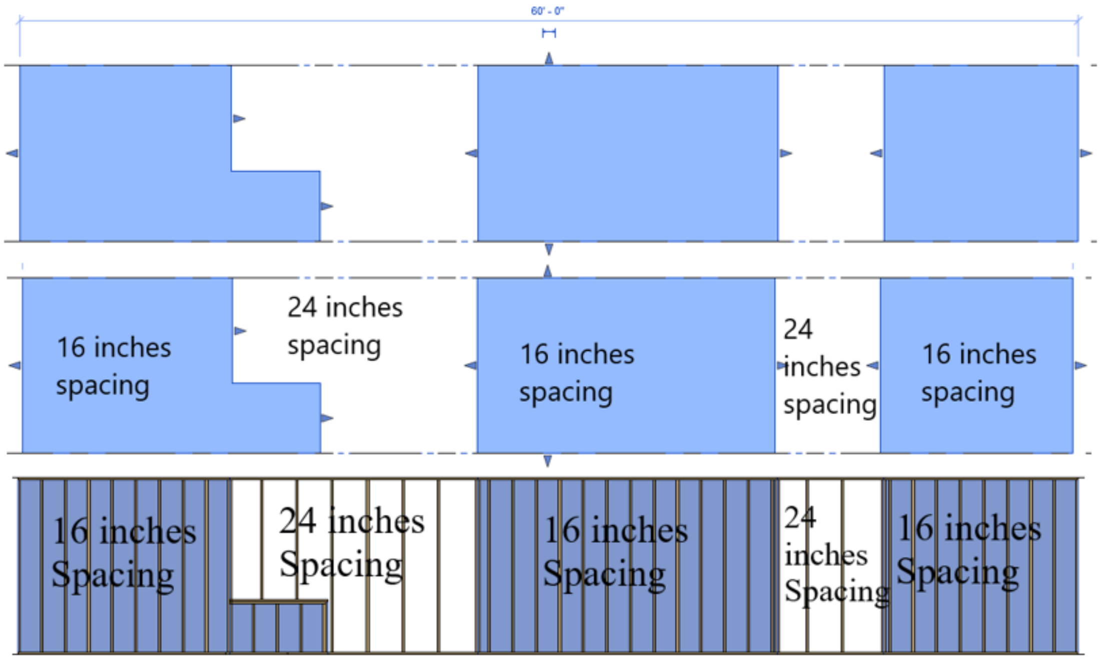


Figure 4.20: Stud Spacing on Multiple walls with shipping openings (Elevation view)

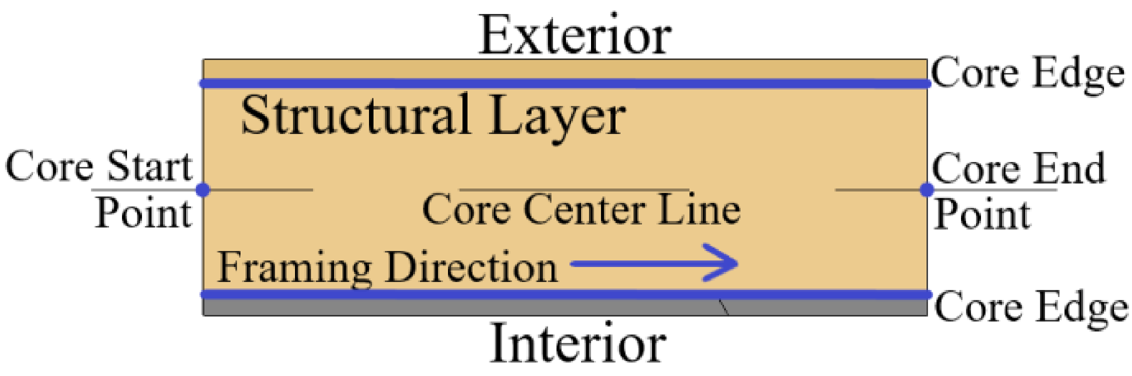


Figure 4.21: Top view for wall layers and boundaries

The developed logic identifies each wall (*W*) attributes in the system based on its function and location. It identifies wall (*W*) boundaries for FrameX parametric as shown in Figure 4.23, wall points represented on a cartesian coordinate system of *x*-, *y*-, and *z*-axes. It is represented on an order according to the point location within the wall (*W*). Once the wall boundaries are recognized by the developed logic, every wall (*W*) and temporary wall (*TW*) is sorted depending on the component characteristics such as length, height, and thickness based on architecture BIM model.

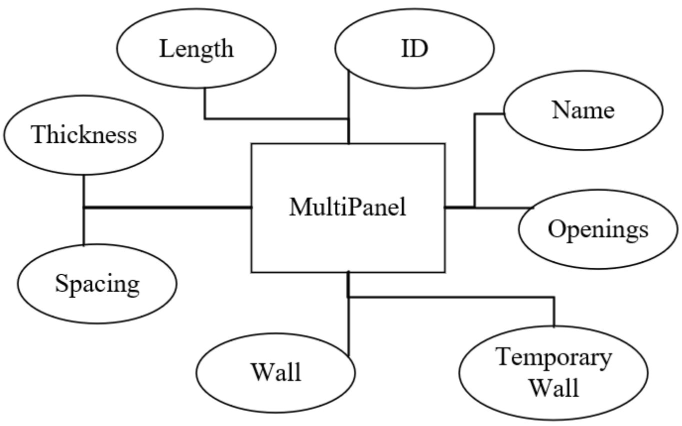


Figure 4.22: Multiple walls attribute

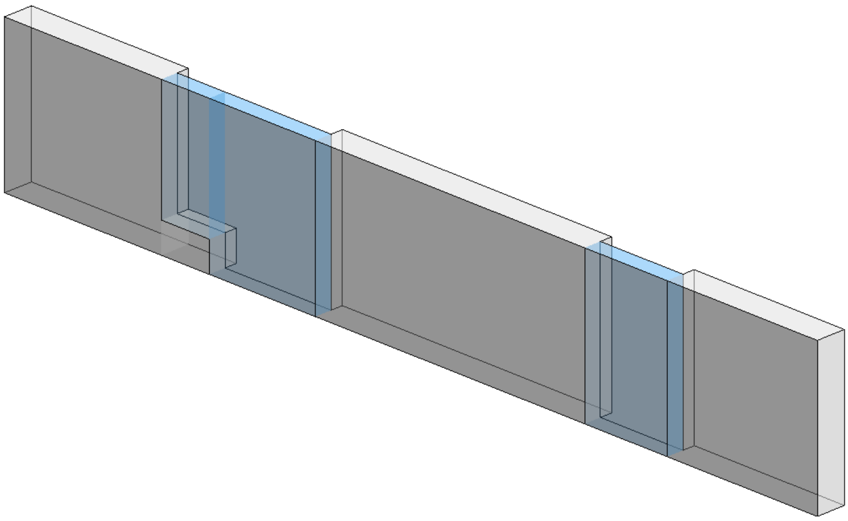


Figure 4.23: Multiple walls are aligned with temporary walls in between

4.1.4 Specific cases of formalized trades know-how

Case	Bonny wall + Shipping wall
Description:	Standard wall + Bonny wall are built as one assembly with the temporary wall for shipping as shown in Figure 4.24. 16 in. on center stud spacing in Standard and bonny wall 24 in. on center stud spacing for the temporary wall.
State (Condition)	If bonny wall of the standard wall of modular, shipping wall will be built on the opening area which would be not rectangular to be filled for shipping. Where one wall is joined in framing between two walls with bonny wall and opening area to be all framed once with different stud spacing for shipping regulations.

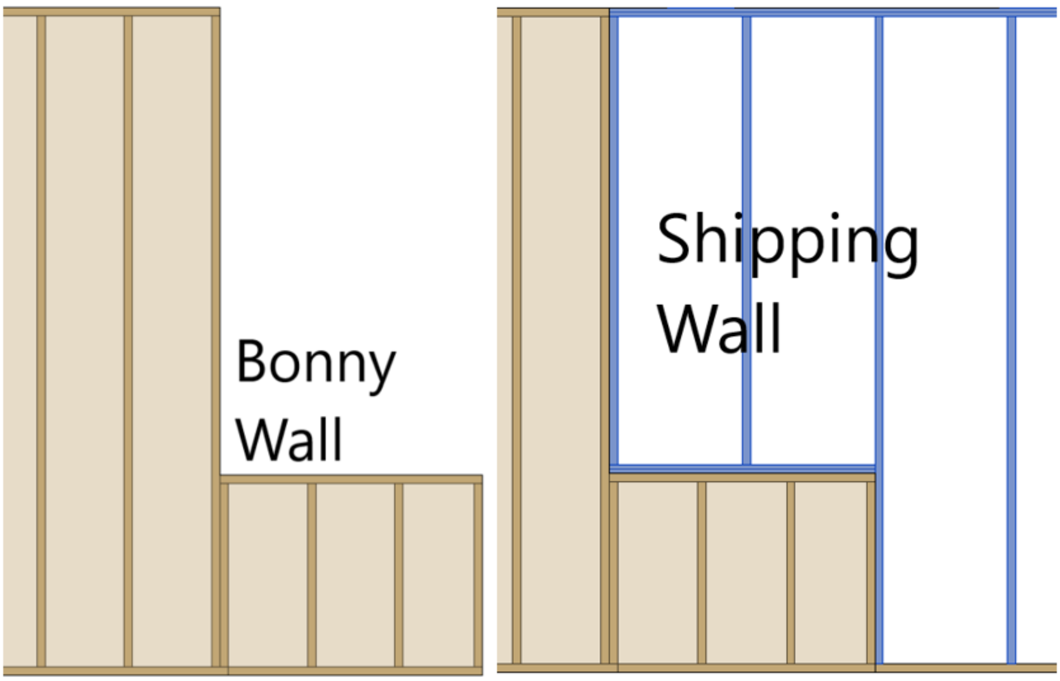


Figure 4.24: Bonny wall + Shipping wall

Case	Different stud type along same wall
Description:	In the case of plumping wall in a loadbearing wall, plumping wall could be 2x3 studs in this special case. Mixed type of stud in this wall. Extra 2x6 studs must support the 2x3 wall which change the 16" on center stud spacing. S1 in this case is a 2x3 stud, which is used for plumbing wall. This long wall has to be built as one wall with different kind of lumbers in one shop drawing. Multi panel works with this case where there are one mechanical wall between two normal walls as shown in Figure 4.25.
State (Condition)	In the case of water pipe going through a loadbearing wall, stud type needs to be thinner. If three walls with different functions and sections on the same line are built as one wall. Top and bottom plate are shared as one piece among the three walls. One quantity schedule for all three walls where they will be built as a one frame with different types of studs.

Figure 4.25: FrameX performance vs practical performance for one wall with thickness differences for mechanical purposes

Case	Double Cripples above openings in loadbearing walls
Description:	In the way of placing the drywall vertically, Double cripples are required to fasten the drywall when placing them vertically in rectangular shapes as shown in Figure 4.26. Figure 4.27: Drywall or Sheathing vertical layout.
State (Condition)	In the case of a jack stud around an opening, double top cripples on the edges of window or door to fasten the rectangular shape of vertical drywall. Figure 4.28: Flow chart represents framing logic around openings cripples. An extra cripple needs to be added at the edge of a door or a window when jack stud is placed.

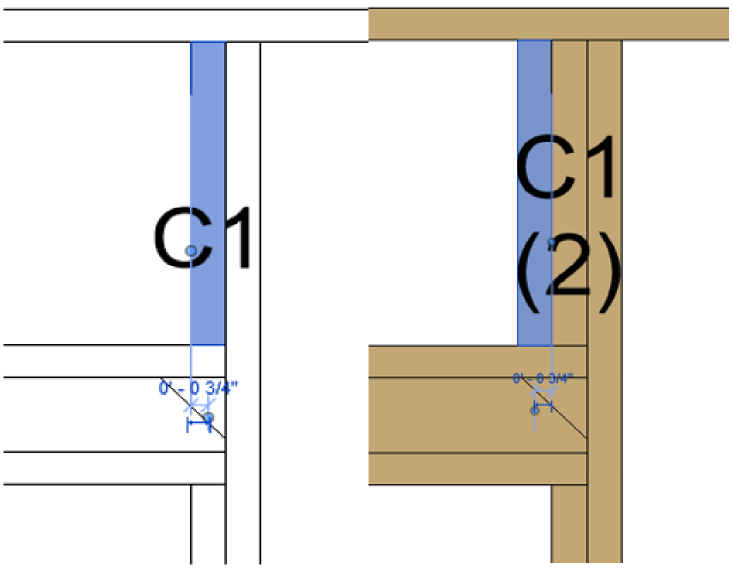


Figure 4.26: Wood framing siding cripples above door opening

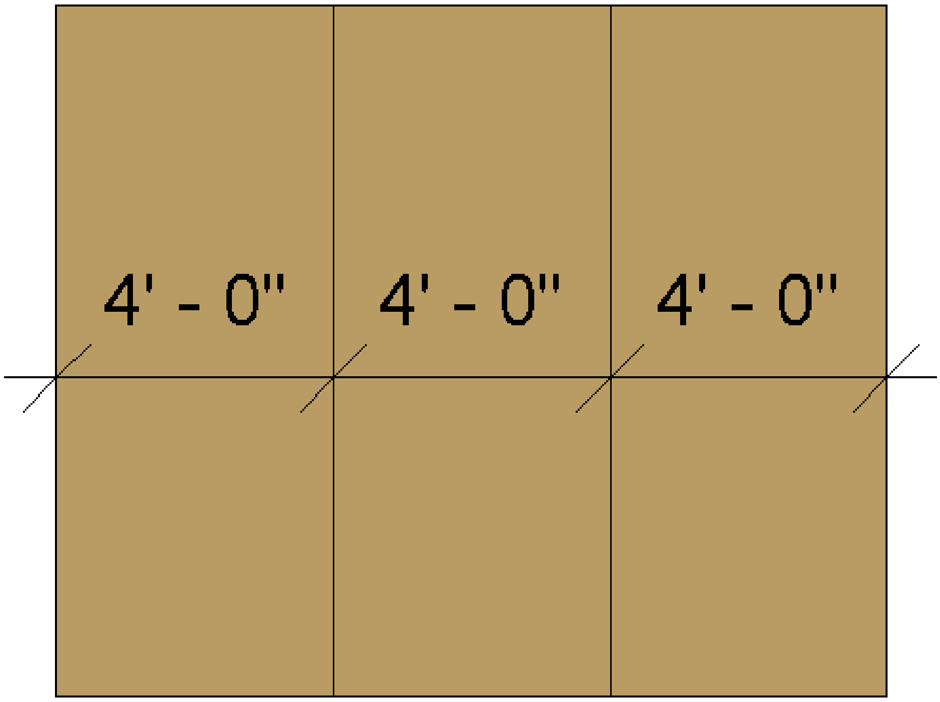


Figure 4.27: Drywall or Sheathing vertical layout

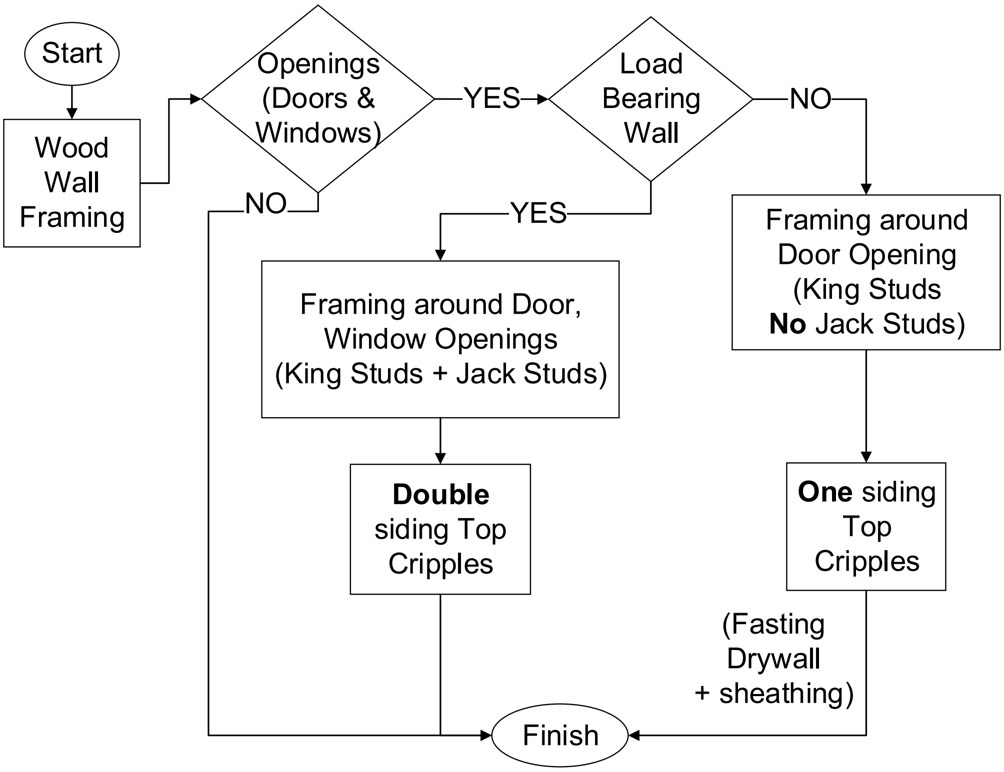


Figure 4.28: Flow chart represents framing logic around openings cripples

Case	Actual length of lumber supplied not always in perfect dimensions.
Description:	1/8 shorter between studs for the actual size of the stud. New option could be added to the software interface (depends on the users) that connected horizontal plates can be 1/8” shorter for perfect fittings where the backing can be easily fit in the spacing between the studs. Updating the bill of material schedule according to the right dimension for efficient framing as shown in Figure 4.29.
State (Condition)	In the case of adding backing members to support elements hosted on the wall, backing should be 1/8” shorter to easily fit it between two-dimensional lumber.

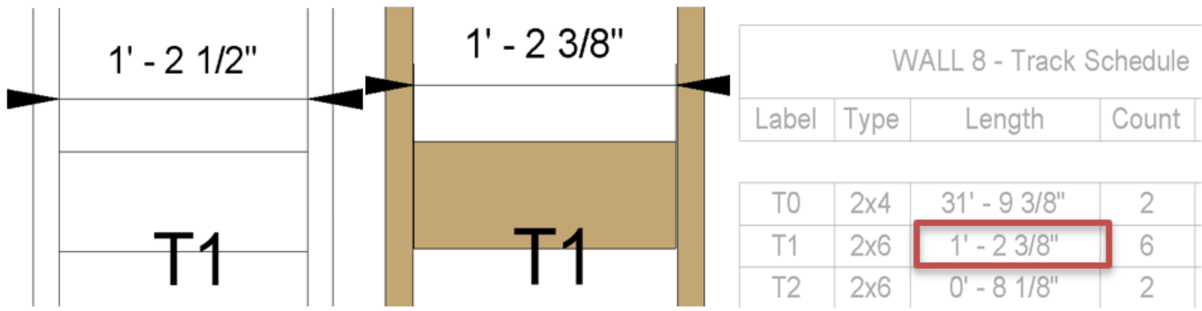


Figure 4.29: Actual length of backing members

Case	Double Backing for extra support for heavy component
Description:	Heavy component needs double backing members such as mobi;ity aid bar as shown in Figure 4.30. Flow chart represents the logic of double backing members is presented in Figure 4.31.
State (Condition)	In the case of a heavy component, Double backing is needed to carry the heavy load. The backing has to be doubled for heavy weight components.

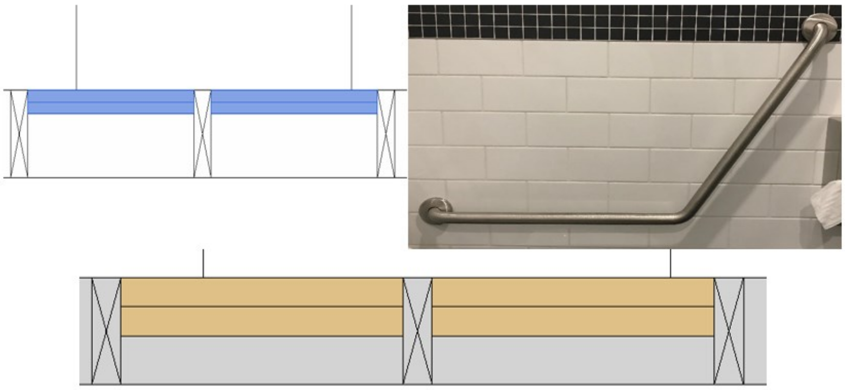


Figure 4.30: Double backing for heavy objects hosted on projects

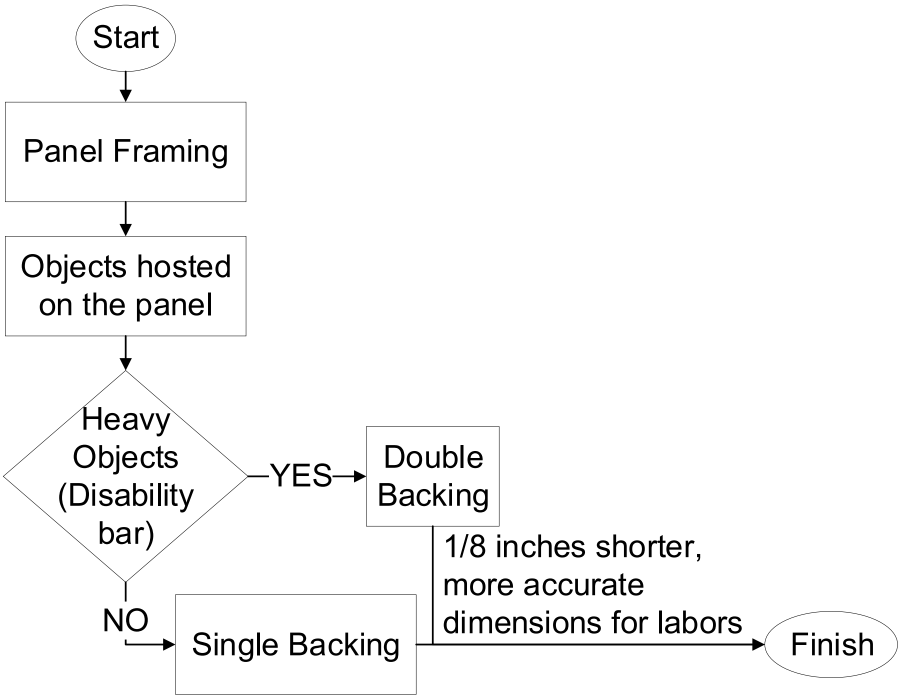


Figure 4.31: Flow chart represents the logic behind the case of double backing

Case: Connections

Case	Connection → 1: T-connection
Description:	Connection studs, one stud would be enough support for the partition wall as shown in Figure 4.32. Saving one 2x6 stud. Figure 4.33 shows a screenshot from current FrameX interface "connections". The minimum use of studs in such connections, one higher scale size stud as a best practice knowledge.
State (Condition)	In the case of T-connection between 2 walls, adding one stud size bigger is enough to support the partition wall. Lateral support is going through all the connection stud of a partition wall and the normal spacing studs are taking the load with no chance of buckling.

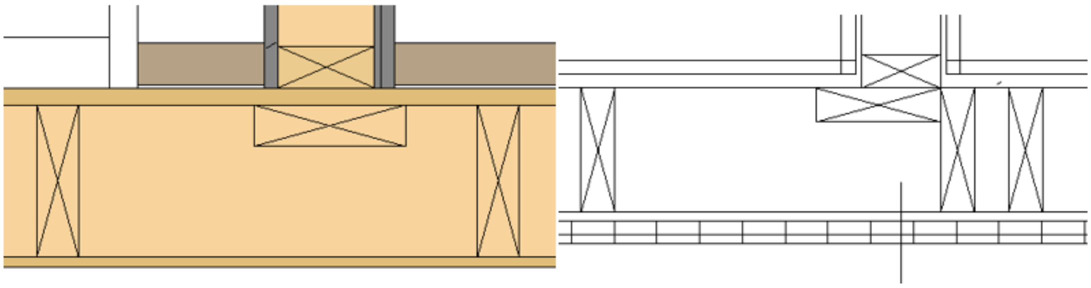


Figure 4.32: Minimum number of studs in T-connection

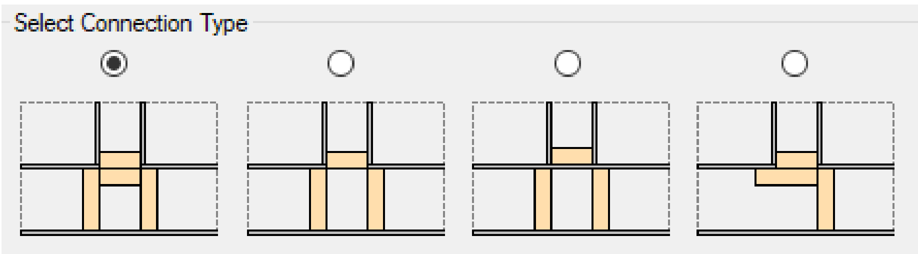


Figure 4.33: Selecting T-connection type using FrameX add-on

Case	Connection → 2: T-connection
Description:	Connection studs, two studs to support for the partition wall, without moving the studs to keep the 16” spacing on center as shown in Figure 4.34. The minimum use of studs in such connections with adding studs to cover the connection area with no movement for main stud spacing as a best practice knowledge.
State (Condition)	In the force of keeping the spacing on center-symmetric, especially in a loadbearing wall, connection studs placed in different locations. If the T-connection is going to break the standard stud spacing in a loadbearing wall, spacing should continue and connection studs are around the regular stud. The importance of keeping the spacing of studs continuous even in the case of other interferences.

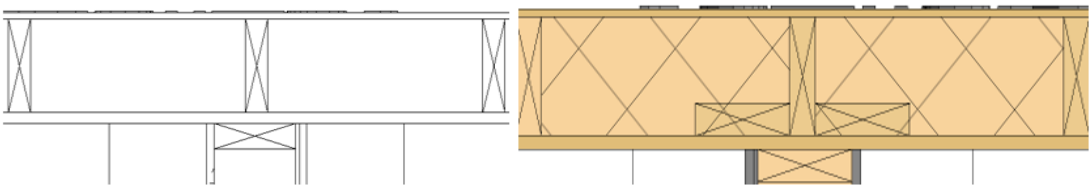


Figure 4.34: Framing around T-connection with a conflict of stud spacing

Case	Connection → 3: three walls connection
Description:	3 wall connections. More than 2 walls connections lead to losing some connection studs. T-Shape connection + Plumbing wall as shown in Figure 4.35
State (Condition)	In the case of three walls connections, Extra studs need to be added in this weak connection. If the connection includes more than two walls, connection studs should be around the regular spacing studs to easily install drywall with no studs overlapping.

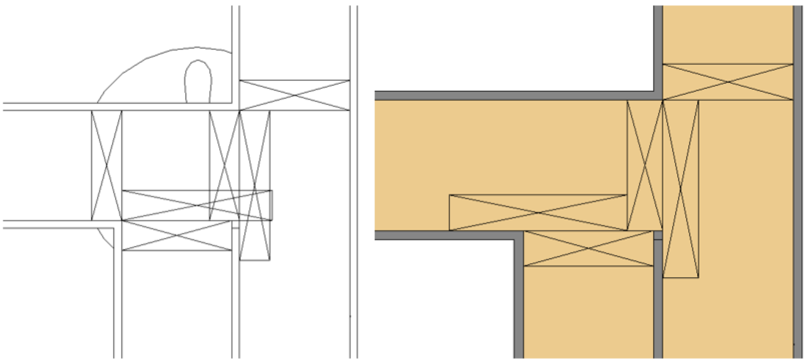


Figure 4.35: Framing around three walls connections

Case	Connection → 4: four walls connection (not aligned)
Description:	Four walls connection would lead to missing connection studs as shown in Figure 4.36
State (Condition)	In the case of 4 not aligned walls connection, extra studs need to be placed to support the partition walls and edges of drywall. Figure 4.36 shows that if a connection of four walls, regular studs and king studs has to be in the right place and surrounded by connection studs.

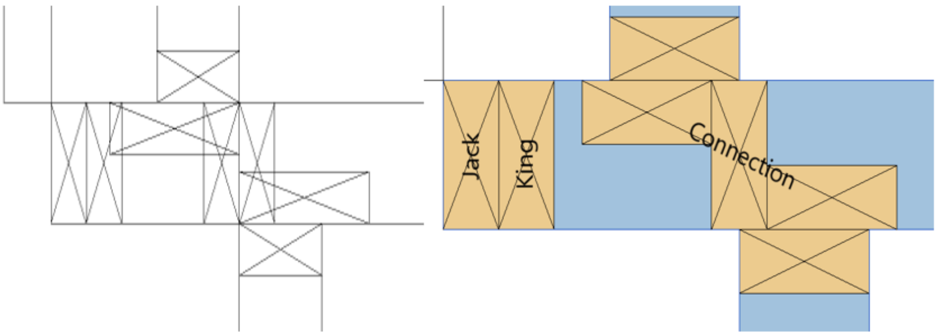


Figure 4.36: Four walls connection (not aligned)

Case	Connection → 5: four walls connection (aligned)
Description:	Two walls connection would lead to missing connection studs and overlap between top plates and bottom plates. Minimum number of studs for connection and drywall nailing area as shown in result Figure 4.37.
State (Condition)	In the case of two walls perpendicular connection, extra studs need to be placed to support the partition walls and edges of drywall. If a connection of four walls, extra studs require to be placed to cover the drywall connection area.

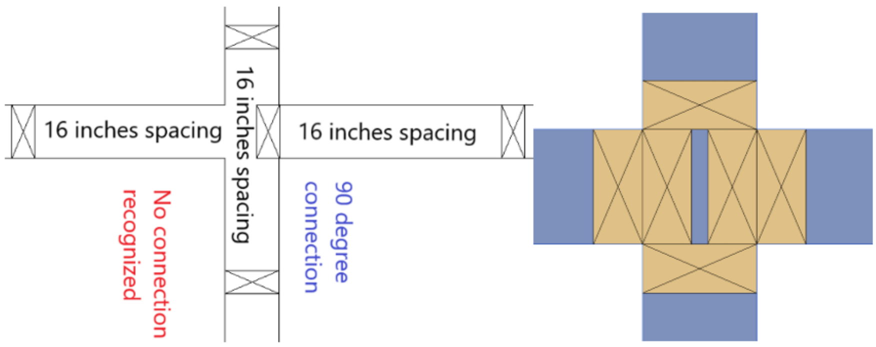


Figure 4.37: Four walls connection (aligned)

4.2 Results and Discussion

In practical terms, design and drafting work is never error-free and mistakes happen most of the time because of human error. However, many of these errors can be avoided and their risk can be mitigated before fabrication starts, and thus the amount of rework will be minimized and subsequently, the cost and time of the project will be reduced. However, these common errors are not due to conflicts with (NBC) and are generally related to material saving and shop drawing details that would result in less effective fabrication. The framing case studies presented in this research indicate that current automated drafting software such as FrameX has to be improved to generate shop drawings and eliminating errors in terms of flexibility and constructability.

In drafting and design tools, manual changes features will always exist in the software to maximize user flexibility. However, one of the existing software tools, namely FrameX, has been developed to improve the work of the designers and drafters. Minimizing the number of manual changes required is one of the objectives of this study, which is achieved by implementing the proposed framework in the existing software. Upgrading and extending the current functions and performance of the current FrameX add-on based on the presented framing cases improves its constructability and flexibility features.

The standardization of detailed framing cases is a practical way to reduce errors. For example, header plates above the opening in loadbearing walls can be standardized for future projects to be built in a U shape for adding thermal insulations. This can be achieved by selecting an appropriate framing case from among several practical stud configurations in modular construction as presented previously according to the industry standards. For instance, the specific case of wood material for headers above openings can be identified as the optimal choice in terms of cost, time, and thermal bridging. The current construction drafting process lacks basic standard specifications for complicated framing cases to improve the framing design and drafting process. Standards must be considered that will elevate the current construction method to achieve the best construction practices. Establishing a set of standards would decrease the decision-making time and effort so that users could avoid discussing complicated framing cases over and over in detail and can instead simply follow the established standardized best practices, such as connection studs in corner and T-shape connections.

Moreover, improvement of construction details through the establishment of clear guidelines that incorporate trade's know-how in an expert system and code & standards requirements is crucial for the automation process. The link between the state of the art academic research and the current practice is targeted by this methodology proposed previously, which would add practicality to modelling FrameX features. Integrating the BIM system for modular construction into an expert system would fill the information gap between current BIM practice and trades' know-how. In this respect, expert knowledge from the field needs to be documented and incorporated into the BIM technology, which would fill the knowledge gap in developing a conceptual design based on different technologies and from different perspectives of the work practicality. Support for the building conceptual designs was based on case-based reasoning applications to provide relevant precedents and examples of practices to increase the knowledge of users. The cases presented in this thesis are extracted from previously constructed projects.

The proposed framework improves the feedback process by reporting all the errors generated by the automated drafting tools. These errors are handled case by case through the proposed framework. Then, these cases are developed on the current version of the used tool (in this case FrameX). The feedback provided after each project supports the objective of this research which are eliminating the shop drawings errors and manual work.

Chapter 5 : CONCLUSIONS

The research presented in this thesis focused on the challenges and difficulties faced in the automation of the design and drafting process in the off-site construction industry. Enhancement of the developed FrameX add-on application was proposed in this research to make it a suitable software solution for a variety of framing configurations. It explores a knowledge-based automated BIM approach to framing design and planning. Also, it is created to improve the drafting process using BIM technology. FrameX is developed using the rule-based approach to determine best practices for the platform framing method incorporating client preferences and building code requirements. Best practices are found through the knowledge-based approach. The applicability of the FrameX add-on is demonstrated and validated by applying this software to real-time construction projects undertaken by local manufacturing companies. Moreover, an approach was proposed to enhance the intelligence system of FrameX software through practical knowledge of framing cases based on the users' feedback on the errors found in the shop drawings. The research also targets the manufacturability of framing techniques that are used in off-site construction. The case studies presented in this study improves the performance of the FrameX add-on. Framing cases such as temporary walls, mechanical openings, shared headers can be an asset in the design and drafting automation process.

The implementation of the proposed framework in real-time case studies shows a reduction in the design and drafting time which in return increases the designer's productivity. The improvement can save the users time and effort by adding more flexibility and constructability to the existing software. The results also show that drafting time can be reduced up to eighty percent compared to the current manual drafting work. Overall, the framing time of the whole project is going to decrease. The new features will prevent the user from applying manual changes and will keep track of the accuracy of the work.

In addition, the material required is going to be decreased through the approach described in this research. The accuracy of the structural elements is increasing due to more automation of the drafting process because FrameX provides quantity take-offs that are essential for estimating the project cost through the bill of materials. If the framing design is accurate, then the material quantity will be accurate. Therefore, this research improves the accuracy of quantity takeoff to prevent any deficiencies in the work flow.

Shop drawings' accuracy is increased due to the increased detailed level generated by FrameX, which will avoid trades from having to make any last minutes decisions (i.e., decisions that might affect the planned production flow). The precision of the quantity takeoff affects the workflow where trades in the wood shop sort the wood packages according to each panel. The flow of the work would stop or be delayed due to missing components in the packages. However, mistakes in the drawings have to be registered and reviewed carefully for future development.

5.1 Research contributions

The research presented in this thesis offers the following contributions:

(1) A rule-based modelling approach was enhanced that is capable of analyzing and designing building frames automatically as per the National Building Code of Canada taking into consideration the constructability and manufacturability features.

(2) The transportation regulations for modular components that affect the design and drafting automation process of the BIM model were analyzed.

(3) The industry best practices database was created using the knowledge-based approach and was integrated with an adaptive intelligent feedback system that shows a high tendency to facilitate the integration of the automation process in design and drafting.

5.2 Research limitations

All the cases that have been illustrated in this research need to be programmed and applied to FrameX. The concept of these framing cases has been proven in this research to be new enhancements for the current version of FrameX.

Limitations inherent in modular construction are that it is affected by the size of the modules where there is a maximum allowable length, width, height, and weight because of transportation regulations. Most of the building can be designed as modules with some modification in the design without affecting the architecture view of the module.

The number of projects that FrameX was tested on is limited. In the future, more projects would be beneficial to evaluate all the functions of this application and to represent its capability in automating the drafting process for the structural elements.

5.3 Future research

Future research might include the development of new functions of FrameX such as drywall and sheathing layout that would be helpful for the precutting of the sheets. In addition, some modules might be identical in the terms of their framing details, which is a potential for new development on how to duplicate the framing elements without negatively affecting the accuracy of quantity takeoff process.

Recycling the temporary walls is a potential research to reuse the temporary studs for different purposes. Reusing the available material to minimize the project material waste during the on-site assembly. Future research could be applied to reuse the temporary material to be utilized in furniture or house yard for example.

Additionally, detailed cost estimation is still a big challenge for the modular industry in the bidding process for new projects and using BIM technology will increase the accuracy of the cost performance by analyzing the model and filtering it according to structural, electrical, and mechanical elements, and more. An automated BIM based cost estimation tool can be developed in order to get a detailed cost assessment that depends on all the projects' elements rather than the existing square footage estimates.

Automation of template creation for representing results may facilitate modification to maximize the efficiency of the detailed shop drawings. Automation of these templates will enable the user to satisfy the clients' requirements. Clients would prefer different visualizations of the shop drawings generated according to each company's standards.

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