University of Alberta

Automation of Design and Drafting for Manufacturing of Panels for Wood Frames of Buildings

by

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Abstract:

Industrialization creates new requirements for design. Designers need to consider not only building performance, but also production plan needs. This requires a well-structured Building Information Model (BIM) to support the manufacturing needs for design and drafting. BIM, in combination with CAD tools such as AutoCAD and ArchiCAD, can be used for this purpose. These, however, are not sufficient to support the level of detail needed for the manufacturing process.

The proposed research establishes a methodology for the automation of design and drafting for the building manufacturing of residential facilities based on the platform construction framing method. The proposed methodology has been incorporated into a computer model called MCMPro, which was developed using Visual Essential for Applications (VBA) as an add-on to a CAD model. MCMPro incorporates BIM technology based on CAD parametric modelling and manufacturing requirements in a 3D-model, in order to generate sets of shop and fabrication drawings.

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Chapter 1: Introduction

1.1 *Motivation*

In 2004, the value of factory-built housing in Canada was $1.2 billion; this was 2.7% of the $80 billion yearly residential construction investment, if we exclude renovations and acquisition costs (Clayton 2006). Significantly, this fraction is projected to expand dramatically in coming decades, which offers the possibility of revamping both the methods and the end products of the construction industry. A primary motivation behind a shift towards manufacturing industrializing the building process is to reduce cost and time-to-build, improve the quality of the buildings, and produce more energy efficient buildings. Factory construction provides opportunities for applying production efficiency strategies in the plant that cannot be replicated at the building site, thereby eliminating waste, including process and material waste, and helping building manufacturers deliver a wider variety of products more responsive to customers' preferences in a shorter time and at a lower cost.

Industrialization creates new requirements for design. Traditionally, building performance has been the only factor considered by architects and engineers, and building drawings and specifications as the outputs of the design and engineering process. In factory-based construction, designers need to consider not only the building performance, but also production plans, transportation plans between the factory and the project site, and installation plans. Creating the detailed set of drawings needed for the manufacturing design process often requires significant time and effort for building component drafting producers. In addition, delays and/or errors in information transfer between design and production can result in hindered quality and reworks. Automating the design and drafting process is the first pillar of the industrialization of the building construction process or modularization. Design and drafting plays a major role in the cost-effectiveness, timeliness, and quality of the entire process. Advantages in terms of reducing redundant design activities, providing an infinite number of solutions, eliminating assumption and design errors, and shortening the time needed for any

modification can be obtained from automating the design and drafting modeling process.

Advanced computer tools utilizing Building Information Modeling (BIM) can be used to prepare smart designs, which integrate these models and coordinate the cross-disciplinary tools used for design, construction, and facility management decisions. Integrating these discipline-specific models with lean thinking and simulation will assist in minimizing or eliminating any *non-value adding tasks* performed by the construction engineer.

1.2 *Research Objectives*

The aim of this research is divided into two main directions: the development of a construction manufacturing technology and an automated system for design and drafting of manufacturing of buildings for the North American building construction industry, focusing on wood-framing construction. The manufacturing technology and the utilization of best practice for the platform-frame method has been incorporated into BIM models as a set of scenario-based analysis (SBA) rules that mimic human intelligence, incorporating the building code requirements and structural and architectural design needs. The objectives of this research are as follows:

1. To develop the modular construction manufacturing (MCM) process:
   a. Reengineering current practice by proposing a manufacturing process that has three main stages: panel prefabrication, production-line in the factory, and on-site unit assembly.
   b. Developing an intelligent design system plan that covers design aspects needed for construction manufacturing to facilitate knowledge and information communication among a projects' different stakeholders.
2. To develop an integrated computer tool for design and drafting for the modular construction manufacturing process. The development of this tool follows four steps:
   a. Developing Scenario-Based Analysis (SBA) rules that represent architectural and structural requirements, manufacturing concepts, and framing best practices.

b. Generating a BIM model for the project, automatically.
c. Upgrading the BIM model according to the manufacturing concept. The upgraded BIM model serves as a core model for the proposed design system. It can be uploaded with data related to project scheduling for the production line, project total estimation, and mechanical and electrical design.
d. Automating the detailing of MCM shop drawings that provide the required information necessary for the manufacturing process.

1.3 *Thesis Organization*

This thesis is organized in four chapters starting with the Introduction in Chapter 1, Literature Review in Chapter 2, Research Methodology in Chapter 3, and finally the Conclusion and Recommendations in Chapter 4.

Chapter 2 has three main sections. The first section focuses on Building Information Modeling (BIM) applications in the construction industry, in particular applying its concepts into a programming language, such as Visual Essential. The second section focuses on the modular construction manufacturing (MCM) process, its challenges, and the potential benefits it provides to the construction industry. The third section describes wood framing practises in the North America Construction Industry, the wall-framing process, and floor-framing process.

Chapter 3 outlines the proposed methodology. It describes the incorporation of architectural design, structural design, modularity concepts, and framing practise into an integrated computer tool called MCMPro, which is developed using Visual Essential for Applications (VBA) by means of CAD software. The Scenario-Based Analysis represented through parametric algorithms as well as 3D modelling, gives MCMPro the capability to mimic human intelligence and provides a graphical representation of the results to front-end users. This chapter then describes the case study applied to test the intelligence system.

Chapter 4 summaries the research general outcomes and their contribution to the construction industry. It also recommends proposed ideas for future research.

Chapter 2: Literature Review

2.1 *Introduction*

This chapter focuses on three main subjects that have been used in the research methodology: Building Information Modeling (BIM) technology, manufacturing of the building process, and wood framing methods. For the purpose of finding articles relevant to these subjects, major construction journals, such as Automation in Construction, Computing in Civil Engineering, Construction Engineering and Management, and Management in Engineering, have been targeted.

2.2 *State-of-the-Art Literature of the Application of Building Information Modeling (BIM) in Construction*

The multidisciplinary nature of modular construction manufacturing, which implies the need for a model to integrate all the different aspects of a project, makes BIM the right technology for the construction industry. BIM provides a core model loaded with project data that facilitates the data transfer process among the different project stakeholders. This research focuses on the development of an intelligent system that utilizes BIM as a technology to integrate the architectural and structural design, modularity concepts, and framing best practices into one model that helps the end-user during the decision-making process.

2.2.1 BIM Applications in the Construction Industry

Entity objects, which have been employed in earlier versions of Computer-Aided Design (CAD) software, have been a direct representation of the geometrical features of an architectural design. On their own, such entities have not provided any information on the characteristics nor the functionality of the structural and architectural elements they represent. They have solely depended on human intelligence to infer a reasonable explanation of those elements (Ibrahim et al. 2003). While entity-object-based software has managed to provide an acceptable representation of construction projects for a number of years, the complexity of construction project, the advanced technology, and the large

amount of information needed to be shared among projects team members has shown the inadequacy of this software. An innovative system that changes the way construction projects are managed during both the design and construction phases is required. As an object-oriented technology, Building Information Modeling (BIM) is perceived as the solution for these demands (Salazar et al. 2006).

In the context of this research, BIM is defined as a 3D object-oriented model of a construction project where hierarchically structured data stipulates the information provided by the Architecture/Engineering/Construction (AEC) sector. BIM helps the construction industry move away from entity-based CAD towards models that collect information about a project and correlate that information through geometric relationships. In BIM, project elements are represented as both records in databases that define elements' distinct characteristics and images that facilitate the visualization of the project end-product (Senescul. 2006).

The collaboration of each discipline to provide the essential information in a construction project is vital to insure that the developed BIM model is capable of providing construction drawings associated with a take-off list of materials, measurements of quantities and specifications, and a cost estimate (Ibrahim et al. 2004). A central model that stores all the needed information about a project and can be used by all members of the various project teams, without duplicating the information, can provide the interoperability needed for the BIM model (Senescl. 2006). When a BIM model is developed properly, it improves construction key performance factors in terms of quality, on-time completion, cost, and safety (Suermann and Issa 2007).

In addition to the digital representation of a construction project using a 3D model associated with project information, BIM technology can grasp human expertise and embed it into a 3D parametric model. The more advanced the technology becomes, the larger and more complicated parametric models BIM can control. These parametric models can capture the complex domain-specific knowledge of a project and incorporate it in developing systems capable of

providing the needed specifications for designing, modeling, manufacturing, and installing construction projects (Lee. 2005).

2.2.2 Limitations and Challenges of Commercial Generic BIM Packages

The current commercial generic BIM applications prevent BIM technology from reaching its optimum efficiency in the construction industry. Factors such as construction projects unique nature and efficient communication methods among the projects various teams have to be focused on when developing a BIM application.

Current BIM applications utilize generic components to represent different types of construction projects; however, they do not account for the unique design requirements and specific details that can vary from one project to another. For instance, a connection between two walls is represented in commercial software without any special details, while the platform framing practice implies that this connection needs to have different types of wooden stud formations (L connection or U connection). Figure 2-1 shows two walls intersecting using an L connection type, first in actuality and then in ArchiCAD, a BIM commercial software.

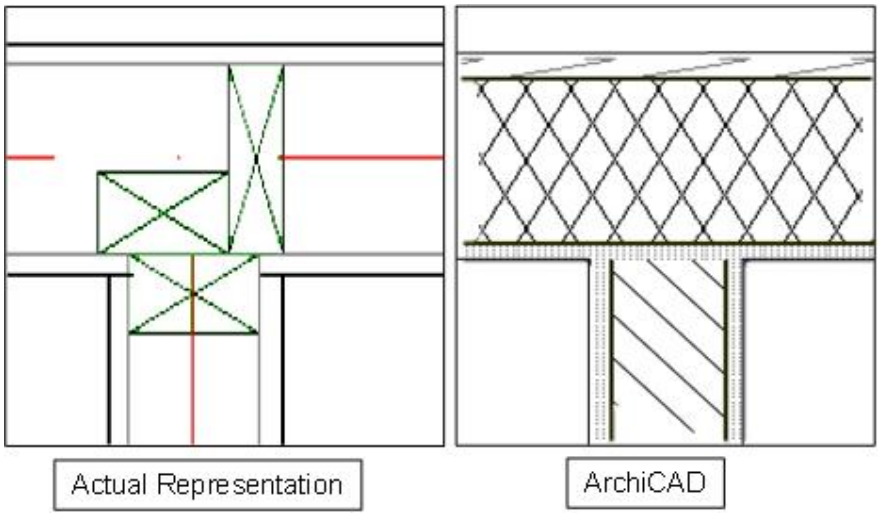


Figure 2-1: Two walls' connection representation comparison

In terms of communication and coordination among AEC teams and the various construction trades, it has been proven that BIM as a technology improves the information transfer process (Salazar et al. 2006). However, current commercial BIM applications are still unable to deal with this feature efficiently: They have

different versions for the projects' various stakeholders, i.e. Architectural AutoCAD, Structural AutoCAD, Mechanical AutoCAD, and hence do not provide a unified platform that clearly reflects the consequences a change in one specific discipline has on an entire project. A proper information transfer process requires not only a tool that allows the information to be shared, but also indicates when to transfer and what type of information needs to be shared. Delays in the completion date, project cost increases, and poor quality of the end-product are expected when sub-optimization of only a single discipline's performance occurs as a result of failing to provide a communication vehicle (Haymaker et al. 2005). A single platform for a project's multi-disciplinary processes provides an environment wherein input data from the various stakeholders are integrated to represent the knowledge of the effect an unplanned change in one discipline has on the others.

2.3 *Modular Construction Manufacturing (MCM)*

Unaccounted for on-site conditions can result in an increased number of changes during the construction phase. This can reduce the effectiveness of advanced technologies such as BIM and Lean construction. Construction manufacturing, in contrast, is a process where building units are manufactured in a factory under controlled conditions and shipped to the construction site to be assembled.

The modular construction manufacturing (MCM) process consists of three main stages: (1) panel prefabrication, (2) production line in the factory, and (3) on-site model installation. The production line is divided into four phases - walls, slabs, electrical, and mechanical - whereby each phase in the production line has a different number of stations. Specific sets of shop drawings are required for each phase. This stage finishes when a unit is manufactured.

2.3.1 Past Research in Modular Construction Manufacturing

Improving performance of construction projects in terms of quality, safety, time, and cost has been the focus of much research that has developed techniques and methodologies to overcome the ambiguity accompanied with the construction

industry. For example, previous research has focused on automating specific building processes through the use of robots (Navon 1996), and employed automated systems to identify construction safety requirements (Wang and Boukamp 2007), while others improved construction component tracking systems in an attempt to optimize project cost and time (Torrent and Caldas 2009).

In today's construction industry, the drawbacks of the stick-built method have led the need to move towards construction automation manufacturing. The nature of on-site construction prevents new technologies, such as Lean construction and the use of robotics, from reaching their optimum efficiency. Although lean manufacturing has been applied to various industries and benefited their productivity, the construction industry still faces real challenges in adapting to lean manufacturing concepts. Because manufacturing plants and construction sites are different in many ways, Lean production theories and practices do not fully fit the construction industry (Salem et al. 2006). Another advanced technology is the use of robots during the construction phase. This technology has not been employed efficiently because robots are stationary in nature, and on-site construction decreases their efficiency due to changing site conditions, adverse weather conditions (including variations in humidity and temperature), as well as constant exposure to dust and dirt on site (Kumar et al. 2008).

To solve the current construction challenges, a shift towards manufacturing the building process is required. This shift entails a special focus on the design process, a core issue in the AEC sector; it plays a major role in the cost-effectiveness, timeliness, and quality of the entire project (Chua et al. 2003). Having a well-defined and detailed set of construction drawings is also essential for better communication and coordination among construction project team members (Gao 2006). Furthermore, research has shown that site safety improvement and management is better applied during the design phase (Wang and Boukamp 2007).

This research methodology demonstrates a modular construction manufacturing (MCM) process and a detailed methodology for the automation of design and drafting for the MCM of residential facilities based on the platform

framing construction method. The MCM tool MCMPro, developed using Visual Basic for applications VBA by means of CAD software generates sets of shop drawings. It is intended to facilitate design and drafting in manufacturing building process by automating the process using 2D CAD and parametric modelling. Furthermore, this research can be used as a basis for other research for incorporating mechanical and electrical systems to the drawings. It will help to eliminate conflicts between various trades by specifying the exact locations where plumbing, HVAC pipes, and electrical wiring interact with the framing system.

2.3.2 Modular Construction Manufacturing Challenges

The construction industry is conservative in accepting changes to the way it operates (Kumar et al. 2008). Despite previous attempts to automate the industry, construction automation has not yet reached its potential, and construction remains by in-large a craft-oriented industry (Maeda 2005). This is in fact due to the nature of the industry that includes uniqueness of building products, site production, and temporary organization. All these characteristics contribute in making mass production in construction rather unappealing (Lauri Koskela 2003). Another challenge is that buildings are spread over different geographical locations and constructed by trades and small contractors, who have only temporary relationships with builders. Introducing new technology or materials becomes difficult since this requires special equipment or skills that may not be readily available.

Any shift towards construction manufacturing requires a clear definition of the path towards the level of construction industrialization, and the impact this shift has on the manufacturing environment technologically, economically, and socially.

2.4 *Background on Wood-Framing Design*

2.4.1 Platform-Framing Method

Wood-frame construction has been the system of choice in Canada for many years. It has also been the subject of much research into optimum-value, engineered-framing design. There are two types of frame construction methods:

platform-frame and balloon-frame. In the balloon-framing method, studs run full height from the sill plate on the first floor to the top plate, a maximum of 20 feet. This method was popular before the 1930s until the development of the platform-framing method, which is now the most commonly used method for framing in houses. The major advantage of the platform method is the ability to erect one storey at a time. In the case of a two-storey or higher building, the first-floor walls are erected and the floor system for the second storey is set on top of the walls. The result is a one-storey-high "platform" on which to begin erection of the second-storey walls. It is easy to perform and provides a work surface at each floor level that is readily adapted to various methods of prefabrications. This makes it most suitable for MCM. Figure 2-2 shows a profile and 3D representation of this method (Kesik 1998).

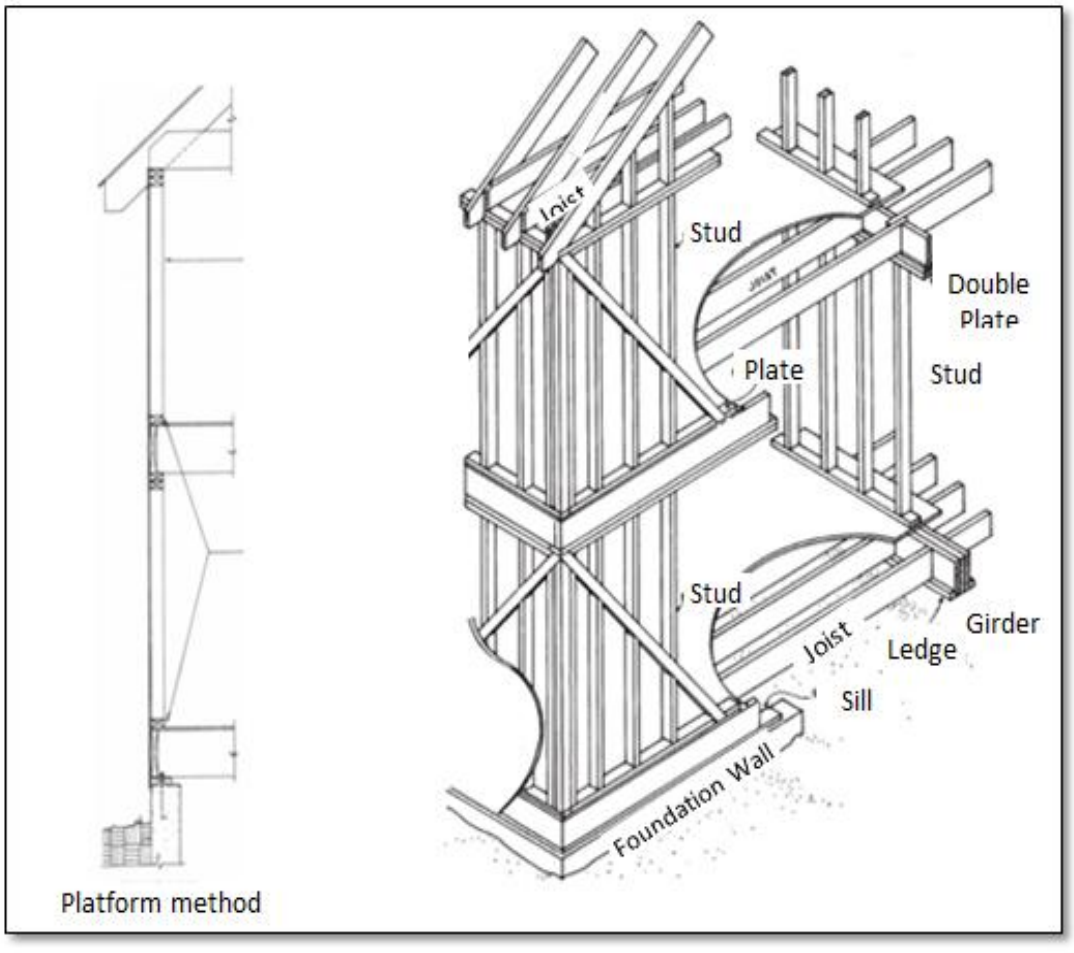


Figure 2-2: Platform framing method

2.4.2 Wall Framing

Wall frames must be of adequate size and strength to support floor and roof loads, as well as the lateral loads applied from wind and earthquake forces. A wall panel in the platform-framing method consist of a bottom plate, studs, top plate, and very top plate. The very top plates are lapped at corners and at partition connections to tie the building into a strong unit. Cripples, jacks and headers are added to this structure when a wall has an opening, a door, or a window. Figure 2-3 shows a wall panel with a door and a window. The information shown in this Figure is based on expertise obtained by shadowing trades people at construction sites and framers at the manufacturing shop using the platform-framing construction method.

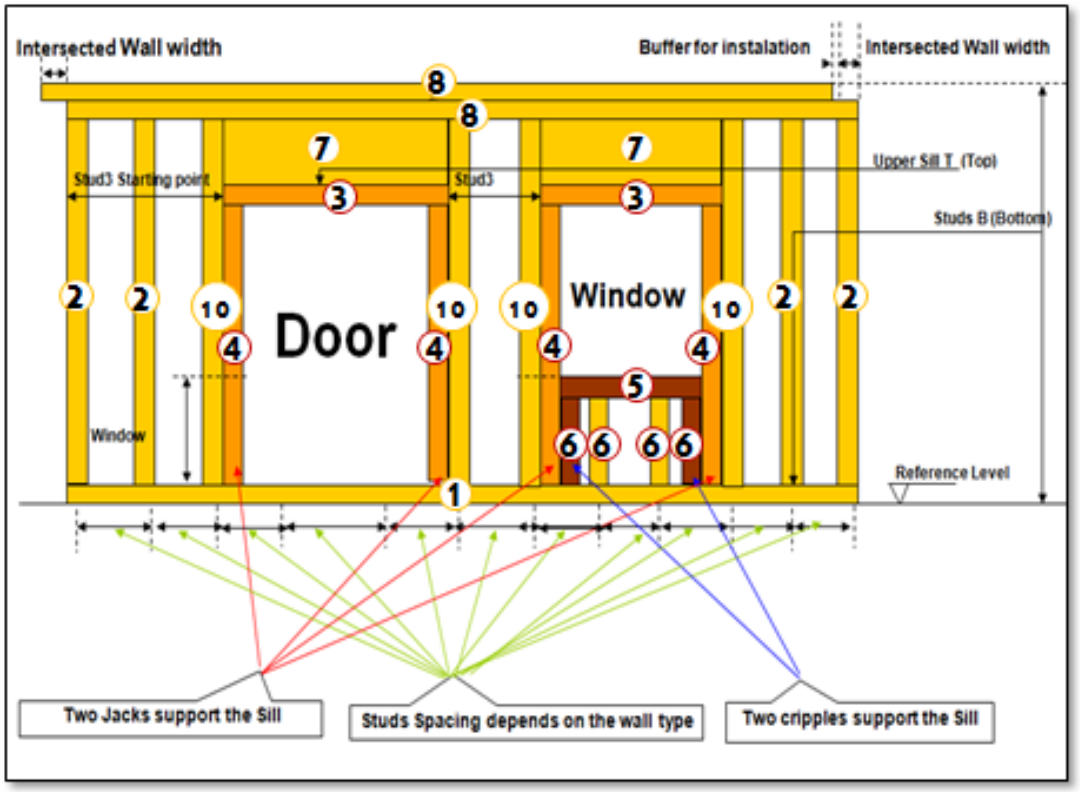


Figure 2-3: Wall panel frames

Stud size and spacing are the factors that determine the strength of a wall panel- the bigger the studs the further spacing can be. A 2x6" wall has become increasingly popular for exterior walls in recent years, primarily because it provides more space for insulation and allows for other minor energy-saving

advantages. A 2x6” wall with studs spaced at 24” .o.c. (the maximum spacing allowed by the national building code) uses about 20% more material for studs and plates than a 2x4” wall with studs with a code-allowed spacing of 16 in. o.c. On the outside, the sheathing has to be 1⁄2” thick (1⁄8” thicker than sheathing on a standard 2x4” wall). Inside, the drywall also has to be 1⁄8” thicker to span the 24” spacing between 2x6” studs.

Wall type as load bearing or non-load bearing affects the design of the upper part of the opening. In the case of a load-bearing wall, a double 2x10” header extends between the two jacks, and based on the wall height and the opening sill height, cripples might be requires to fill the gap if one exists. When a non-load-bearing wall has an opening, no headers are used. Figure 2-4 illustrates the three scenarios for opening headers (Kesik 1998).

The components that need to be considered when framing a wall is the connection between these two walls that could have a shape of U or L as illustrated in Figure 2-5.

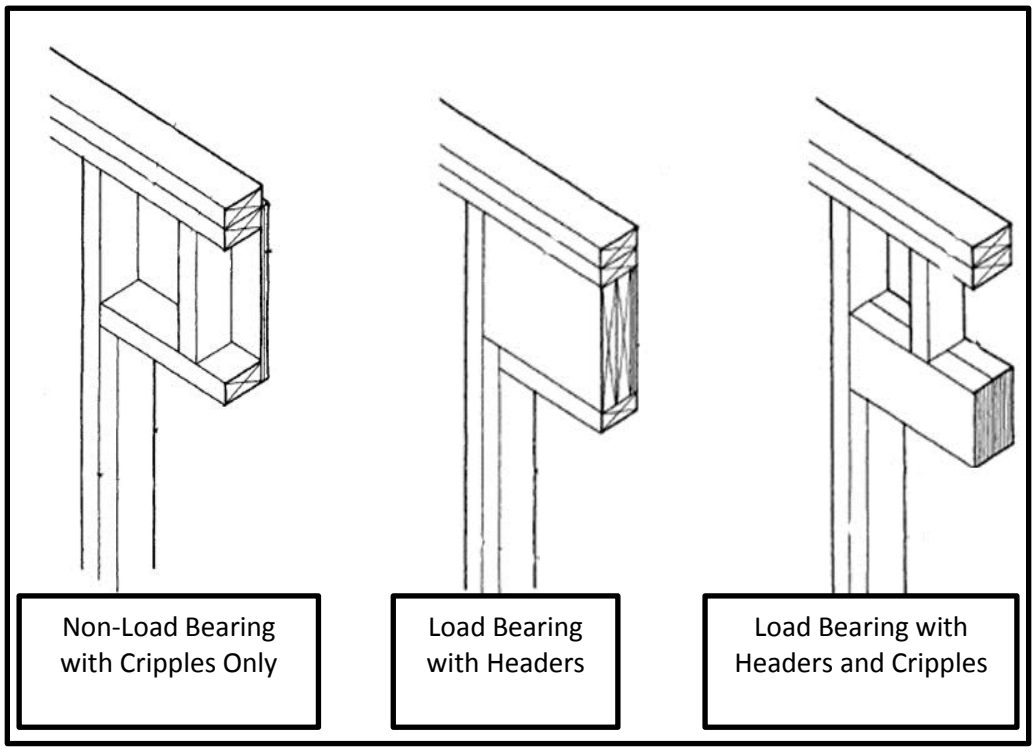


Figure 2-4: Load bearing and non-load bearing wall with an opening

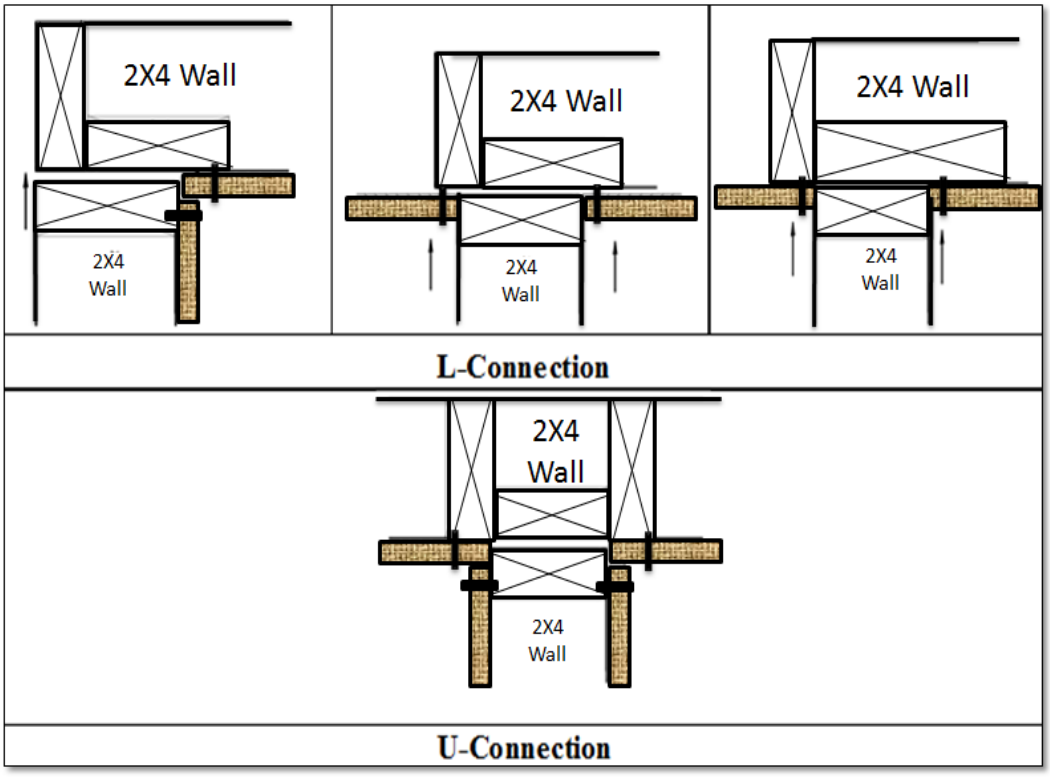


Figure 2-5: Walls connections types

2.4.3 Floor Framing

It is common to use engineered wood for floor systems. Engineered wood products (EWPs) provide equivalent or even superior performance to dimension lumber. Engineered wood floor systems give builders and designers strength, dependable performance, and design flexibility. A variety of floor framing and wood structure panel products can be used in floor construction. To select the appropriate products and floor design, it is essential to define the predicted loads and to consider both the structural requirements and compatibility with the finished floor requirements.

Floor framing consists of a system of joists, headers, and sub-flooring that provides support for floor loads and gives lateral support to exterior walls. Adequately nailed subflooring will maintain the upper edges of floor joists in proper alignment. Nailing the ends of joists to the headers provides additional joist support that, under normal conditions, eliminates the need for intermediate bridging. Figure 2-6 shows framing of tail joists by framing anchors.

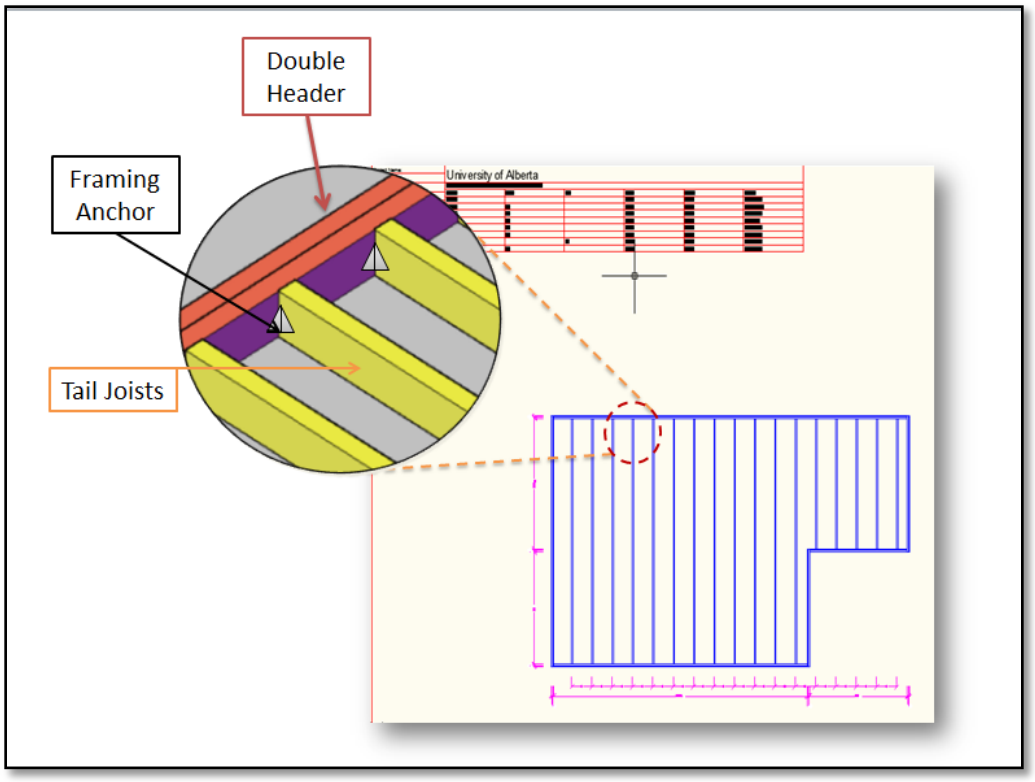


Figure 2-6: Framing of tail Joists by the framing anchors

2.5 *Previous Research*

Utilizing BIM technology to support the design and drafting process of wood framing has been the focus of several research. The home building industry was a primary area of interest for a previous study (Manrique 2008). A core model loaded with a project's information was used as an information management system, which provides the needed data to automatically develop shop drawings for wall panels. The development of repetitive drafting tasks was supported by 3D and parametric modeling, which facilitates the generation of construction drawings for wood framing, sheathing, and interior drywall.

In addition to shop drawings, the core model provided a take-off list of materials, optimum materials' cut list, and advanced construction methods incorporating innovative technologies, such as optimization methods, into that model.

Chapter 3: Research Methodology

This research focuses on two main objectives: the development of a construction manufacturing process and an automated system for design and drafting of MCM for the North American construction manufacturing industry, with regard to wood-framing design and construction drawings. For the purpose of fully automating the design and drafting for modular construction manufacturing, Scenario-Based Analysis (SBA) and Building Information Modeling (BIM) have been used as an integrated computer design tool called Modular Construction Manufacturing Tool (MCMPro).

3.1 *Modular Construction Manufacturing Process*

Conversion to factory-based production in construction is perceived as difficult since it requires strict process control, levelled production flow, and prompt coordination. This research proposes a structured manufacturing process to integrate industrialized building systems into the current building process. Three subtasks are proposed:

1. *Support the construction process to incorporate industrialized building systems:* The transformation from site-built to factory-based construction has far-reaching impacts on a company's business model. To fully understand the problem and provide a practical solution, a complete analysis of the current building process is needed to develop future strategies that allow integrating industrialization technologies and lean principles.
2. *Information management systems:* In current practice, the construction process is often fragmented with information exchange among the partners involved in the process. Identifying the builders' design needs is essential for the development of an integrated building information system that assists in coordinating the process. Two core requirements of the system are identified: 1) to integrate design and engineering information details; and 2) to provide an interactive scheduling system to promote production flow.

3. *Installation:* Site installation accounts for a significant portion of overall cost and plays a major role in determining construction quality, performance, and durability. The degree of installation difficulty varies as the level of prefabrication changes. Figure 3-1 shows three examples of installation: panel (a), complex roof structure (b), and a module (c). Efficient and standardized installation practices need to be considered. Such practices include benchmarking installation quality and performance; developing standard working procedures; devising systems to effectively track the performance of installation; and developing a formalized lean problem-solving loop that identifies bottlenecks, investigates root causes, develops long-term solutions, and integrates solutions into standard working procedures.

(a) (b) (c)

Figure 3-1: On-site installation of prefabricated building components

3.1.1 Definitions and Degrees of Industrialization

This research proposes five degrees of industrialization: prefabrication, mechanization, automation, robotics and reproduction (Richard 2002, 2007-a, 2007-b, and 2005).

Prefabrication: Prefabrication generally implies the factory-building of components or full modules, which are similar to what is constructed on a traditional job site, often using the same processes and the same materials. Prefabrication potentially reduces construction costs and ensures better quality due to the following factors: *1) Climatic protection:* Work is conducted under a roof and protected from weather conditions and material damage by water, snow, or solar radiation. *2) Tasks are along a production line:* The main assembly line is

fed by sub-assemblies. *3) Specialized tooling:* Tasks are subdivided and made simple through pre-adjusted tools and jigs. *4) Salary scale:* trade certification is not generally required for some phases of the production sequence, whereas computer skills are necessary for Computer Numerical Control (CNC) operations. *5) Bulk material purchasing:* Cost-saving and better quality due to factory-direct delivery.

Mechanization: Mechanization exists whenever machinery is employed to ease the work of a labourer (power tools, material handling equipment).

Automation: Tooling is progressively taking over tasks traditionally performed by labourers. A production line will reproduce the operations using machinery in a more straightforward way, e.g. nailing a full stud in a single operation, with a multi-point nailing machine.

Robotics: Hand-in-glove with tooling technology is the multi-axis flexibility to autonomously perform diversified tasks. Perhaps a robot is too expensive to be used simply for nailing wood studs or laying brick. However, the future of construction-based robotics is largely related to computer-aided manufacturing (CAM), accommodating individualization within mass production to what is now called mass-customization.

Reproduction: The word "reproduction" is borrowed from printing technology: Once the plate is set-up, a large number of pages may be printed in succession. Reproduction implies research and development for the introduction of an innovative technology capable of simplifying the multiplication of complex products; its purpose is to shortcut the repetitive linear operations, which are the trademarks of the handicraft approach.

3.1.2 Main Stages of the Modular Construction Manufacturing Process

This research proposed process follows the procedure shown in Figure 3-2, where three main stages have been identified including, panel prefabrication, production-line in the factory and on-site unit assembly.

The production line is divided into four phases—walls, slabs, electrical and mechanical—through which all the project units pass in order to produce the final products that are ready for on-site installation. Each phase has a different number

of stations accordingly. The process starts with assembling the walls; these walls are tagged with discrete numbers which will be used when connected to framed units. The second step includes slab and ceiling components. At this stage, a framed unit is produced and is ready for the following stages: Mechanical and electrical systems including plumbing pipes, fixtures, HVAC units, HVAC pipes, electrical wiring, electrical panels and different types of plugs are installed, and a unit is manufactured and ready for the final stage on-site installation.

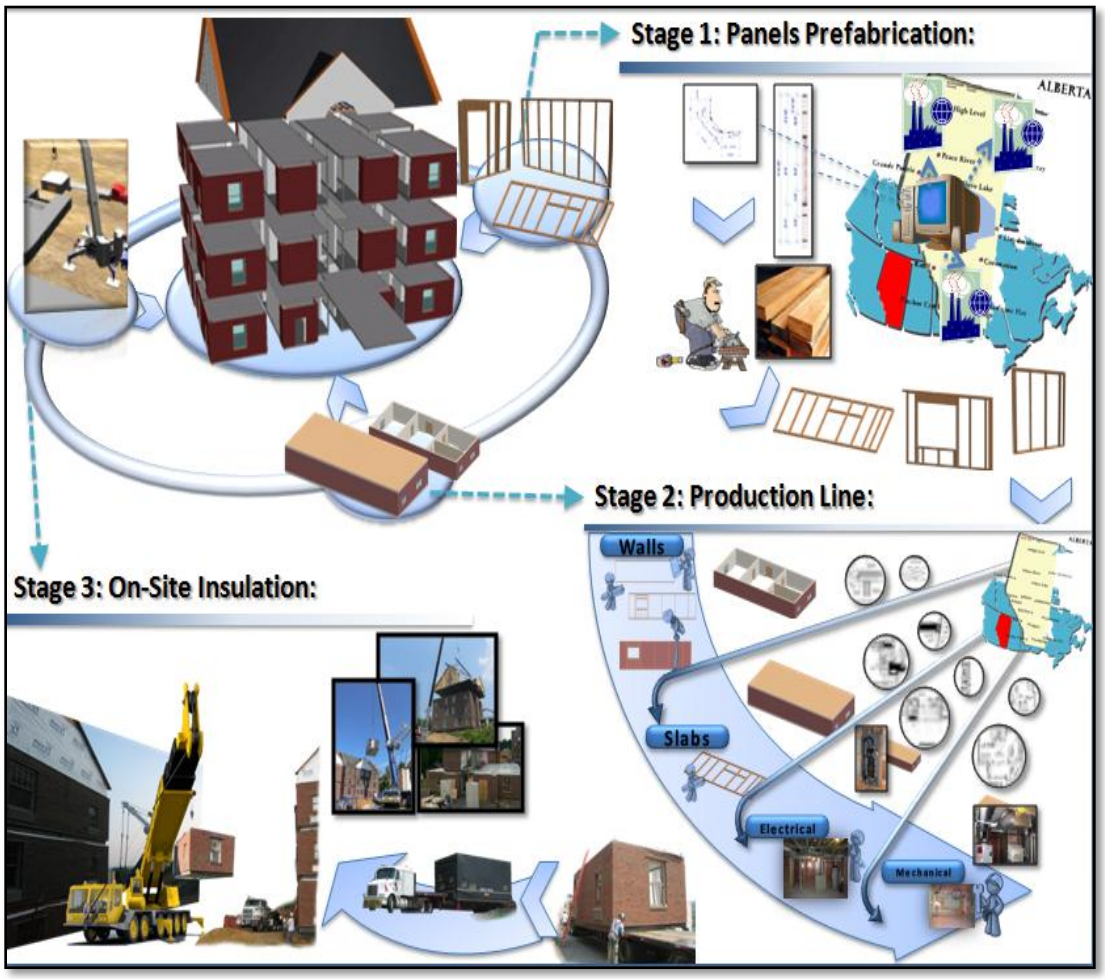


Figure 3-2: Modular construction manufacturing process

3.1.3 Design System for Modular Construction Manufacturing

This research proposes an intelligent design system to be used for the different stages of the manufacturing process. The system provides the needed set of detailed shop drawings that incorporates the architectural, structural, mechanical,

and electrical designs .As illustrated in Figure 3-3, the design process is divided into three branches: structural, electrical, and mechanical. The three branches interact together in order to generate the needed detailed set of drawings needed for the production line stages and the prefabrication of panels. Architectural and Structural design plans and requirements are used as input for the structural design branch. This branch generates two BIM models: a BIM and an upgraded BIM that incorporates the manufacturing concepts. The upgraded BIM represents the core BIM model for the entire design process and contains databases related to the structural and architectural designs. The electrical and mechanical branches upload additional databases to the core model to integrate the requirement associated with the electrical and mechanical designs. As illustrated in Figure 3-3, advanced construction technology has been incorporated into the three branches. This research focuses on the structural branch (See Figure 3-3 – shaded area), which generates the core BIM and the design and drafting for the manufacturing process, taking into account the architectural and structural design requirements. The structural branch utilizes logic-decision rules to mimic the manufacturing concepts rules used when dividing a 2D layout into distinct modules. Another example is the incorporation of building code regulations related to electrical design to a corresponding branch.

Having developed a fully-detailed set of shop drawings, Lean construction concepts can be utilized to optimize the work flow in the production line based on the amount of work needed to be performed in each station. As a result, a project scheduling for the production line stage is developed. Construction cost databases can be incorporated into the core BIM model to provide cost estimation for the project.

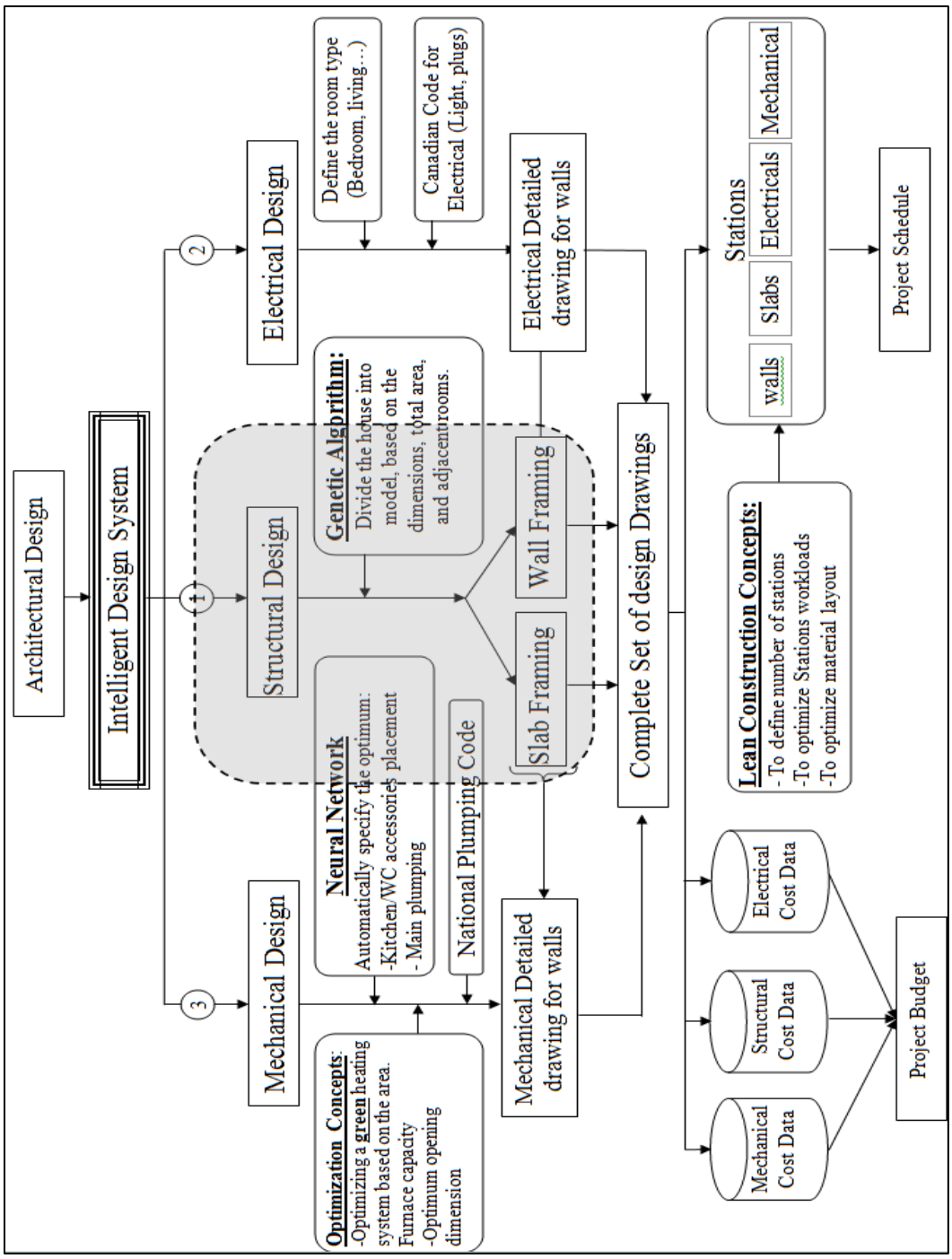


Figure 3-3: Intelligent design system for construction manufacturing process

3.2 *Automated System for Design and Drafting for Modular Construction Manufacturing*

The second objective of this research is the automation of design and drafting for modular construction manufacturing through an integrated computer tool

called MCMPro, which is developed using Visual Essential for Applications (VBA) by means of CAD software. This tool utilizes a scenario based analysis (SBA) in order to automatically generate the needed sets of shop drawings. SBA interprets the tool input, criteria, and standards into sets of rules that incorporate human intelligence, national building codes requirements, city bylaws, the framing method, manufacturing concepts, architectural and structural designs, etc., into the tool core BIM. Figure 3-4 shows the input, standards, and criteria required by the SBA in order to generate the core BIM, the upgraded model based on the construction manufacturing concepts, detailed sets of construction drawings and take-off lists of materials. This research proposes the development of cutting lists of materials and beyond optimization analysis by implementing optimization techniques on the take-off lists of materials.

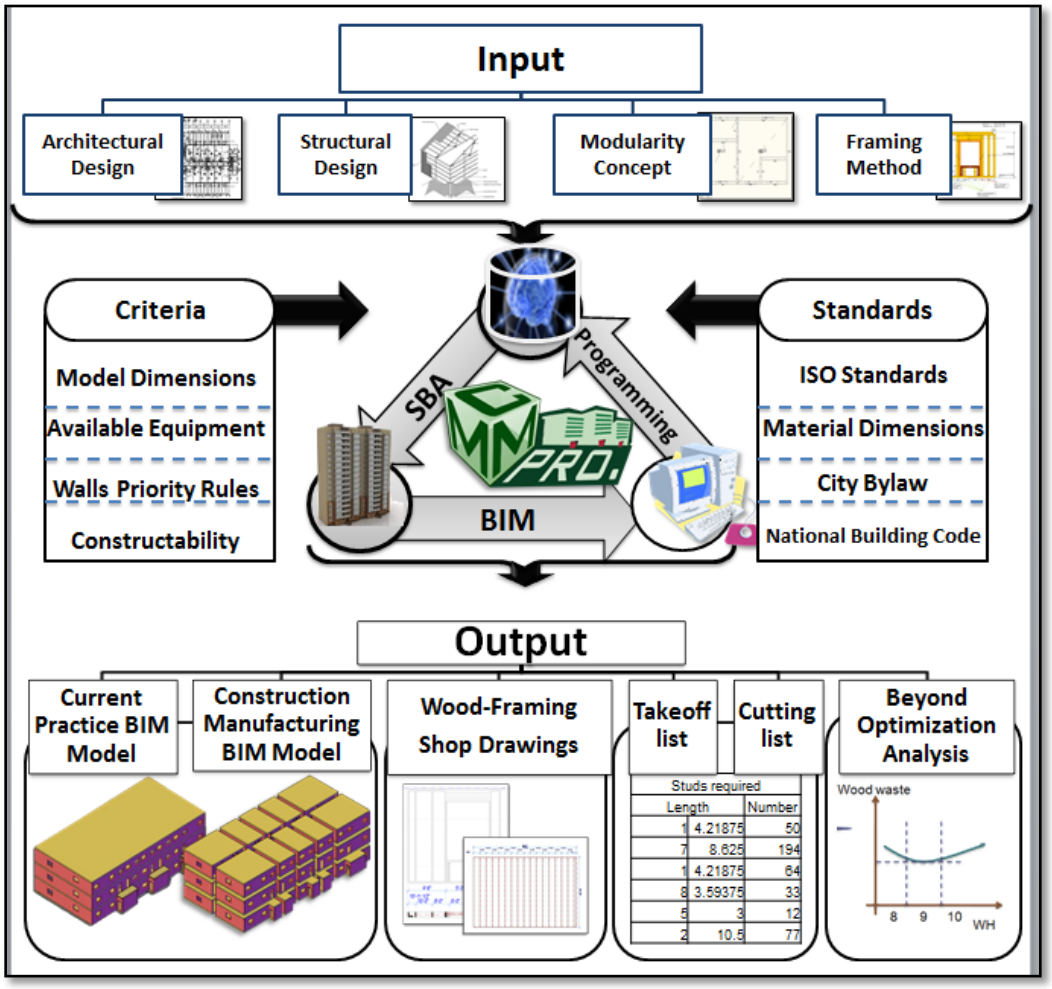


Figure 3-4: MCMPro analysis process

The automated system MCMPro provides the needed set of structural shop drawings needed for modular construction manufacturing. This system is designed using AutoCAD Visual Essential for Applications (VBA) 2009. The shop drawings developed in the CAD environment require essential information from four main sources: architectural components, structural requirements, modular concepts, and framing method. Architectural components are represented through the 2D layout of the project—the layout specifying all essential design information including spaces, openings, wall locations, story heights, etc. The architectural design must yield to city bylaw requirements in terms of the size and number of windows and doors, setback, and indoor air quality. Structural requirements specified by a design in line with building codes are used for defining the element components for each wall, door, window, beam, and column. Modular concepts provide a set of rules needed when dividing the layout into a number of units. This set specifies allowable model dimensions based on road regulations, acceptable dividing elements, dividing roles and procedures, and rules related to slab thickness adjustment for each unit. The framing method uses framing best practice to specify different types of wall connections, framing elements, and openings. These requirements are included in the parametric algorithm (referred to as MCMPro).The parametric algorithm passes through three main stages, each stage composed of numbers of steps as follows:

Stage 1: Generation of the Building Information Model

1. Transform lines into wall groups, windows groups, door groups, connections, balconies, and corridors.
2. Assign openings and connections to each wall.
3. Generate a BIM.

Stage 2: Generation of Modular Construction Manufacturing BIM

1. Divide the layout into modules using interior walls as separation walls.
2. Generate a slab element defined by each modules boundary.
3. Generate an upgraded BIM.

Stage 3: Detailed Shop Drawings Generation

1. Adjust walls thickness according to the structural design.

2. Adjust walls length in order to generate accurate connection based on the framing method.
3. Analyse each module and frame its walls.
4. Generate shop drawings and take-off list.

The research proposes that the take-off list can be optimized in order to generate cutting lists that minimizes wood waste. Having generated the optimum cut length for a specific wall height, an analysis that goes beyond optimization can be performed. This analysis utilizes wall heights as input data to generate several optimums cut lists. The effect of wall-height on wood waste will be displayed using a curve with wall height as the horizontal axis and wood waste as the vertical one. Figure 3-5 shows the automation system proposed methodology. Figure 3-6 illustrates the beyond optimization analysis, and Figure 3-7 shows the structure of the developed tool (MCMPro).

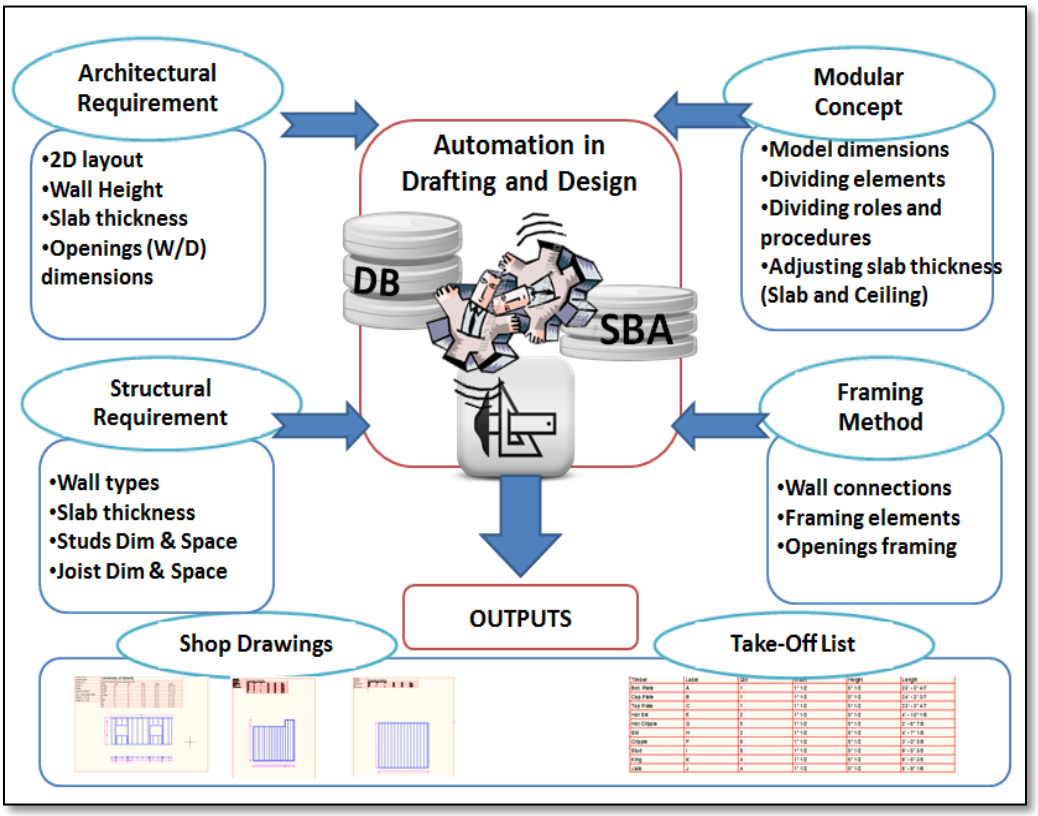


Figure 3-5: Proposed methodology for the automation of design and drafting

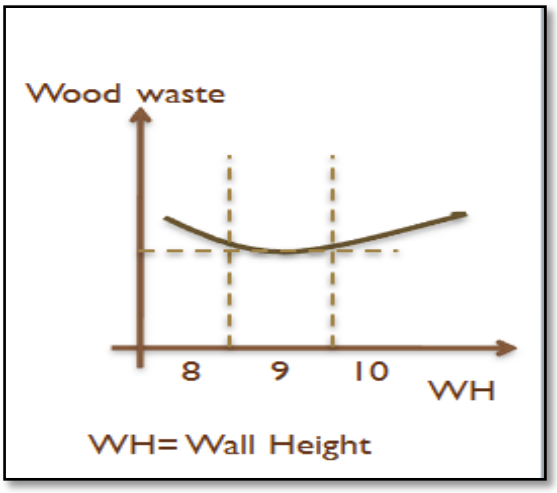


Figure 3-6: Beyond optimization analysis

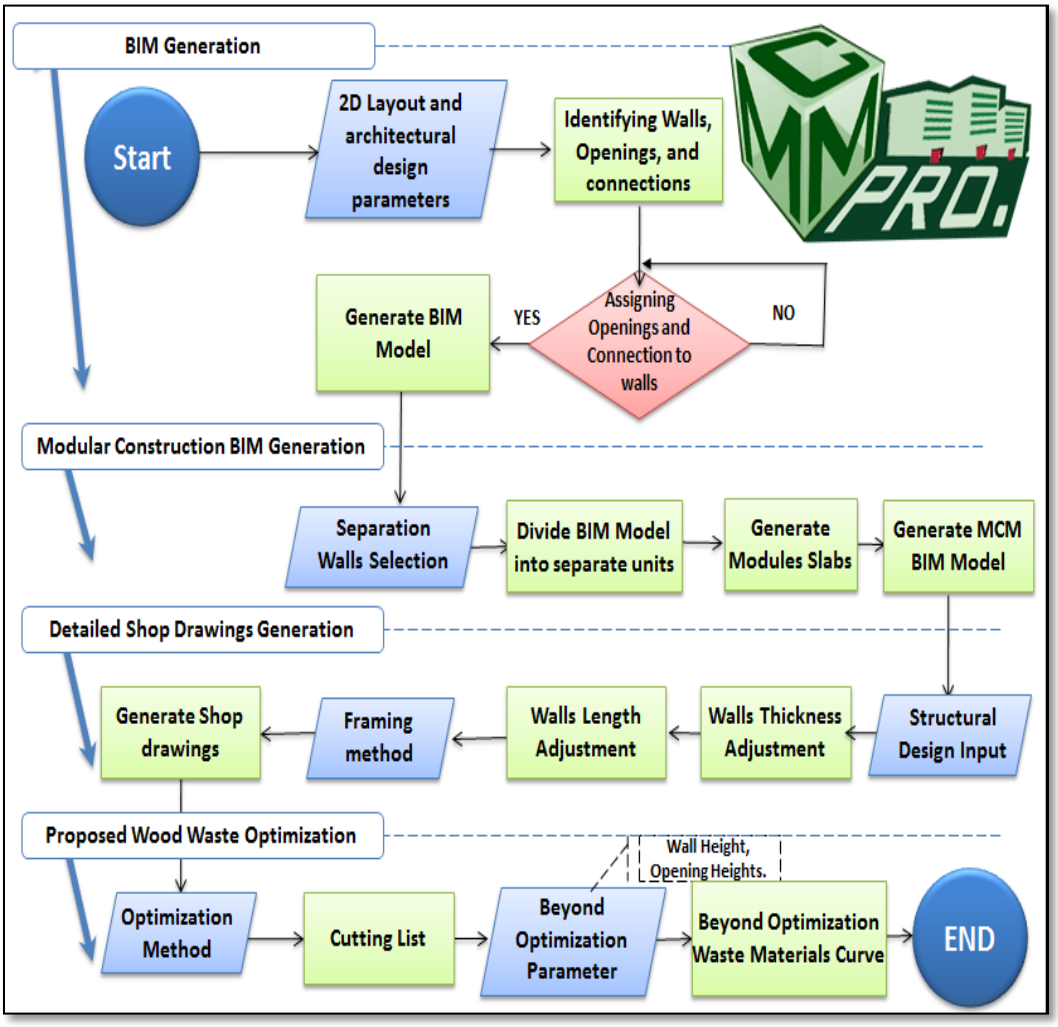


Figure 3-7: The structure of the tool (MCMPro)

Chapter 4: Implementation and Application of MCMPro Process—Case Study

4.1 *Building Information Model Generation*

The 2D layout analysis input and output data are stored into a structured database. The database includes Lines Table, Windows Type, and Layers Tables as input data, and Walls, Connection, Openings, Balconies, and Corridors tables as output data. Figure 4-1 shows the relationship among the 2D parametric database tables. Table 4-1 describes the contents of each table.

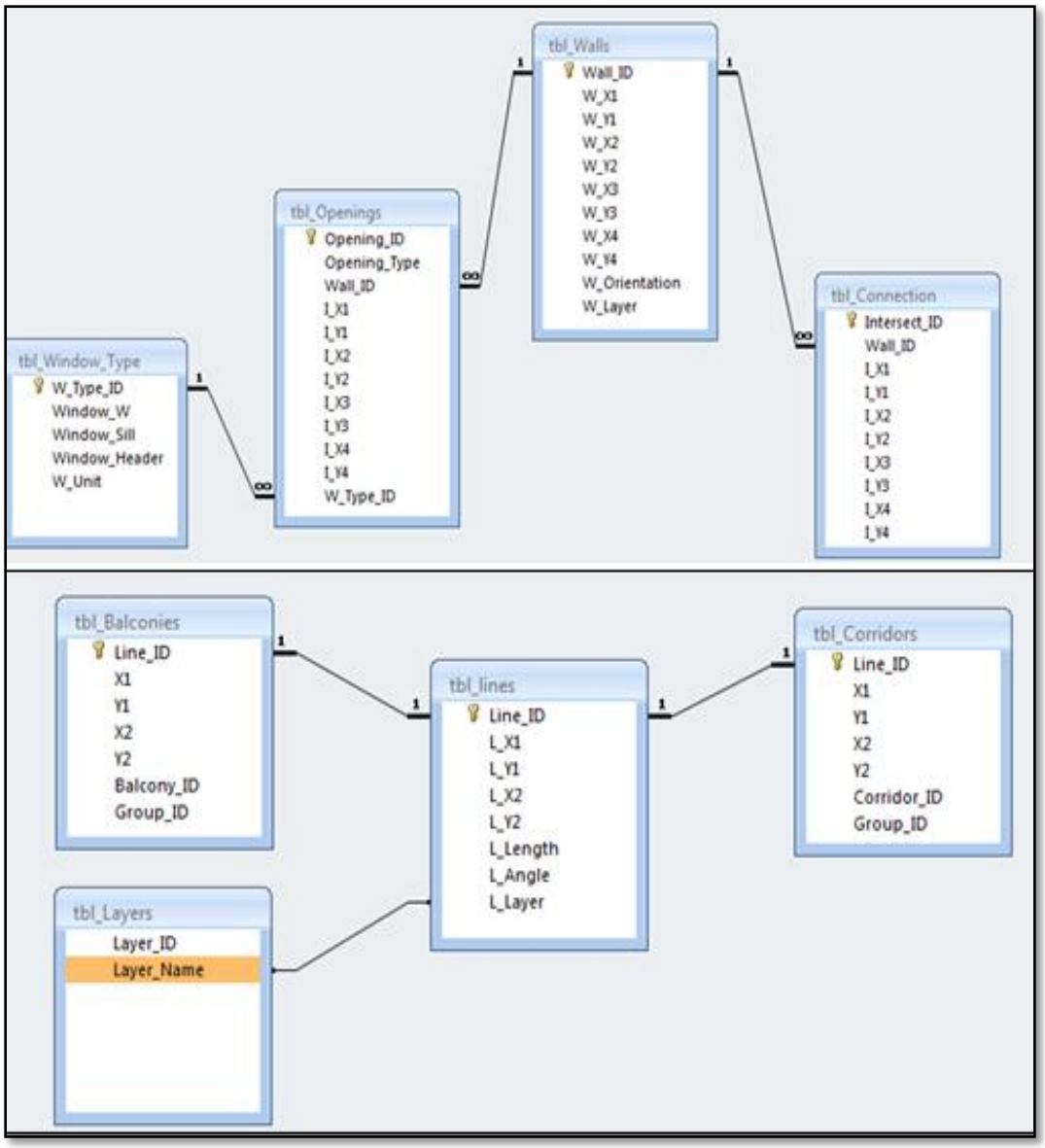


Figure 4-1: The 2D parametric database tables relationship

Table 4-1: 2D CAD database

Table	Content
Lines Table	This table has the 2D layout line data stored as line ID, X and Y coordinates of start and end point of each line, its length, its angle, and its layer.
Layers Table	Layer ID is used to identify the layer and Layer Name.
Window Type Table	Different windows have different elevations data. This table stores windows data that has to be specified or modified by the user. It includes Window Type ID, Window Width, Window Sill, Window Header, and Window Unit.
Walls Table	Wall ID, X and Y coordinates of a wall's corner points, Wall Orientation as parallel to X, parallel to Y, or Inclined wall, Wall Layer.
Wall Connection Table	Every time a connection between an interior, exterior, or mechanical wall occurs a connection is stored. Each wall could have more than one connection. Identifying a connection location on a wall is essential because of its importance in the framing process. A wall connection table includes Connection ID, Wall ID to indicate the wall that the connection belongs to, the connection end points' X and Y coordinates for the two defining lines of that connection.
Openings Table	This table stores data related to wall openings. It includes Opening ID, Opening type (door or window), Wall ID, X and Y coordinates of its corner points, and Window type ID, which indicates the type of the window to specify its elevation data for the purpose of framing and 3D modeling.
Balconies Table	Balconies are used for the joist shop drawing. The balconies table includes Line ID, X and Y coordinates of the lines' end points, Balcony ID, and Group ID, which indicates a special ID for each line in one balcony. For example, if balcony 1 consists of 4 lines with different Line ID, their group IDs are 1, 2, 3, and 4.
Corridors Table	The same data as the balconies

For the purpose of generating the BIM, the developed tool MCMPro includes a predefined set of knowledge-based rules that accommodate for the expertise needed to read a 2D CAD properly. This set of rules is used to transform the lines in the 2D layout into a BIM that includes the project's different components that are represented by these lines. Figure 4-2 shows the building information model generation process.

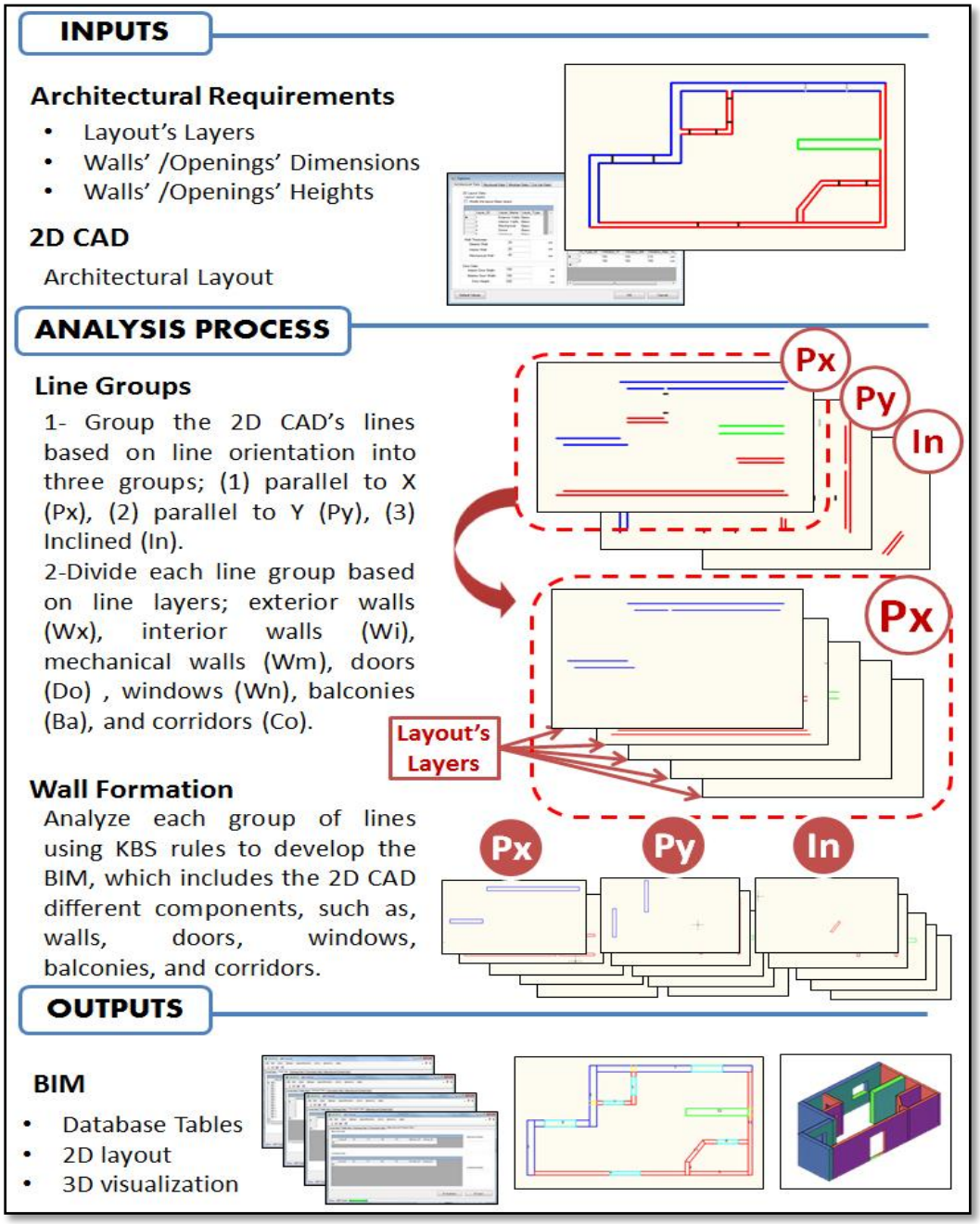


Figure 4-2: Building information model generation process

As illustrated in Figure 4-2, the input data is 2D CAD and the architectural requirements. The data extracted from the 2D CAD is the project's layers, and the X and Y coordinates' values of the start and end points of the lines that represent the project's components. The layers data specifies walls' classification (Exterior, Interior, and Mechanical), opening types, and structural components such as balconies and corridors. The architectural requirements provide data related to the 2D and 3D architectural design. Walls' thicknesses and openings' widths represent the 2D design requirements data. In conjunction with X and Y coordinates' values obtained from the 2D CAD, the 2D design data specifies the project's components properties, includes walls locations, lengths, thickness, and openings that belong to a specific wall. The 3D architectural design data includes information related to walls height, doors height, slab thickness, windows sills and header elevation, etc. This data is used to provide a 3D visualization for the BIM. Figure 4-3 shows the implementation of the architectural requirements as input data to MCMPro. Table 4-2 shows the architectural design parameters in the MCMPro options dialog box.

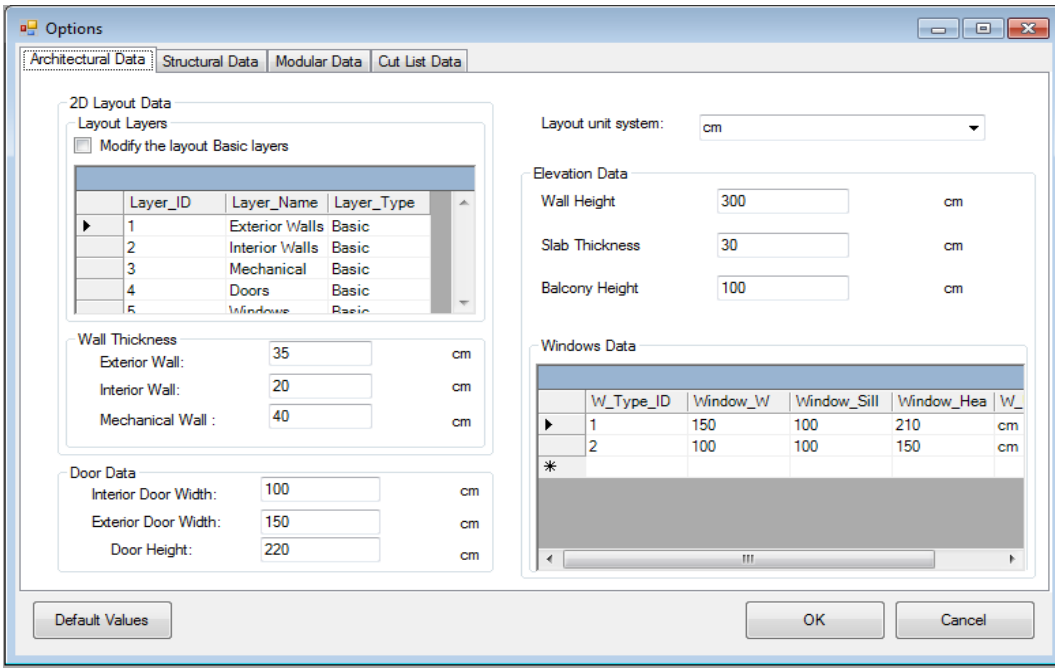


Figure 4-3: Architectural design input data screen shot from MCMPro

Table 4-2: Architectural data attributes of options dialog box

Parameter	Functionality
Layout Unit System	This parameter indicates the main unit that is used in the 2D layout. The user is prompted to choose the right system units.
2D Layout Layers	This table specifies data related to Layer ID, Layer Name, and Layer Type. Layer ID identifies each layer. Layer Name is used to read the lines data from the analyzed 2D CAD and this name will be used in the BIM. Layer Types specify the layer importance for the analysis process. There are two layer types, essential and non-essential. Essential means that the layer must exist for the tool to start the analysis. Non-essential means that the tool will run whether this layer exists or not.
Modify the Layout Essential Layer	This check box enables the user to modify the default 2D layout layers properties in order to match the analyzed CAD file.
Wall Thickness	The user is prompted to specify Exterior, Interior, and Mechanical walls' thicknesses.
Door Data	The data here indicate doors' essential information including door height, exterior wall width, and interior wall width. The user is prompted to indicate this data.
Elevation Data	In order to add the third dimension to the 2D layout, the user must indicate the elevation data, which includes Wall Height, Balcony Height, and Slab Thickness. This data is used for the framing process as well as for development of the 3D visualization.
Windows Data	Different windows have different elevation data. This table has: Window ID, which identifies the widow data; Window Sill, which is the lower height of the window; Window Header, which represents the upper height of the window; and Window Unit, which indicates the unit used when writing this data. The last unit must match Layout System Unit.

The data included in the "Architectural data" tab of "Options" dialog box represent default values for the architectural standards and requirements parameters. The default values are as follows:

1- The 2D CAD measuring units = Centimetres.
2- Layers' names, as exterior walls, interior walls, mechanical walls, doors, windows, balconies, and corridors.
3- Exterior, interior, and mechanical wall thicknesses are equal to 35 cm, 20 cm, and 40 cm, respectively.
4- Exterior doors width = 150 cm, interior doors width = 100 cm, and doors height = 220 cm.
5- Elevation parameter values for wall height, slab thickness, and balcony's slab thickness are equal to 300 cm, 30 cm, and 20 cm, respectively.
6- Windows parameters values for windows width, sill, and header are 150 cm, 100 cm, 210 cm, respectively, for windows type 1, and 100 cm, 100 cm, 150 cm respectively for windows type 2.

The majority of buildings have these values as standards values, and this is why the tool uses them as default values. Figure 4-4 shows dialog the boxes for the main tool and new project interfaces.

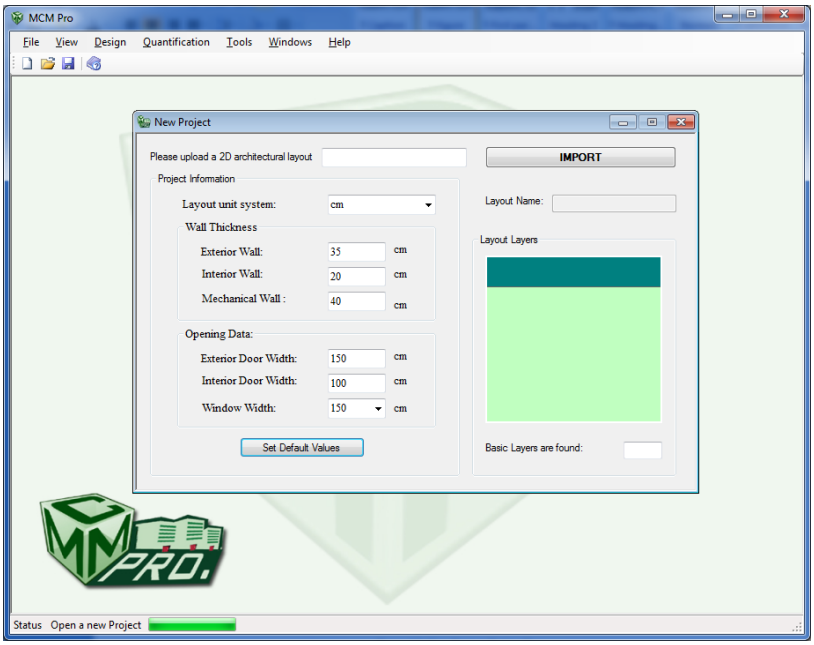


Figure 4-4: New project dialog box screen shot from MCMPro

Before initiating the analysing process, the tool checks the existence of the five essential layers, which are exterior walls, interior walls, mechanical walls, doors, and windows. These layers are essential for any construction project, and failing to deliver them can only be interpreted as an error in the architectural design. In addition to the essential layers, two non-essential layers that can be found are balconies and corridors. The layers are essential for the process performed by the tool to identify the project's different elements and to use them in the modelling process. Figure 4-5 illustrates the different layers of a 2D CAD. By analyzing the 2D layout, the tool then generates the lines database for the purpose of further analysis. Figure 4-6 shows the lines data table.

Priority rules are applied in the 2D wall analysis (See Table 4-3). These rules define whether a wall should be cut or kept intact when two or more walls intersect.

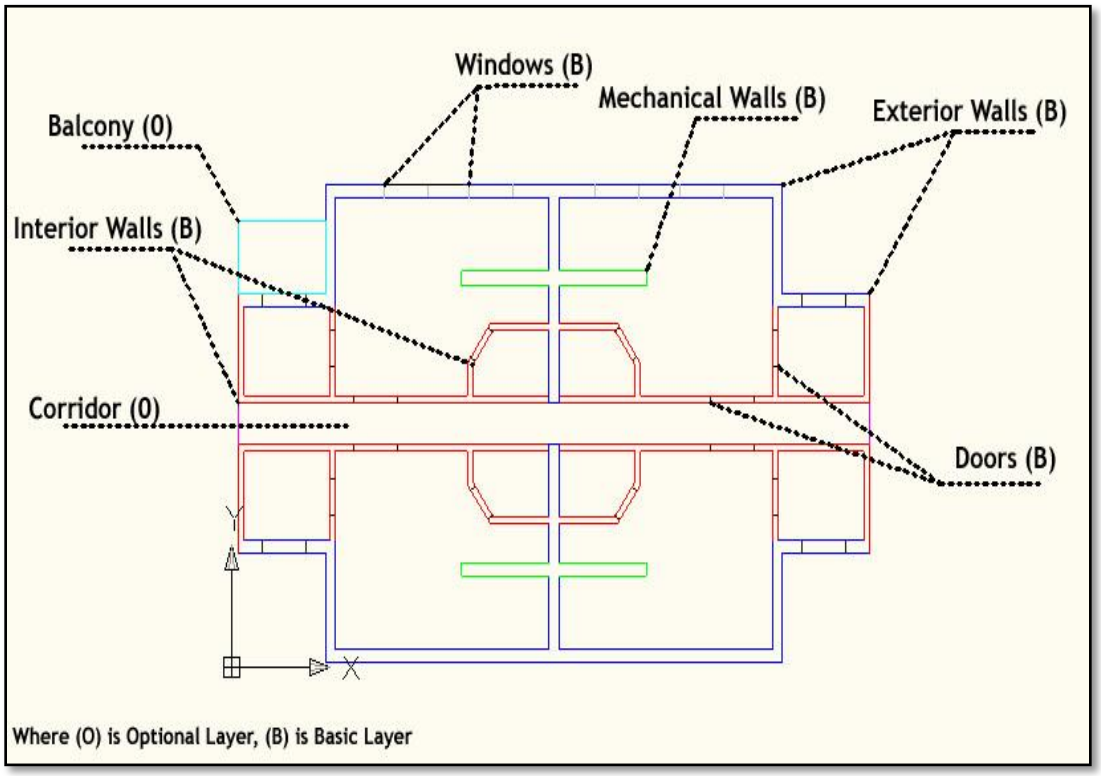


Figure 4-5: 2D CAD layers of a four-unit floor architectural design

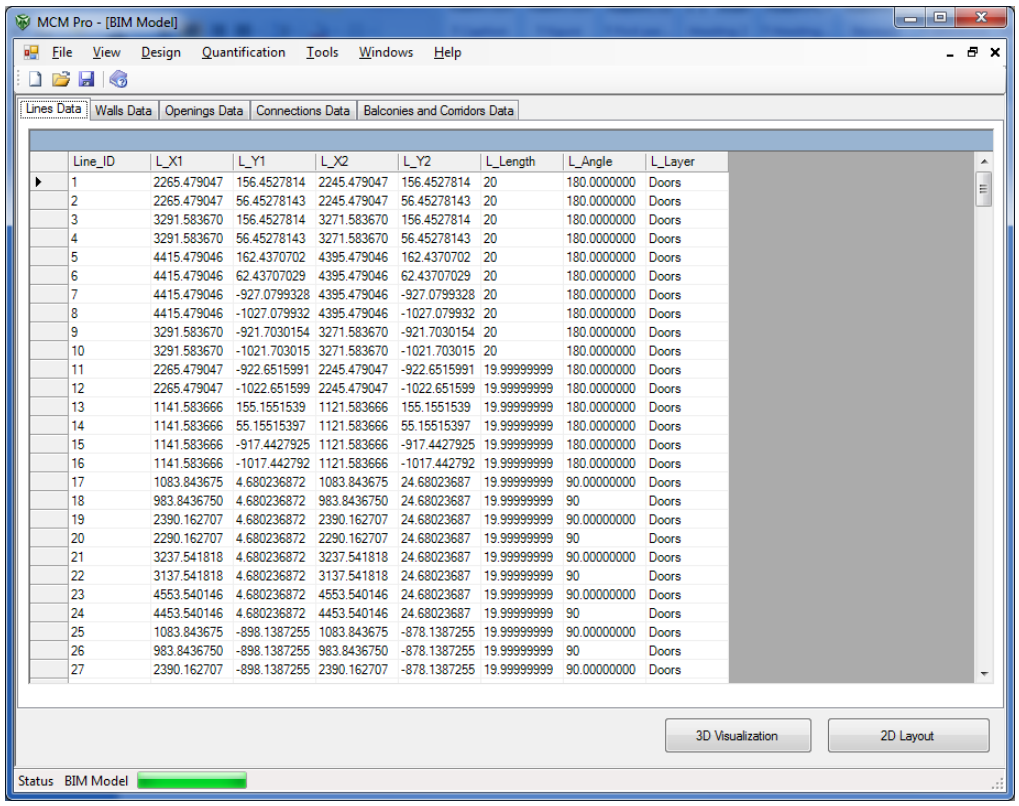


Figure 4-6: A view of 2D CAD's lines data table

Table 4-3: Wall priority rules.

Wall Type	Priority
Exterior Wall Parallel to Y	1
Exterior Wall Parallel to X	2
Exterior Wall (Inclined)	3
Interior Wall Parallel to Y	4
Interior Wall Parallel to X	5
Interior Wall (Inclined)	6
Mechanical Wall Parallel to Y	4
Mechanical Wall Parallel to X	5
Mechanical Wall (Inclined)	6

Where 1= highest priority, 6= lowest priority

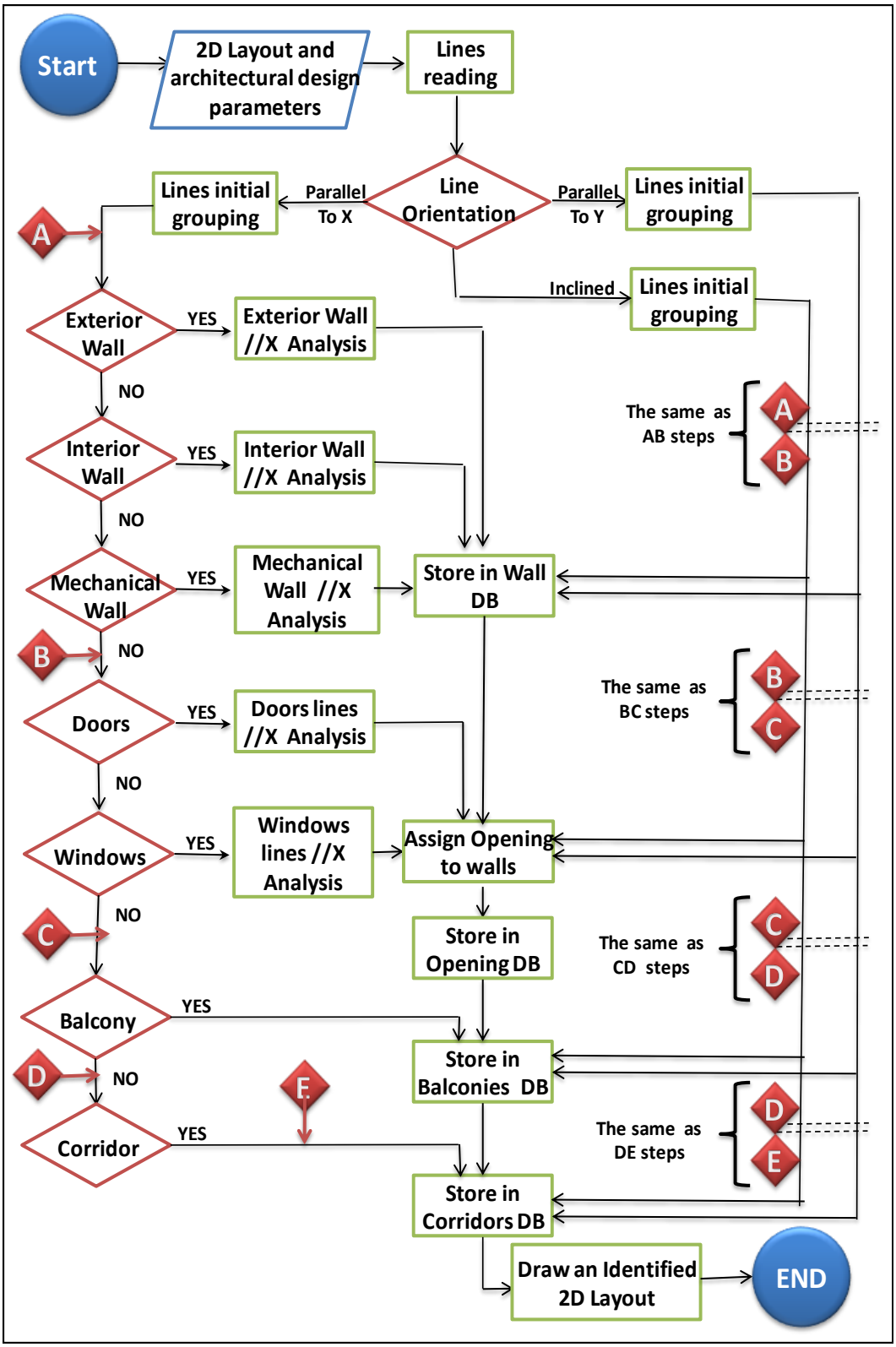


Figure 4-7: The flowchart for 2D Layout Analysis

The 2D analysis starts by grouping lines based on line orientation and line layer (As illustrated in Figure 4-7). Line orientations are (1) parallel to X (Px), (2) parallel to Y (Py), and (3) Inclined (In). Essential layout layers are: exterior walls (Wx), interior walls (Wi), mechanical walls (Wm), doors (Do), and windows (Wn), the two non-essential layers are balconies (Ba) and corridors (Co).

The number of line groups is calculated satisfying equations 1 and 2 based on the corresponding layers (Essential or non-essential):

$$LGn = LOn \times ELn = 3 \times 5 = 15 \quad [1]$$

$$LGn = LOn \times (ELn + NELn) = 3 \times (5 + 2) = 21 \quad [2]$$

Where:

LGn= The number of lines groups

LOn= the three lines' orientations

ELn= the number of the essential layers

NELn= the number of the non-essential layers

The grouping process is essential to apply wall priority rules through the analysis. Figure 4-7 shows a flowchart for the process of transforming the 2D layout into the identified 2D layout. Having divided the 2D layout lines into groups, a wall analysis is performed on each group of lines. The wall analysis considers all possible cases when dealing with each line group. A detailed illustration of the analysis structured steps made on an exterior wall parallel to X is found in Appendix A.

The wall generation of the BIM can be summarized as follows:

- Exclude the redundant lines: Redundant lines are lines with lengths equal to walls' thicknesses. These lines are used by the architect to represent a wall edge. The wall analysis doesn't require these lines, moreover, their presence could affect the analysis
- Develop wall groups: A wall group is defined as the set of points that define series of wall with the same alignment.
- Define Walls: This process defines the end, start, and connection points of each wall using the data extracted from the lines database and applying a scenario-based analysis (SBA). The SBA is composed of set of rules that are used

in interpreting a group of lines drawn in a 2D layout as project different components, such as walls, opening, balconies, and corridors. The SBA rules define these points by analysing each pair of points in a wall group (point i and point j) based on their X and Y coordinates values, and then sorting the wall groups for the purpose of the wall-defining process.

An example of this analysis is illustrated in Figure 4-8, where an exterior wall parallel to X (Wall D in Figure 4-8) is connected to two exterior walls parallel to Y (Wall A and Wall C in Figure 4-9) and an interior wall parallel to Y (Wall B in Figure 4-9) that rests on Wall D in the middle. Wall D is defined by the lines a-f, b-c, and d-e, which belong to the same wall group. Since the wall orientation is Px, the X coordinate is considered as the main coordinate and Wall D group points are sorted based on X coordinates' values. In this case there are three pair of points (points i and j): points a and b are the first pair, points c and d are the second, and points e and f are the last pair. The wall-defining process analyses each pair of points and defines the start, end, and connection point of the wall. The following cases are found in this example:

Case 1: A connection between the start edge of an exterior wall parallel to X (Wall D) with an exterior wall parallel to Y (Wall A) (See Figure 4-8-A).

This case satisfies equations 3 and 4 prospectively.

$$X_b - X_a = Ex \quad [3]$$

$$Y_b - Y_a = Ex \quad [4]$$

Where:

$$Ex = An\ exterior\ wall\ thickness$$

Based on the walls priority rules, Wall A has a higher priority than Wall D, which implies that Wall D is cut by Wall A and point 1 X coordinate's value needs adjustment to the point with the bigger X coordinate's value (See Equation 5), as illustrated in Figure 4-8-A, point a moved from its original location, referred to using white triangle, to the final position that has X coordinate's values equal to point b, referred to using a shaded triangle (the dashed-line shows the difference in X_a value that is equal to an exterior wall thickness).

$$X_a = X_b \quad ; X_b > X_a \qquad [5]$$

Case 2: A connection between the end edge of an exterior wall parallel to X (Wall D) with an exterior wall parallel to Y (Wall C) (See Figure 4-8-C).

This case satisfies equations 6 and 7 prospectively. The X coordinate's values needs adjustment to the point with the less X coordinate's value (See Equation 8), as illustrated in Figure 4-8-A, point f moved from its original location, referred to using white triangle, to the final position that has X coordinate's values equal to point e, referred to using a shaded triangle (the dashed-line shows the difference X_f value that is equal to an exterior wall thickness).

$$X_f - X_e = Ex \qquad [6]$$

$$Y_e - Y_f = Ex \qquad [7]$$

$$X_f = X_e \quad ; X_f > X_e \qquad [8]$$

Case 3: A connection between an interior wall parallel to Y (Wall B) that rests on an exterior wall parallel to X (Wall D) and (See Figure 4-8-B).

This case satisfies equations 9 and 104 prospectively.

$$X_d - X_c = In \qquad [9]$$

$$Y_d - Y_c = Ex \qquad [10]$$

Where:

$$In = \text{An interior wall thickness}$$

$$Ex = \text{An exterior wall thickness}$$

Based on the walls priority rules, Wall D has a higher priority than Wall B, which implies that points 3 and 4 are considered as connection points and Wall D keep going intact.

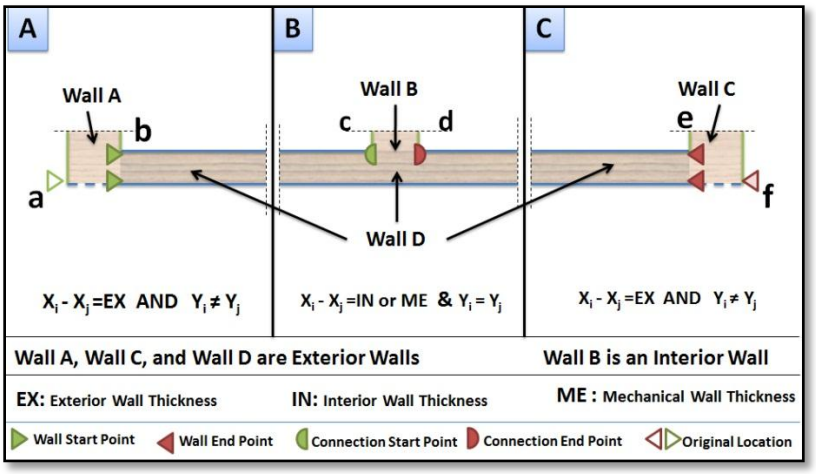


Figure 4-8: Wall defining process

All possible cases can be found in Appendix A.

Form Walls: A wall is defined by a start point followed by an end point. A wall starting corner has minimum X and Y coordinates. Moving counter clockwise when parallel to X, and clockwise when parallel to Y. Walls' corner points satisfy the equations from 11 to 18. Figure 4-9 shows the wall formation process.

First Corner Points

$$X_1 = X_{min} \quad [11]$$

$$Y_1 = Y_{min} \quad [12]$$

Second Corner Points

$$X_2 = X_{max} \quad [13]$$

$$Y_1 = Y_{min} \quad [14]$$

Third Corner Points

$$X_3 = X_{max} \quad [15]$$

$$Y_3 = Y_{max} \quad [16]$$

Forth Corner Points

$$X_4 = X_{min} \quad [17]$$

$$Y_4 = Y_{max} \quad [18]$$

Where X_1, Y_1, X_2, Y_2, X_3, Y_3, X_4, Y_4: wall's X and Y coordinates for its four corner points.

Walls data are stored in the Wall Table, which has the following items: Wall ID, (X_1, Y_1, X_2, Y_2, X_3, Y_3, X_4, Y_4), Wall Orientation, and Wall Layer. Figure 4-10 shows the wall data table. Figure 4-11 shows the scenario-based analysis rules followed in exterior wall parallel to X analysis as an example of the wall parallel to X or Y analysis.

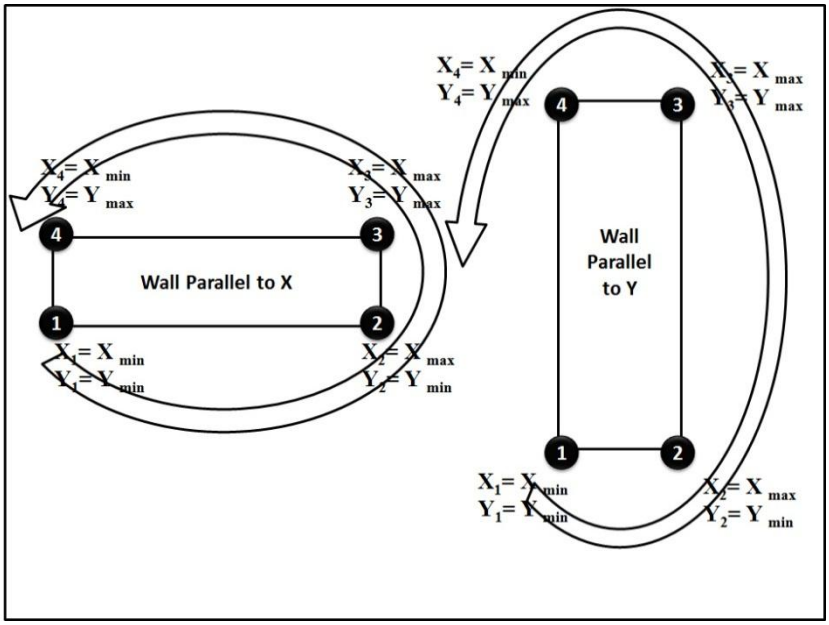


Figure 4-9: Wall formation process

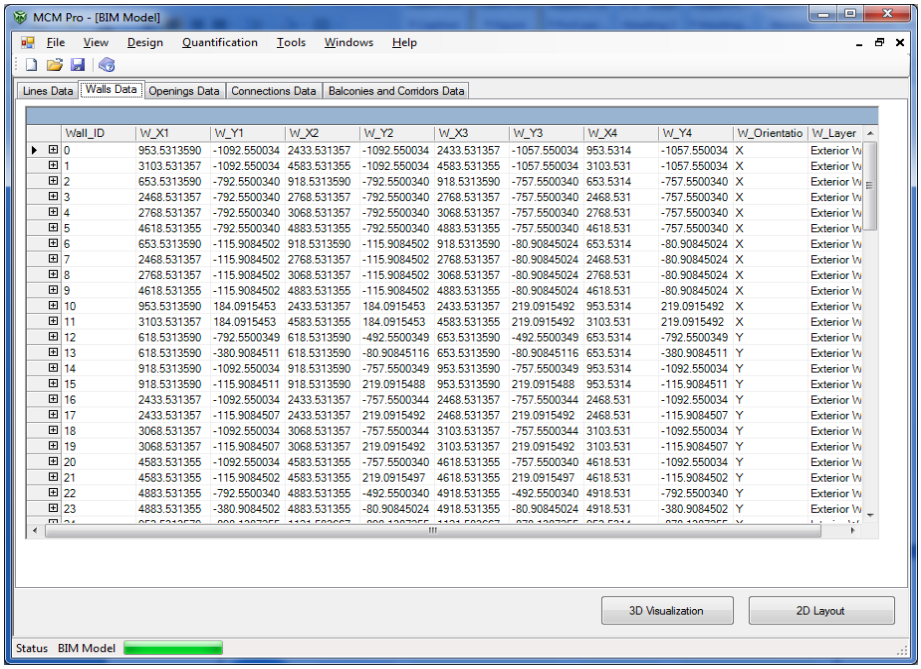


Figure 4-10: A view of walls' data table

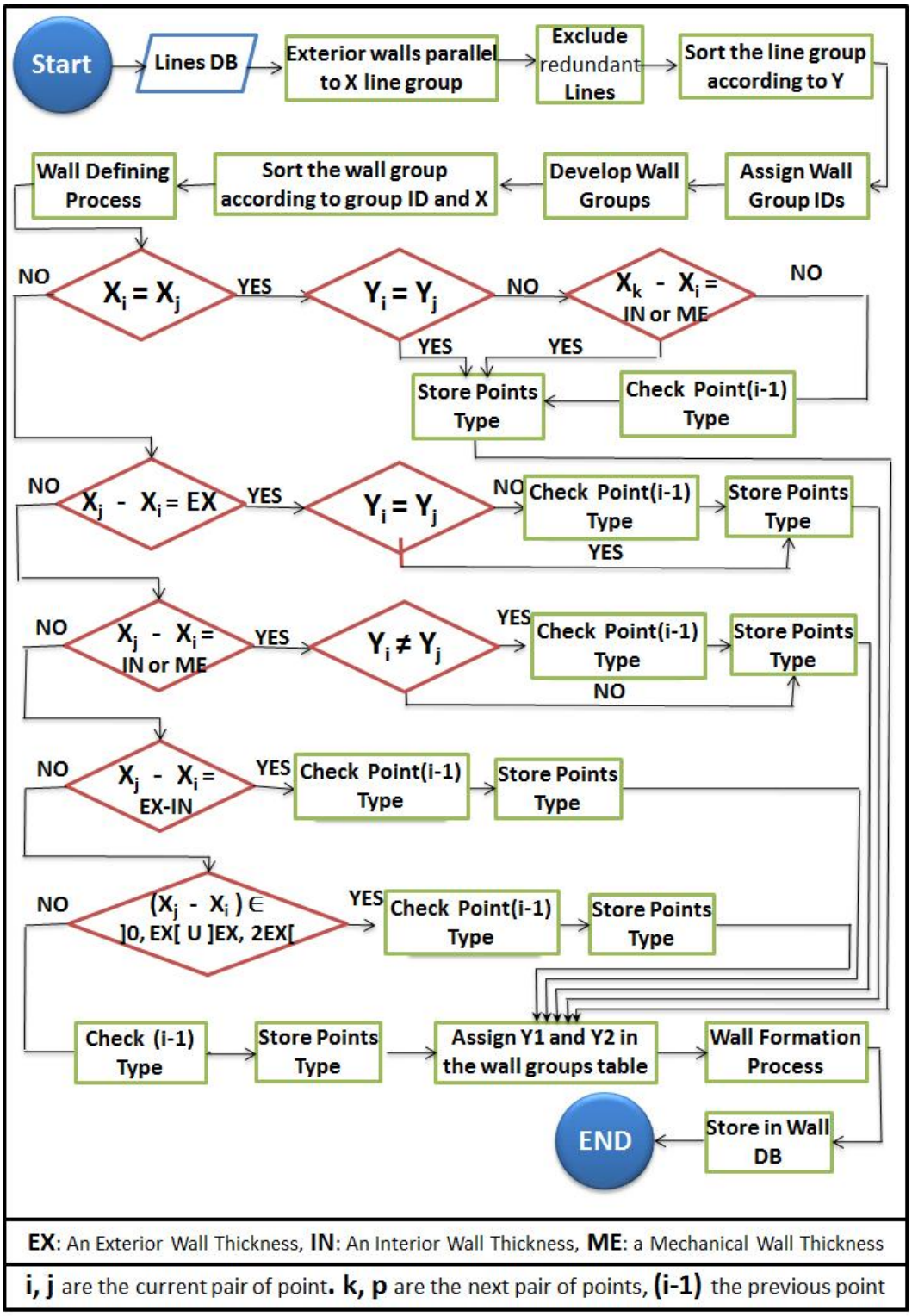


Figure 4-11: Scenario-based analysis for exterior walls parallel to X

The analysis applied for inclined walls is the same as for the exterior, interior, and mechanical walls. It applies the same concepts as those for parallel X and Y walls but with different steps. These steps are as follows:

1- Develop wall groups: A line belongs to a wall group if it has the same angle as the other lines in the group. The angle measurement begins at the X axis and proceeds in a counter clockwise direction around the line's first point. This implies that two parallel lines could have different angles if drawn from two opposite directions; however, the difference between these two angles is 180° (See equations 19, 20, and 21). In other words, line i and line j belong to the same group if one of these conditions is satisfied:

$$\alpha(i) = \alpha(j) \quad [19]$$

$$\alpha(i) = \alpha(j) + 180 \quad [20]$$

$$\alpha(i) = \alpha(j) - 180 \quad [21]$$

Where:

$\alpha(i)$ = the first line angle

$\alpha(j)$ = the second line angle

Based on the line angle (referred to as α), wall groups are found and stored into inclined wall groups.

2- Form Walls: An inclined wall consists of two inclined lines that belong to the same wall group with a distance equal to a wall's thickness (See equation 22). Using an experimental range for the distance between two points of two inclined lines, an inclined wall is formed when the distance between the end point of the first line and the start or end point of the second one is within:

$$Distance = \ ]Ex, 2 \times Ex[\quad [22]$$

Where:

Ex= Exterior Wall Thickness

Using start and end points coordinates of the two inclined lines (line i, line j), wall four corner points satisfy equations 23, 24, 25, and 26 respectively:

First Corner Points

$$X_1 = X_{i1} \quad [23]$$

$$Y_1 = Y_{i1} \quad [24]$$

Second Corner Points

$$X_2 = X_{i2} \quad [25]$$

$$Y_2 = Y_{i2} \quad [26]$$

The distance between the second corner point and the start and end points of the second line in the line group is used to identify the 3rd and 4th wall corner points. The shorter distance is used to identify the third corner points, and the fourth corner points satisfy equations 27, 28, 29, and 30 respectively:

Third Corner Points

$$X_3 = X_{j1\ OR}\, X_{j3} \quad [27]$$

$$Y_3 = Y_{j1\ OR}\, Y_{j1} \quad [28]$$

Fourth Corner Points

$$X_4 = X_{j2\ OR}\, X_{j1} \quad [29]$$

$$Y_4 = Y_{j2\ OR}\, Y_{j1} \quad [30]$$

Once analysed, walls data are stored in the Wall Data Table in the main database. Openings, doors, and windows are represented in the 2D layout as two short lines with a distance equalling the opening width. These openings have the same orientations as those of the walls, i.e. Px, Py, and In. The openings' orientation implies two different structures for the opening analysis: Opening parallel to X or Y (OP), and inclined opening (OI). Both structures are divided into two main steps—to form an identified opening and to assign this opening to an identified wall.

OP Analysis: This analysis follows the same steps for both orientations, parallel to X and parallel to Y, with a difference in the main and sub-coordinate, which is X as the main coordinate and Y as the sub-coordinate for the parallel to X opening group, and vice versa.

OP analysis is based on a peer comparison of the openings' line groups. When two lines have the same Y coordinates and their X coordinates' difference is equal to an opening width, an opening is formed and assigned a distinct ID. These

openings are formed in the same way as the walls they belong to: their start corner point has the minimum X and Y coordinates of the defining lines, and the formation process moves counter clockwise to create the other three corner points.

Having identified the opening, the opening is to be assigned to its wall using the wall's distinct IDs. An opening belongs to a wall when their Y coordinates are the same and the opening's X coordinates belong to the wall's X coordinate range of values (See Figure 4-12).

$$Opening\ (Y\ max, Y\ min) \ = \ Wall\ (Y\ max, Y\ min) \quad [31]$$

$$Opening\ [X\ min, X\ max] \ \subseteq \ Wall\ ]X\ min, X\ max[\quad [32]$$

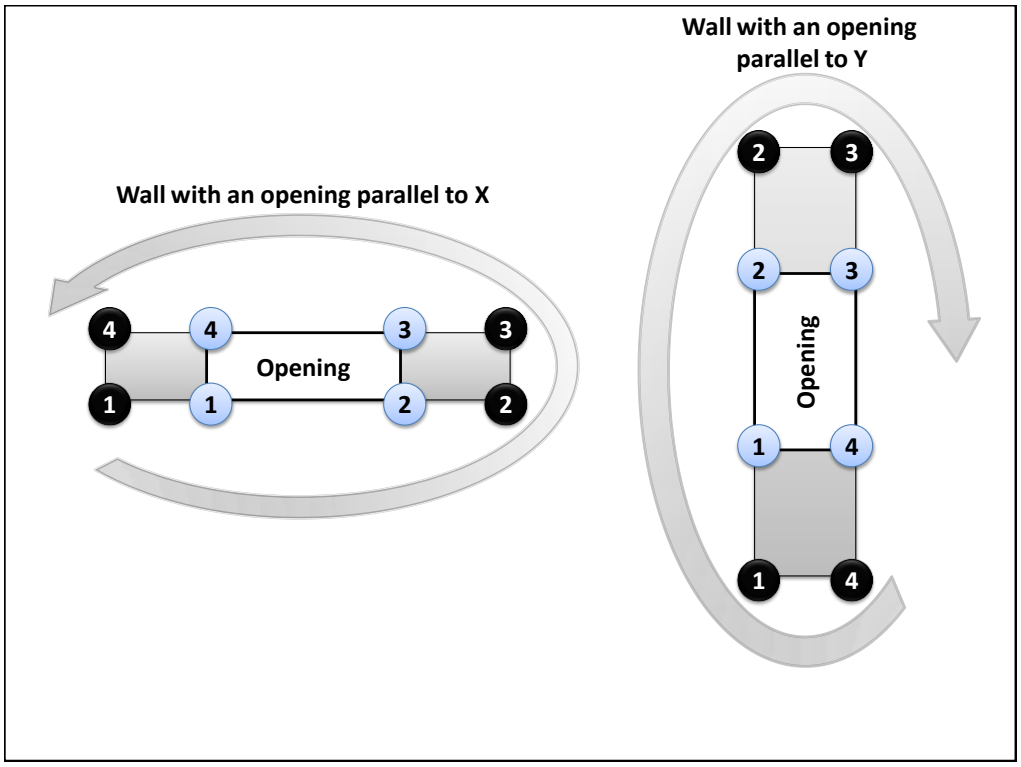


Figure 4-12: Opening analysis process

OI Analysis: The opening's inclined lines are divided into groups based on their angle (referred to as Alpha). An inclined opening is defined by a similar analysis as the inclined walls analysis but utilizes the opening width instead of an inclined wall thickness. Having formed an inclined opening, the opening assignment analysis is to be performed. To assign an inclined opening to an inclined wall, a simple mathematical logic is employed. The equation of an inclined line is:

$$Y = b \times X + c \quad [33]$$

Where:

$$b = Tan(\alpha) = \frac{(Y2 - Y1)}{(X2 - X1)} \quad [34]$$

$$c = Y - b \times X = Y_1 - b \times X_1 \quad [35]$$

The parameters b and c can be found for an inclined wall when applying $point_1$ and $point_2$ X and Y coordinates' values into equations 34 and 35.

An opening belongs to a specific wall when an opening corner point belongs to an inclined wall's two parallel side. When this condition is satisfied, the wall ID is assigned to the opening and stored in the Opening database. Figure 4-13 shows the Opening database table.

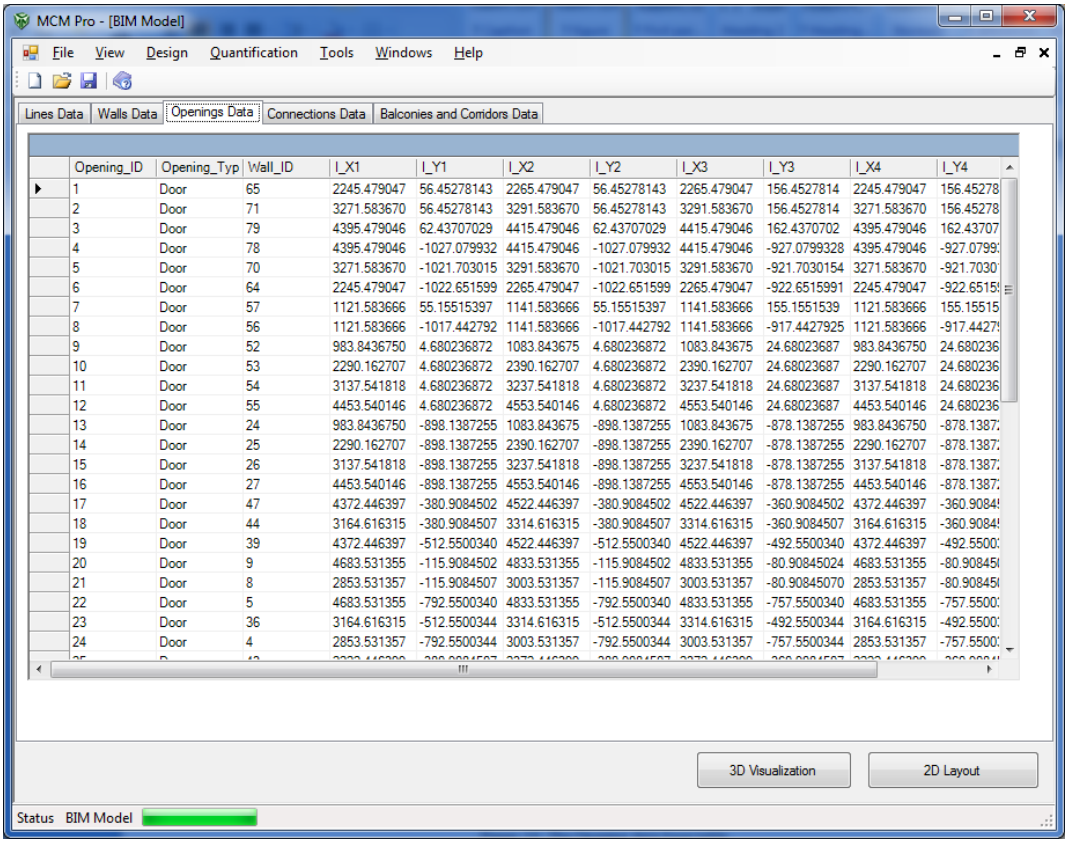
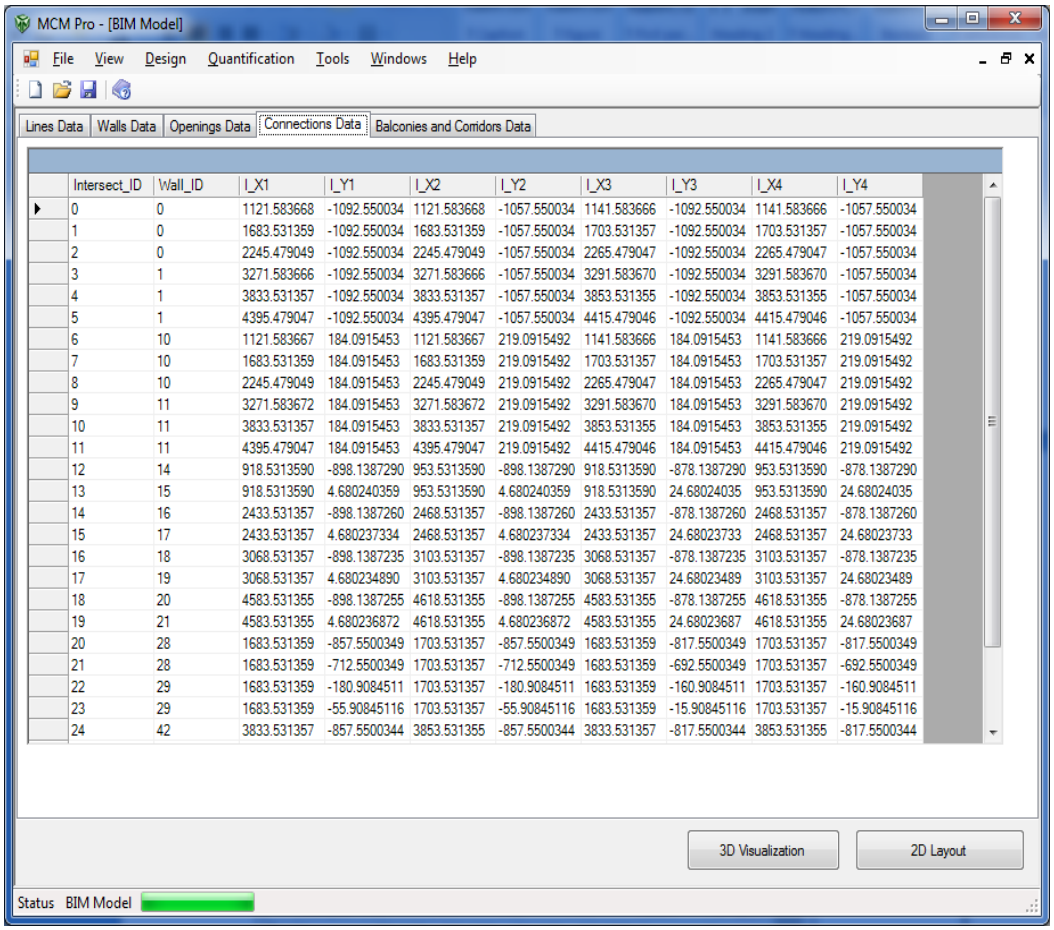


Figure 4-13: A view of the Opening database table

A wall connection is defined when a type 2 point (a connection start point) is followed by a type 3 point (a connection end point). Each wall connection belongs to a wall and occurs between wall start and wall end points. When a wall connection is formed during the wall formation process, MCMPro stores the wall

ID in the Connections Data Table. This ID is used to assign a wall connection to a wall. Figure 4-14 shows the Wall Connection database.



Intersect_ID	Wall_ID	I_X1	I_Y1	I_X2	I_Y2	I_X3	I_Y3	I_X4	I_Y4
0	0	1121.583668	-1092.550034	1121.583668	-1057.550034	1141.583666	-1092.550034	1141.583666	-1057.550034
1	0	1683.531359	-1092.550034	1683.531359	-1057.550034	1703.531357	-1092.550034	1703.531357	-1057.550034
2	0	2245.479049	-1092.550034	2245.479049	-1057.550034	2265.479047	-1092.550034	2265.479047	-1057.550034
3	1	3271.583666	-1092.550034	3271.583666	-1057.550034	3291.583670	-1092.550034	3291.583670	-1057.550034
4	1	3833.531357	-1092.550034	3833.531357	-1057.550034	3853.531355	-1092.550034	3853.531355	-1057.550034
5	1	4395.479047	-1092.550034	4395.479047	-1057.550034	4415.479046	-1092.550034	4415.479046	-1057.550034
6	10	1121.583667	184.0915453	1121.583667	219.0915492	1141.583666	184.0915453	1141.583666	219.0915492
7	10	1683.531359	184.0915453	1683.531359	219.0915492	1703.531357	184.0915453	1703.531357	219.0915492
8	10	2245.479049	184.0915453	2245.479049	219.0915492	2265.479047	184.0915453	2265.479047	219.0915492
9	11	3271.583672	184.0915453	3271.583672	219.0915492	3291.583670	184.0915453	3291.583670	219.0915492
10	11	3833.531357	184.0915453	3833.531357	219.0915492	3853.531355	184.0915453	3853.531355	219.0915492
11	11	4395.479047	184.0915453	4395.479047	219.0915492	4415.479046	184.0915453	4415.479046	219.0915492
12	14	918.5313590	-898.1387290	953.5313590	-898.1387290	918.5313590	-878.1387290	953.5313590	-878.1387290
13	15	918.5313590	4.680240359	953.5313590	4.680240359	918.5313590	24.68024035	953.5313590	24.68024035
14	16	2433.531357	-898.1387260	2468.531357	-898.1387260	2433.531357	-878.1387260	2468.531357	-878.1387260
15	17	2433.531357	4.680237334	2468.531357	4.680237334	2433.531357	24.68023733	2468.531357	24.68023733
16	18	3068.531357	-898.1387235	3103.531357	-898.1387235	3068.531357	-878.1387235	3103.531357	-878.1387235
17	19	3068.531357	4.680234890	3103.531357	4.680234890	3068.531357	24.68023489	3103.531357	24.68023489
18	20	4583.531355	-898.1387255	4618.531355	-898.1387255	4583.531355	-878.1387255	4618.531355	-878.1387255
19	21	4583.531355	4.680236872	4618.531355	4.680236872	4583.531355	24.68023687	4618.531355	24.68023687
20	28	1683.531359	-857.5500349	1703.531357	-857.5500349	1683.531359	-817.5500349	1703.531357	-817.5500349
21	28	1683.531359	-712.5500349	1703.531357	-712.5500349	1683.531359	-692.5500349	1703.531357	-692.5500349
22	29	1683.531359	-180.9084511	1703.531357	-180.9084511	1683.531359	-160.9084511	1703.531357	-160.9084511
23	29	1683.531359	-55.90845116	1703.531357	-55.90845116	1683.531359	-15.90845116	1703.531357	-15.90845116
24	42	3833.531357	-857.5500344	3853.531355	-857.5500344	3833.531357	-817.5500344	3853.531355	-817.5500344

Figure4-14: A view of wall connection database table

Balconies and corridors are represented by a series of lines that form a closed region. The analysis followed to form them is based on a point-tracking method. It starts with one line's end point and searches for a line with a start point that has the same coordinates as that point, then keeps going till it reaches the first line's starting point. Each line in that series has a group ID to represent its position in that series, and each series (a closed region) is identified using a distinct ID (i.e. balcony ID or a corridor ID). Figure 4-15 shows the Balconies and Corridors database tables. By utilizing the created database, a 2D layout is and 3D model of the BIM model is developed. Figure 4-16 and Figure 3-17 show the 2D layout and 3D visualization of the current practice BIM model that represents a four-unit floor.

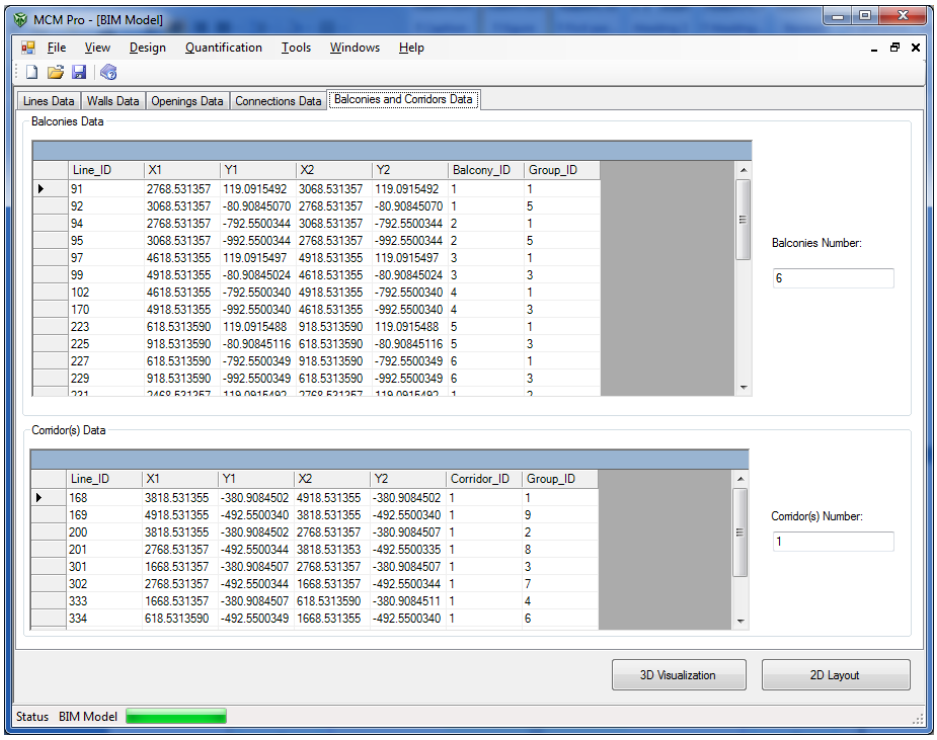


Figure 4-15: A view of the balconies and corridors data tables

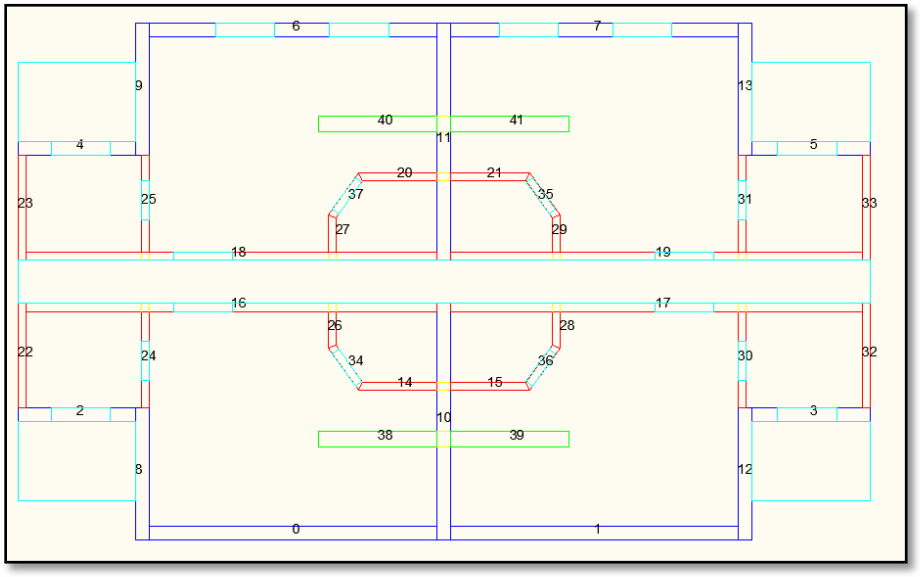


Figure 4-16: 2D layout of a four-unit floor

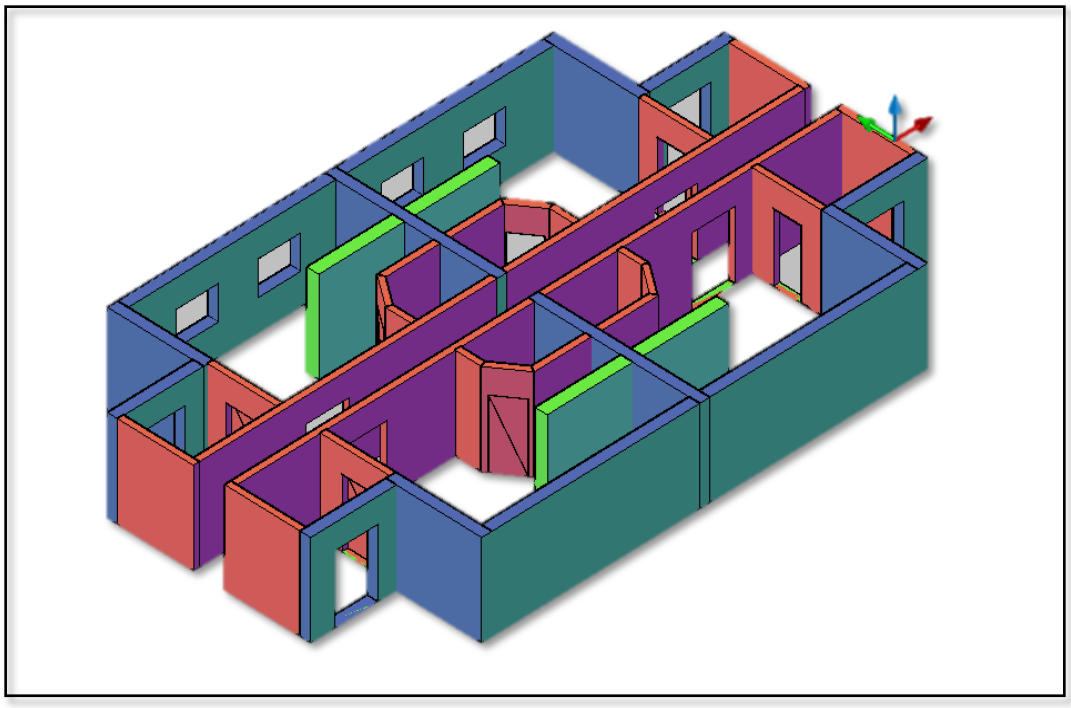


Figure 4-17: 3D visualization of a four-unit floor

4.2 *Modular Construction Manufacturing BIM Model Generation*

4.2.1 Module Creation

Modules analysis is the process that divides the 2D CAD into separate modules with distinct Module IDs. Separation Walls (Sw) and Row of Modules (RoM) are two concepts used during this analysis. Separation walls are interior walls parallel to the Y axis, which define the edges of each module. When selecting a separation wall using its distinct Wall ID, a separation position must be identified. A separation position is the point that defines where the previous module ends and the current one starts. It takes one of the following three values: (1) Left (L) indicates that the separation wall belongs to the current module; (2) Centre (C) indicates that the separation wall belongs to both modules, previous and current ones. (3) Right (R) indicates that the separation wall belongs to the previous module (See Figure 4-18). Right and left separation positions are used when a double wall (two walls share one edge) separates two modules, and only one of the two positions is used for a specific double wall.

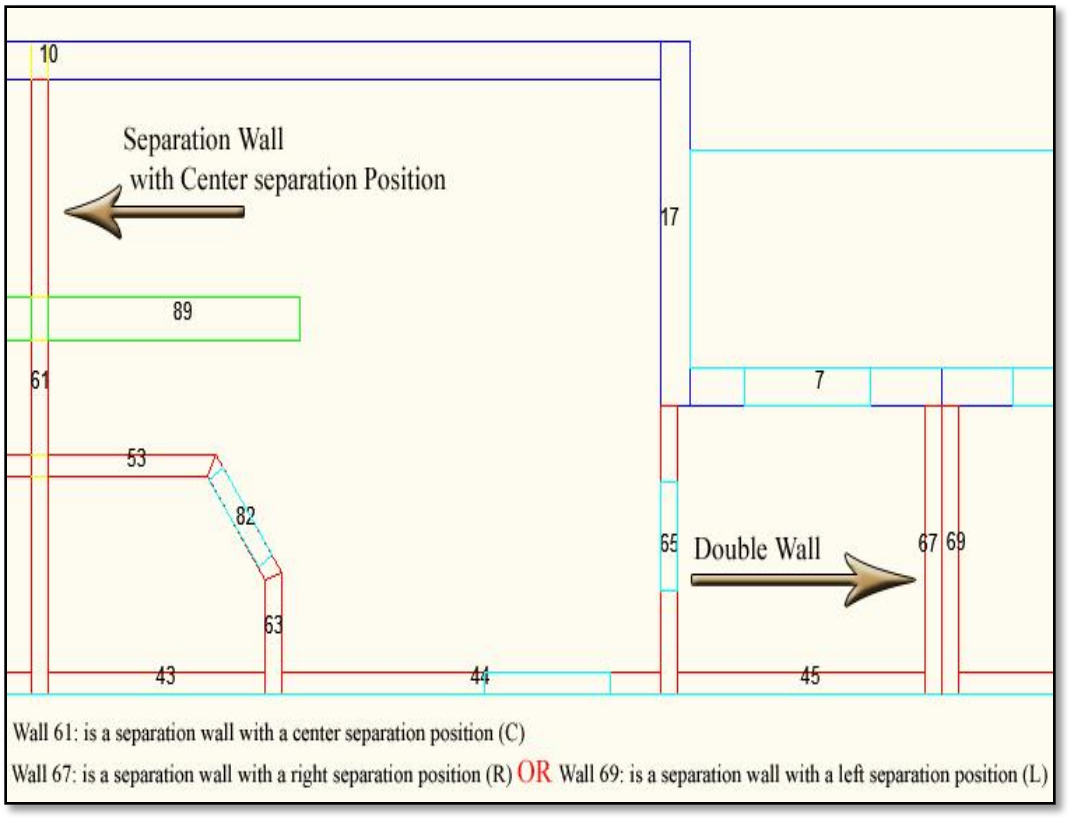


Figure 4-18: Separation walls

Row of Modules (RoM) is a number of modules that share at least one separation wall. When a project has two rows of modules, they are defined by a row separation using its maximum (Y_{max}), minimum (Y_{min}), and mean (Y_m) values of Y coordinates. A row separation is (1) a corridor (Co), (2) a single row of walls (SnglW), or (3) a double row of walls (DblW). Figure 4-19 shows the three cases for two rows of modules.

$$Y_m = \frac{(Y_{max} - Y_{min})}{2} + Y_{min} \quad [36]$$

Where:

Y_m=Separation row mean Y coordinate's value

Y_{max}=Separation row maximum Y coordinate's value

Y_{min}=Separation row minimum Y coordinate's value

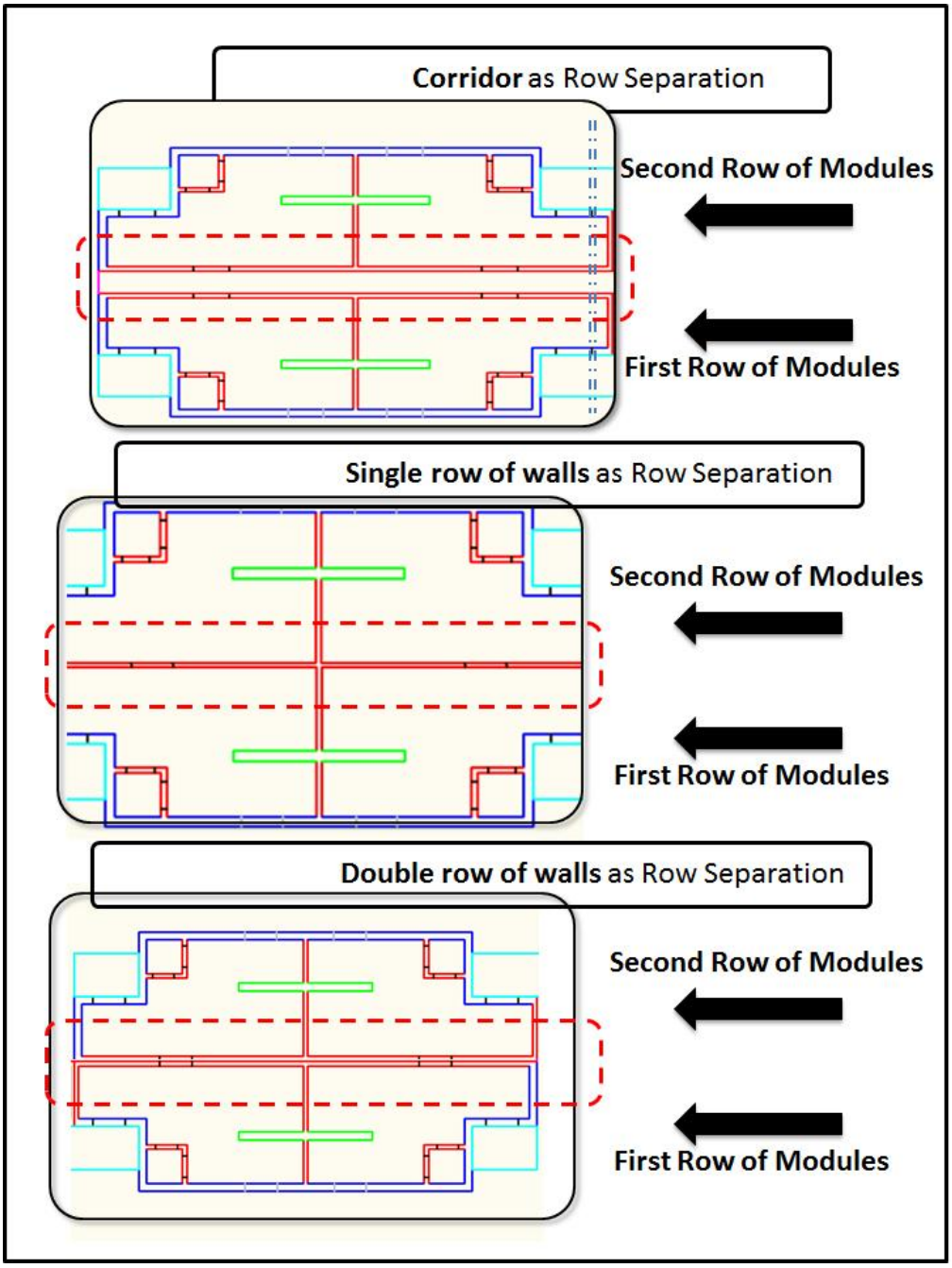


Figure 4-19: Row of modules separations

New tables are added to the current MCMPro database for the purpose of storing the modules data. These tables are Separation Walls Table, Row of Walls Table, Modules Table, Modules Slab Table, Modules Balconies Table, and Modules Opening Table. Table 4-4 summarizes each table contents. Figure 4-20 shows the modules tables.

Table 4-4: Modules data tables.

Table	Content
Separation Walls Table	This table stores the Wall ID and separation position of the separation walls.
Row of Walls Table	When Row of Modules separation is a single or double row of walls, Wall IDs are stored in this table.
Modules Table	This table has the following items: Module ID, Wall ID, Wall Orientation, X and Y coordinates of the wall's four corner points, wall length, wall thickness, and wall layer. Wall length and wall thickness will be used during the framing process.
Modules Slab Table	This table contains data related to the X and Y coordinates of the series of lines forming a module slab. The wall ID of each line is stored for the purpose of the framing process. It contains the Module ID, Wall ID X1, Y1, X2, and Y2.
Modules Balconies Table	This table stores each module's balconies' X and Y coordinates. It includes Module ID, X1, Y1, X2, and Y2.
Modules Opening Table	This table stores data related to modules openings. It includes Module ID, Wall ID, Opening ID, Opening Type (door or window), X and Y coordinates of its corner points, and Window Type ID, which indicates the type of window to specify its elevation data for the purpose of framing and 3D modeling.

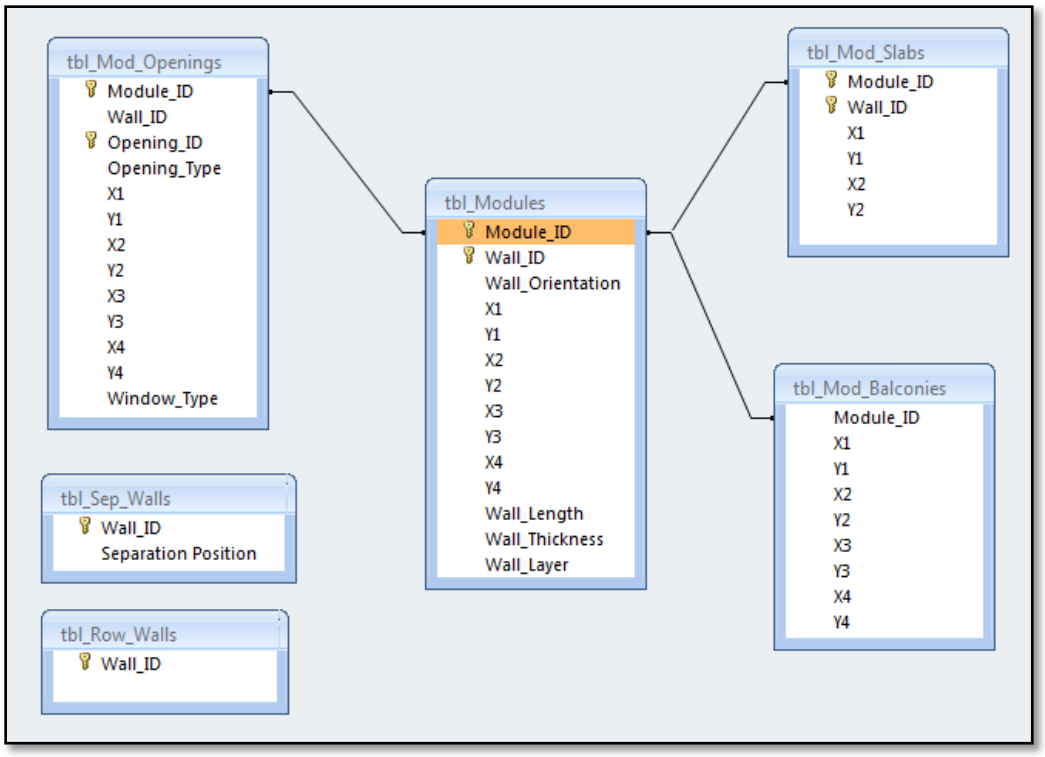


Figure 4-20: The modules tables

The first step in the modules creation process is defining the separation walls and rows of modules separations. The Separation walls dialog box enables the user to enter the related parameters (See Figure 2-21). Having selected the separation walls, a module dimensions check is performed. The check is based on the provincial road rules that specify the maximum allowable dimensions of a vehicle. Alberta provincial road rules have been used for this analysis. The dimensions are found in the "Options" dialog box under the "Modules Data" tab (See Figure 4-22). When exceeding these dimensions, a warning message is displayed to inform the user of the violation and its type, a width or length violation (See Figure 4-23). The user has the choice to *Abort* the analysis, *Retry* the analysis by changing the wall separation selection or the modules data (i.e. maximum allowable length and width), or *Ignore* the warning message and proceed with the analysis.

The modules analysis is divided into three main steps: (1) Modules walls process, (2) Modules slabs creation, and (3) Modules opening assignment (See Figure 4-24).

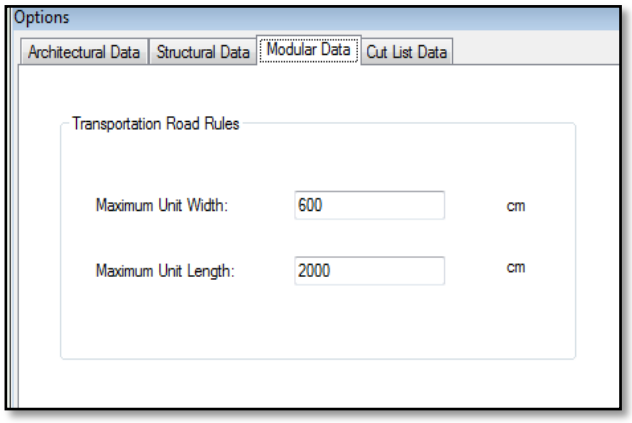


Figure 4-22: Maximum allowable dimensions

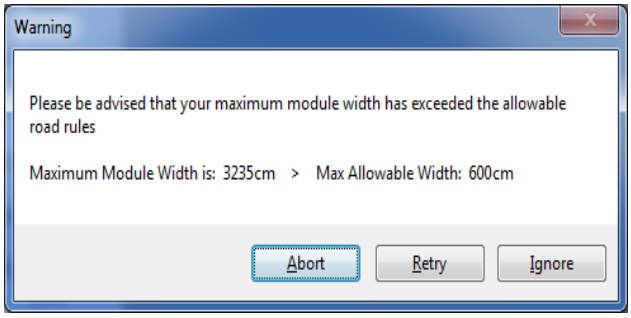


Figure 4-23: Dimension violation message box

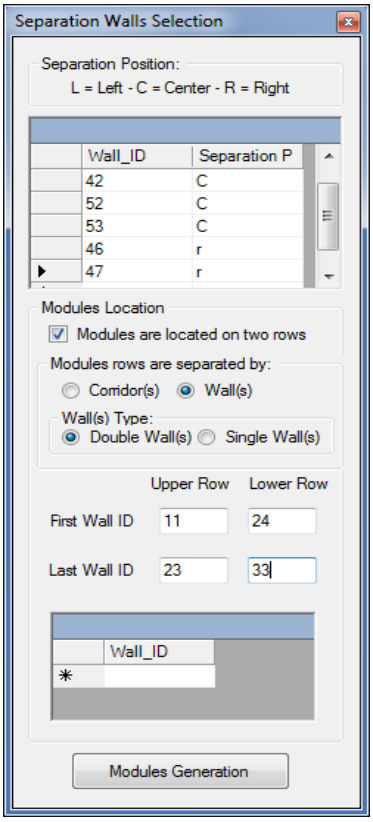


Figure 4-21: Separation walls dialog box

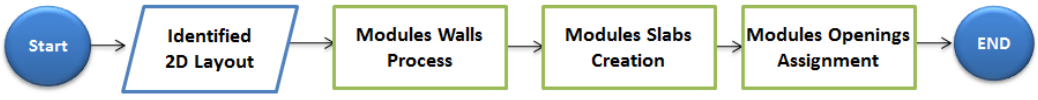


Figure 4-24: Modules analysis

The Modules Walls Process defines module walls based on separation walls (Sw), separation row (Sr), and walls' X and Y coordinates. It starts by assigning the separation walls to specific modules, followed by assigning the modules' walls. Separation wall assignment is based on the separation position (as described above). In the case of two rows of modules, further analysis is required

for a separation wall. When a separation wall is used to define modules in both rows, Y_m is used to assign the separation wall to the two rows of modules (See Figure 4-25- A, B).

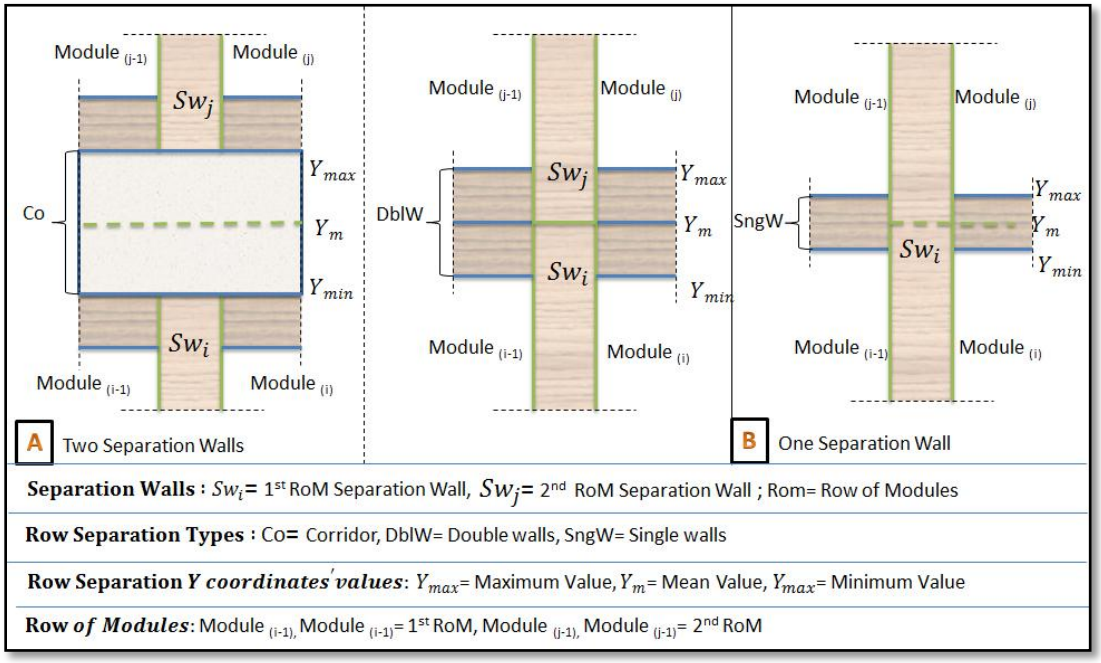


Figure 4-25: Modules walls assignment - Separation walls

The Modules' walls analysis requires module classification that is based on the module's relative location in the row of modules. It has the following values: First, last, or in-between. This classification is essential for the process of specifying the X coordinates range of values for each module. The X coordinates range of values is defined by a module's start X point and a module's end X point. Table 4-5 shows X start and end values for each module.

Table 4-5: Modules X coordinates range

Module Classification	Start X	End X
The First	- ∞	First separation wall dividing X
In-between	Previous separation wall dividing X	Current separation wall dividing X
The Last	Last separation wall dividing X	+ ∞

Where: **- ∞, + ∞:** Practically defined by big negative and positive values.

'Sw dividing X value: Defined by the separation walls' X coordinate values and the separation position.

Based on the walls' orientation, a module's walls analysis passes through the following steps:

Py Walls: A wall parallel to Y is defined by its four corner points, $point_1$, $point_2$, $point_3$, and $point_4$, where $point_1$ has the minimum X and Y coordinate values, and the other points are defined by moving in a clockwise motion. Py walls cannot belong to different modules on the same RoM. However, they can belong to modules on different RoM. Using $point_1$ and $point_2$, the RoM analysis and Y_m, a wall parallel to Y could fall into one of the following cases:

Case 1: The wall belongs to the current module from the first RoM, only (See Figure 4-26-A).

In this case no adjustment on wall's $point_2$ and $point_3$ Y coordinates' values is needed, and the following equation is satisfied:

$$Y_2 \leq Y_m \quad [37]$$

Case 2: The wall belongs to two modules (See Figure 4-26-B).

This case satisfies the following equation:

$$Y_2 > Y_m \quad [38]$$

Adjustments on a wall's $point_2$ and $point_3$ Y coordinates' values are needed according to the following equation:

$$Y_2 = Y_m \quad [39]$$

$$Y_3 = Y_m \quad [40]$$

Case 3: The wall belongs to the current module from the second RoM, only (See Figure 4-26-C).

In this case no adjustment on a wall's $point_2$ and $point_3$ Y coordinates' values is needed, and the following equation is satisfied:

$$Y_1 \geq Y_m \quad [41]$$

Case 4: The wall belongs to two modules (See Figure 4-26-D).

This case satisfies the following equation:

$$Y_1 < Y_m \quad [42]$$

Adjustments on walls' $point_1$ and $point_4$ Y coordinates' values are needed according to the following equation:

$$Y_1 = Y_m \quad [43]$$

$$Y_4 = Y_m \quad [44]$$

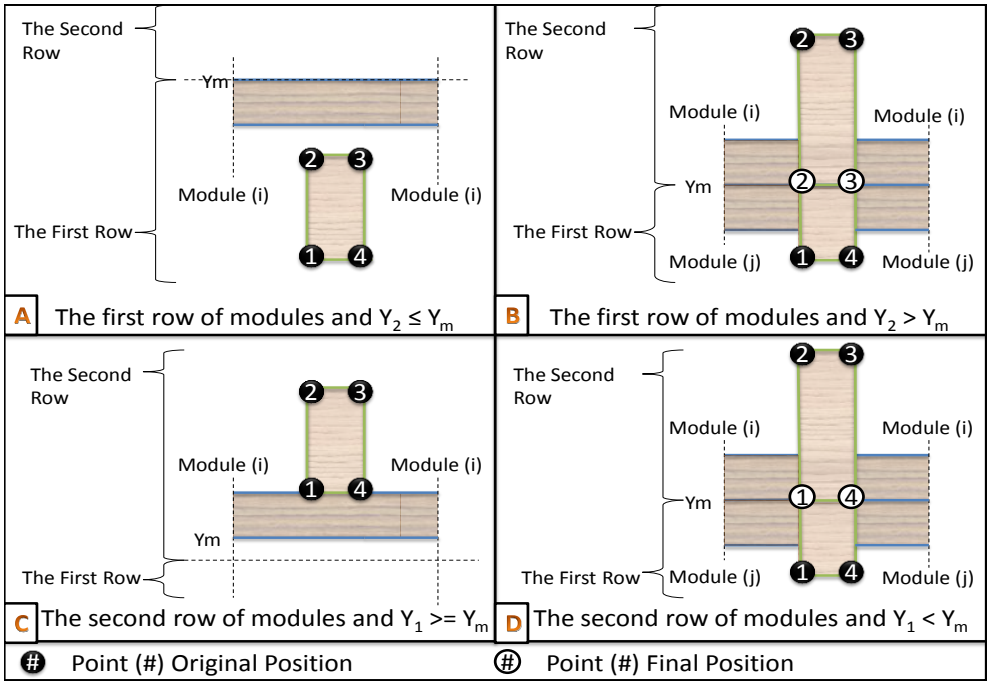


Figure 4-26: Modules walls assignment -Parallel to Y walls

Px Walls: A wall parallel to X $point_1$ also has the minimum X and Y coordinate values. However, $point_2$, $point_3$, and $point_4$ are defined by moving in a counter clockwise motion. This type of wall cannot belong to modules from different rows; nevertheless, it could belong to more than one module on the same row. Using Y_m, a wall belongs to the first row of modules if $Y_1 <= Y_m$, and it belongs to the second row of modules if $Y_4 >= Y_m$. The analysis on both rows follows the same steps. By utilizing the wall's main points, the module start X (X_{st}), and its end X (X_{en}), a wall parallel to X could fall into one of the following cases:

Case 1: The wall belongs to the current module, only (See Figure 4-27-A).

In this case no adjustment is needed, and the following equation is satisfied:

$$X_1 \geq Xst \quad [45]$$

$$X_2 \leq X_{en} \quad [46]$$

Case 2: The wall extends beyond the current module from the wall's start edge side (See Figure 4-27-B).

This case satisfies the following equations:

$$X_1 < X_{st} \quad [47]$$

$$X_2 \leq X_{en} \quad [48]$$

Adjustments on a wall's start points (i.e. $point_1$ and $point_4$) X coordinates' values are needed according to the following equation:

$$X_1 = X_{st} \quad [49]$$

$$X_4 = X_{st} \quad [50]$$

Case 3: The wall extends beyond the current module from the wall's start and end edges sides (See Figure 4-27-C).

This case satisfies the following equations:

$$X_1 < X_{st} \quad [51]$$

$$X_2 > X_{en} \quad [52]$$

Adjustments on a wall's four corner points X coordinates' values are needed according to the following equation:

$$X_1 = X_{st} \quad [53]$$

$$X_4 = X_{st} \quad [54]$$

$$X_2 = X_{en} \quad [55]$$

$$X_3 = X_{en} \quad [56]$$

Case 4: The wall extends beyond the current module from the wall's end edge side (See Figure 4-27-D).

This case satisfies the following equations:

$$X_1 \geq X_{st} \quad [57]$$

$$X_2 > X_{en} \quad [58]$$

Adjustments on walls' end points (i.e. $point_2$ and $point_3$) X coordinates' values are needed according to the following equation:

$$X_2 = X_{en} \quad [59]$$

$$X_3 = X_{en} \quad [60]$$

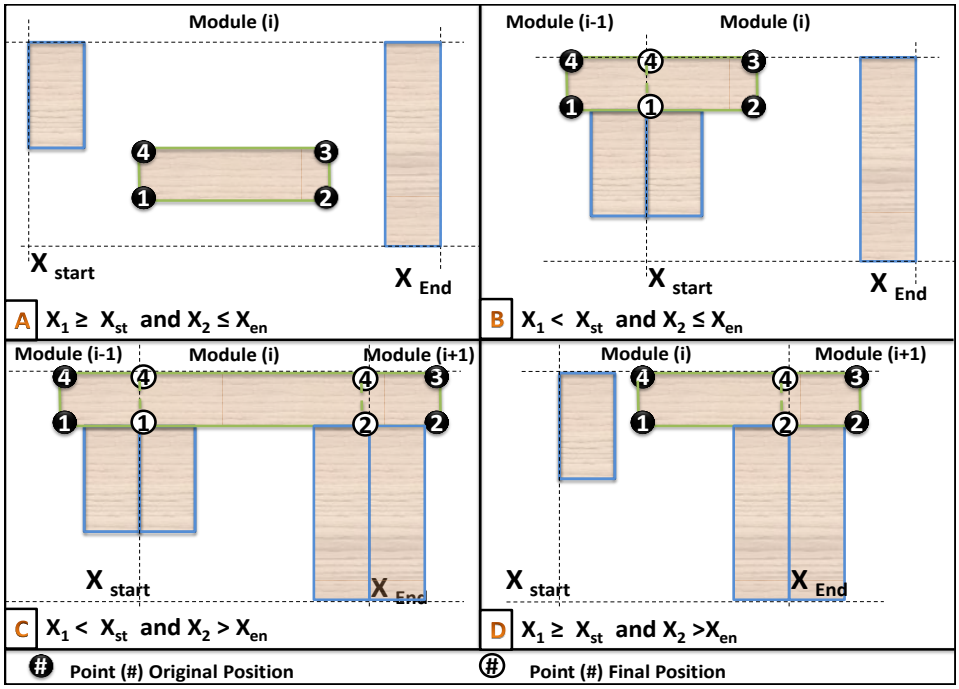


Figure 4-27: Modules walls assignment -Parallel to X walls

In Walls:

An inclined wall belongs to one module only, because based on the wall priority table, it has the lowest priority, which means it can't extend over a module's boundaries. In order to assign an inclined wall to a module, the first case of a wall parallel to X is applied.

4.2.2 Modules Slabs Creation

The architectural 2D layout doesn't have a slab element for the project; it relies on human intelligence to define one using the other elements' data. The modularity concept implies that each module must have a floor and a ceiling. The

module's floor and ceiling are composed of slab elements that define the boundaries of that module. A module's slab is a closed surface that surrounds a module. It is divided into three categories: wall slab, balcony slabs, and corridor slabs. Wall slabs are defined by the outer edge of the walls that surround the module. Balcony slabs are the ones surrounded by the balcony edges and the exterior wall facing that balcony. Corridor slabs extend between two rows of modules. The modules' slabs creation process starts by developing the wall and corridor slabs, and then it develops balcony slabs and assigns them to the modules.

Wall and corridor slabs development analysis defines a base point for each module. A progressive search for the lines that define a module's slab starts from the base point and continues until it closes the slab surface by reaching that base point again. This search passes through three types of elements: separation walls, exterior walls, and row separation. Row separation is either a series of walls or a corridor. In both cases, the mean of the Y coordinate values of the row separation is the value that is used in this analysis. Rows of modules and modules classification concepts are utilized to define the base point and the direction that the progressive search follows (See Figure 4-28).

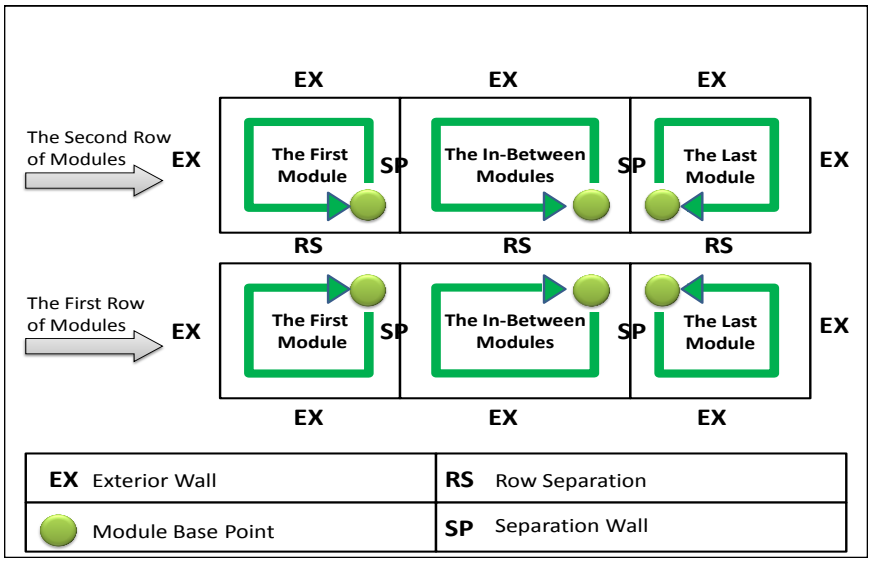


Figure 4-28: Wall slabs progressive search

After defining the base point of each module, the search moves towards the exterior walls. It goes through the exterior edge of these walls, and once it reaches

a separation wall or a row separation, it goes directly back to the base point to close the slab surface and create a module slab element. The analysis followed in the progressive search, while passing through the exterior walls, indicates which point to consider when moving from one exterior wall to another. The starting point and wall orientation for the current wall and the next one provide different scenarios for the analysis. This analysis is structured into a number of cases as follows:

Case 1: Current Wall Parallel to Y (CWY), Next Wall Parallel to X (NWX) (See Figure 4-29).Table 4-6 illustrates the possible scenarios in this case.

Case 2: Current Wall Parallel to X (CWX), Next Wall Parallel to Y (NWY) (See Figure 4-30). Table 4-7 illustrates the possible scenarios in this case.

Table 4-6: Slab analysis case 1

Scenario	Starting point (CWY)	Direction	Next Point (CWY)	Comparing points (CWY)	(NWX)	Conditions	Modify	Next Point (NWX)	Figure
1-1	P4	Upward	P3	P3	P3	$Y_i = Y_j$ $\lvert X_i - X_j \rvert = Ex$	-	P4	37-A
1-2	P1	Upward	P2	P2	P4	$Y_i = Y_j$ $\lvert X_i - X_j \rvert = Ex$	-	P3	37-B
1-3	P3	Downward	P4	P4	P2	$Y_i = Y_j$ $\lvert X_i - X_j \rvert = Ex$	-	P1	37-C
1-4	P2	Downward	P1	P1	P2	$Y_i = Y_j$ $\lvert X_i - X_j \rvert = Ex$	-	P2	37-D
1-5	P1	Upward	P2	P2	P2	$X_i = X_j$ $\lvert Y_i - Y_j \rvert = Ex$	$Y_i = Y_i - Ex$	P1	37-E
1-6	P4	Upward	P3	P3	P1	$X_i = X_j$ $\lvert Y_i - Y_j \rvert = Ex$	$Y_i = Y_i - Ex$	P3	37-F
1-7	P2	Downward	P1	P1	P2	$X_i = X_j$ $\lvert Y_i - Y_j \rvert = Ex$	$Y_i = Y_i + Ex$	P1	37-G
1-8	P2	Downward	P1	P1	P1	$X_i = X_j$ $\lvert Y_i - Y_j \rvert = Ex$	$Y_i = Y_i + Ex$	P2	37-H

Where Ex= Exterior wall thickness, i= the current point, j= the next point.

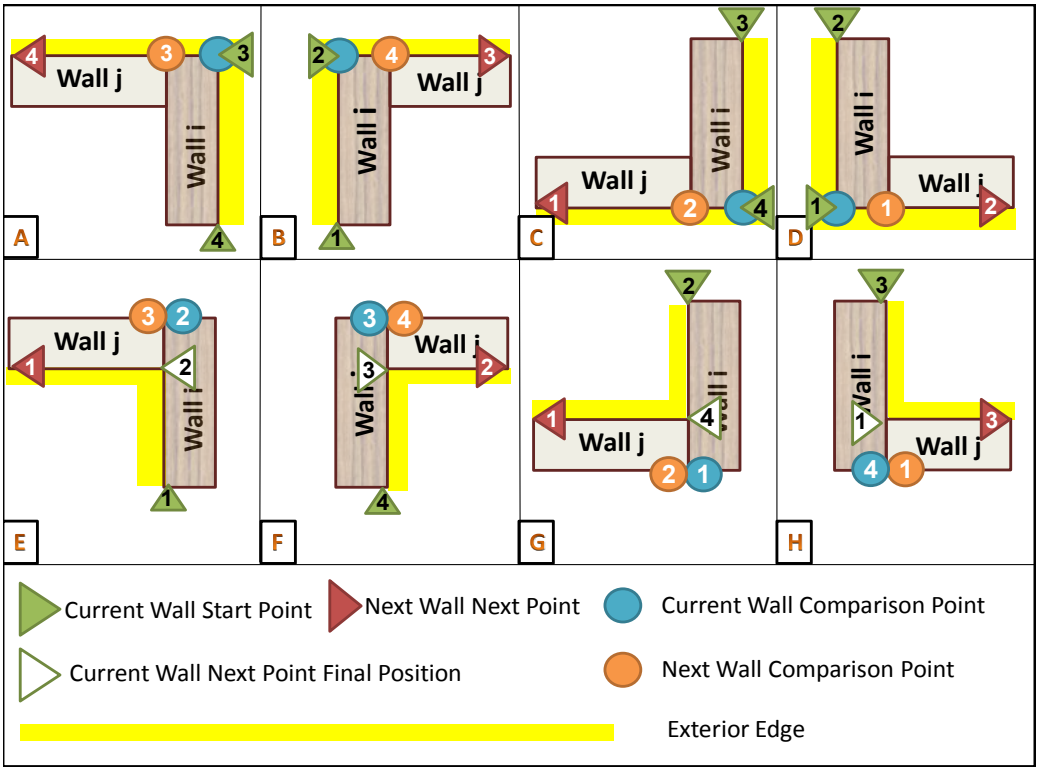


Figure 4-29: Slab analysis case 1

Table 4-7: Slab analysis case 2.

Scenario	Starting point (CWX)	Direction	Next Point (CWX)	Comparing points (CWX)	(NWY)	Conditions	Next Point /Modify	Next Point (NWY)	Figure
2-1	P4	Right	P3	P3	P2	$Y_i = Y_j$ $X_i = X_j$	P3	P4	38-A
2-2	P3	Left	P4	P4	P3	$Y_i = Y_j$ $X_i = X_j$	P2	P1	38-B
2-3	P1	Right	P2	P2	P1	$Y_i = Y_j$ $X_i = X_j$	P4	P3	38-C
2-4	P2	Left	P1	P1	P4	$Y_i = Y_j$ $X_i = X_j$	P1	P2	38-D
2-5	P1	Right	P2	P2	P2	$X_i = X_j$ $\lvert Y_i - Y_j \rvert = Ex$	-	P1	38-E
2-6	P2	Left	P1	P1	P3	$X_i = X_j$ $\lvert Y_i - Y_j \rvert = Ex$	-	P4	38-F
2-7	P4	Right	P3	P3	P1	$X_i = X_j$ $\lvert Y_i - Y_j \rvert = Ex$	-	P2	38-G
2-8	P2	Left	P1	P1	P4	$X_i = X_j$ $\lvert Y_i - Y_j \rvert = Ex$	-	P3	38-H

Where Ex= Exterior wall thickness, i= the current point, j= the next point.

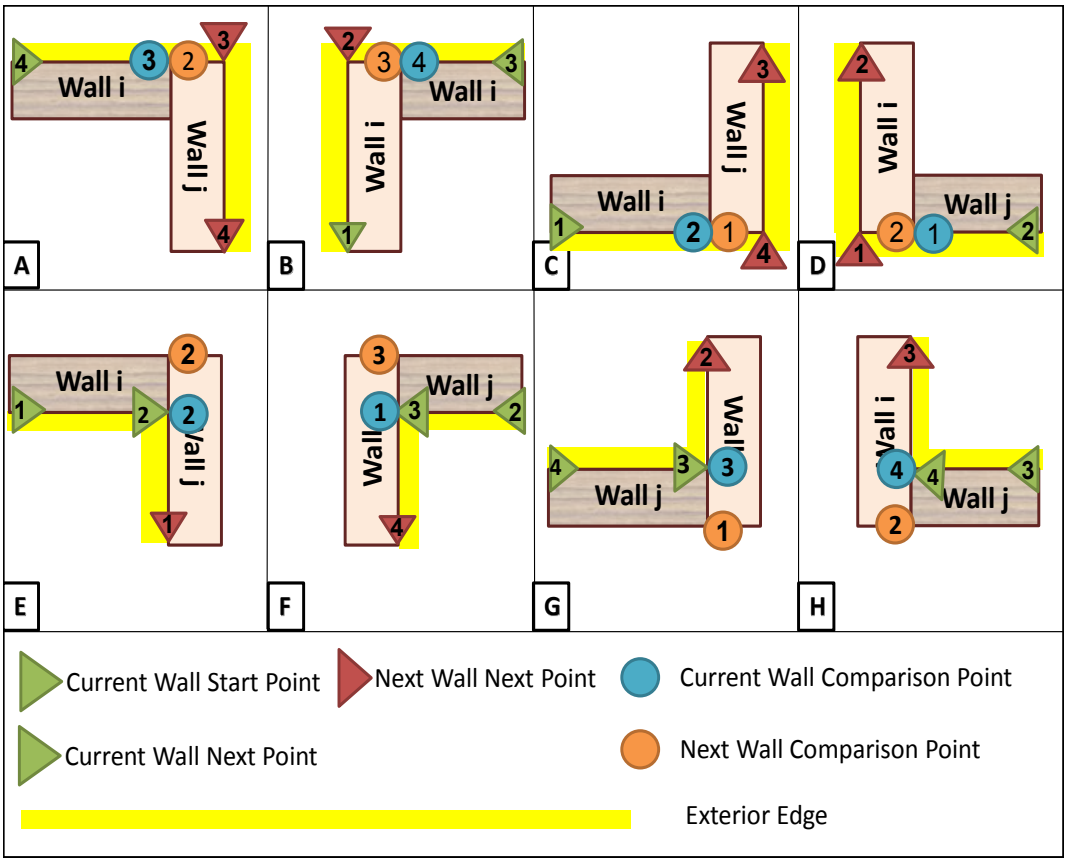


Figure 4-30: Slab analysis case 2

Other cases include:

Case 3: Current Wall Parallel to Y (CWY), Next Wall Inclined (NWI).

Case 4: Current Wall Parallel to X (CWX), Next Wall Inclined (NWI).

Case 5: Current Wall Inclined (CWI), Next Wall Parallel to Y (NWY).

Case 6: Current Wall Inclined (CWI), Next Wall Parallel to X (NWX).

Case 7: Current Wall Inclined (CWI), Next Wall Inclined (NWI).

Inclined walls are defined by two parallel lines with a perpendicular distance between them equal to a wall's thickness. These two lines are defined by two points, either $point_1$ and $point_2$ or $point_3$ and $point_4$. Whenever an inclined wall is the current or the next wall, the same analysis is applied. When the start point is $point_1$ or $point_3$, the next point is $point_2$ or $point_4$, and vice versa.

After defining the module's wall slabs and corridor slabs, balconies slabs are assigned to each module. The analysis followed for balconies slabs is similar to that followed for assigning walls parallel to X.

Openings have the same thickness as the wall they belong to. When dividing an identified 2D layout into modules, walls properties, such as wall length and thickness, could change, which in turn affects the opening properties. For this reason, when an opening belongs to a wall parallel to X, only its minimum and maximum Y coordinates values are used in the opening database table, and X coordinates are used from the modified wall X coordinates, and vice versa. Since inclined walls cannot belong to wall separation or separation row, their thickness is kept intact, and thereby openings that belong to an inclined wall use all the X and Y values from the opening database.

The final result of the modules analysis is stored in the modules database tables (See Figure 4-31 to Figure 4-25). Figure 4-36 and Figure 4-37 illustrate 2D layout and 3D visualization of the modular construction manufacturing BIM model for an 8-units floor, and Figure 4-38 and Figure 4-39 show the same representations for one module in that floor.

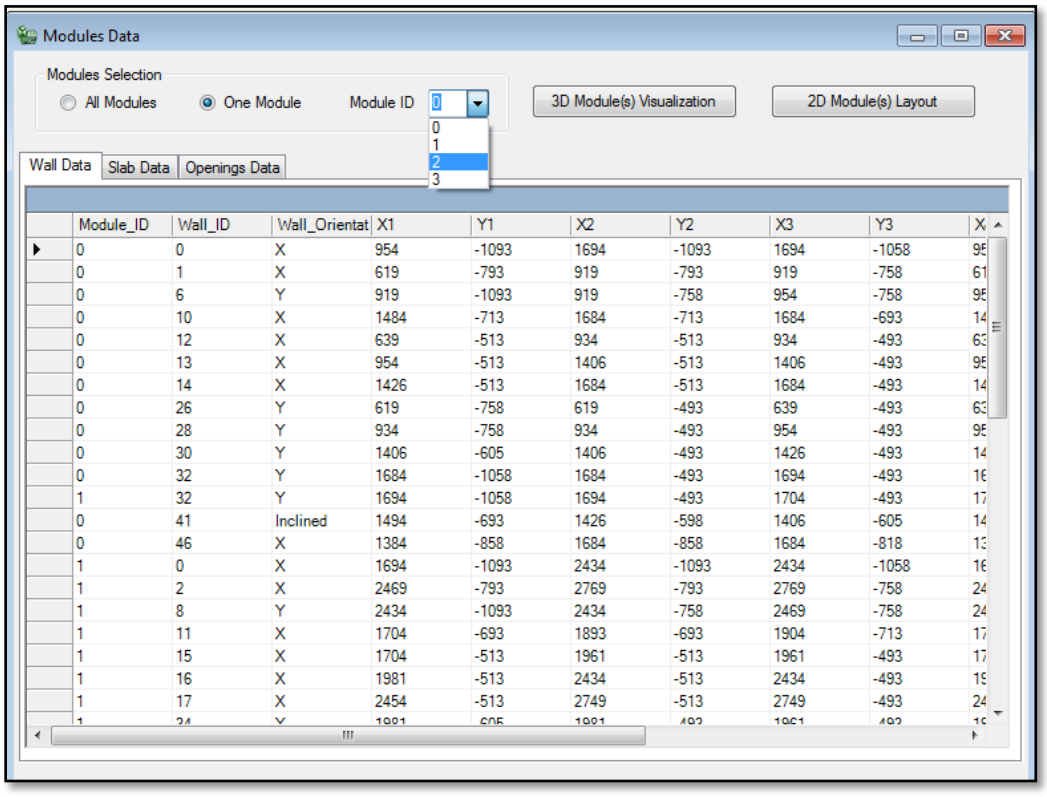
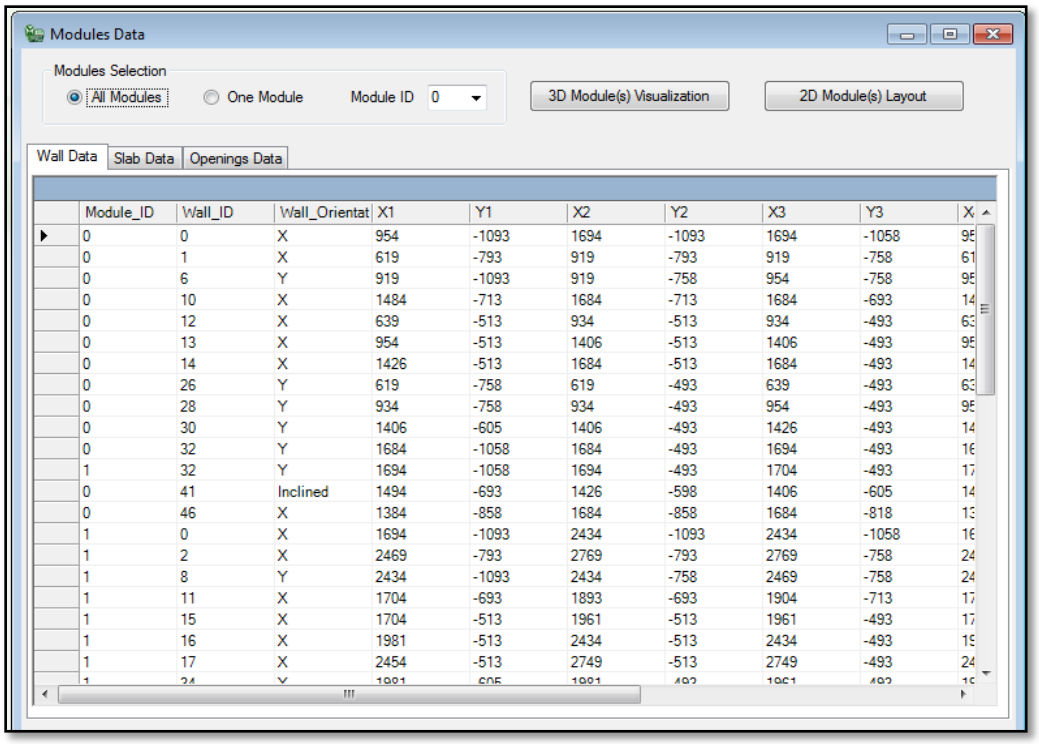
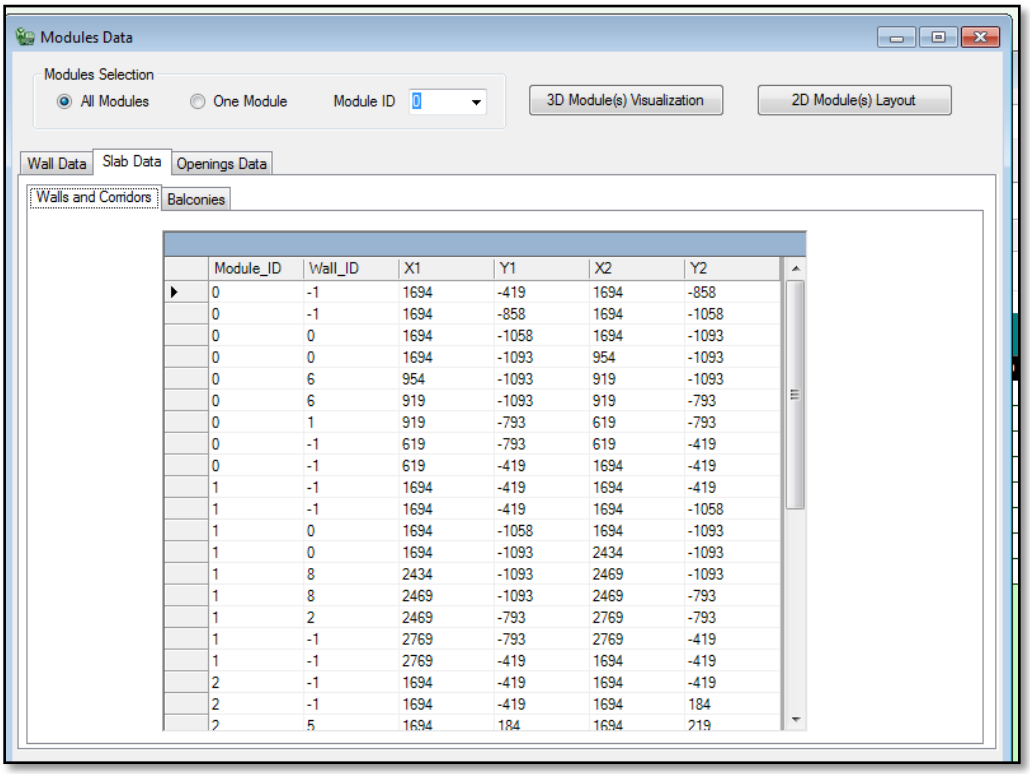


Figure 4-31: A screen shot of the modules selection process using MCMPro



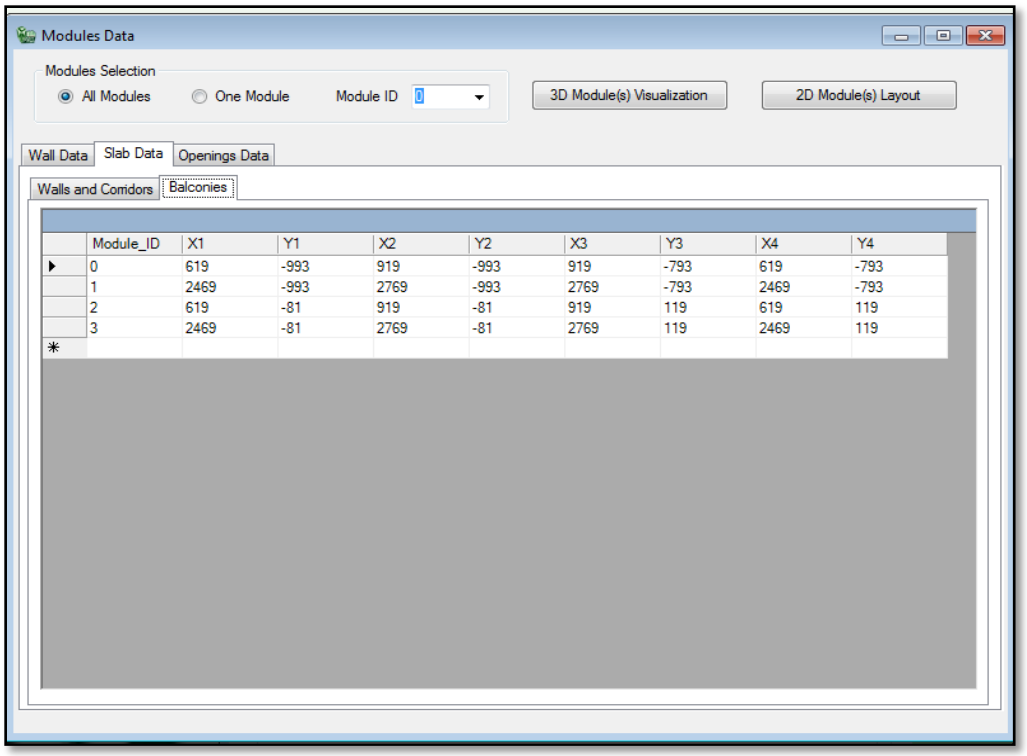
Module_ID	Wall_ID	Wall_Orientat	X1	Y1	X2	Y2	X3	Y3	X
0	0	X	954	-1093	1694	-1093	1694	-1058	95
0	1	X	619	-793	919	-793	919	-758	61
0	6	Y	919	-1093	919	-758	954	-758	95
0	10	X	1484	-713	1684	-713	1684	-693	14
0	12	X	639	-513	934	-513	934	-493	63
0	13	X	954	-513	1406	-513	1406	-493	95
0	14	X	1426	-513	1684	-513	1684	-493	14
0	26	Y	619	-758	619	-493	639	-493	63
0	28	Y	934	-758	934	-493	954	-493	95
0	30	Y	1406	-605	1406	-493	1426	-493	14
0	32	Y	1684	-1058	1684	-493	1694	-493	16
1	32	Y	1694	-1058	1694	-493	1704	-493	17
0	41	Inclined	1494	-693	1426	-598	1406	-605	14
0	46	X	1384	-858	1684	-858	1684	-818	13
1	0	X	1694	-1093	2434	-1093	2434	-1058	16
1	2	X	2469	-793	2769	-793	2769	-758	24
1	8	Y	2434	-1093	2434	-758	2469	-758	24
1	11	X	1704	-693	1893	-693	1904	-713	17
1	15	X	1704	-513	1961	-513	1961	-493	17
1	16	X	1981	-513	2434	-513	2434	-493	19
1	17	X	2454	-513	2749	-513	2749	-493	24

Figure 4-32: A view of modules walls data



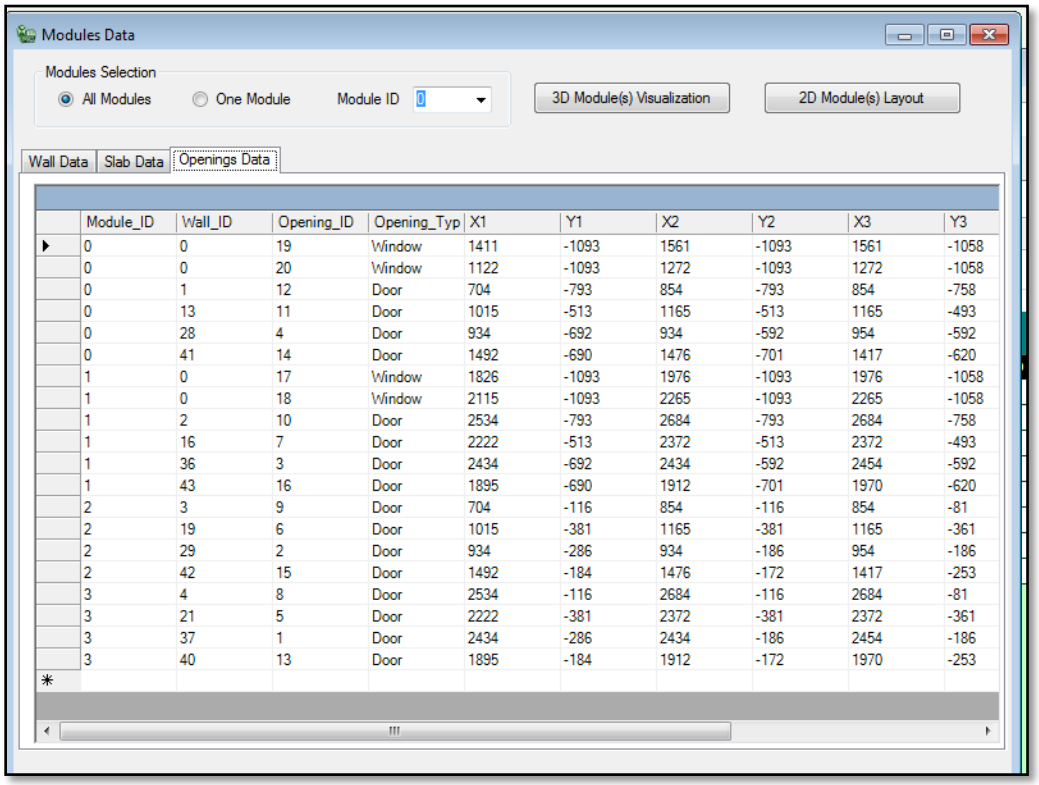
Module_ID	Wall_ID	X1	Y1	X2	Y2
0	-1	1694	-419	1694	-858
0	-1	1694	-858	1694	-1058
0	0	1694	-1058	1694	-1093
0	0	1694	-1093	954	-1093
0	6	954	-1093	919	-1093
0	6	919	-1093	919	-793
0	1	919	-793	619	-793
0	-1	619	-793	619	-419
0	-1	619	-419	1694	-419
1	-1	1694	-419	1694	-419
1	-1	1694	-419	1694	-1058
1	0	1694	-1058	1694	-1093
1	0	1694	-1093	2434	-1093
1	8	2434	-1093	2469	-1093
1	8	2469	-1093	2469	-793
1	2	2469	-793	2769	-793
1	-1	2769	-793	2769	-419
1	-1	2769	-419	1694	-419
2	-1	1694	-419	1694	-419
2	-1	1694	-419	1694	184
2	5	1694	184	1694	219

Figure 4-33: A view of modules walls and corridor slabs Data



Module_ID	X1	Y1	X2	Y2	X3	Y3	X4	Y4
0	619	-993	919	-993	919	-793	619	-793
1	2469	-993	2769	-993	2769	-793	2469	-793
2	619	-81	919	-81	919	119	619	119
3	2469	-81	2769	-81	2769	119	2469	119

Figure 4-34: A view of modules balconies slabs data



Module_ID	Wall_ID	Opening_ID	Opening_Typ	X1	Y1	X2	Y2	X3	Y3
0	0	19	Window	1411	-1093	1561	-1093	1561	-1058
0	0	20	Window	1122	-1093	1272	-1093	1272	-1058
0	1	12	Door	704	-793	854	-793	854	-758
0	13	11	Door	1015	-513	1165	-513	1165	-493
0	28	4	Door	934	-692	934	-592	954	-592
0	41	14	Door	1492	-690	1476	-701	1417	-620
1	0	17	Window	1826	-1093	1976	-1093	1976	-1058
1	0	18	Window	2115	-1093	2265	-1093	2265	-1058
1	2	10	Door	2534	-793	2684	-793	2684	-758
1	16	7	Door	2222	-513	2372	-513	2372	-493
1	36	3	Door	2434	-692	2434	-592	2454	-592
1	43	16	Door	1895	-690	1912	-701	1970	-620
2	3	9	Door	704	-116	854	-116	854	-81
2	19	6	Door	1015	-381	1165	-381	1165	-361
2	29	2	Door	934	-286	934	-186	954	-186
2	42	15	Door	1492	-184	1476	-172	1417	-253
3	4	8	Door	2534	-116	2684	-116	2684	-81
3	21	5	Door	2222	-381	2372	-381	2372	-361
3	37	1	Door	2434	-286	2434	-186	2454	-186
3	40	13	Door	1895	-184	1912	-172	1970	-253

Figure 4-35: A view of modules openings data

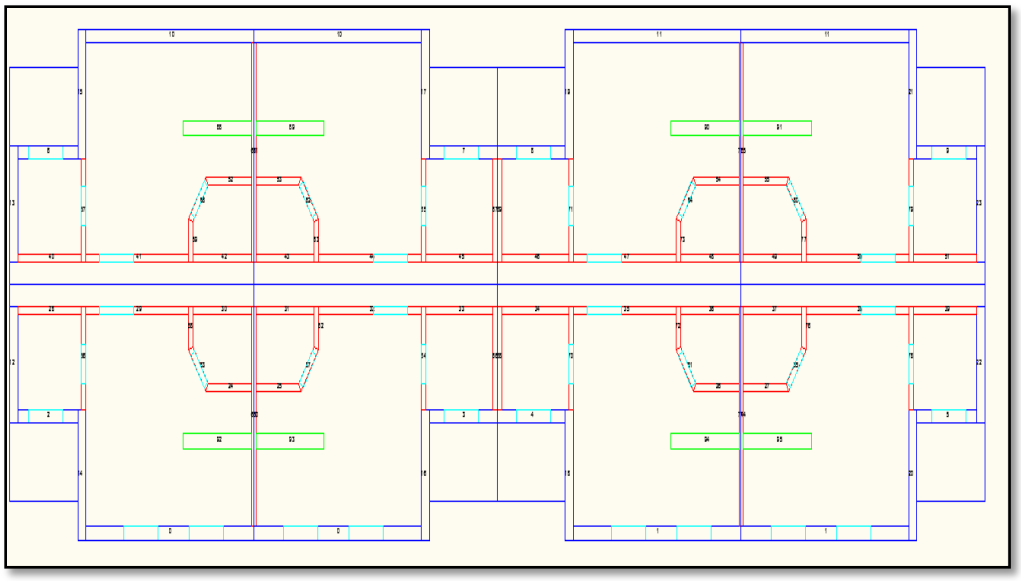


Figure 4-36: 2D layout of modular construction manufacturing BIM model (8-units floor)

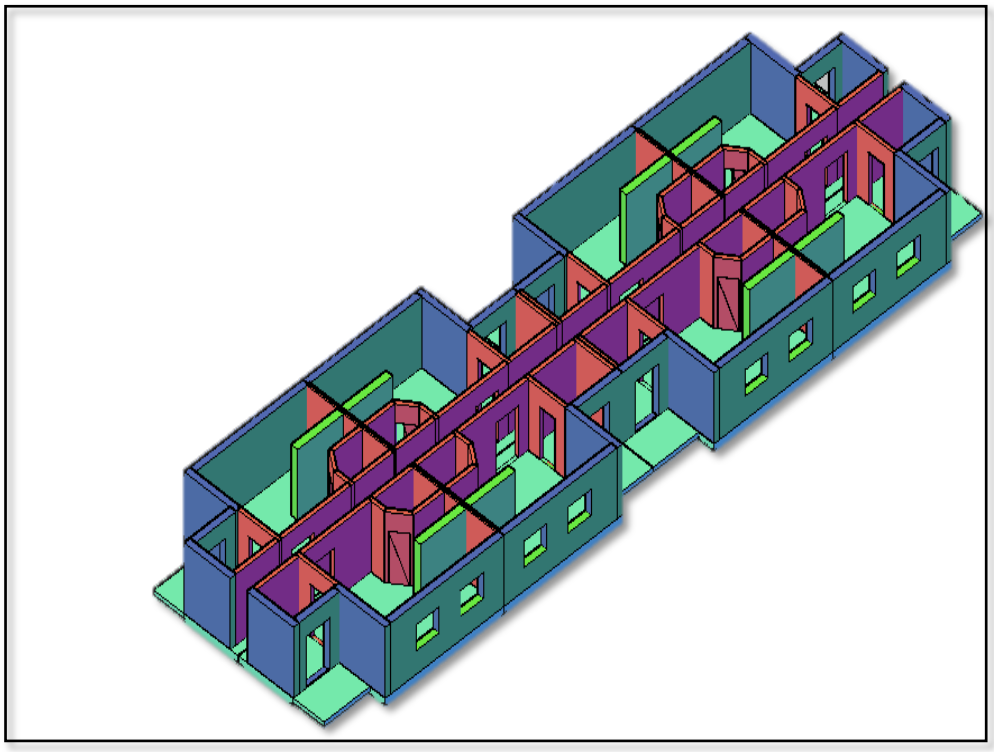


Figure 4-37: Visualization of modular construction manufacturing BIM model (8-units floor)

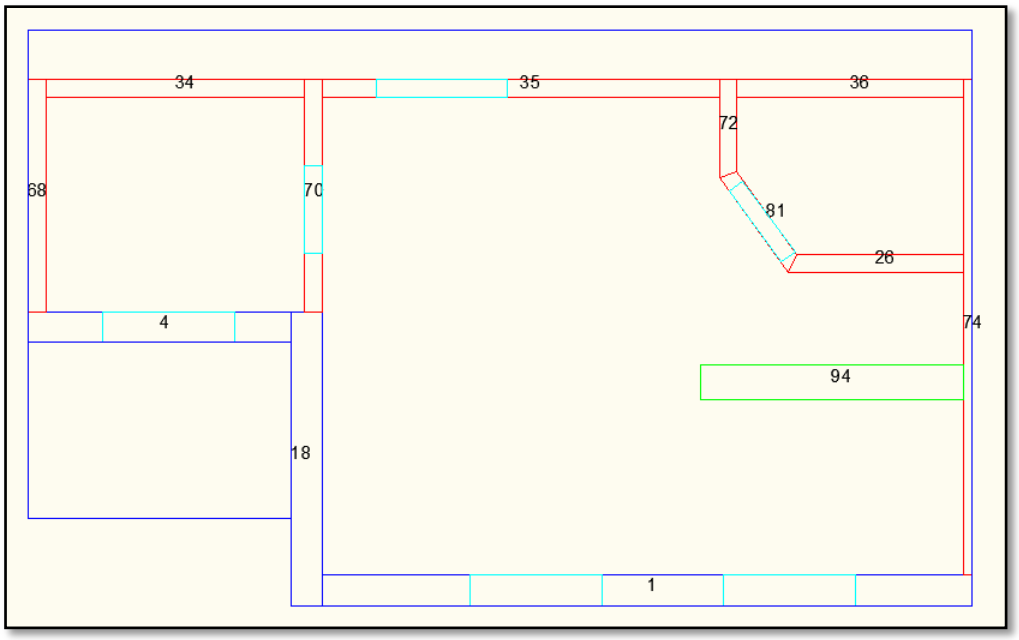


Figure 4-38: 2D layout of modular construction manufacturing BIM model (one module)

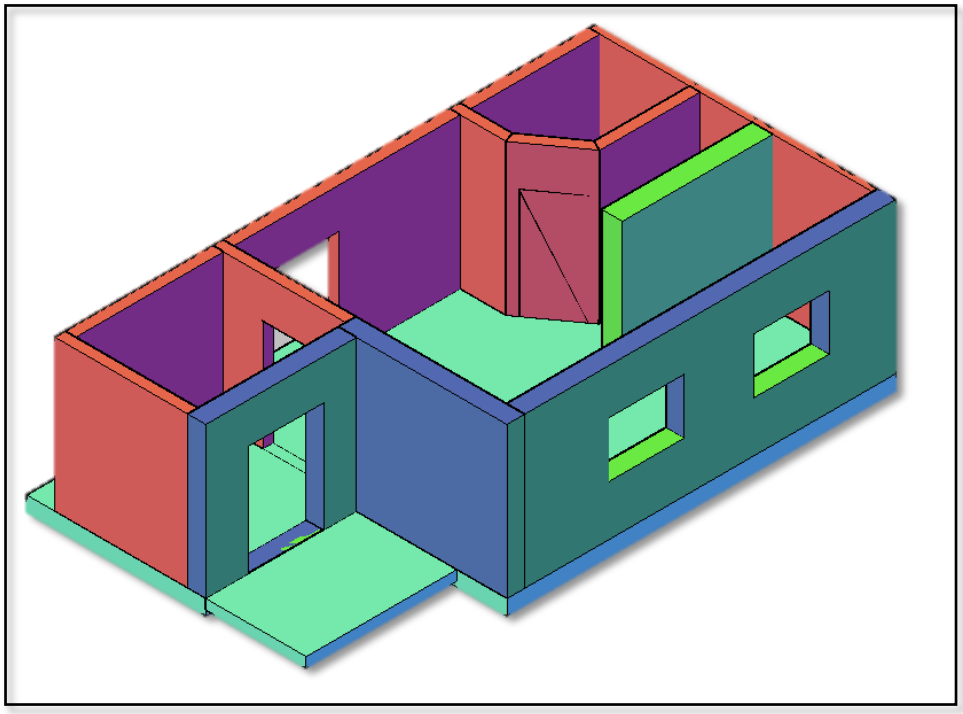


Figure 4-39: Visualization of modular construction manufacturing BIM model (one module)

4.2.3 Shop Drawings Generation Process

Structural design and wood-framing requirements are applied on the modular construction manufacturing BIM to provide the detailed shop drawings needed for manufacturing of the module's wall, floor, and ceiling. These requirements specify the dimensions and spacing of different components used for the wood-framing process. Factors such as wall classification, load direction, and wall connection types affect these requirements. Walls are classified according to the structural design and the modularity concepts. These classes are exterior walls parallel to X, exterior walls parallel to Y, interior walls, mechanical walls, separation walls, and row separation walls. Load direction divides the walls into two groups—load-bearing and non-load-bearing walls—which affect the wood-framing components, in particular when framing an opening in a wall.

MCMPro includes the shop drawings requirements in the Option dialog box under the Structural Data tab. Figure 4-40 shows the default values used for the structural data.

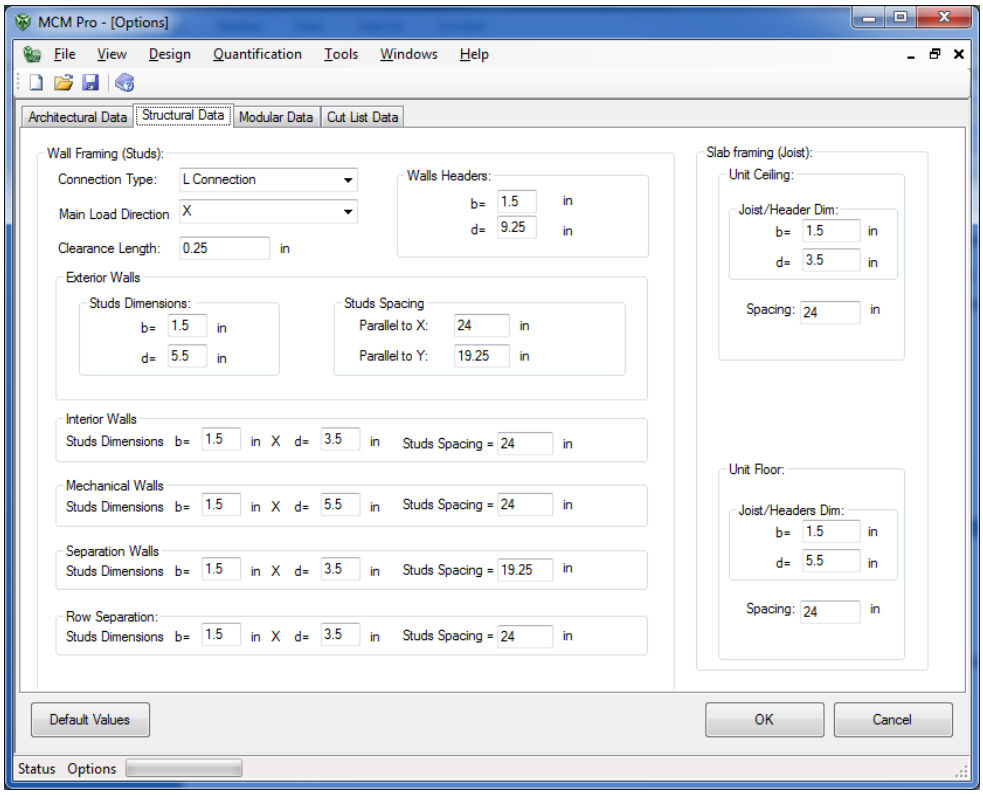


Figure 4-40: A view of the structural input parameters default values of MCMPro

A wall section thickness (W_t) is composed of different thicknesses corresponding to the composition of the wall (W_{ti}).

$$Wt = \sum_{i=0}^{n} Wti \qquad [61]$$

Where n= the number of the walls' different thicknesses.

Walls' thickness and length adjustments are needed to account for the structural design requirements. Figure 4-41 shows comparison between the architectural and structural walls dimensions, which is illustrated on three walls.

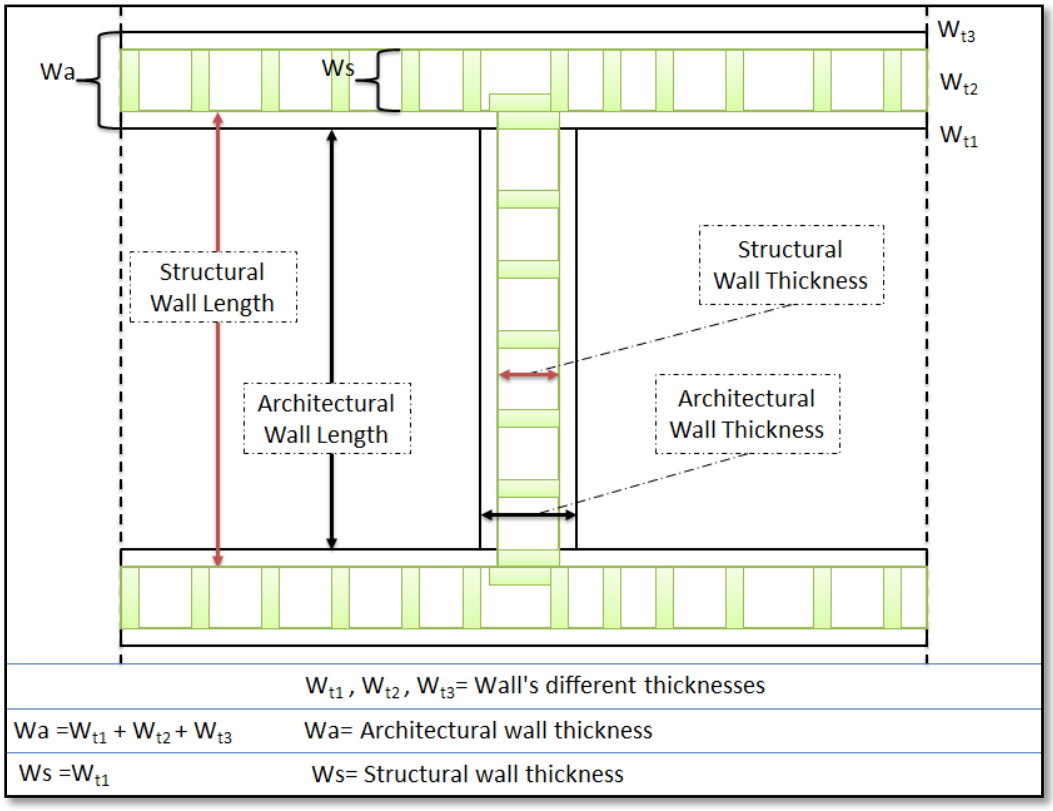


Figure 4-41: A comparison between architectural and structural wall dimensions

The structural design might entail a change in the total wall thickness (W_s) from that in the architectural design (W_a). For instance, if an exterior wall thickness based on the architectural design is 127 mm = 5", according to the structural design (0.5" dry-wall + 3.5" wooden studs + 0.5" sheathing) it can be 4.5". The wall thickness difference entails a shift in the wall location; this shift must comply with the structural design in term of wall thickness and to the architectural design in terms of final layout boundaries. To comply with the layout boundaries, the exterior edges of the surrounding walls are kept aligned to

the original walls locations. The module's surrounding walls are exterior walls' E_w, separation walls S_w, and row separation walls RS_w, and the central line of the interior walls I_w are also kept aligned to the original central lines. Figure 4-42 shows the adjustments in walls' locations, lengths, and thicknesses based on the structural design.

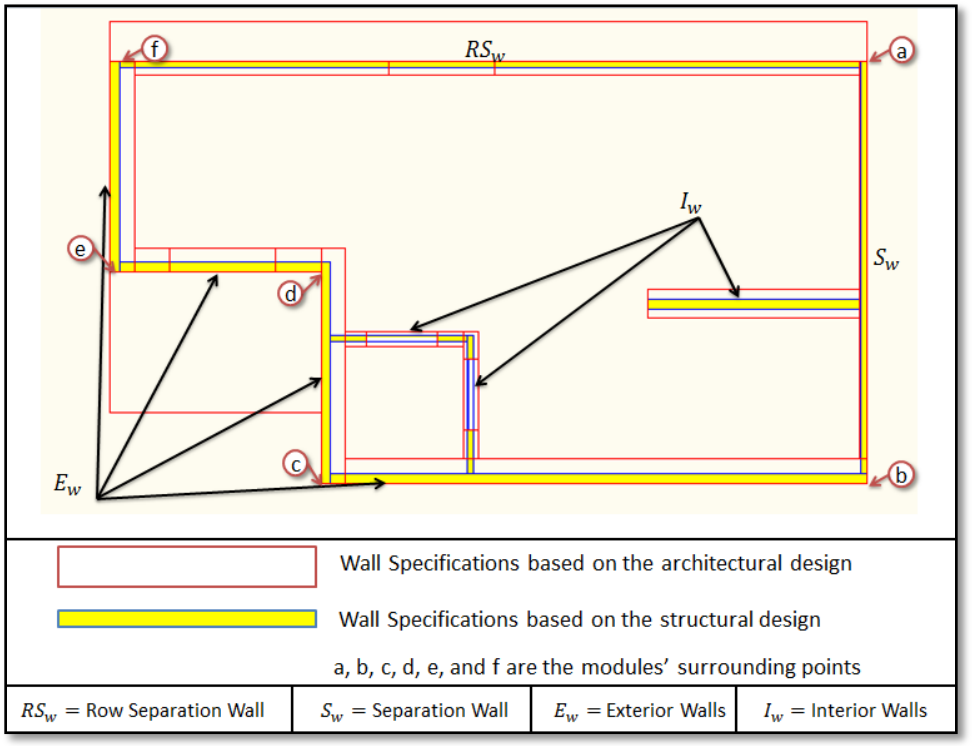


Figure 4-42: Architectural and structural wall specifications

MCMPro recognizes the exterior edges of the modules' surrounding wall's that are defined by points (a, b, c, d, e, and f) (See Figure 4-42) using a base-point concept in conjunction with the wall's four corners points. A wall has two main edges, edge 1-2 and 3-4. Base-point (point "a" in Figure 4-42) takes a value of 1, 2, 3, or 4, which represents one of the wall four corners. If the walls' base-point is 1 or 2, then edge 1-2 is exterior and vice versa. The assignment of wall's base-point follows the same progressive search used to form the module's slab element. Having assigned walls' base-points (points a, b, c, d, e, and f), wall lengths (L) and thicknesses (Th) adjustment are preformed, and the X and Y coordinates of the walls' corner points are modified. To store the framing data, additional data tables are added to the database. Table 4-8 shows the data tables

added to the database to account for the framing properties, and Figure 43 shows the relationship among the framing data tables.

Table 4-8: Framing data tables

Data Table Name	Data Table Description
tbl_Framing	This table stores the modules walls' properties, such as X and Y coordinates values of walls' corner points, wall length, thickness, layer, type, and base-point.
tbl_Fra_Slabs	It stores the modules slabs' X and Y coordinates values of walls' corner points.
tbl_Fra_Balconies	It stores the modules balconies' X and Y coordinates' values.
tbl_Fra_Connections	It stores the modules walls' connections properties, such as X and Y coordinate values, connection orientation, type, and the wall IDs of the two intersecting walls.
tbl_Fra_Openings	This table stores the modules openings' properties, such as X and Y coordinate values and opening type.

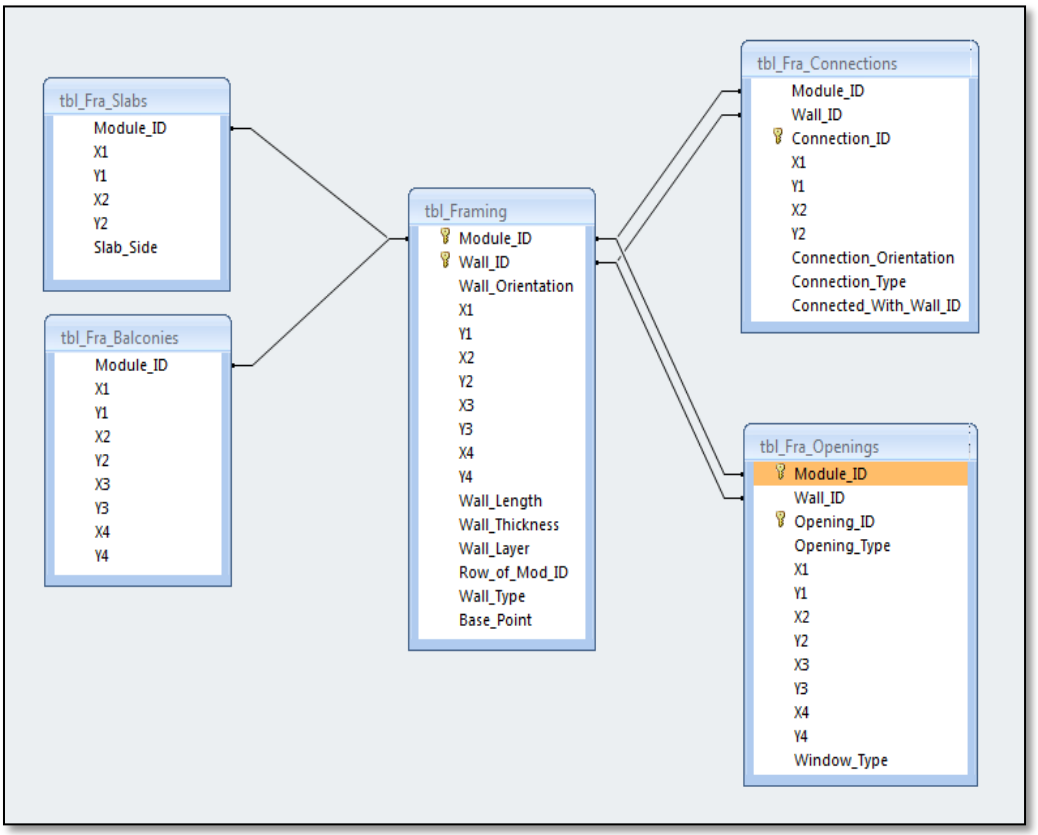


Figure 4-43: The relationship amongst the framing Data Tables

Wood-framing method implies five different types of wall connections: start extend (Se), end extend (Ee), start cut (Sc), middle (M), and end cut (Ec) as shown in Figure 4-44 a, b, c, d, and e. Each connection type has a special design configuration that enables the two intersected walls to be installed properly. Cut and extend connection types are assigned alternatively when two walls intersect. When $wall_i$ intersects with $wall_j$, the wall with higher priority has a cut connection type, start cut or end cut (See Figure 4-44 a and b, respectively), and the wall with lower priority has an extend connection type, start extend or cut extend (See Figure 4-44, c and e, respectively). If $wall_i$ has a cut start or cut end, the cap plate (See Figure 4-51, B1, B2) is cut so that $wall_j$ cap plate (See Figure, 3-44, B) extends to fill that gap, and a special studs configuration, L-Connection or U-Connection, is applied. When $wall_i$ rests on $wall_j$, $wall_j$ has a middle (See Figure 4-51, d) connection type and has an extend connection type. Figure 4-44 shows a profile and a section of the different types of connection using L-Connection configuration.

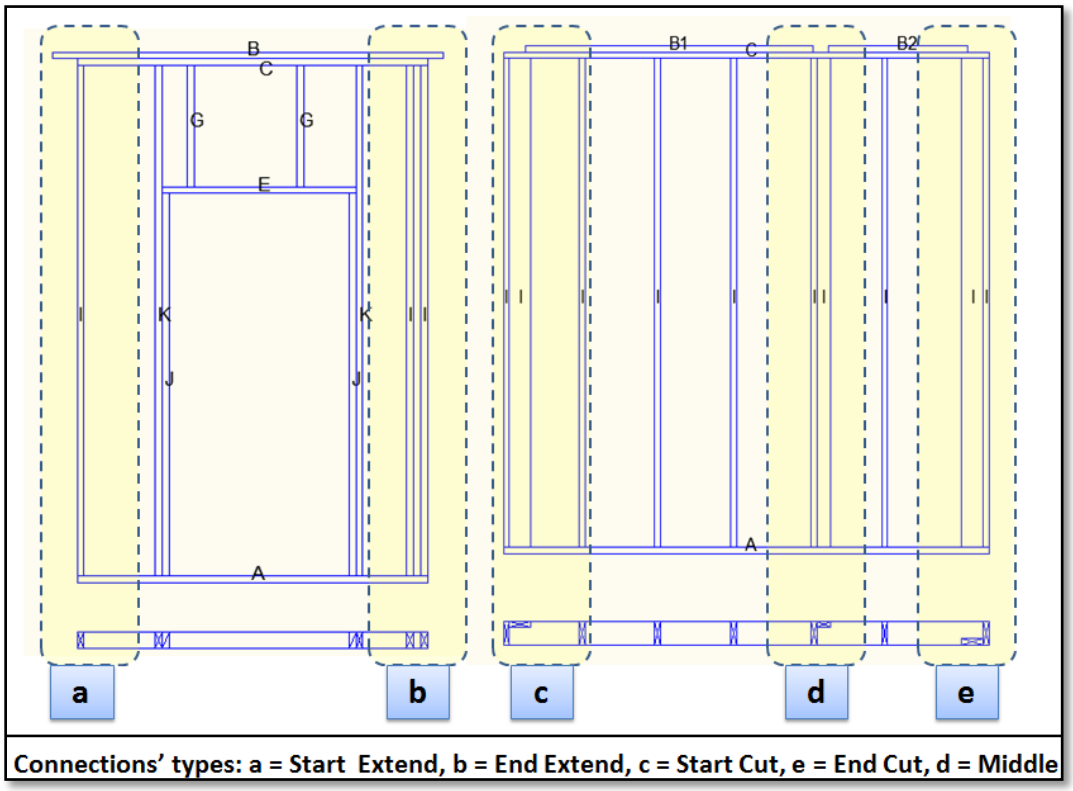


Figure 4-44: Walls connection types

After adjusting the walls' dimensions and locations according to the structural design, a load-bearing or non-load-bearing classification is performed based on load direction. For instance, if the load direction is Y, then the surrounding walls parallel to X are load-bearing and vice versa. Based on the wood-framing method, interior walls in a specific module are considered non-load-bearing as the load is transferred from the ceiling to the floor through the surrounding walls. This classification indicates the wood-framing components used to frame an opening in a wall.

The wood-framing process starts by utilizing walls, openings, and connections X and Y coordinates' values in conjunction with studs dimensions and spacing to specify the different components properties used to frame a wall. These components' are bottom plate, top plate, cap plate, header, header sill, cripple, header cripple, sill, stud, jack, and king (See Figure 4-45, A, C, Bi, D, E, F, G, H, I, J, and K respectively).

Timber	Label	Qtn	Width	Height	Length
Bot. Plate	A	1	1" 1/2	5" 1/2	26' - 6" 1/2
Cap Plate	B1	1	1" 1/2	5" 1/2	9' - 10" 4/7
Cap Plate	B2	1	1" 1/2	5" 1/2	15' - 7" 1/8
Top Plate	C	1	1" 1/2	5" 1/2	26' - 6" 1/2
Header	D	2	1" 1/2	9" 1/4	4' - 10" 1/8
Hdr Cripple	G	3	1" 1/2	5" 1/2	1' - 11" 1/6
Sill	H	1	1" 1/2	5" 1/2	4' - 7" 1/8
Cripple	F	5	1" 1/2	5" 1/2	3' - 0" 3/8
Stud	I	19	1" 1/2	5" 1/2	9' - 5" 3/5
King	K	2	1" 1/2	5" 1/2	9' - 5" 3/5
Jack	J	2	1" 1/2	5" 1/2	6' - 9" 1/6

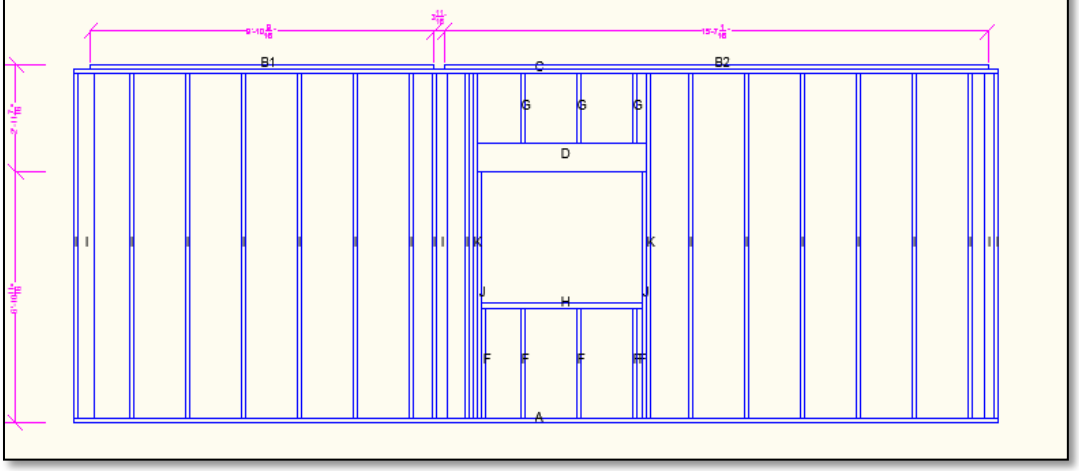


Figure 4-45: Wood-framing's different components.

After analyzing the framing data, two groups of data tables are stored. Detailed data tables contain data related to each component, its X and Z coordinates' width, height, and length. Layout data tables summarize the detailed tables and display the take-off list of materials needed for each wall panel, floor, and ceiling (See Figure 4-46). This data is used to provide the detailed shop drawing needed to frame modules' walls, floors, and ceiling. Figure 4-47 to Figure 4-52 show the generated framing data tables Figure 4-53 shows the Analysing dialog box that displays the progress status of wall panels shop drawings generation. Figure 4-54, Figure 4-55, and Figure 4-56 show the shop drawings.

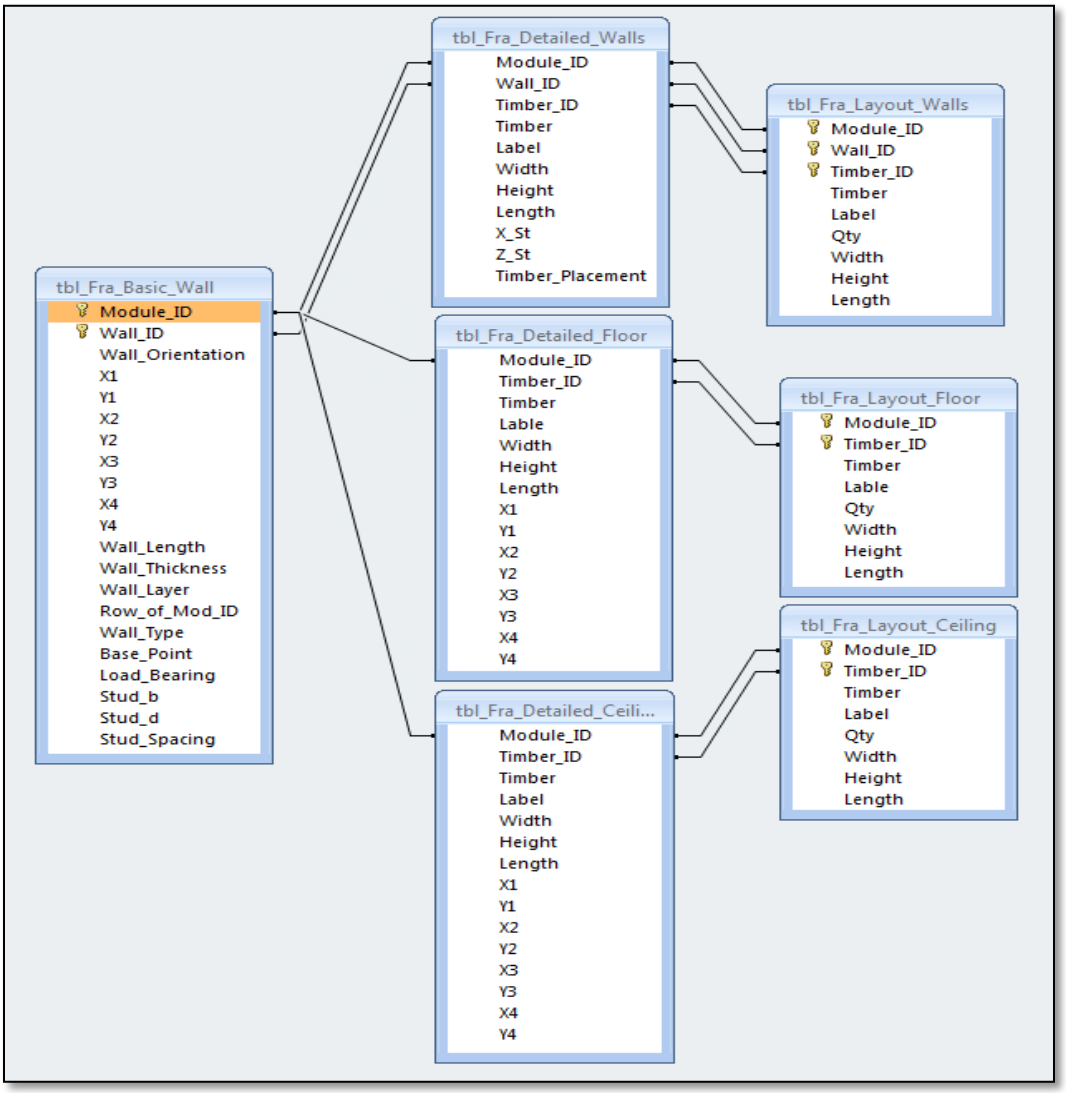


Figure 4-46: Shop drawings data tables

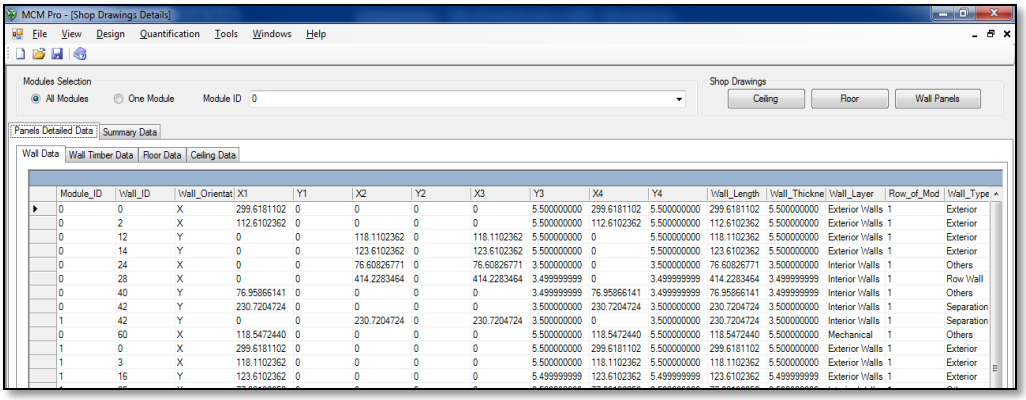
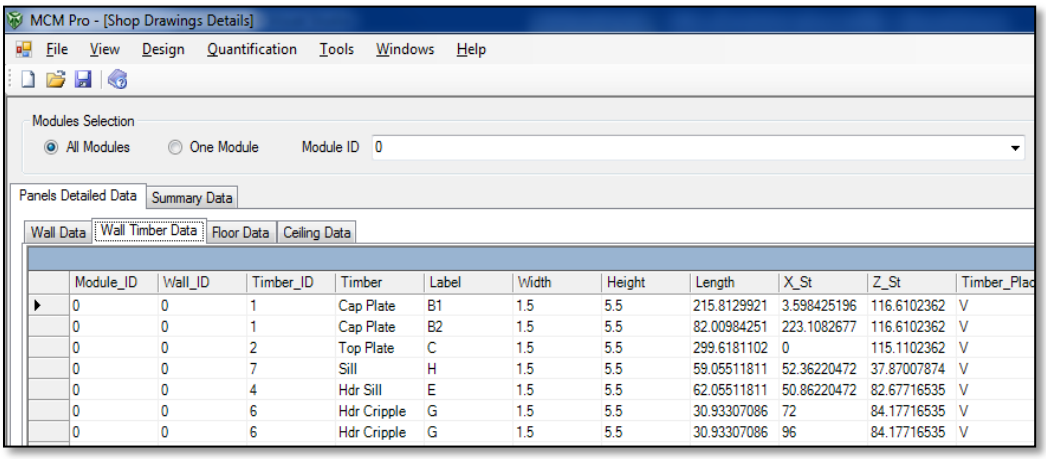


Figure 4-47: A view of walls' essential wood-framing data table



Module_ID	Wall_ID	Timber_ID	Timber	Label	Width	Height	Length	X_St	Z_St	Timber_Plac
0	0	1	Cap Plate	B1	1.5	5.5	215.8129921	3.598425196	116.6102362	V
0	0	1	Cap Plate	B2	1.5	5.5	82.00984251	223.1082677	116.6102362	V
0	0	2	Top Plate	C	1.5	5.5	299.6181102	0	115.1102362	V
0	0	7	Sill	H	1.5	5.5	59.05511811	52.36220472	37.87007874	V
0	0	4	Hdr Sill	E	1.5	5.5	62.05511811	50.86220472	82.67716535	V
0	0	6	Hdr Cripple	G	1.5	5.5	30.93307086	72	84.17716535	V
0	0	6	Hdr Cripple	G	1.5	5.5	30.93307086	96	84.17716535	V

Figure 4-48: A view of walls' timber detailed data table

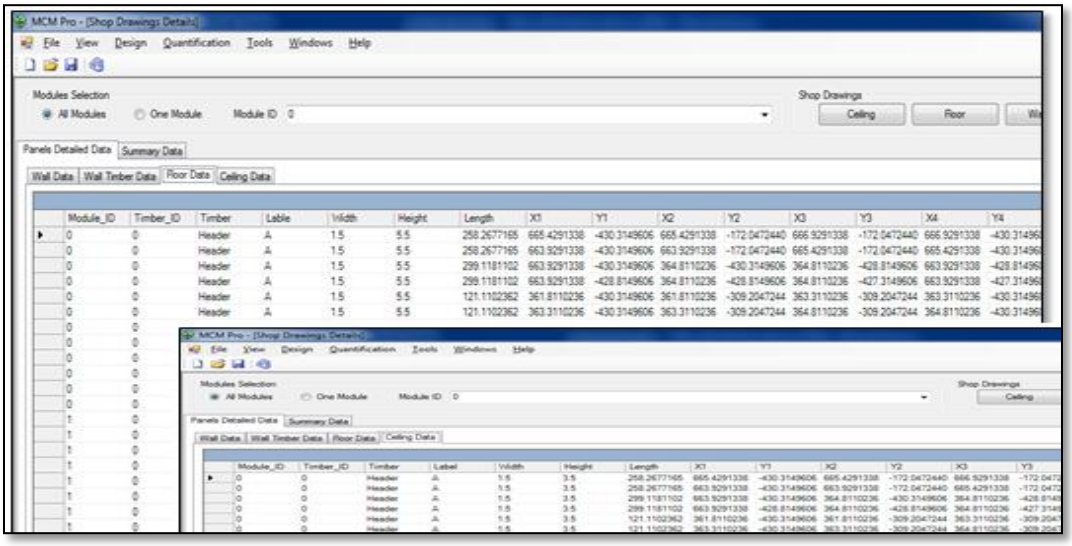
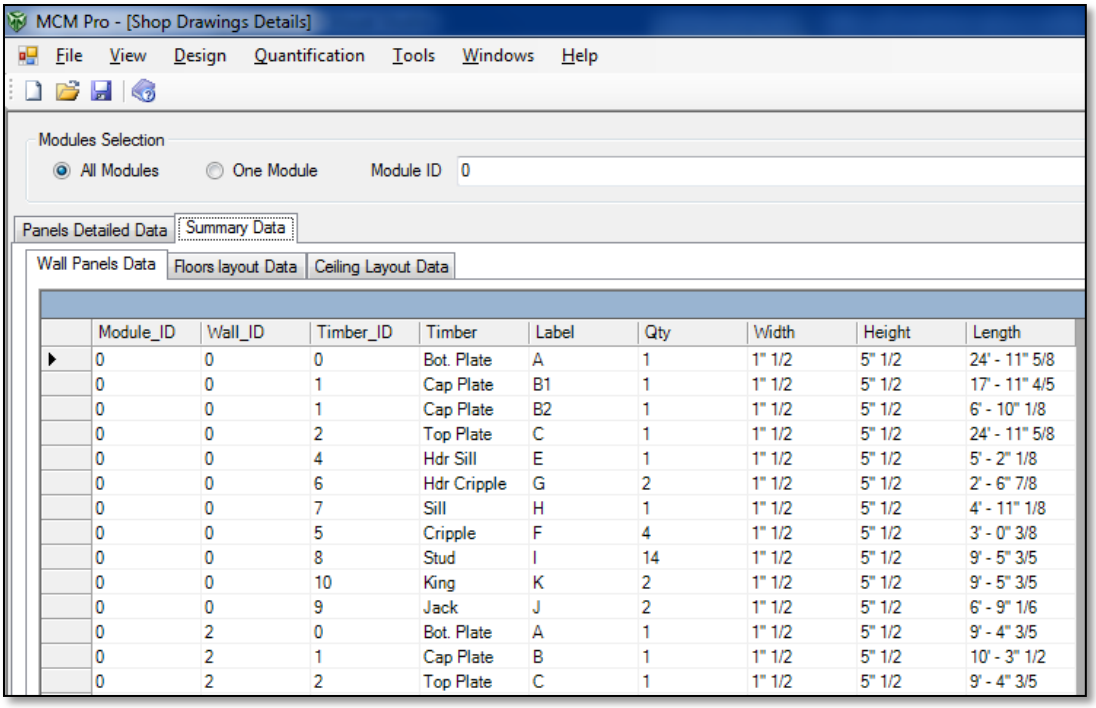
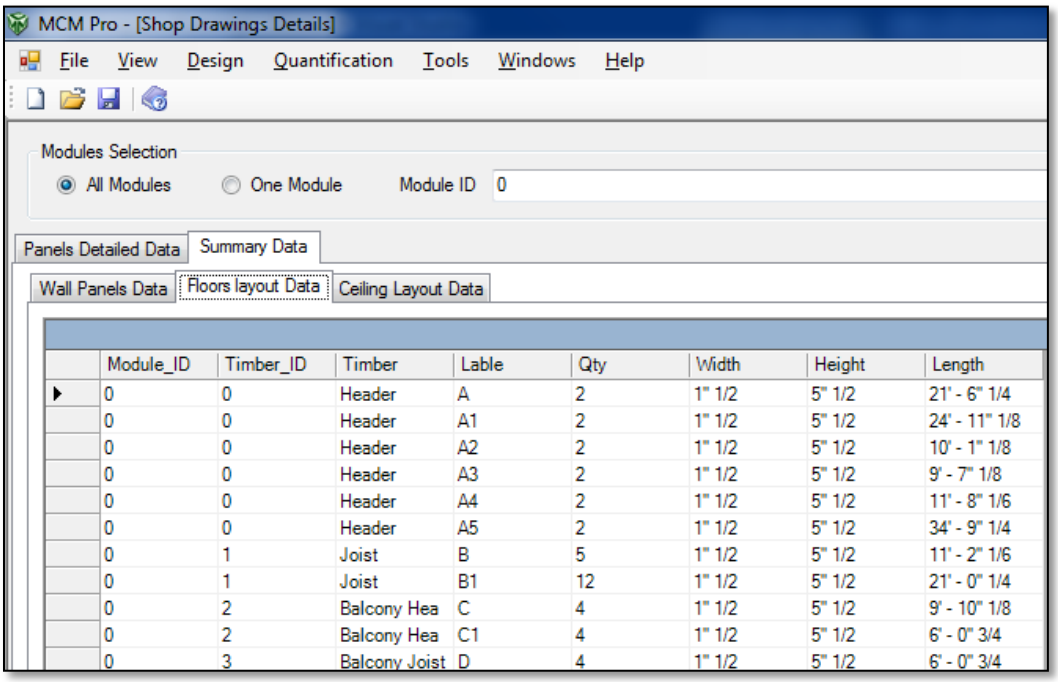


Figure 4-49: A view of floors' and ceiling timber detailed data table



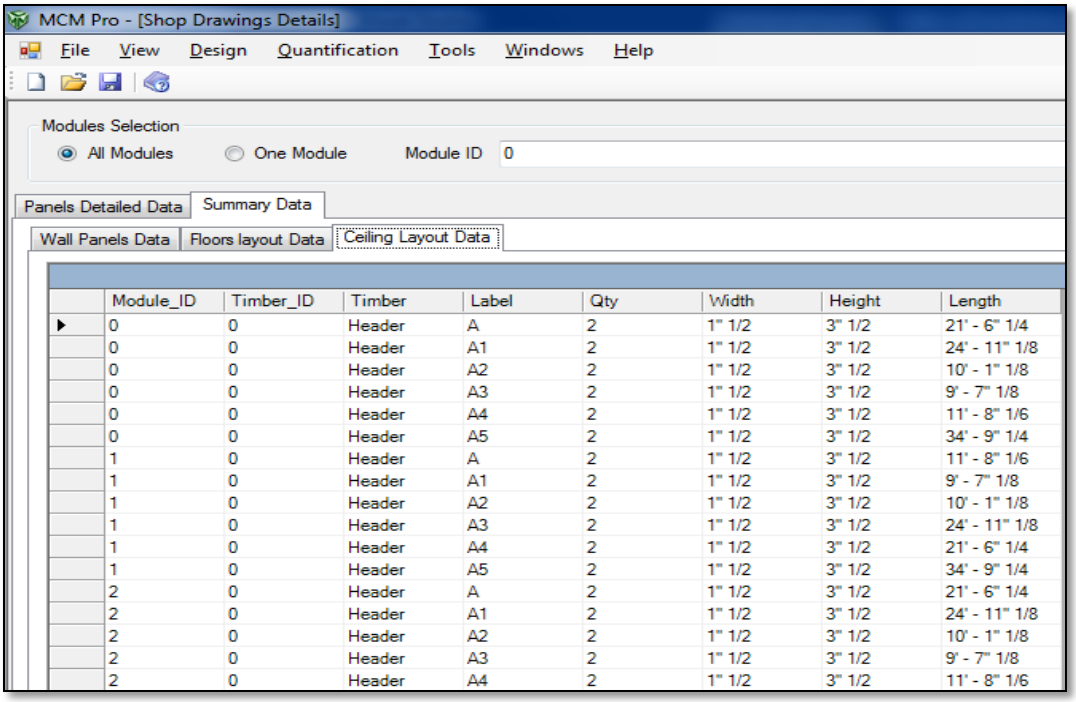
Module_ID	Wall_ID	Timber_ID	Timber	Label	Qty	Width	Height	Length
0	0	0	Bot. Plate	A	1	1" 1/2	5" 1/2	24' - 11" 5/8
0	0	1	Cap Plate	B1	1	1" 1/2	5" 1/2	17' - 11" 4/5
0	0	1	Cap Plate	B2	1	1" 1/2	5" 1/2	6' - 10" 1/8
0	0	2	Top Plate	C	1	1" 1/2	5" 1/2	24' - 11" 5/8
0	0	4	Hdr Sill	E	1	1" 1/2	5" 1/2	5' - 2" 1/8
0	0	6	Hdr Cripple	G	2	1" 1/2	5" 1/2	2' - 6" 7/8
0	0	7	Sill	H	1	1" 1/2	5" 1/2	4' - 11" 1/8
0	0	5	Cripple	F	4	1" 1/2	5" 1/2	3' - 0" 3/8
0	0	8	Stud	I	14	1" 1/2	5" 1/2	9' - 5" 3/5
0	0	10	King	K	2	1" 1/2	5" 1/2	9' - 5" 3/5
0	0	9	Jack	J	2	1" 1/2	5" 1/2	6' - 9" 1/6
0	2	0	Bot. Plate	A	1	1" 1/2	5" 1/2	9' - 4" 3/5
0	2	1	Cap Plate	B	1	1" 1/2	5" 1/2	10' - 3" 1/2
0	2	2	Top Plate	C	1	1" 1/2	5" 1/2	9' - 4" 3/5

Figure 4-50: A view of walls' timber layout data table



Module_ID	Timber_ID	Timber	Lable	Qty	Width	Height	Length
0	0	Header	A	2	1" 1/2	5" 1/2	21' - 6" 1/4
0	0	Header	A1	2	1" 1/2	5" 1/2	24' - 11" 1/8
0	0	Header	A2	2	1" 1/2	5" 1/2	10' - 1" 1/8
0	0	Header	A3	2	1" 1/2	5" 1/2	9' - 7" 1/8
0	0	Header	A4	2	1" 1/2	5" 1/2	11' - 8" 1/6
0	0	Header	A5	2	1" 1/2	5" 1/2	34' - 9" 1/4
0	1	Joist	B	5	1" 1/2	5" 1/2	11' - 2" 1/6
0	1	Joist	B1	12	1" 1/2	5" 1/2	21' - 0" 1/4
0	2	Balcony Hea	C	4	1" 1/2	5" 1/2	9' - 10" 1/8
0	2	Balcony Hea	C1	4	1" 1/2	5" 1/2	6' - 0" 3/4
0	3	Balcony Joist	D	4	1" 1/2	5" 1/2	6' - 0" 3/4

Figure 4-51: A view of floors' timber layout data table



Module_ID	Timber_ID	Timber	Label	Qty	Width	Height	Length
0	0	Header	A	2	1" 1/2	3" 1/2	21' - 6" 1/4
0	0	Header	A1	2	1" 1/2	3" 1/2	24' - 11" 1/8
0	0	Header	A2	2	1" 1/2	3" 1/2	10' - 1" 1/8
0	0	Header	A3	2	1" 1/2	3" 1/2	9' - 7" 1/8
0	0	Header	A4	2	1" 1/2	3" 1/2	11' - 8" 1/6
0	0	Header	A5	2	1" 1/2	3" 1/2	34' - 9" 1/4
1	0	Header	A	2	1" 1/2	3" 1/2	11' - 8" 1/6
1	0	Header	A1	2	1" 1/2	3" 1/2	9' - 7" 1/8
1	0	Header	A2	2	1" 1/2	3" 1/2	10' - 1" 1/8
1	0	Header	A3	2	1" 1/2	3" 1/2	24' - 11" 1/8
1	0	Header	A4	2	1" 1/2	3" 1/2	21' - 6" 1/4
1	0	Header	A5	2	1" 1/2	3" 1/2	34' - 9" 1/4
2	0	Header	A	2	1" 1/2	3" 1/2	21' - 6" 1/4
2	0	Header	A1	2	1" 1/2	3" 1/2	24' - 11" 1/8
2	0	Header	A2	2	1" 1/2	3" 1/2	10' - 1" 1/8
2	0	Header	A3	2	1" 1/2	3" 1/2	9' - 7" 1/8
2	0	Header	A4	2	1" 1/2	3" 1/2	11' - 8" 1/6

Figure 4-52: A view of ceilings' timber layout data table

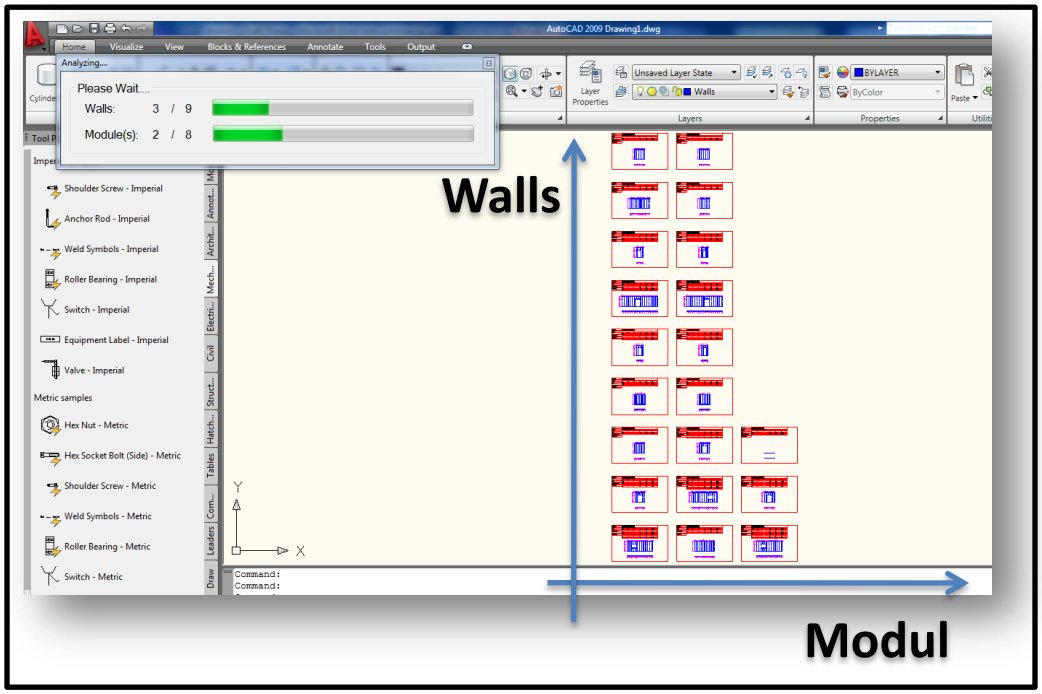


Figure 4-53: Wall panels shop drawings generation

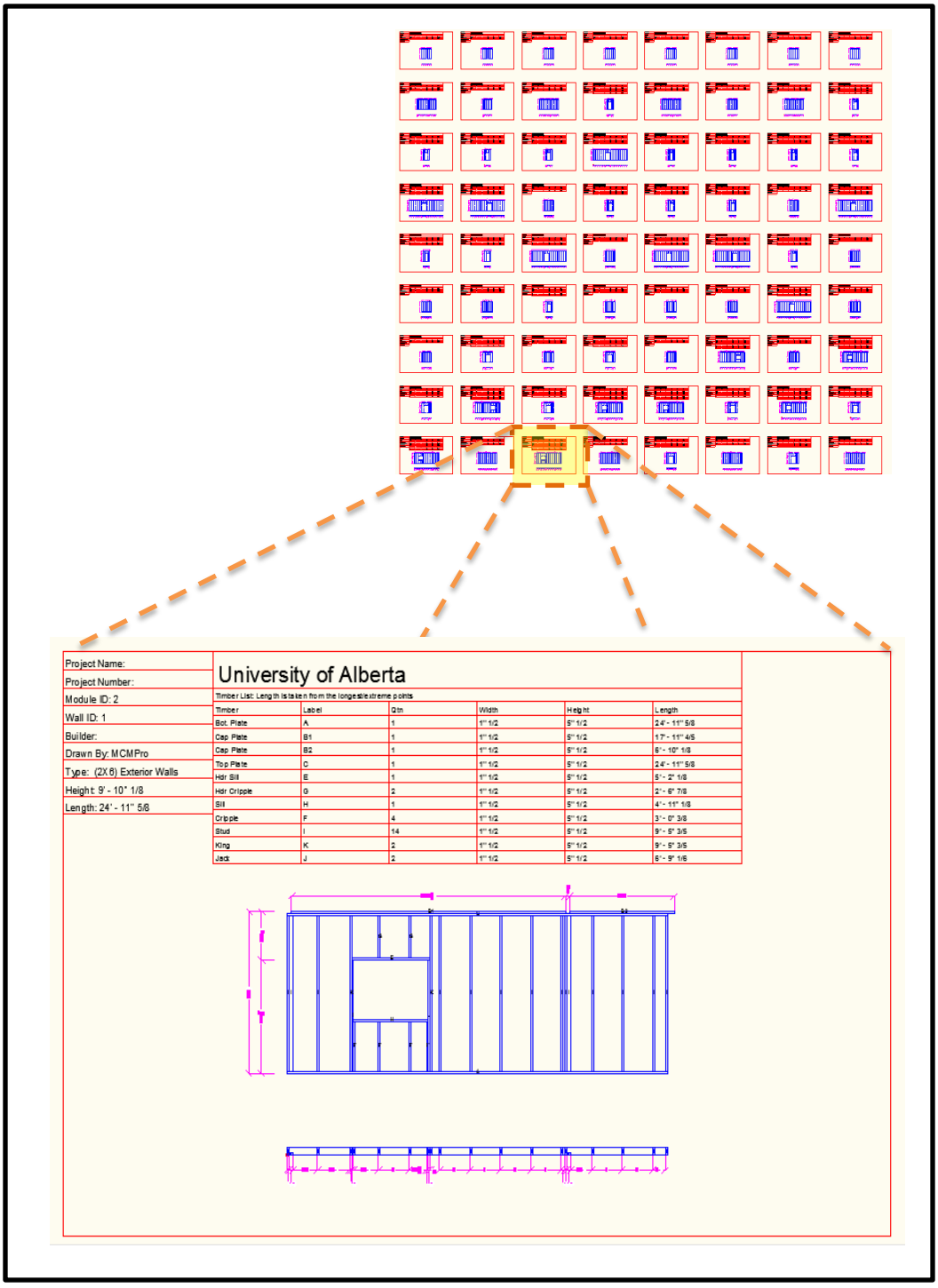


Figure 4-54: Walls' panels shop drawings

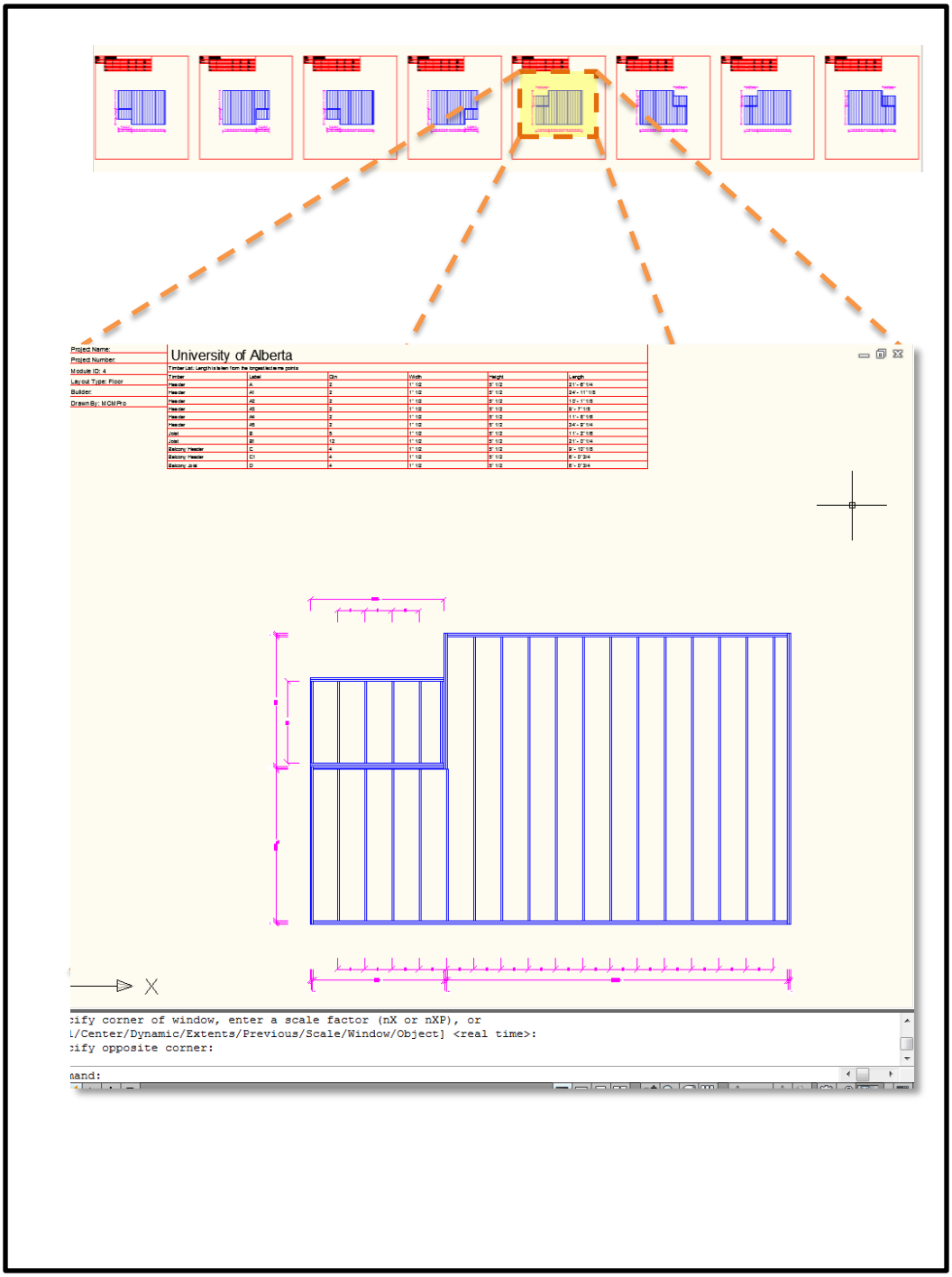


Figure 4-55: Floors' shop drawings

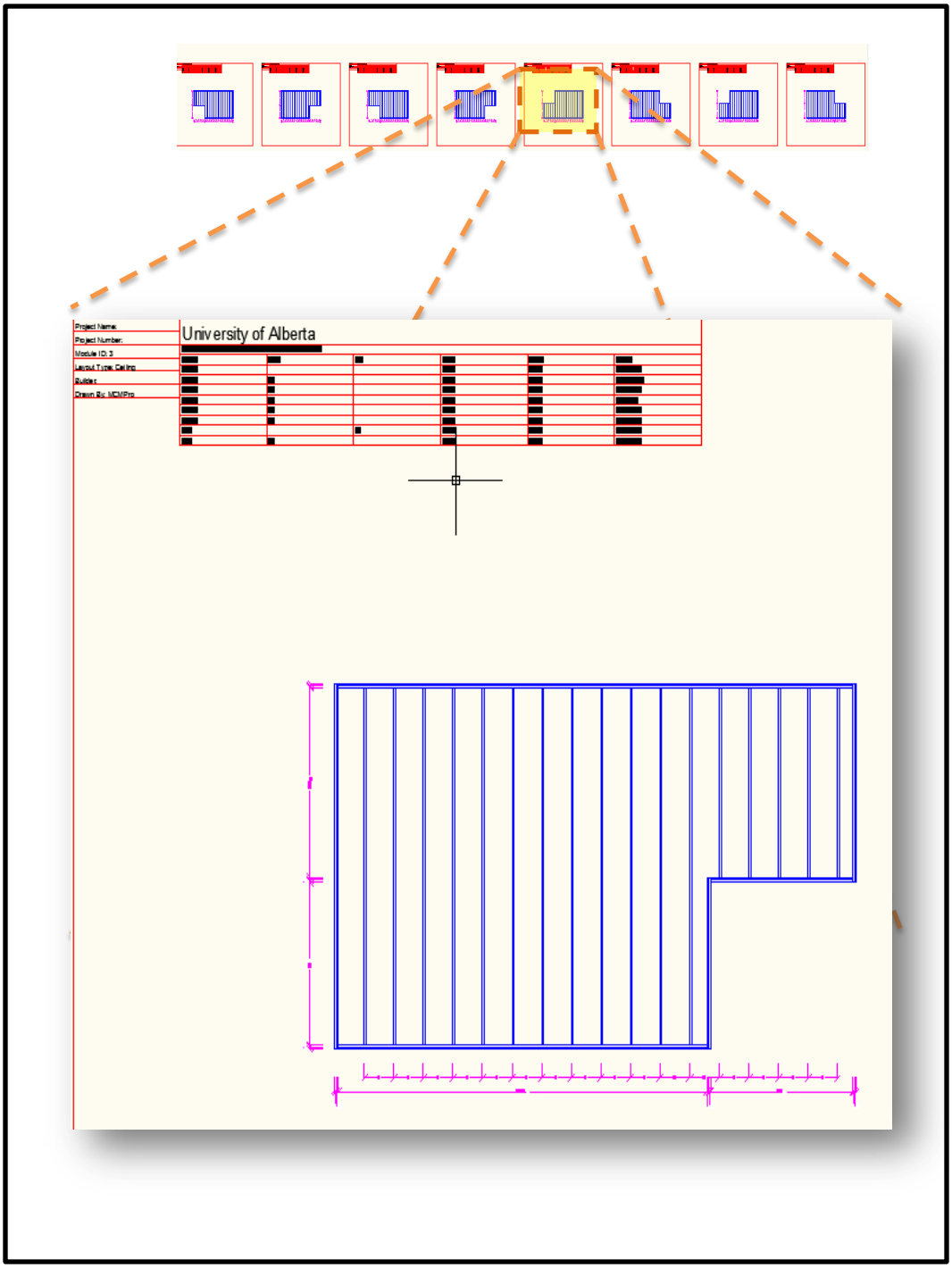


Figure 4-56: Ceilings shop drawings

This tool has been validated using Building 3 – Grade Housing – University of Alberta Campus. The architectural standard values for the case study are illustrated in Table 4-9. The structural requirements are illustrated in Figure 4-57

Table 4-9: The case study's standard values

Input Parameter	Value	Unit
Exterior wall thickness	26	cm
Interior wall thickness	12	cm
Mechanical wall thickness	12	cm
Interior door width	90	cm
Exterior wall width	100	cm
Window width	150	cm
Wall Height	300	cm
Slab thickness	30	cm
Door Height	220	cm
Window Sill	100	cm
Window Header	220	cm

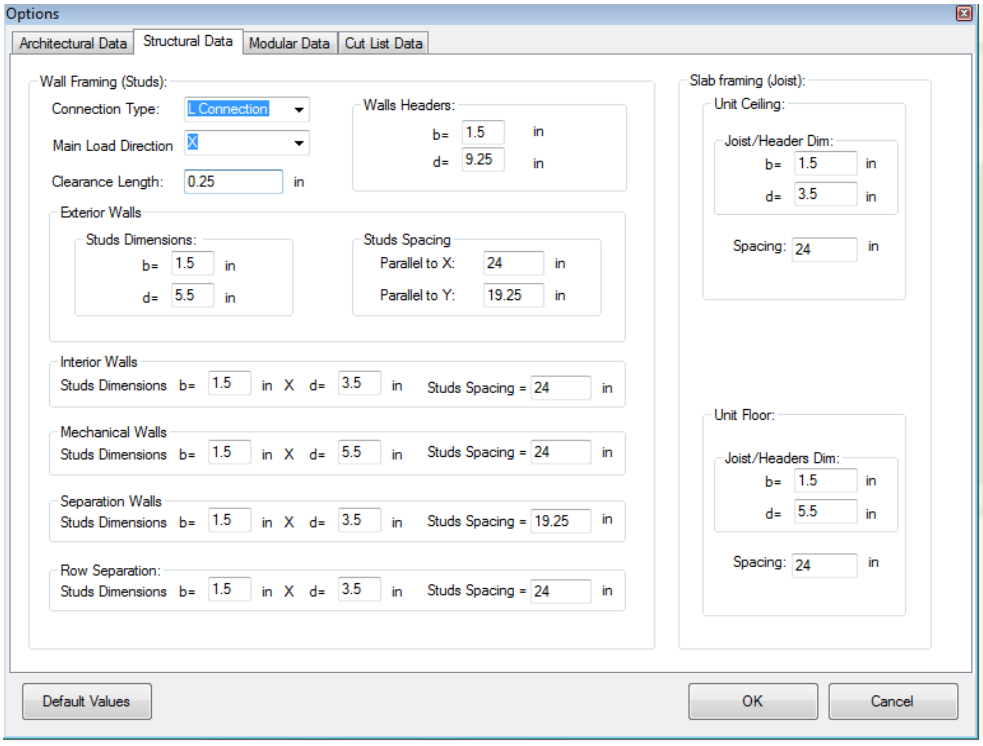


Figure 4-57: A view of the case study's structural requirements standard values

The case study 2D CAD input drawings for the lower floor, main floor, and second and third floor, a 2D and 3D BIM model, a 2D and 3D MCM BIM, and shop drawings. (See Figures 3-58 to 3-81).

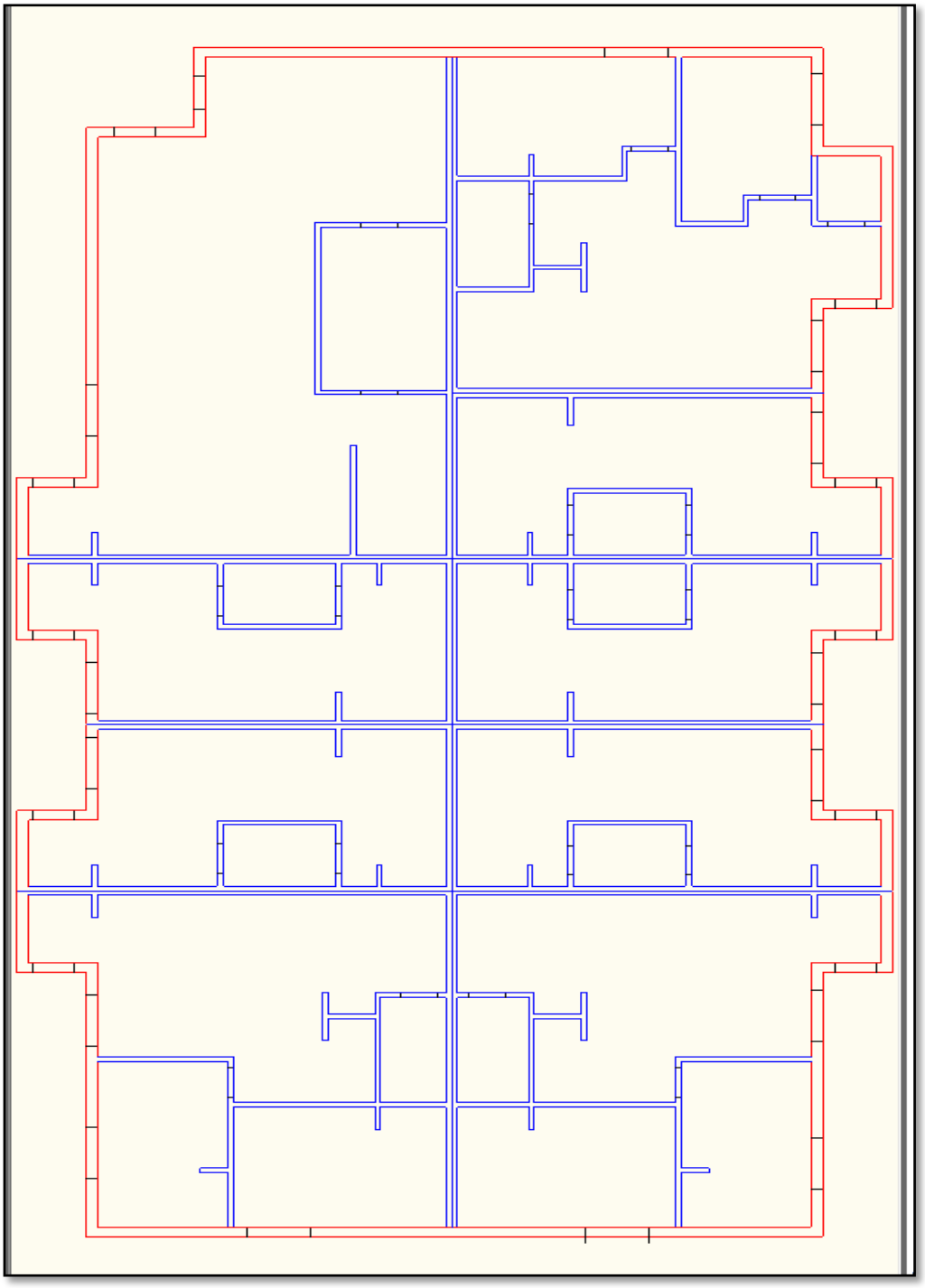


Figure 4-58: Lower floor 2D CAD (Input data)

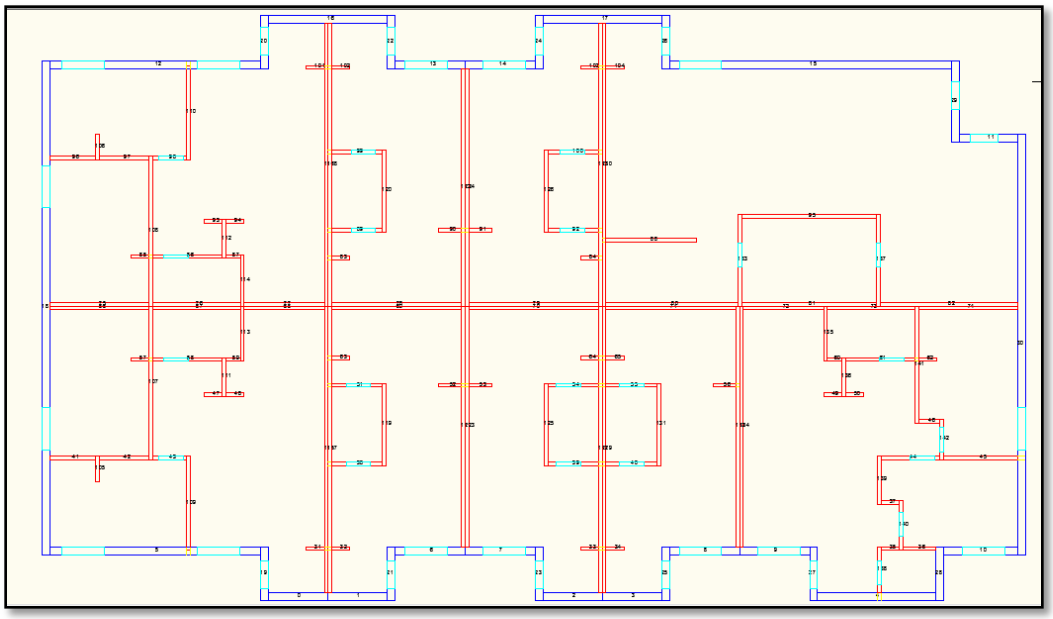


Figure 4-59: Lower floor 2D BIM layout

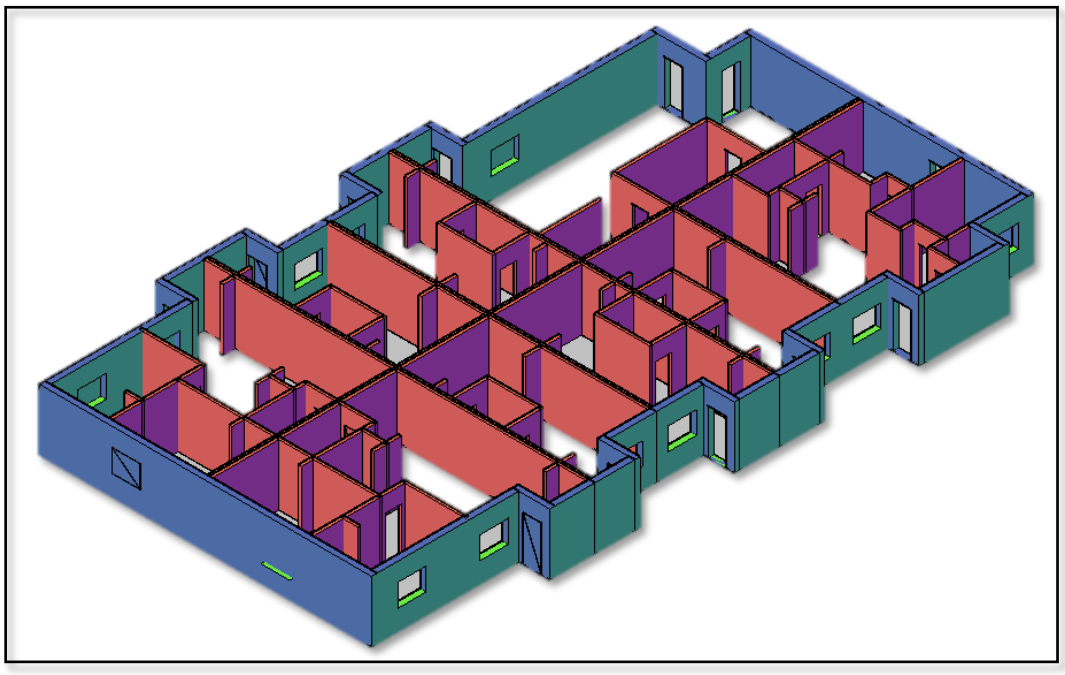


Figure 4-60: Lower floor 3D BIM visualization

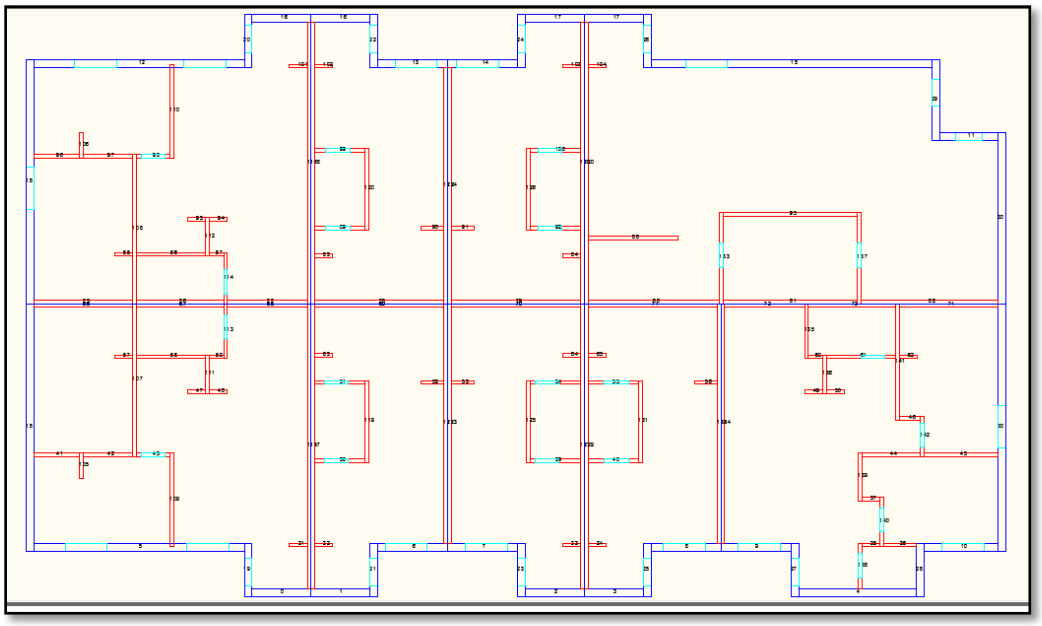


Figure 4-61: Lower floor 2D MCM BIM layout

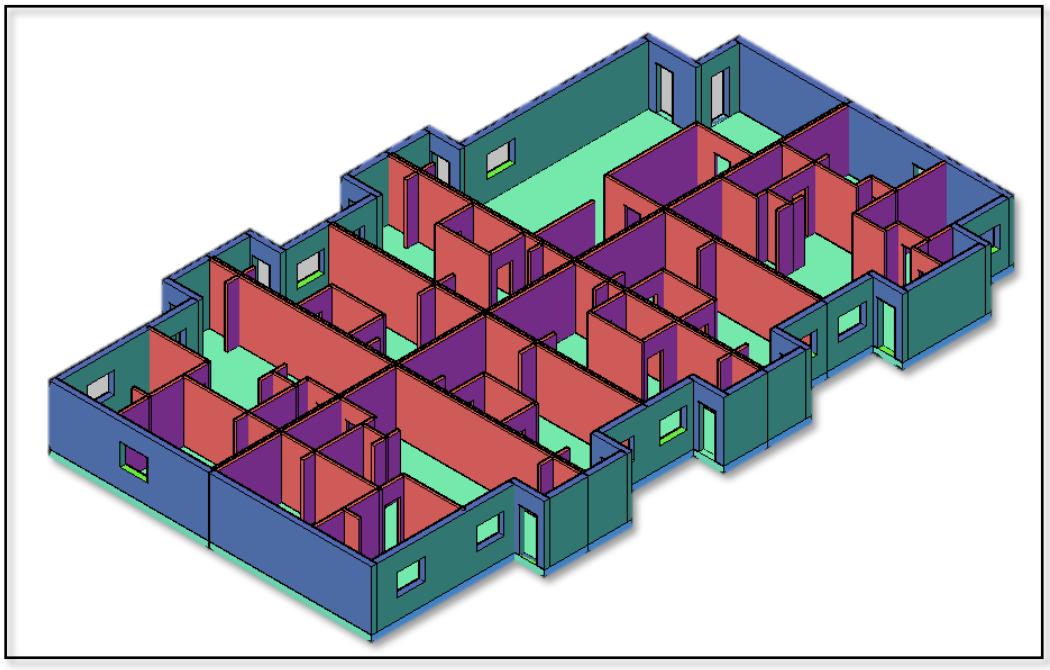


Figure 4-62: Lower floor 3D MCM BIM visualization

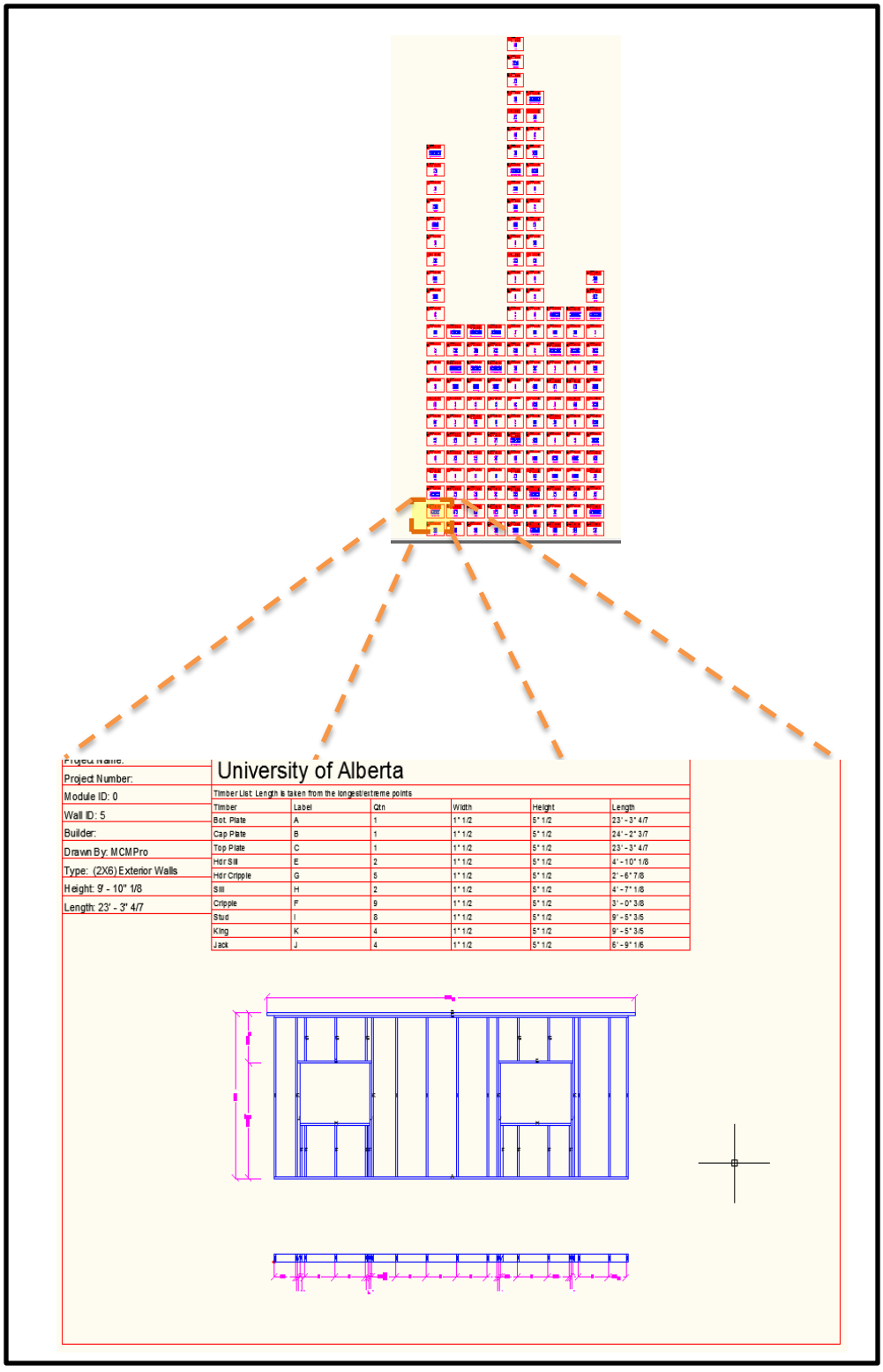


Figure 4-63: Lower floor – wall shop drawings

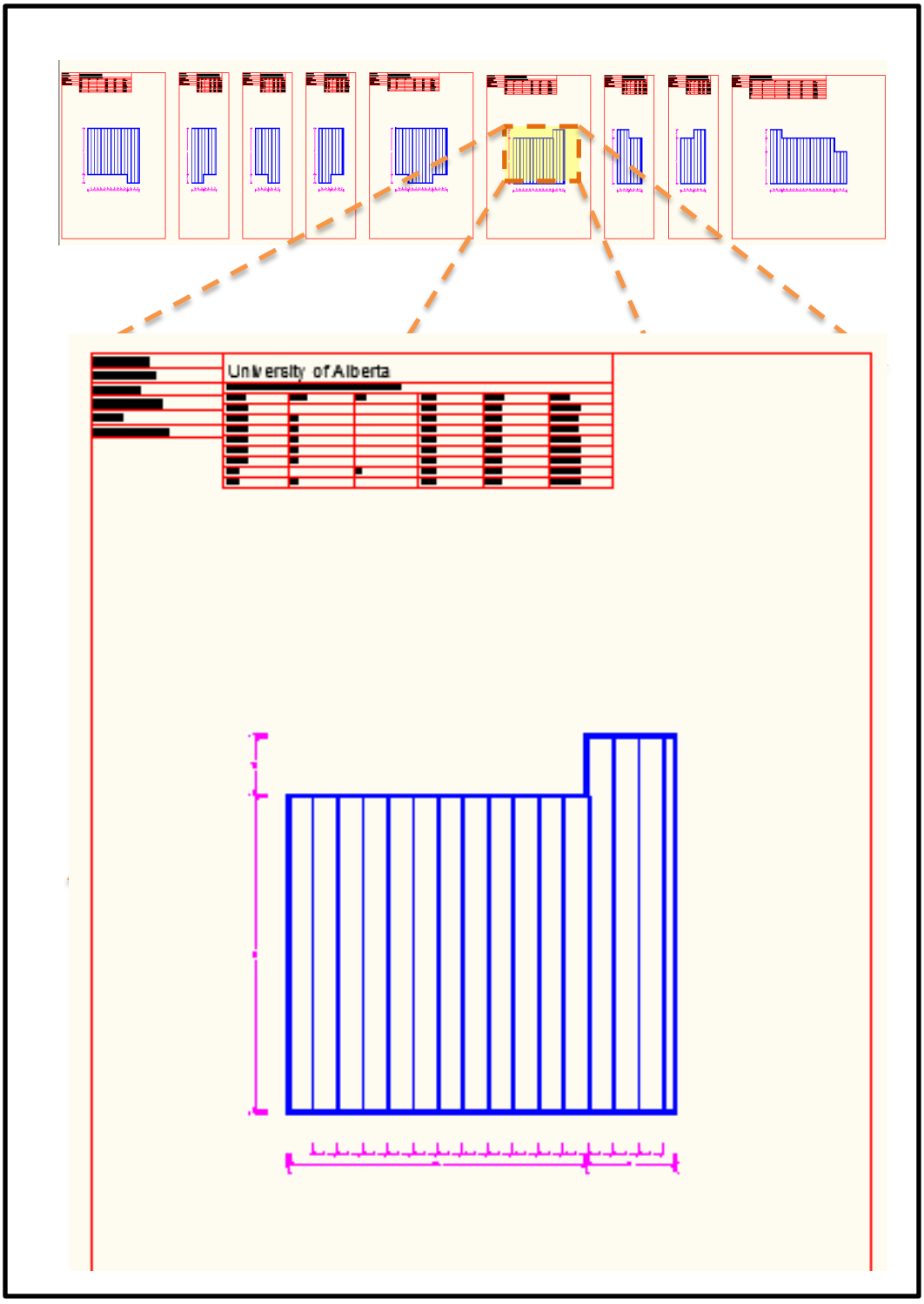


Figure 4-64: Lower floor – floors shop drawings

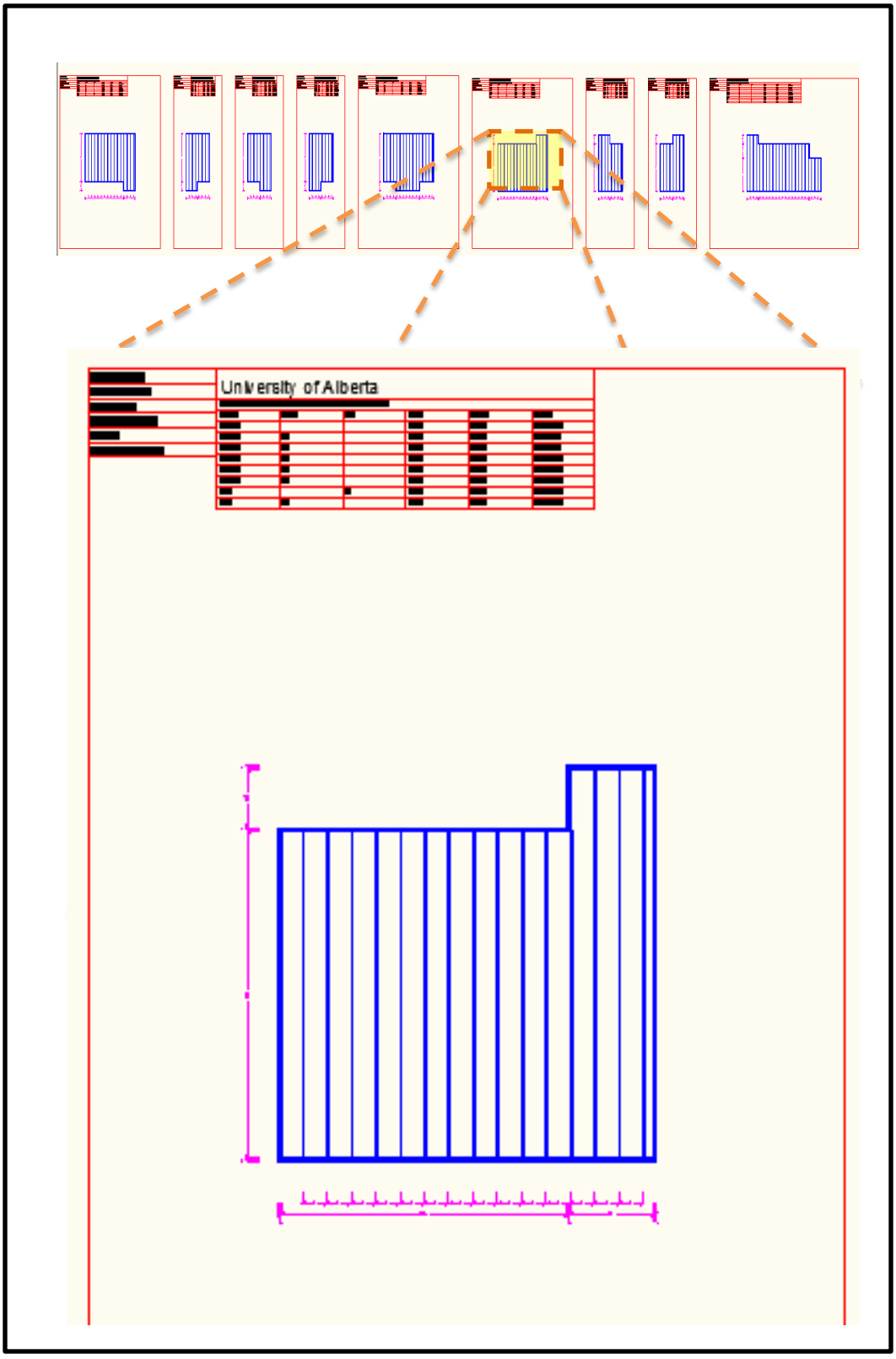


Figure 4-65: Lower floor – ceilings shop drawings

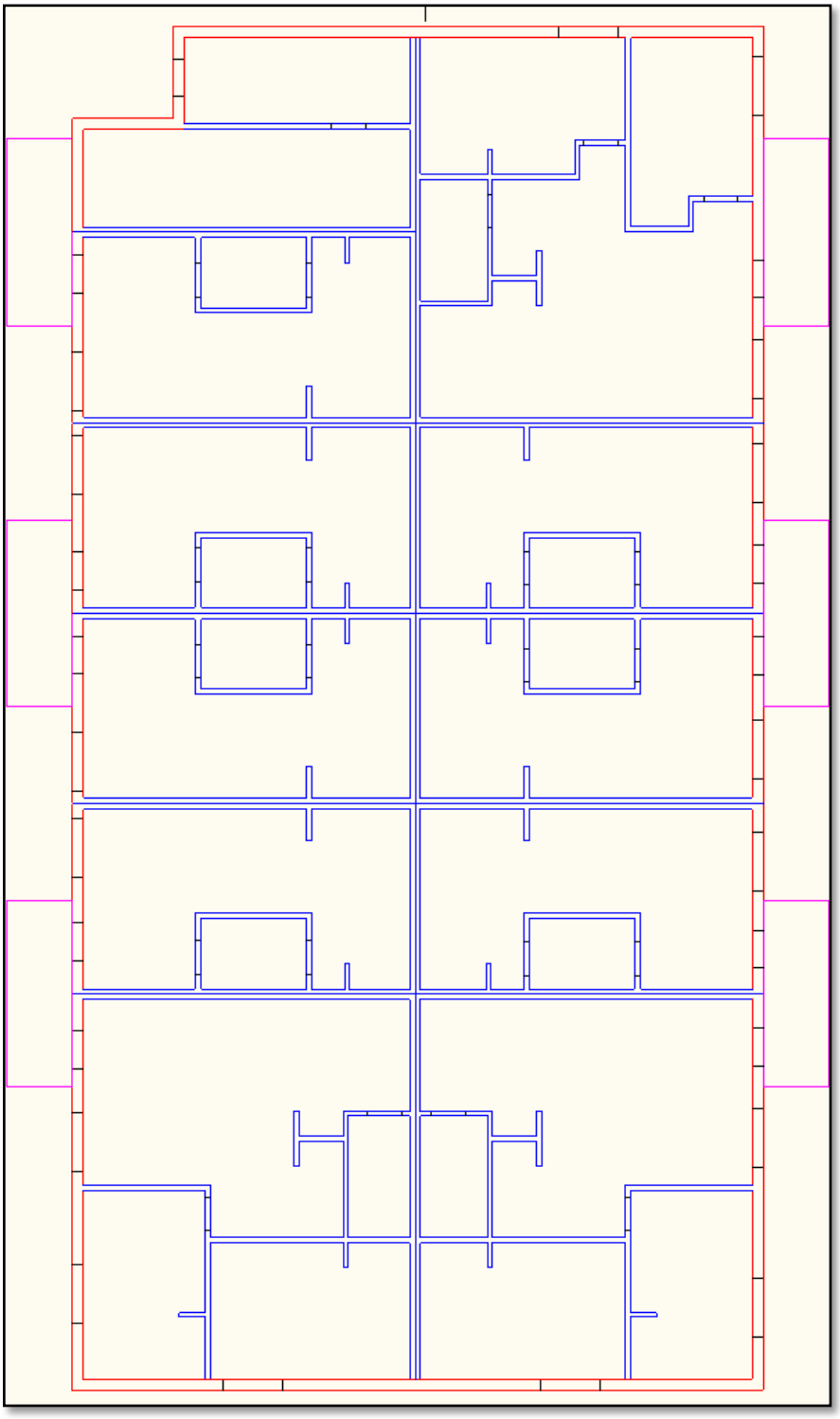


Figure 4-66: Main floor 2D CAD (Input data)

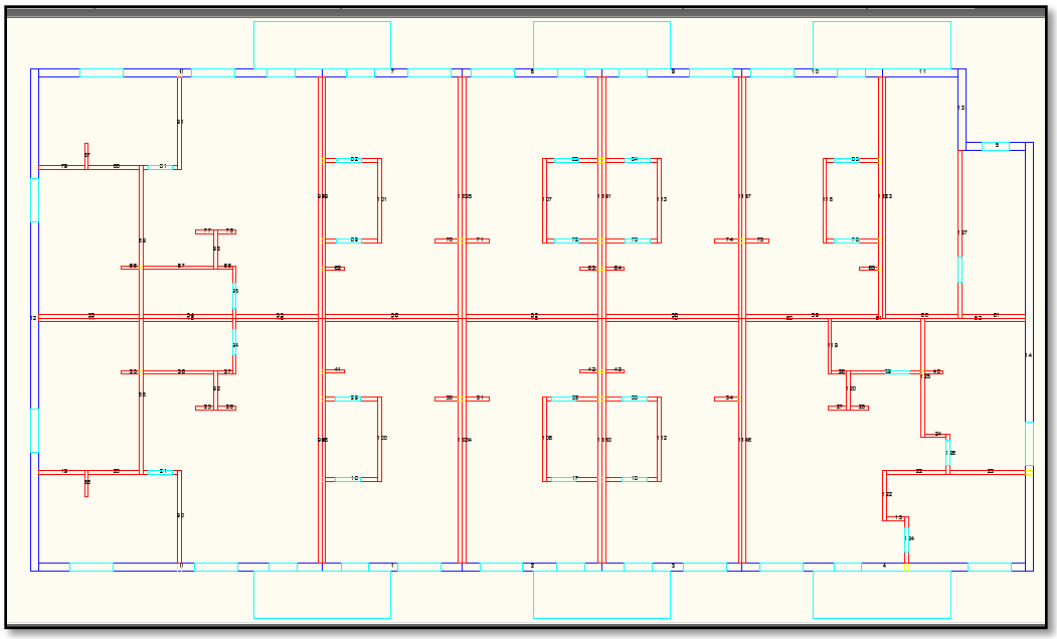


Figure 4-67: Main floor 2D BIM layout

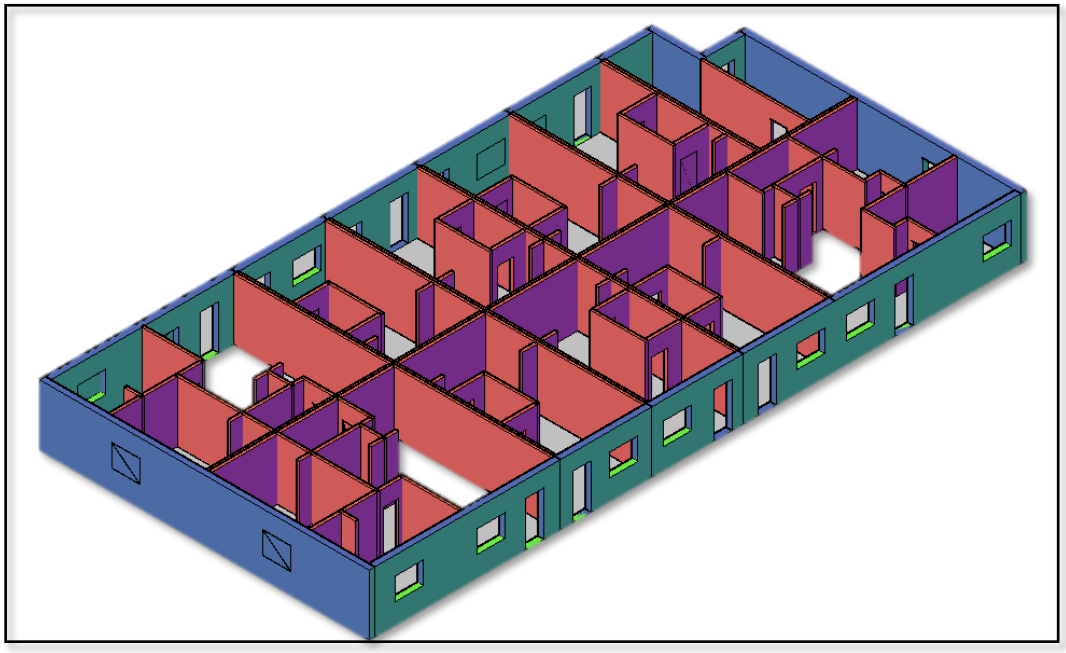


Figure 4-68: Main floor 3D BIM visualization

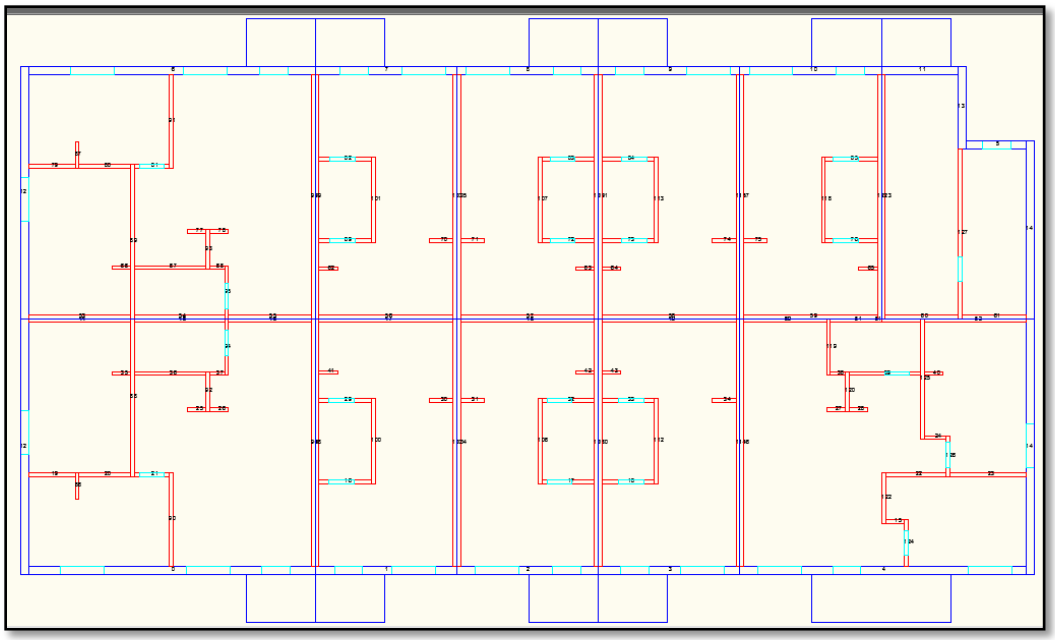


Figure 4-69: Main floor 2D MCM BIM layout

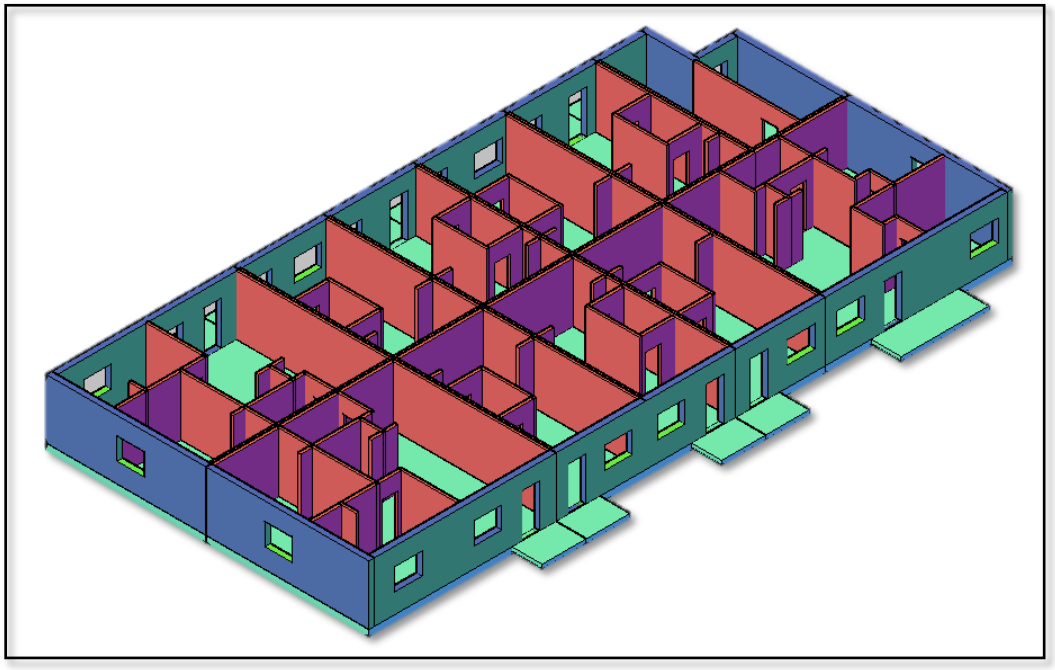


Figure 4-70: Main floor 3D MCM BIM visualization

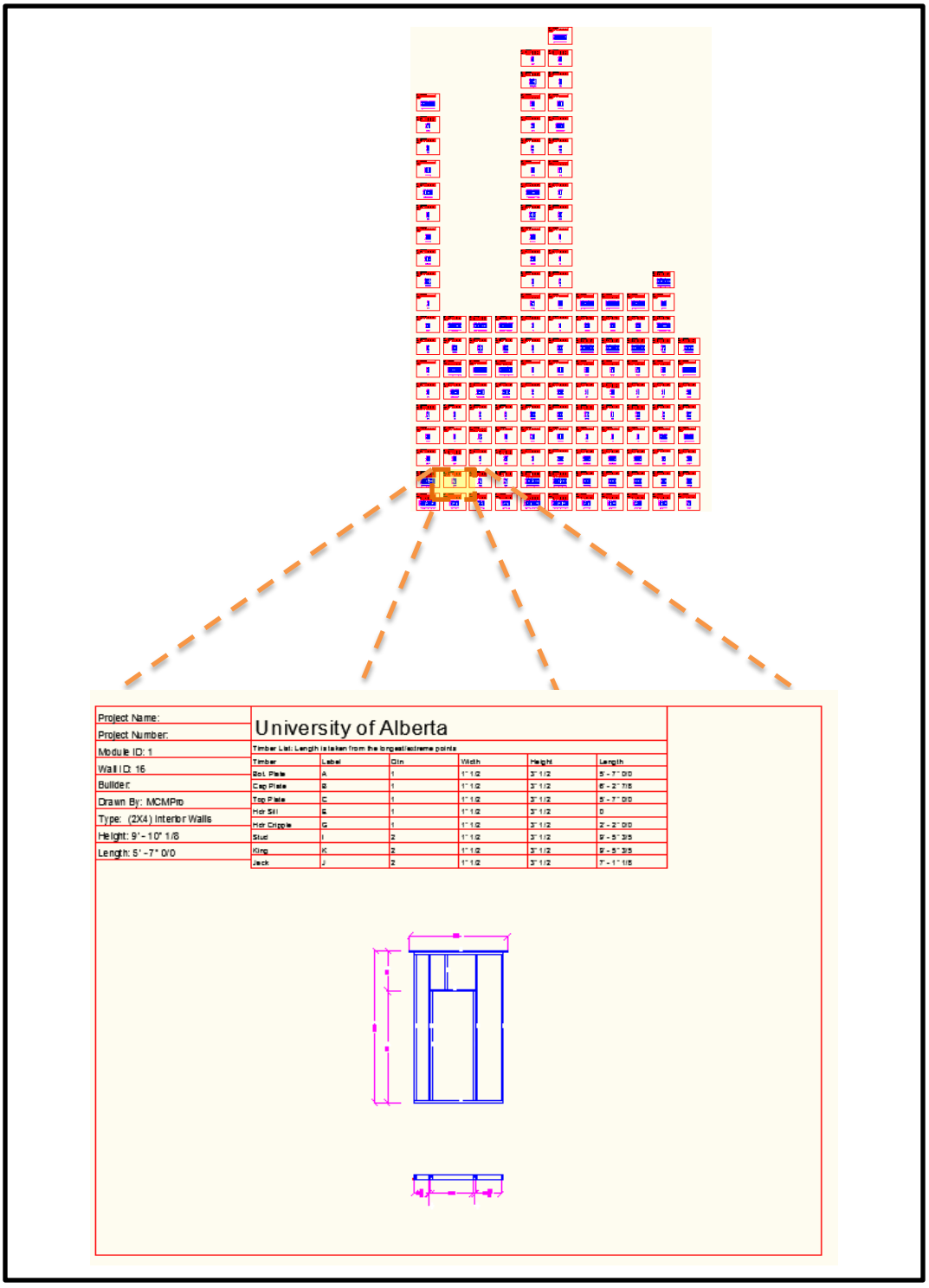


Figure 4-71: Main floor – walls shop drawings

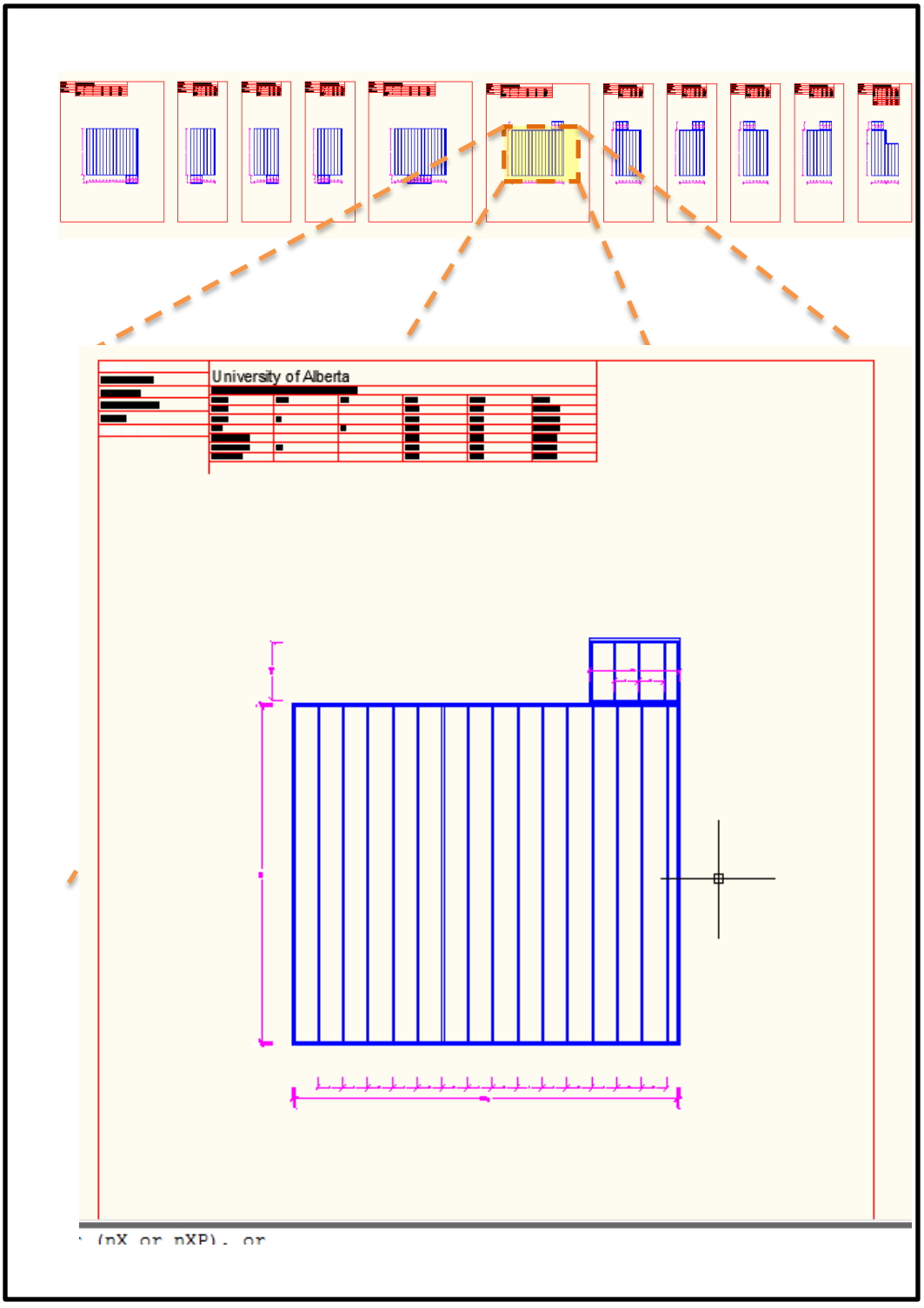


Figure 4-72: Main floor – floors' shop drawings

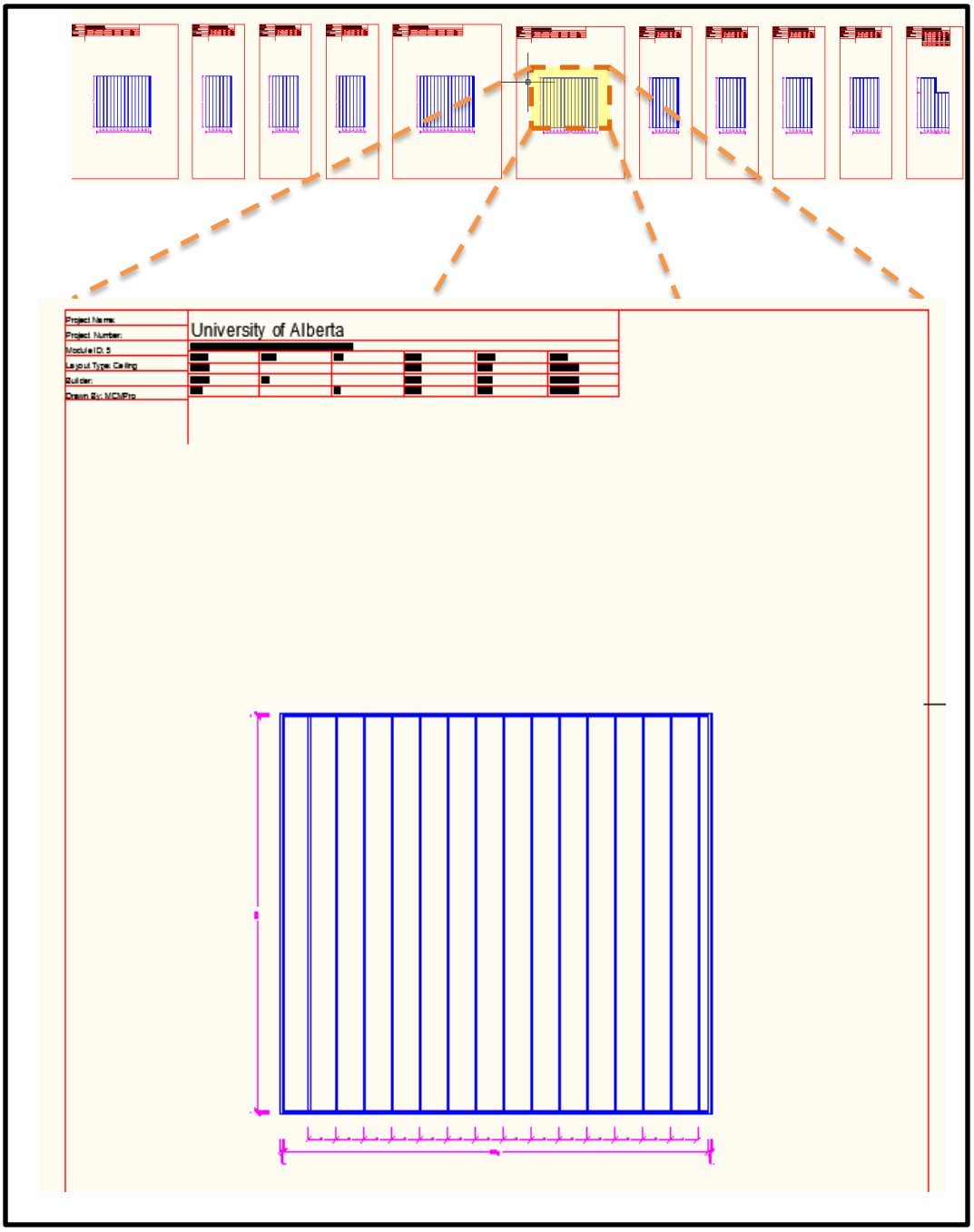


Figure 4-73: Main floor – ceilings shop drawings

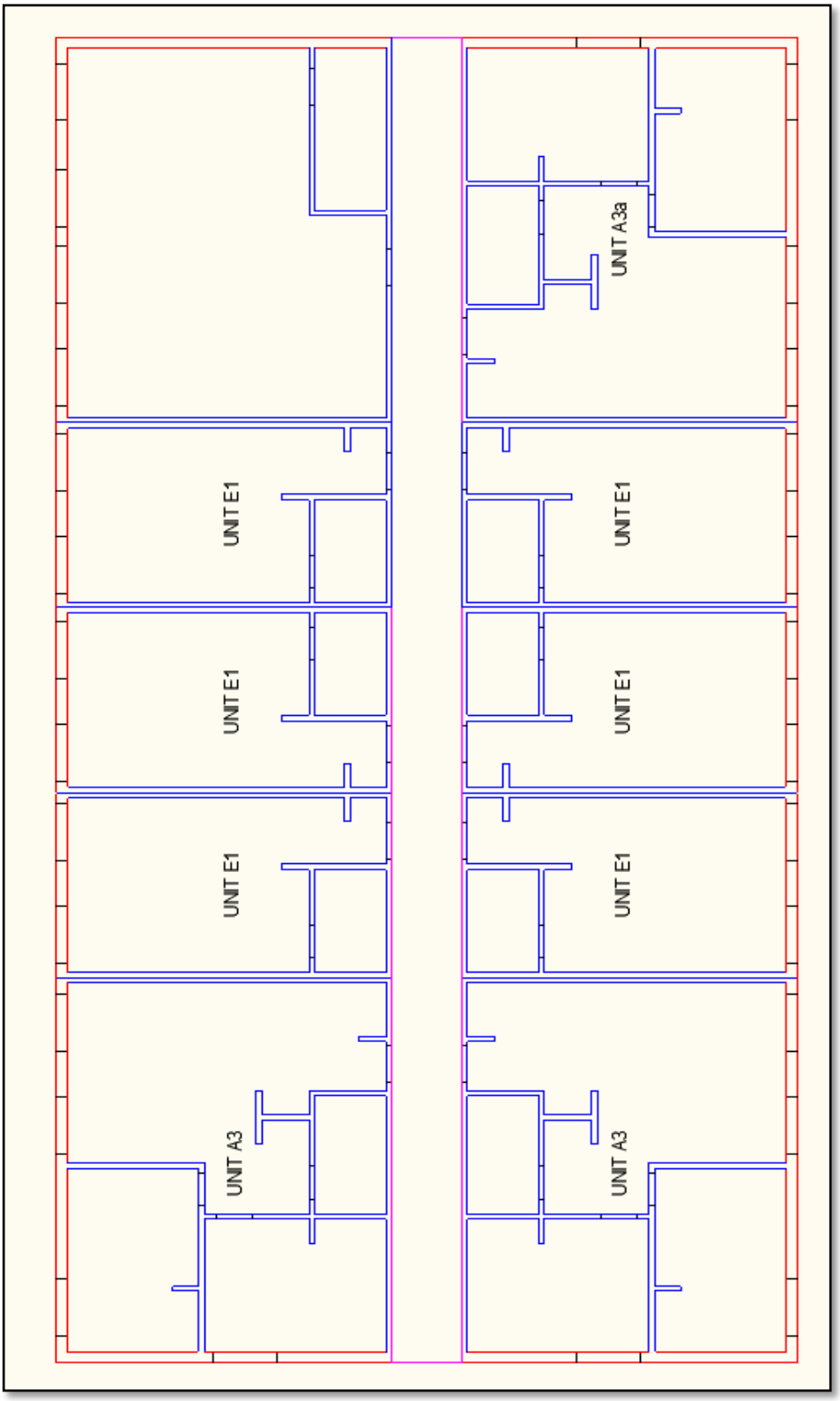


Figure 4-74: Second/third floor 2D CAD (Input data)

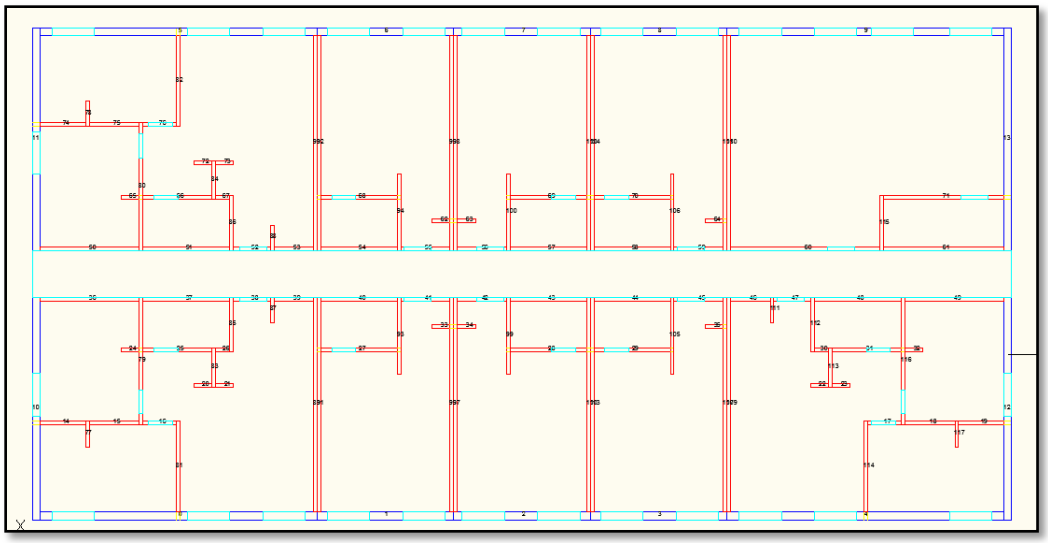


Figure 4-75: Second/third floor 2D BIM layout

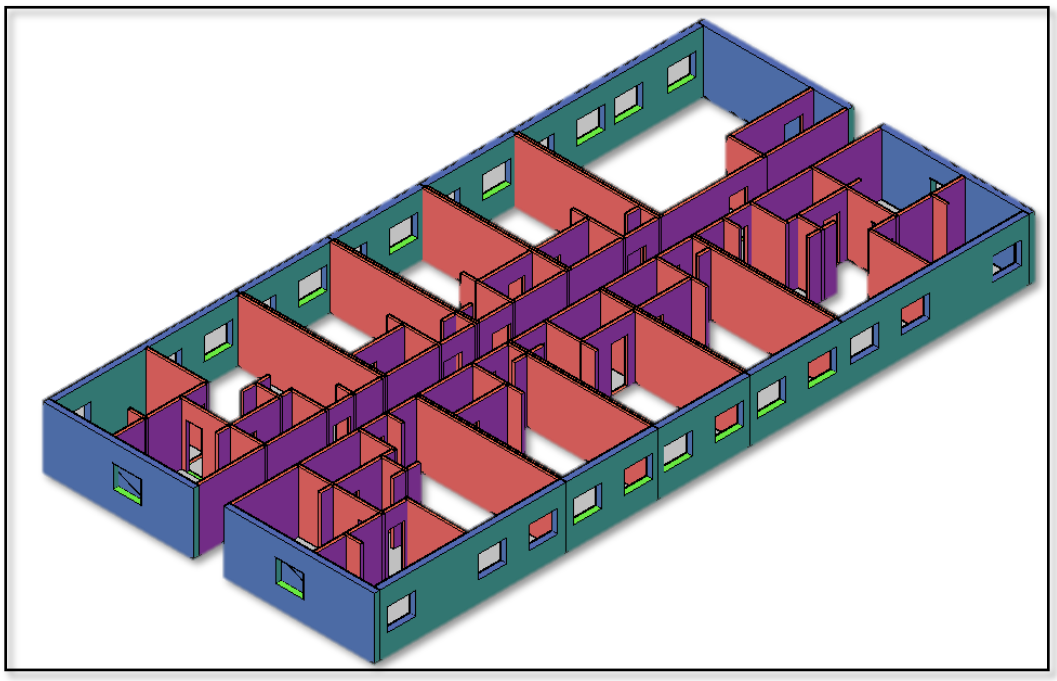


Figure 4-76: Second/third floor 3D BIM visualization

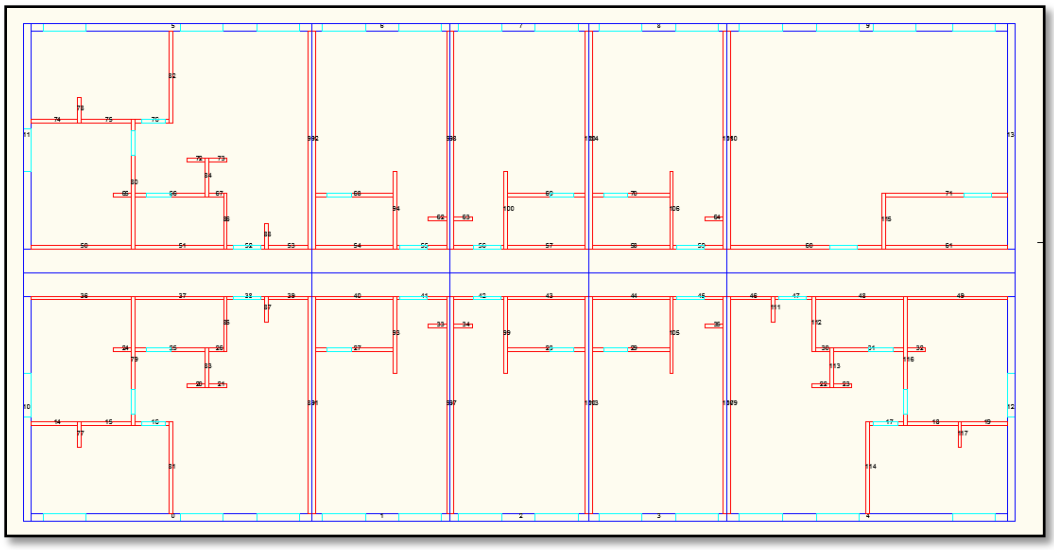


Figure 4-77: Second/third floor 2D MCM BIM layout

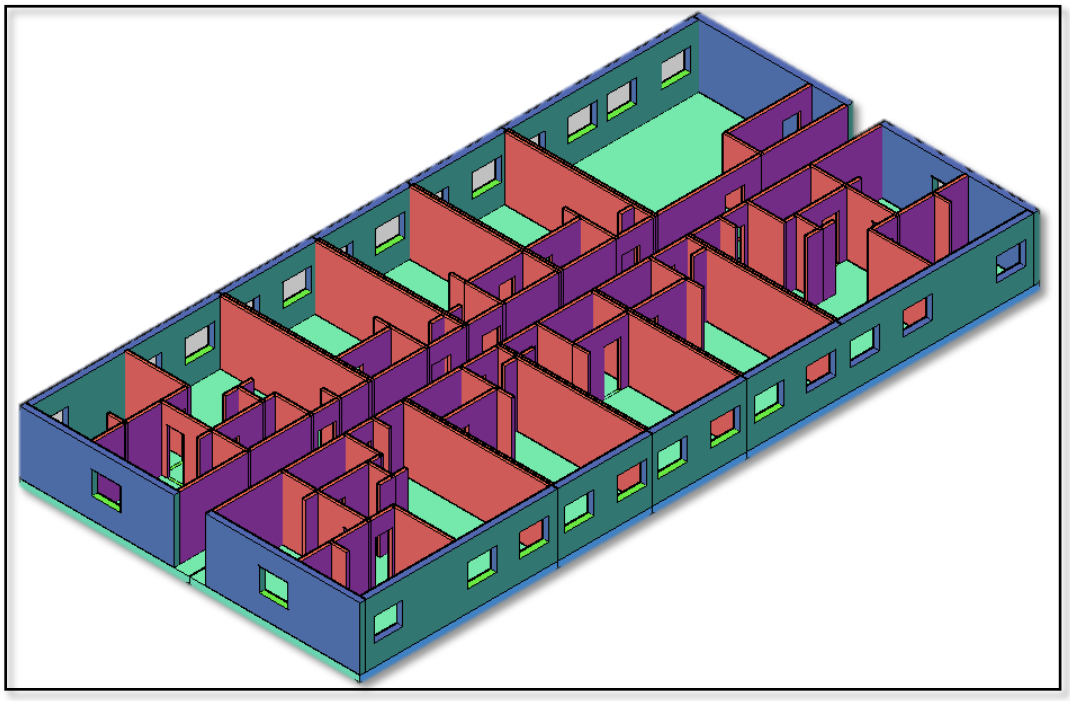


Figure 4-78: Second/third floor 3D MCM BIM visualization

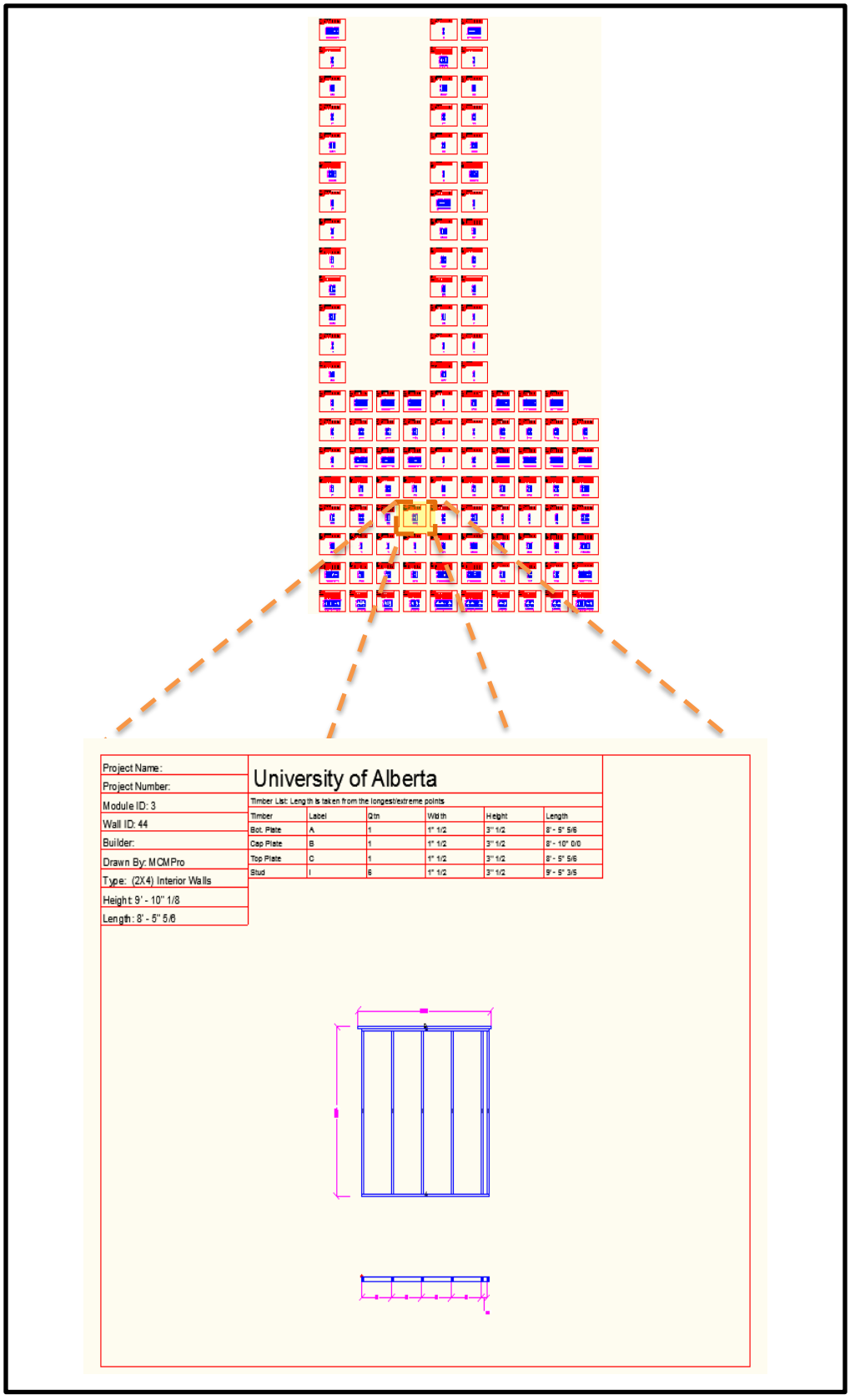


Figure 4-79: Second/third floor – wall shop drawings

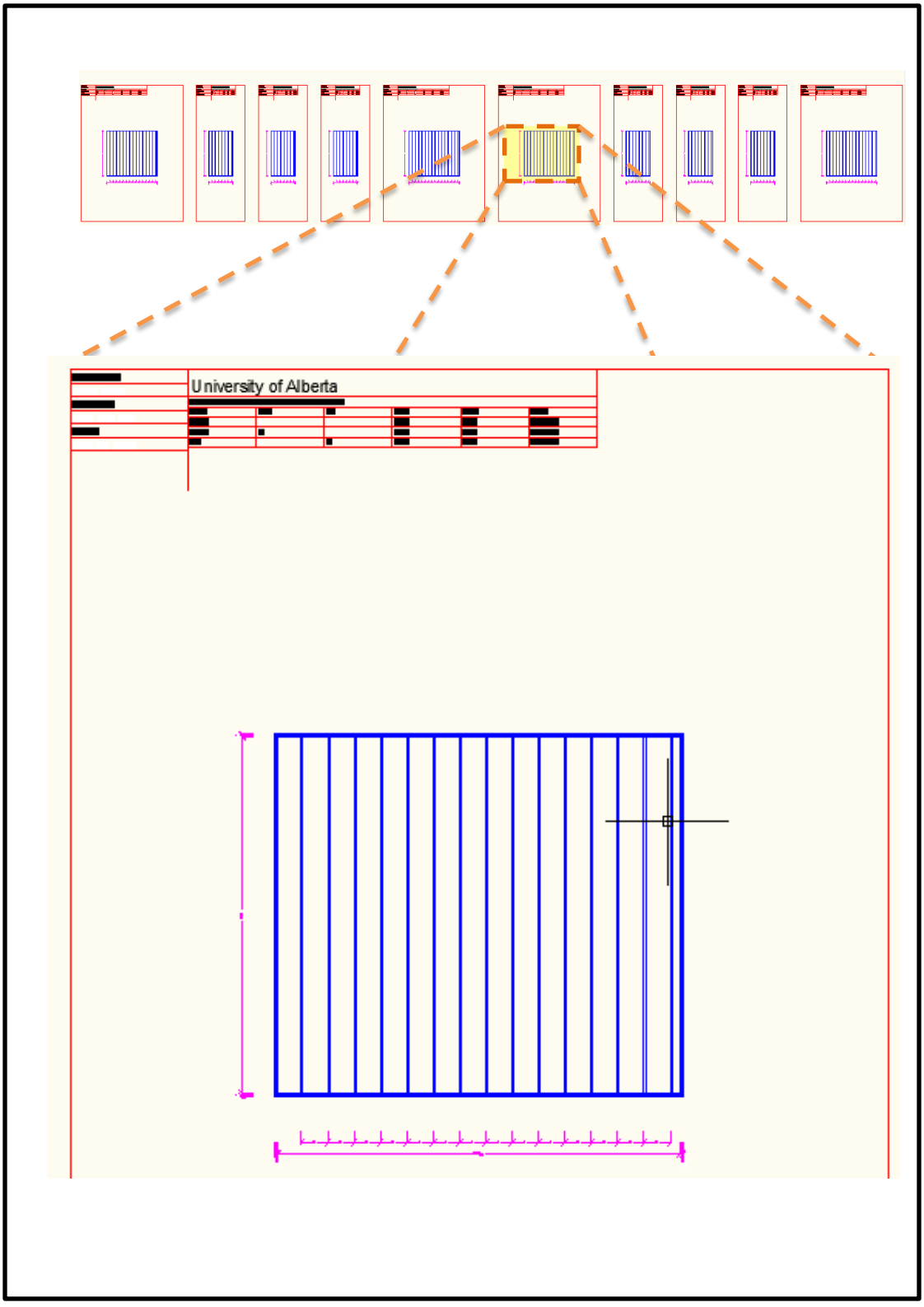


Figure 4-80: Second/third floor – floors shop drawings

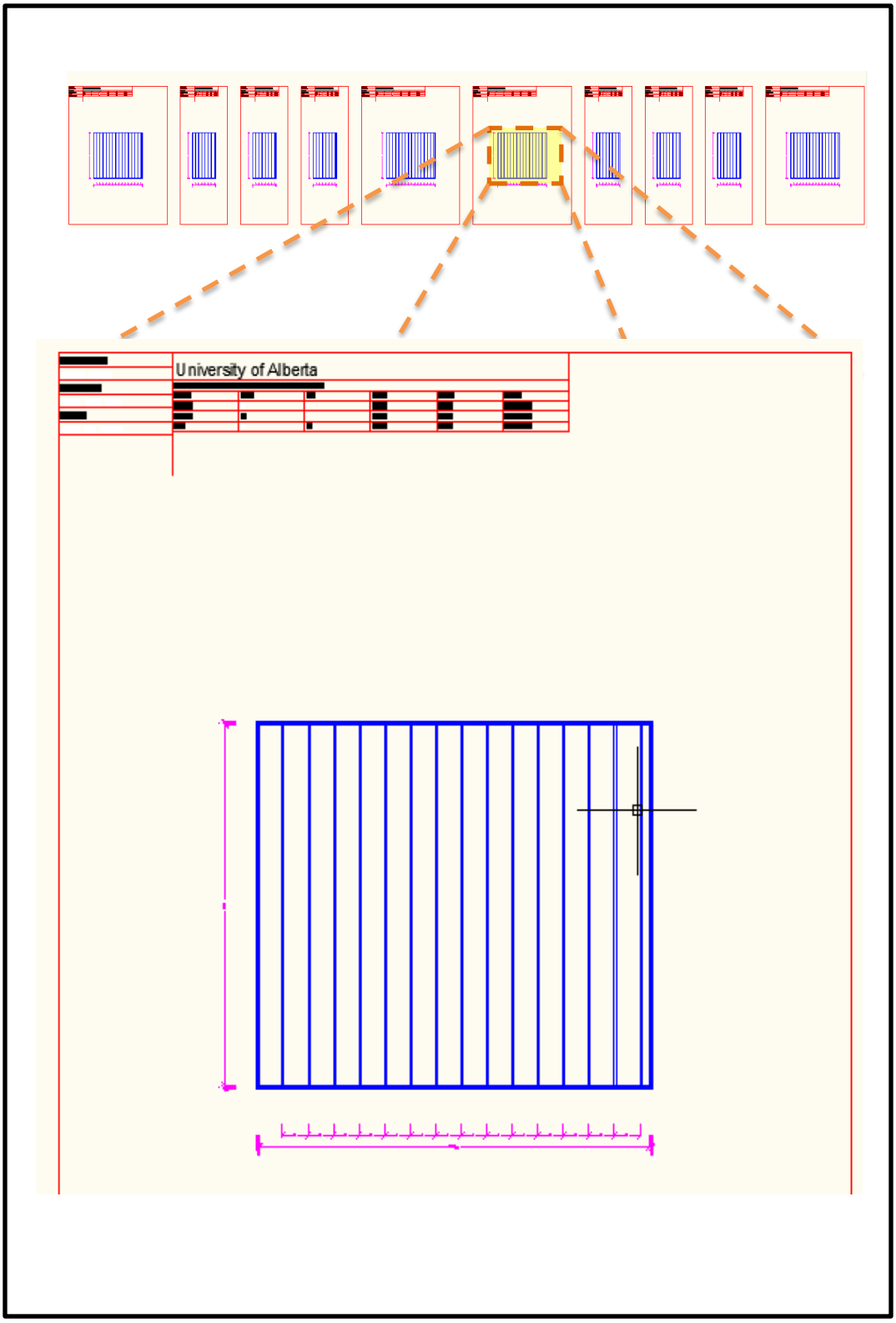


Figure 4-81: Second/third floor – ceilings shop drawings

Chapter 5: Conclusion

5.1 *General Conclusions*

Unpredictable weather conditions, temporary work sites, and limited storage areas are drawbacks associated with the stick-built method. The cost effectiveness, timeliness and quality of the entire project have been negatively affected by these drawbacks. To solve the current construction challenges, a shift towards construction automation manufacturing is required. However, a new construction method entails new requirements for design. Production design and drafting plans, transportation plans between the factory and the project site, and installation plans needed to be considered by the designers, which makes the design process a time-consuming task that requires special knowledge in the manufacturing different processes. Automating the design and drafting process provides advantages in terms of reducing redundant design activities, providing an infinite number of solutions, eliminating assumption and design errors, and shortening the time needed for any modification can be obtained from automating the design and drafting modeling process. Furthermore, the use of the 3D models generated from BIM models will add another dimension to the design process by assisting in communication for the project and facilitating understanding. By virtue of the implementation of parametric modeling into a CAD interface, the need for long drafting hours is also eliminated through the automation of the process. Errors can also be detected easily by checking the construction/shop drawings from the architectural model, thus enhancing the quality for design and drafting.

This research methodology describes a modular construction manufacturing (MCM) process and a detailed methodology for the automation of design and drafting for the MCM of residential facilities based on the platform framing construction method. The MCM tool MCMPro generates sets of shop drawings needed for framing the modules' walls, floors, and ceiling on the production line. It is intended to facilitate design and drafting in manufacturing the building process by automating the process using 2D CAD and parametric modelling.

5.2 *Research Contributions*

- The development of a well-defined process for modular construction manufacturing that specifies the manufacturing main stages, which helps to reduce cost and time-to-build, improve the quality of the buildings, and produce more energy efficient buildings. Factory construction provides opportunities for applying production efficiency strategies in the plant that cannot be replicated at the building site, thereby eliminating waste and helping building manufacturers deliver a wider variety of products more responsive to customers' preferences in a shorter time and at a lower cost.
- The introduction of a manufacturing design system that generates the needed detailed set of drawings needed for the production line stages and the prefabrication of panels through the integrations of architectural, structural, mechanical, and electrical design plans.
- The development methodology uses a scenario-based analysis through its design to accommodate the architectural and structural designs, national building code requirements, city bylaws, the framing method, and manufacturing concepts. The extended use of the development computer tool MCMPro is to automatically (1) develop BIM from the 2D CAD and architectural requirements, (2) upgrade the BIM to manufacturing BIM by utilizing the structural requirements and manufacturing concepts, and (3) provide detailed shop drawings and take-off lists needed to manufacture modules' wall, slab, and ceiling wood-frames by using the manufacturing BIM and the framing method.
- The development prototype was tested using the case study (Building No.3—Grade Housing Residence—University of Alberta Campus).

5.3 *Research Limitations*

This research focuses on the design of residential buildings. The scenario-based analysis rules used to generate BIM from a 2D CAD cover the majority of scenarios of construction projects; nevertheless, unaccounted scenarios could

exist, which entails manual corrections for the structural component using the interactive database tables provided by MCMPro. Upgrading the BIM into manufacturing BIM is based on common residential design, which implies that modules are located on one or two, where the two rows of modules are parallel to the X axis and the separation walls that separate adjacent modules are parallel to the Y axis.

5.4 *Recommendations for Future Research*

This research is the first step in a long journey towards manufacturing of the building process. An intelligent design system that covers construction manufacturing various aspects is expected as the final outcome of this research. A collaboration among various fields, such as engineering (construction, structural, material, indoor environment, building envelope, electrical, and mechanical), computing science (3D-simulation, sensors, and controls for smart buildings), public health science, social science, and occupational health and therapy, is needed for the design system. In terms of the engineering field, improvements to the current design system can be attained by considering number of steps that are described as follows:

1. To include the 2D sheathing design into the shop drawings.
2. To optimize the take-off list to provide an optimum cut list to minimize the wood waste.
3. To perform a beyond optimization analysis. This analysis utilizes walls and/or opening dimensions as input data to generate several optimums cut lists. The effect of these parameters on wood waste will be displayed using a curve with wood waste as the vertical axis and the parameters as the horizontal one.
4. To include the mechanical and electrical design when developing the shop drawing to specify the exact location of mechanical pipes and electrical wiring, this eliminates any potential conflict that might happen when installing these two systems.

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Appendix A: Current Practice BIM Model Generation Structured Steps

1- To exclude the short line: These shorts lines are used by the architect to represent an edge to a wall. The wall analysis doesn't require these lines. Moreover, their presence could affect the analysis.

2- To sort the lines according to their Y coordinate in order to handle the central lines: The central line is created when two walls share one face. These two walls are represented by three lines (the first wall's face, the shared face, and the second wall's face). The analysis recognizes a wall as two parallel lines with a distance equal to wall thickness, which implies that the central line between the two walls needs to be handled twice.

3- To assign wall group IDs: A wall group is a series of walls on the same alignment. The wall grouping process analyzes each line and assigns them to a distinct group ID based on the line's Y coordinates. A line belongs to a wall group if it has the same Y coordinate as the groups other lines, or the difference in Y coordinates is equal to an exterior wall thickness. Assigning a distinct Wall ID has two loops: The first loop defines the first line in this wall group, this first line in a wall group can't be assigned to any other group (i.e. Group ID = 0). The second loop is where a pair comparison is made between the first line and every line in the line group that has not been assigned to a Group ID when has the same Y coordinates, or has not been assigned to a Central Line group ID or Group ID when the difference in Y coordinates is equal to an exterior wall thickness. The sorting process is essential for the grouping process because the first line in a wall group can't be a central line, otherwise the wall group will have lines from the two adjacent walls. The sorting process forces this logic because a central line will already have a Group ID from the first wall group, which means it can't be the first line in a wall group.

4- To develop wall groups: A wall group is a group of points with a distinct wall Group ID. In order to transform wall group lines into points, a line break down process needs to be done; this break-down process is affected by the line group orientation. A wall group is defined as follows:

Total_[Wall Orientation]_[Layer ID] (0 to Total_[Wall Orientation]_Count[Layer ID]-1, 0 to 6)

For example, an exterior wall parallel to X wall groups table is defined as: *Total_X1(0 to Total_X1_Count-1, 0 to 5).*

Where:

Total_X1_Count = 2 * X_Count1 - 1 + 2 * Central Line Count

- **Total_X1_Count**: The total number of wall groups records (i.e. analysed points)
- **X_Count1:** The number of line in a specific line group. in our example, an Exterior wall parallel to X line group.
- **Central Line Count:** The number of central lines in a specific line group.

Each record in the wall group has the following items (**0) Line ID, (1) X, (2) Group ID, (3) Type, (4) Y1, (5) Y2.**

Where:

- **Line ID**: The original line ID from Line table
- **X**: X coordinates of the point (the main coordinate).
- **Group ID**: a distinct ID describes to which wall group a point belong to.
- **Type**: an integer number to identify a point position and role in a wall, (0 = a wall starting point, 1 = a wall ending point, 2 = a wall connection starting point, 3 = a wall connection ending point). (To be filled later on)
- **Y1**: Y coordinates of the point.
- **Y2**: A wall parallel to X other Y coordinates of the point. Absolute (Y2-Y1) = an exterior wall thickness. (To be filled later on)

5- To sort the wall groups matrix: A wall group matrix is sorted on two levels, first based on Group ID. Then, within each Group ID, another sorting process is made based on X coordinates for each point.

6- To define a Wall process: This process specifies each point "Type," the fourth column in the wall groups matrix, by analyzing each pair of points in a wall

group (point i, and point j) based on their X and Y coordinates. Sorting the wall groups' matrix is essential for a correct point pairing selection during the wall defining process.

When analysing an exterior wall parallel to X, the following scenario-based rules apply:

Main Case 1: A pair of points with the same X coordinates ($X_i = X_j$).

Sub Case 1-1: ($Y_i = Y_j$): Two points with the same X and Y coordinates.

This represents a wall separation (i.e. an end for the previous wall and a start for the current wall). In this case point i type (referred to as Type i) = 1, and point j type (referred to as Type j)=0. (See Figure A-1-A).

Sub Case 1-2: ($Y_i \neq Y_j$): Two points with the same X and different Y.

A further analysis is needed to define the points' type. If the current pair of point is not the last one in the current wall group of points, then a comparison between the current pair of points and the next one is performed. The next pair of point is referred to as point k and point p.

Sub Case 1-2-1: ($X_k - Xi$) = an interior wall thickness, or (X_k - Xi) = A mechanical wall thickness.

This case represents an exterior wall parallel to X with two interior or mechanical walls on each side (See Figure A-1-B).

In this case, the analysis assigns the two pairs types as follow:

Type i= 2, Type j=Ignore, Type k= 3, Type p=Ignore. In a wall connection only two points are used to define a connection. For this reason Points j and p have been ignored.

Sub Case 1-2-2: (X_k - X_i) ≠ An interior Thickness, and (X_k - X_i) ≠ A mechanical Thickness], or [Point k, Point p don't exist in the current wall group.

This case represents a pair of point that define a wall end or a wall start based on the previous point type. The previous point is referred to as Point (i-1).

Sub Case 1-2-2-1: Type (i-1) =1 or Point (i-1) doesn't exist.

Type i=0, Type j=0 (See Figure A-1-C).

Sub Case 1-2-2-2: Type (i-1) =0.

Type i=1, Type j=1 (See Figure A-1-D).

- **Main Case 2**: A pair of points with an X coordinates difference, (X_j - X_i), equal to an exterior wall thickness.

  This case represents a connection between an exterior wall parallel to X with an exterior wall parallel to Y.

  Sub Case 2-1: ($Y_i = Y_j$): Two points with the same Y coordinates.

  This case represents an end of the previous wall and a start for the current one.

  Type i=1, Type j=0 (See See Figure A-1-E).

  Sub Case 2-2: ($Y_i \neq Y_j$): Two points with different Y.

  This case represents a pair of point that defines a wall end or a wall start based on the previous point type. In order to account for the walls priority rules, an adjustment is needed in the pair of points X coordinate. The walls priority rules followed in this analysis spcifies that an exterior wall parallel to Y has a higher priority than an exterior wall parallel to X.

  Sub Case 2-2-1: Type (i-1) =1 or Point (i-1) doesn't exist.

  Type i=0, Type j=0 (See Figure A-1-F).

An exterior wall parallel to X start pair of points implies that these two points are to be cut to the point with higher X coordinate value.

$X_i = X_j$; $X_i < X_j$

Sub Case 2-2-2: Type (i-1) =0.

Type i=1, Type j=1 (See Figure A-1-G).

An exterior wall parallel to X end pair of points implies that these two points are to be cut to the point with lower X coordinate value.

$X_j = X_i$; $X_i < X_j$

Main Case 3: A pair of points with an X coordinates difference, ($X_j - X_i$), equal to an interior wall thickness or a mechanical wall thickness.

This case represents a connection between an exterior wall parallel to X with an interior or a mechanical wall parallel to Y. This connection can take a T shape or L shape based on Y coordinates.

Sub Case 3-1: ($Y_i \neq Y_j$): Two points with different Y coordinates (i.e. L shape connection).

L shape connection implies that a pair of points represents a start or an end to a wall, and in accordance to walls priority rules, an exterior wall has higher priority than an interior or a mechanical wall, X coordinate's adjustment is required.

Sub Case 3-1-1: Type (i-1) =1 or Point (i-1) doesn't exist.

Type i=0, Type j=0 (See Figure A-1-H).

An exterior wall parallel to X start pair of points implies that these two points are to be extended to the point with lower X coordinate value.

$X_j = X_i$; $X_i < X_j$

Sub Case 3-1-2: Type (i-1) =0.

Type i=1, Type j=1 (See Figure A-1-I).

An exterior wall parallel to X end pair of points implies that these two points are to be extended to the point with higher X coordinate value.

$X_i = X_j$; $X_i < X_j$

Sub Case 3-2: ($Y_i = Y_j$): Two points the same Y coordinates (i.e. T shape connection).

T shape connection implies that a pair of points represents a start and an end to a wall connection.

Type i= 2, Type j=3 (See Figure A-1-J)

- **Main Case 4:** A pair of points with an X coordinates difference, ($X_j - X_i$), equal to the difference between an exterior and an interior wall thickness.

  This case represents a start or an end to a wall. Therefore, an X coordinates adjustments is required.

  Sub Case 4-1: Type (i-1) =1 or Point (i-1) doesn't exist.

  Type i=0, Type j=0 (See Figure A-1-K).

  An exterior wall parallel to X start pair of points implies that these two points are to be cut to the point with higher X coordinate value.

  $X_i = X_{j;}$ $X_i < X_j$

  Sub Case 4-2: Type (i-1) =0.

  Type i=1, Type j=1 (See Figure A-1-L).

  An exterior wall parallel to X end pair of points implies that these two points are to be cut to the point with lower X coordinate value.

  $X_j = X_{i;}$ $X_i < X_j$

- **Main Case 5:** A pair of points with an X coordinates difference, ($X_j - X_i$) within the range of:

$$]0, An\ exterior\ wall\ thickness[\ U\ ]An\ exterior\ wall\ thickness, 2 \times An\ exterior\ wall\ thickness[.$$

This case represents a connection between an exterior wall parallel to X with an inclined wall. The range of values is based on experimental evaluation of the possible values when this type of connection occurs (See Figure A-2).

Since this range of values is experimental, a connection type check is applied by comparing this pair of points X and Y coordinates with those of the inclined lines group. Once this condition is satisfied a start or an end to a wall is specified. No X coordinates adjustments are required.

Sub Case 5-1: Type (i-1) =1 or Point (i-1) doesn't exist.

Type i=0, Type j=0 (See Figure A-1M).

Sub Case 5-2: Type (i-1) =0.

Type i=1, Type j=1 (See Figure A-1-N).

An inclined connection check is activated for this pair of point for the purpose of further analysis.

- **Main Case 6**: If none of the previous cases is satisfied, a start and an end of a wall is specified.

  Sub Case 6-1: Type (i-1) =1 or Point (i-1) doesn't exist.

  Type i=0, Type j=1 (See Figure A-1-O).

  Sub Case 6-2: Type (i-1) =0.

  Type i=1, Type j=0 (See Figure A-1-P).

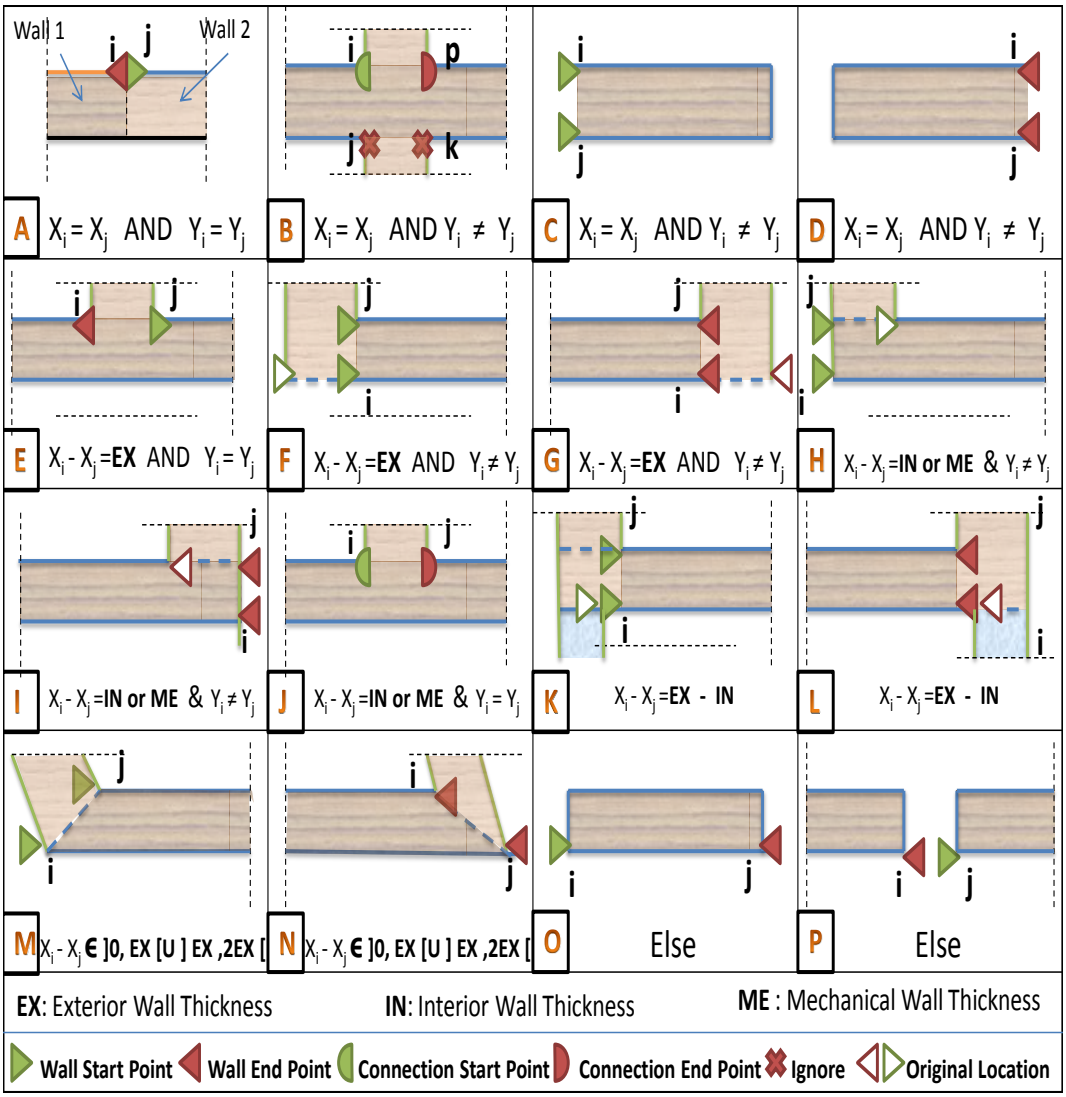

Figure A-1: Wall-defining process

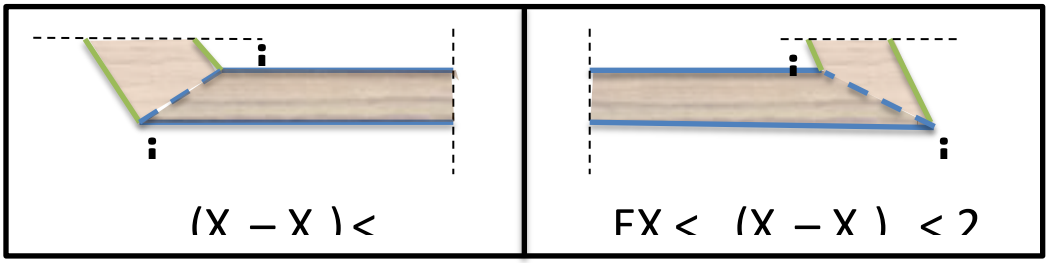

Figure A-2: Inclined wall connection

7- To assign Y1 and Y2 in the wall groups table: X coordinates in the wall groups table define walls start and end points; whereas, Y_1 and Y_2 defines a wall thickness ($Y_1<Y_2$ and Y_2-Y_1=Wall Thickness). In a wall group, Y_1 is Y coordinates of the wall group points, which has two values that represent the wall

group thickness. Through this step, Y_1 and Y_2 are found for each wall group and assigned to all their points.

7- To start wall formation process: Using wall groups table, a wall is defined by a start point followed by an end point. Using X, Y_1, Y_2 coordinates of these points, wall four corner points are defined.

$(X_i < X_j)AND\ (Y_1 < Y_2) =>$

$X_{min} = X_i$ $X_{max} = X_j$ $Y_{min} = Y_1$ $Y_{max} = Y_2$

A wall starting corner has minimum X and Y coordinates. Moving counter clock wise when parallel to X, and clock wise when parallel to Y, the next three corner points are defined.