Automation of Quantity Takeoff and Material Optimization for Residential Construction Manufacturing

By

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Abstract

Quantity takeoff is repetitive work in the modular construction industry. The current process, which is typically carried out manually, is time consuming and error-prone. This thesis proposes a methodology to automate the quantity takeoff process. The central aim of this research is to create a bridge between the building information modelling (BIM) 3D model and a database that can be used to hold data extracted from the model. This bridge allows the automatic transfer of material quantities from the BIM model to the database. Another issue associated with residential construction is material waste, especially for 1D and 2D framing materials, which is caused by insufficient planning of cutting processes. Hence, this thesis also presents a methodology to optimize material usage (focusing on lumber and sheathing). 1D and 2D materials are extracted from the BIM 3D model and then organized in order to establish optimized lumber and sheathing cutting plans.

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List of Abbreviations

BIM: Building Information Modelling

1D: One-dimensional

2D: Two-dimensional

3D: Three-dimensional

OSB: Oriented Strand Board

GA: Genetic Algorithms

ACO: Ant Colony Optimization

C1: Category 1

C2: Category 2

C3: Category 3

Chapter 1 Introduction

1.1 Research Motivation

Quantity takeoff, serving as a foundation for downstream tasks in the management of modular construction, is repetitive work. The process in current practice involves manual interventions, which is time consuming and error-prone. The challenge of transitioning construction companies to a better and more efficient method is multifaceted; one challenge is incorporating a cost breakdown structure that is formulated according to the company's classification systems into building information modelling (BIM). This study develops a methodology which enables construction practitioners to obtain quantity takeoff in an automated manner. The main concept is to preload the unique classification information into the BIM model so that the quantity of materials in the BIM model can be extracted and stored into a database automatically in accordance with the preloaded classification system. The unique classification information, along with formulas for derived material quantities, is front-loaded into the database. As a result, the explicitly extracted quantities are converted by means of the preloaded formulas in the database to the required format for the purpose of ordering and purchasing materials. A prototype system is developed based on Autodesk Revit through the Revit Application Programming Interface. A case study of the manufacturing of a modularized house reveals that, a considerable amount of time saving and increased accuracy for project estimation are achieved as a result of utilizing automated quantity takeoff.

Another deficiency in the current residential construction process is the waste of materials. One reason for this has been the general lack of focus on material saving methods. From 2005 to 2008, Western Canada observed a rise in housing costs partially due to the shortage of experienced trades personnel, which in turn led to a relative decrease in the cost of material comparing with the cost of labour. As such, efforts to optimize material usage in Western Canada's construction market have been relatively limited in recent years. As a consequence, material has been misused, and large amounts of waste have been generated (Manrique 2009). Among the most highly wasted products, solid sawn wood, engineered wood (e.g., lumber, sheathing), and drywall account for over 60% of all waste by weight (Home Innovation Research Labs 2001) (Figure 1.1). A common cause of waste among the aforementioned materials is the necessity of cutting these materials on site, and the current cutting practice depends on the intuition and guesswork of the worker (which leads to error) rather than adhering to a comprehensive plan. In specific, the large amount of primary materials wasted can be attributed to the lack of a predetermined cutting plan. This underscores the distinct need for a practical methodology to optimize the use of primary materials.

Figure 1.1: Construction waste on site (Waste Management World 2014).

This study proposes a decision support system to address these challenges within a computer environment. The designated system integrates mathematical algorithms with the BIM concept in order to aid practitioners with the material cutting process by providing 1D (lumber) and 2D (sheathing) material cutting plans prior to construction, and reduce the amount of primary material waste. The system is also able to provide estimators with accurate and practical quantities of lumber and sheathing.

1.2 Research Objectives

This research is built on the following hypothesis:

"*Automation of quantity takeoff and material utilization optimization can potentially improve the efficiency of the quantity takeoff process and reduce material waste.*"

This research aims to improve the productivity of the modular construction industry through two main tasks automation of quantity takeoff and material optimization. The objectives of the research are summarized below:

- To develop a deep understanding of the current quantity takeoff process
- To front-load the information into the Revit model and database
- To obtain a precise quantity takeoff in a timely manner
- To build and implement an algorithm to minimize the material (lumber and sheathing) waste
- To create and visualize sheathing layouts on exterior walls in the Revit model automatically
- To provide a practical quantity of lumber and sheathing for ordering purposes
- To report the revised material quantity quickly due to design changes.

1.3 Thesis Organization

Chapter 1 (Introduction) describes the research motivation and objectives and provides an overview of the research.

Chapter 2 (Literature Review) provides a description of BIM application in current construction practices, as well as a summary of state-of-the-art BIM-based quantity takeoff and material optimization.

Chapter 3 (Proposed Methodology) describes the proposed methodology utilized to perform quantity takeoff and material optimization.

Chapter 4 (Case Study) applies the developed programs to two Revit models for demonstration.

Chapter 5 (Conclusion) summarizes the research contributions, limitations, and future work.

Chapter 2 Literature Review

2.1 Introduction

In this chapter, previous and current research related to quantity takeoff and material optimization is described.

2.2 Building Information Modelling

Building Information Modelling (BIM) is a proven, an effective technology in the architecture, engineering, and construction (AEC) domain (Azhar 2011). The term *Building Information Modelling* was introduced by van Nederveen and Tolman (1992). BIM constitutes a 3D geometric modelling paradigm in which information stored in a data-rich BIM model can be implemented for prediction and analysis in different applications, such as energy consumption quantification, structural performance, and cost, scheduling, and facilities management (Kensek 2014). One notable characteristic of BIM is the ability to manage changes, such as design and schedule changes, through the database stored in the BIM system ("Building Information Modeling" 2002), and it also offers a potential capacity to share digital resources among project participants throughout the project lifecycle (Sabol 2008).

BIM is an emerging paradigm which is spreading quickly in the construction industry, and a considerable number of BIM software applications have been developed, such as Autodesk Revit, Graphisoft ArchiCAD and Vico Office Suite.

Most of these software applications are equipped with an application programming interface (API) function, and the function can be broadened by using the specialized programs written by external application developers (Modeling 2008). Among the software, Autodesk Revit provides a rich and powerful .NET API to perform automation of repetitive tasks and extension of the core functionality of Revit in simulation, conceptual design, construction and building management, as well as other functionalities (Autodesk Developer Network 2015).

2.3 Quantity Takeoff

Quantity takeoff is an important part of the construction process, and it is performed by general contractors, subcontractors, cost consultants, and quantity surveyors. Such tasks simply include measuring and counting the utilization of materials within a certain construction project in order to determine the associated materials and total labour usage. In current practice, the quantity takeoff process is typically carried out manually using a printout, a pen, and a calculator, which is an outdated method (Beyond the Paper 2006). Since the process of manual quantity takeoff depends on human interpretation, it is difficult to obtain accurate measurements and avoid errors (Monteiro and Poças Martins 2013). The development of BIM provides a better environment for quantity takeoff. In recent years, an increasing number of practitioners have been adopting BIM, as it provides a feasible means to develop a more efficient quantity takeoff system (Firat et al. 2010). BIM enables project teams to generate cost estimates quickly and accurately, and the output can be used to assist in material ordering and cost estimation, not only early in the design phase but throughout the project lifecycle (Autodesk 2013).

For the stick-built onsite construction practice, Autodesk has developed commercial software called "Autodesk Quantity Takeoff", which is widely used by the construction industry. It enables cost estimators to read and extract information (geometry, images, and data) from BIM tools, such as Revit Architecture, Revit Structure, and Revit MEP. After importing the data from other software, Autodesk Quantity Takeoff is able to automatically measure, count, and price building objects in minutes, and the takeoff results can be exported in different file formats such as Microsoft Excel and Design Web Format (DWF) (Autodesk 2015); however, this tool is not designed to support modular and offsite construction.

2.4 Material Optimization

In North America, timber, drywall, cardboard, metals, concrete, and plastic are common construction materials that account for the majority of construction material waste. As illustrated in Figure 2.1, among these types of waste, wood-based waste makes up 89% of the total waste (by volume) during the framing stage (Mah 2008). The loss from this waste is not only material cost, but also the expense to dispose of it. A survey conducted by the National Association of Home Builders (NAHB) has indicated that, a typical 2,000 sq ft house will produce 8,000 lb solid waste, which includes 3,000 lb wood waste. A builder needs to pay over $500 for construction waste disposal for each house (Home Innovation Research Labs 2001).

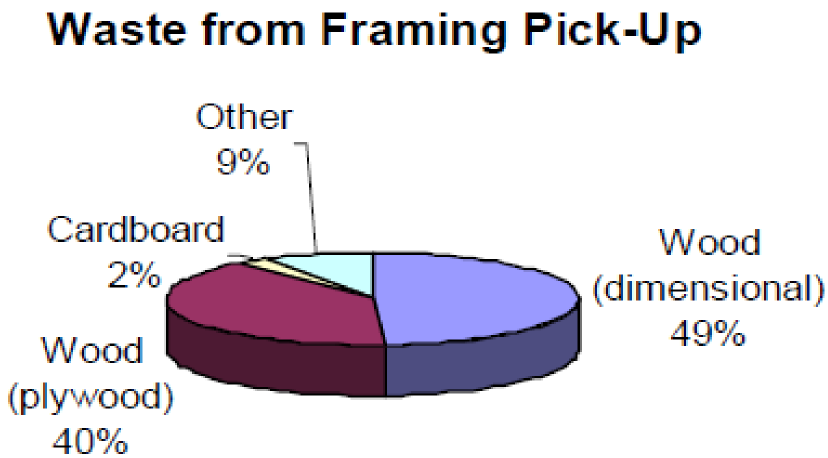


Figure 2.1: Material waste from framing (by volume) (Mah 2008).

The quantification of construction material waste has garnered significant attention among researchers, but few studies have focused on methods to decrease material waste beginning at the design phase (Manrique 2009). Since the majority of waste is caused by insufficient cutting plans, it is necessary to develop an approach to reduce wood-based waste before construction begins.

A well-known approach to optimize material usage is the coupling of combinatorial analysis and linear programming, which began to appear in the 20th century (Manrique 2009). In the early 1960s, Gilmore and Gomory (1961) proposed a practical method to solve the 1D cutting stock problems. They transformed each cutting pattern and the demand requirements to integer arrays, and enabled the constraints to satisfy the requirements by combining different cutting patterns. Early adaptation was challenging due to the considerable number of equations and large calculation tasks; however, this has become much more manageable with the development of complex computational software (David et al. 2009).

Numerous individual and combinatorial optimization algorithms have been implemented to solve 2D cutting stock problems. Genetic Algorithms (GA) and Ant Colony Optimization (ACO) are suitable to solve constraint satisfaction and combinatorial optimization problems. Costa and Sassi (2012) developed a guillotine cutting process (*Guillotine* cutting refers to a cutting pattern for rectangular forms where the cutting edge begins at one side and continues towards the opposite side without stopping; it is also called *edge-to-edge* cutting (Aryanezhad et al. 2012)) for the glass industry based on the combination of GA and ACO; however, this cutting process was only sufficient for a small number of objects. If the number of glass pieces to be cut from the same plate was increased, the time to calculate the optimal solution would also increase in a factorial relation. Furthermore, when the work complexity is high, the required time necessary to complete the task becomes unacceptable. MacLeod (1993) applied an $O(n^3)$ approximation algorithm to the 2D guillotine cutting stock problem, and the concept of this algorithm is to locate each rectangle from a stock pile onto a feasible position on the stock piece, and a position will only be located for a certain rectangle if and only if such a feasible placement exists. In order to speed up the calculation process, Manrique (2011) proposed a combinatorial algorithm called *CUTEX* to amalgamate BIM and optimization. The algorithm was applied to optimize lumber and sheathing usage to satisfy project demand as extracted from Autodesk CAD drawings, and the results showed that CUTEX could reduce wood waste from the construction of dwellings by 96%. The research presented in this thesis is built on Manrique (2011) combining of combinatorial analysis and linear programming utilizing advanced BIM technologies.

Chapter 3 Proposed Methodology

3.1 Quantity takeoff

In this chapter, the methodology of performing quantity takeoff is described. Compared with current conventional software, the proposed program is capable of generating quantity takeoff reports in a self-customized format, and of allowing the user to edit formulas in the database in order to modify the extracted quantity to a practical quantity. In addition, the proposed quantity takeoff program runs inside the BIM software, which circumvents the processes of exporting (from BIM software) and importing (into quantity takeoff software) models.

As the overview of the methodology in Figure 3.1 shows, the main process is to front-load a unique material information classification system (e.g., Part Number and Unit Number) into the BIM 3D model and database template, and to extract the material quantity in accordance with the Part Number and Unit Number to the database. A certain portion of directly extracted quantities are inadequate to be utilized for inventory, and the front-loaded formulas in the database are designed to process and classify the quantities. A detailed explanation is given in the following sections.

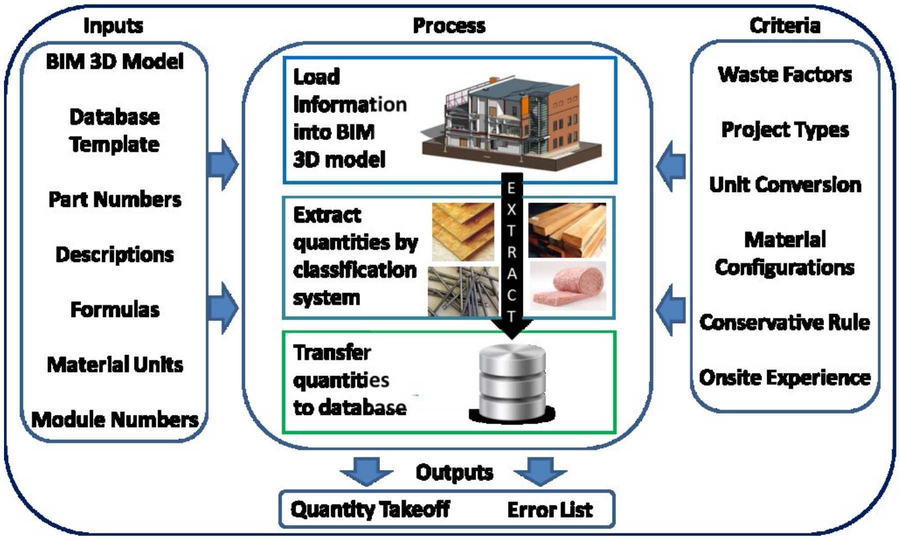


Figure 3.1: Overview of methodology of quantity takeoff.

3.1.1 Preloading the BIM model with a unique classification system

The concept of quantity takeoff involves (1) integrating BIM software with a company's inventory database coherently through a unique classification system, and (2) quantifying the items from the BIM software model into the database template. The "bridge" used to link the two ends is *Part Number*, which is a numeric identifier of an item. To extract the quantities of materials, Part Numbers are preloaded into the BIM 3D model and assigned to each item. However, under certain circumstances, Part Number is not sufficient to classify items for modular construction. The nature of this construction method is such that a single project comprises multiple independent modules. To distinguish the modules, each one is assigned a property referred to as *Unit Number*, and all the materials belonging to the same module are assigned the identical Unit Number.

3.1.2 Quantification Measurement

To facilitate the quantity extraction, material usage is quantified through various measurements: *each*, *linear length*, and *contact area*. In this study, materials are separated into three categories corresponding to the different measurement units and front-loaded information to the 3D model (Figure 3.2).

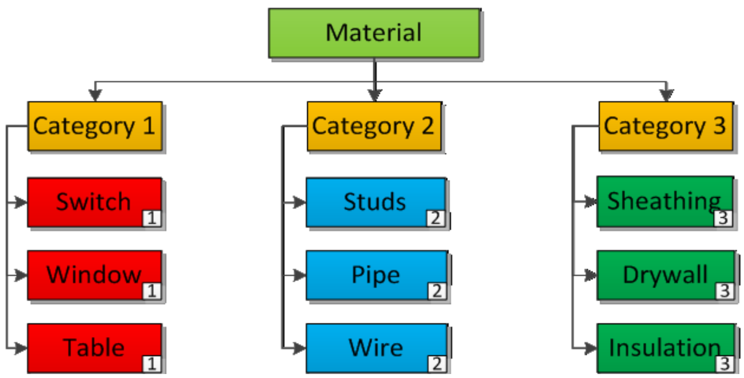


Figure 3.2: Material category classification.

- Category 1 (C1): Materials counted by *each* (e.g., doors and windows).
- Category 2 (C2): Materials counted by *linear length* (e.g., lumber and pipe).
- Category 3 (C3): Materials counted by *contact area* (e.g., OSB sheathing and drywall).

3.1.2 Format database template

A *standardized database template* is a prerequisite to automating the quantity takeoff. Generally, the database template contains all the necessary items for construction of the module; it thus could be commonly modified from a company's *Inventory File*.

At least five properties are recorded in the database: *Part Number*, *Description*, *Unit*, *Module Number*, and *Quantity*. Part Number and Module Number are the primary and secondary indicators used to conduct the quantity extraction. Description and Unit are supplementary properties for description of a certain material. All the properties except Quantity are constant and front-loaded into the database; the Quantity input is left blank to hold the quantity that will be extracted from the BIM 3D model. In most cases, the content in the database template needs to be duplicated a few times, and the number of duplications should be equal to the quantity of the units (modules) within a model. After each copy of the content, different Module Numbers are assigned. However, this database structure is still not fully feasible for quantity takeoff due to three considerations: (1) inevitable waste, (2) actual construction method, and (3) unit conversion.

Among the three material categories, the items in the first category (C1) do not need any further processing after being extracted, and the quantities are regarded as 100% accurate. For example, "five windows and four doors" are extracted from the model, which precisely indicates that five windows and four doors are required for the project. However, the quantities of items in the second category (C2) have less accuracy than the first category, since the C2 materials always realistically require extra processing work (e.g., cutting of lumber or pipe). The third category (C3) has the lowest accuracy, since C3 materials usually necessitate 2D cuts in order to obtain suitable sizes. The additional processes of C2 and C3 materials cause inevitable waste, which leads to a significant deviation in quantity estimation. Hence, a waste factor, f_w, is designed to issue extra materials in addition to the directly extracted quantities in Equation 3.7.

Correspondingly, the system configuration of BIM software is unable to properly quantify the quantity of C3 materials, which refers to the actual construction demand. A wall surface in Autodesk Revit, which is a widely utilized BIM software, is selected for the purpose of explanation. The wall comprises multiple layers of C3 materials, such as insulation and house wrap (Figure 3.3(a)); the default assumption in Revit is that C3 materials hosted by a wall have a contact area equivalent to the wall surface area (see Figure 3.3(b) and Equation 3.1).

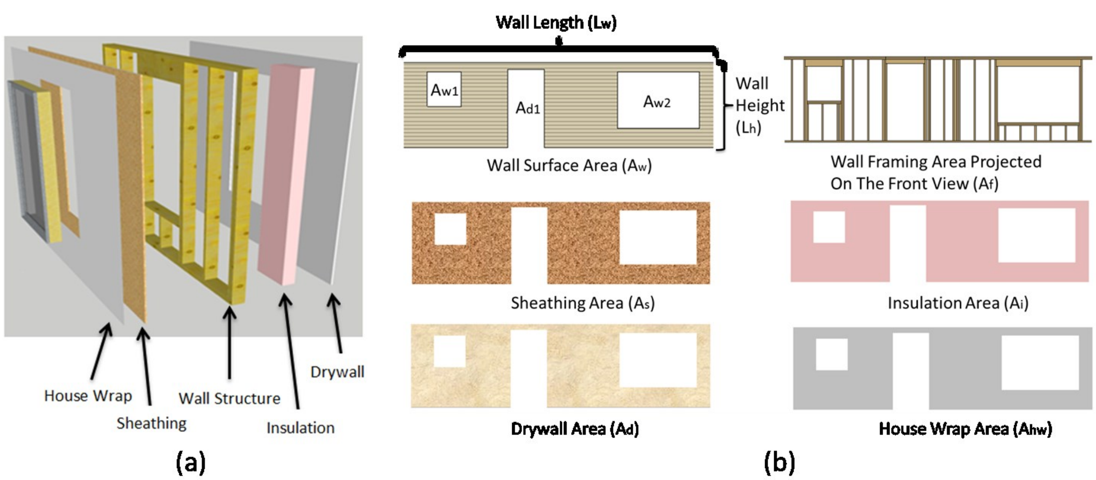


Figure 3.3: Decomposition of wall materials.

$$A_{ws} = A_s = A_i = A_d = A_{hw} = L_w \times H_w - \sum_{i=0}^{n} A_{wi} - \sum_{i=0}^{m} A_{di} \tag{3.1}$$

A_{ws}: $Wall\ Surface\ Area$

A_s: $Extracted\ Sheathing\ Area$

A_i: $Extracted\ Insulation\ Area$

A_d: $Extracted\ Drywall\ Area$

A_{hw}: $Extracted\ House\ Wrap\ Area$

L_w: $Wall\ Length$

H_w: $Wall\ Height$

A_{wi}: $Area\ of\ ith\ window\ opening$

A_{di}: $Area\ of\ ith\ door\ opening$

This is further explained through an example, as shown in Figure 3.4: while installing home wrap onto a window opening, the part overlaid across the opening is broken by a crossing cut. Four formed triangles are pushed inside of the opening for the purpose of sealing window edges, and the surplus portions are wasted. Hence, given that a window opening creates a gap in actual surface area, the extracted quantity of house wrap should be less than the actual demand if windows exist on a wall.

$$A_{hw} = L_w \times H_w - \sum_{i=0}^{n} A_{wi} - \sum_{i=0}^{m} A_{di} \tag{3.2}$$

$$A_{HW} = L_w \times H_w > A_{hw} \tag{3.3}$$

A_{hw}: $Extracted\ House\ Wrap\ Area$

L_w: $Wall\ Length$

H_w: $Wall\ Height$

A_{wi}: $Area\ of\ ith\ window\ opening$

A_{di}: $Area\ of\ ith\ door\ opening$

A_{hw}: $Extracted\ House\ Wrap\ Area$

A_{HW}: $Demanded\ House\ Wrap\ Area$

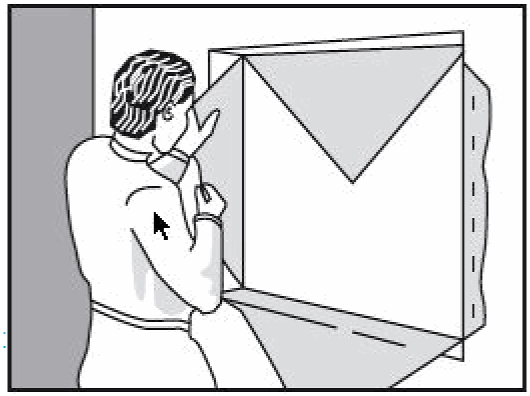


Figure 3.4: House wrap membrane installation (Insulation-Online 2014).

Conversely, insulation strips are only placed in the spaces between studs rather than on top of the studs (Figure 3.5), so the extracted area (A_i) must be larger than the actual need (A_I).

$$A_i = L_w \times H_w - \sum_{i=0}^{n} A_{wi} - \sum_{i=0}^{m} A_{di} \tag{3.4}$$

$$A_I = A_i - A_f \tag{3.5}$$

A_i: $Extracted\ Insulation\ Area$

L_w: $Wall\ Length$

H_w: $Wall\ Height$

A_{wi}: $Area\ of\ ith\ window\ opening$

A_{di}: $Area\ of\ ith\ door\ opening$

A_I: $Demanded\ Insulation\ Area$

A_f: $Wall\ Framing\ Area\ in\ the\ front\ view$

Figure 3.5: Insulation installation between two studs ("Basement Wall Insulation Blanket - Viewing Gallery" 2014).

In consideration of the aforementioned scenarios (house wrap and insulation placement), it is advisable to be cautious of the variability of material usage, and issue more or less than the extracted quantities as appropriate based on the designed construction factor, f_c, in Equation 3.7. In particular, project estimators often allocate more material than may be needed in order to avoid being short of materials, and most of the percentages are decided based on site observation and experience.

Even if the previous considerations are disregarded, a certain portion of quantities extracted directly from a model are still not proper for cost estimation or purchasing purposes due to the fact that the default units of materials in BIM software do not entirely match the units in the database. For example, most OSB sheathing is provided in 4 ft x 8 ft sheets, so each sheet has an area of 32 sq ft. In this regard, the sheathing quantity from the BIM 3D model needs to be divided by

32 to convert the unit from square feet to piece. The unit converting process can be achieved by using the unit conversion factor f_u in Equation 3.7.

The situations mentioned above are common in reality, so to procure an applicable quantity, an auxiliary property of material, called Raw Quantity (Q_R), is added to the database. This property is designated to temporarily hold the extracted quantities without any extra processes, and the converted quantity is transferred to the property of Quantity (Q) by adding equations into the database (Figure 3.6).

$$Q = f(Q_R) \tag{3.6}$$

$$Q = Q_R * f_u * (1 + f_w) * (1 + f_c) \tag{3.7}$$

$Q: Quantity$

$Q_R: Raw\ Quantity\ Without\ Processes$

$f_w: Material\ Waste\ Factor$

$f_c: Construction\ Factor$

$f_u: Unit\ Conversion\ Factor$

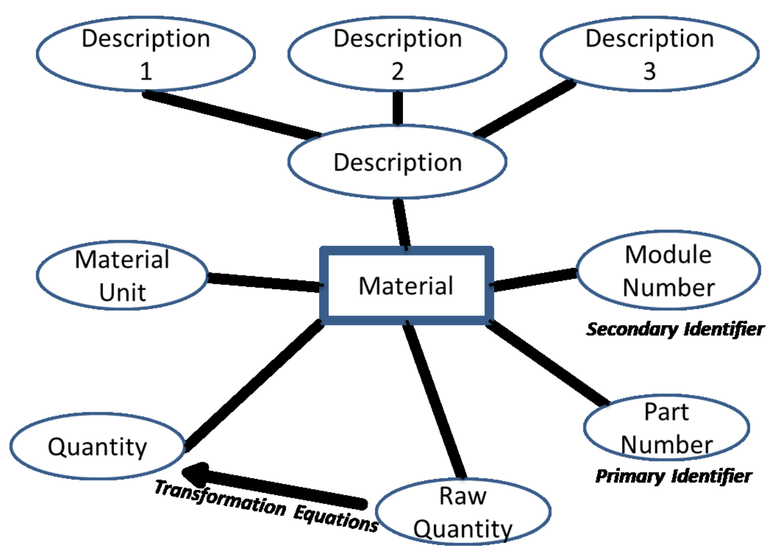


Figure 3.6: Database property structure.

3.1.3 Quantity Extraction

Once the BIM 3D model and database template are preloaded with the required information, the material quantities are ready to be extracted according to different categories (C1, C2, and C3).

All the materials in the BIM 3D model are collected, and the materials with the identical Part Number and Module Number are accumulated to generate the quantity, which is in turn imported to the database and assigned to the property of Raw Quantity.

For Category 1, the quantity is the sum of the material counts.

For Category 2, the material lengths ($l_{(p_i \,\&\, m_J)}$) are extracted and accumulated in order to obtain the quantity.

$$L_{(p_i \,\&\, m_J)} = \sum_{\substack{0 \le i < m \\ 0 \le j < n}} l_{(p_i \,\&\, m_J)} \tag{3.8}$$

For Category 3, the material areas ($a_{(p_i \,\&\, m_J)}$) are extracted and accumulated in order to obtain the quantity.

$$A_{(p_i \,\&\, m_J)} = \sum_{\substack{0 \le i < m \\ 0 \le j < n}} a_{(p_i \,\&\, m_J)} \tag{3.9}$$

p_i: $the\ part\ number\ of\ a\ material$

m_j: $the\ module\ number\ of\ a\ material\ belongs\ to$

m: $the\ quantity\ of\ different\ types\ of\ materials\ in\ the\ BIM\ 3D\ model$

$n: the\ quantity\ of\ modules\ in\ the\ BIM\ 3D\ model$

As the quantities are assigned to the property of Raw Quantity, the front-loaded formulas simultaneously calculate and transfer the processed values to Quantity, which is regarded as the final output of quantity takeoff.

3.2 Material Optimization

This section summarizes the proposed methodology to optimize both 1D (lumber) and 2D (sheathing) materials.

3.2.1 Lumber Optimization

Lumber is one of the most highly demanded materials in wood-based residential construction. Poor planning of lumber cutting is common in the industry, and results in a redundant cutting process that decreases project efficiency, generates unnecessary waste, and reduces profit. Therefore, this research proposes to optimize the utilization of lumber in the BIM software environment. As Figure 3.8 illustrates, the main objective of the methodology is a BIM 3D model with the walls framed by lumber. Two algorithms, *greedy* and *Simplex*, are applied to the model to optimize the lumber utilization with the same inputs and criteria. To clarify the optimization methodology, four terms are mentioned frequently in the following content, thus they need to be defined in advance.

- *Dimensional Lumber*: Lumber cut to standardized width and depth dimensions (see Figure 3.7(a)).

- *Regular Length* (L_R): Commercially available length of "Dimensional Lumber" (see Figure 3.7(a))

- *Lumber Piece*: The lumber existing in the structure of wall framings in the model, which is cut from dimensional lumber (3.7(b)).

- *Piece Length* (l_i): The length of "Lumber Piece".

Figure 3.7: Examples of dimensional lumber, regular length, and lumber pieces (Pekin Hardwood 2015; Build Your Own House 2011).

For the greedy algorithm, the lumber pieces in the model are collected and ranked by piece length (l_i), and only one type of dimensional lumber can be applied for optimization, so only one lumber length (L_R) is provided for the cutting task. The rule for the greedy algorithm is to preferentially cut the longest lumber pieces from the regular lumber. With respect to the Simplex algorithm, the collected lumber pieces are grouped and ranked by piece length (l_i), and more than one lengths (L_R) can be combined for the cutting task. The exhausted cutting patterns, unit costs of regular lumber, and extracted lumber pieces constitute a relationship of matrix representation, which is solved by the Simplex algorithm to generate a cutting plan with minimized material cost.

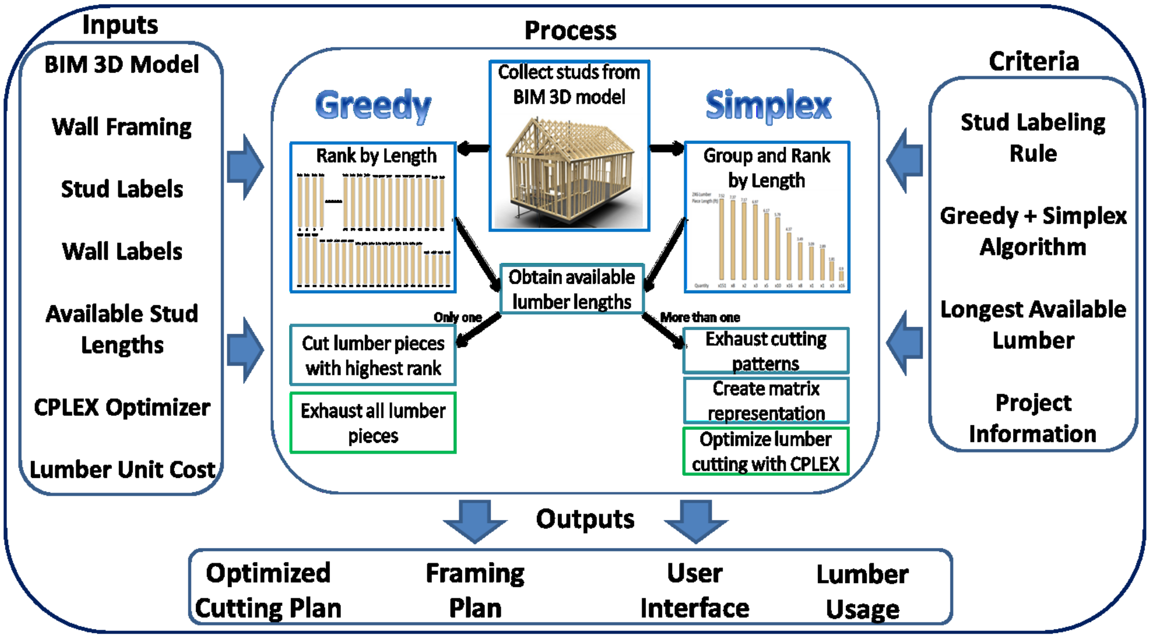


Figure 3.8: Overview of methodology of lumber optimization.

3.2.1.1 Greedy Algorithm

The greedy algorithm is a straightforward approach to optimize the cutting of studs. As the optimization starts, all the lumber pieces in the BIM model with identical base dimensions (e.g., 2x3, 2x4) are collected and placed in a virtual *Lumber Pool* (e.g., 2x3 pool, 2x4 pool). In each pool, lumber pieces are ranked by length in descending order (Figure 3.9). Only one regular length (L_R) can be used for cutting.

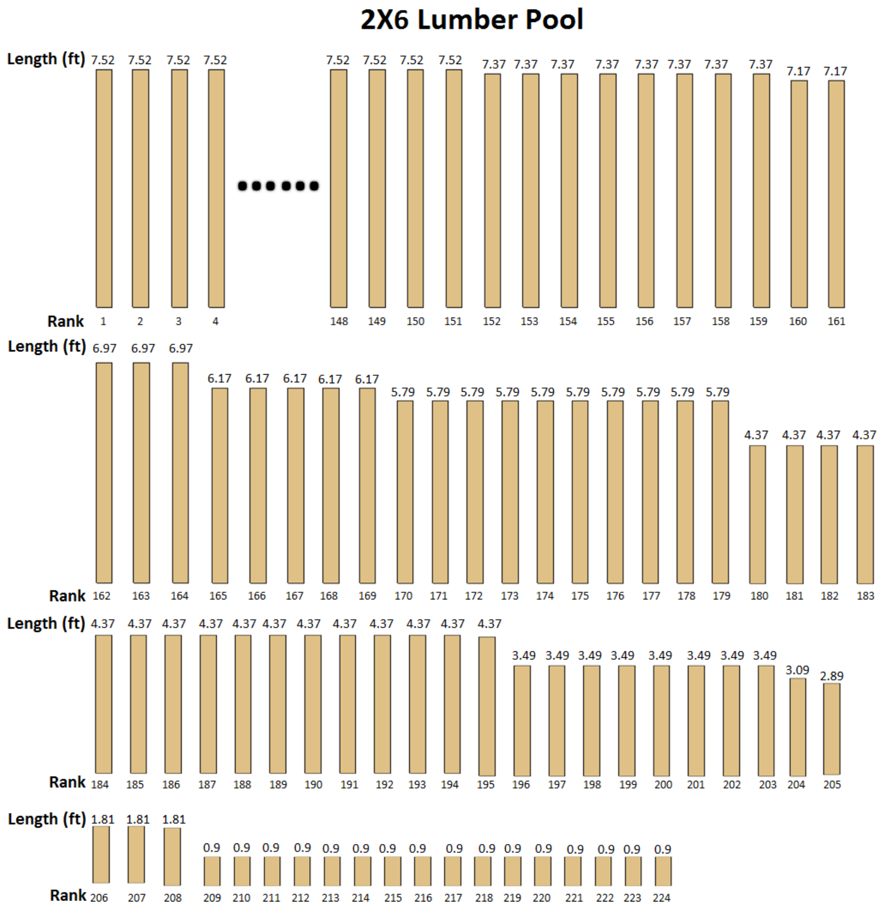


Figure 3.9: Virtual lumber pool (2x6).

Once all the lumber pieces (l_i) are collected in the pool, the lumber piece with the greatest length (l_1) is primarily selected to be cut from dimensional lumber, and the cut lumber piece is then removed from the pool; next, according to the length of the remaining part of the dimensional lumber, the current longest piece in the pool (i.e., the piece that uses the greatest length of remaining lumber) is then cut. If the remaining part of dimensional lumber is not long enough to hold the current longest piece, this lumber piece is skipped, and the same process is implemented on the following pieces successively. The process pauses when no pieces can be cut from the remaining portion of current dimensional lumber, which is regarded as waste. Thereafter, the lumber pieces left in the pool resume being cut from the next dimensional lumber, until the lumber pieces in the pool are exhausted. The flowchart of the lumber cutting process is pictured in Figure 3.10.

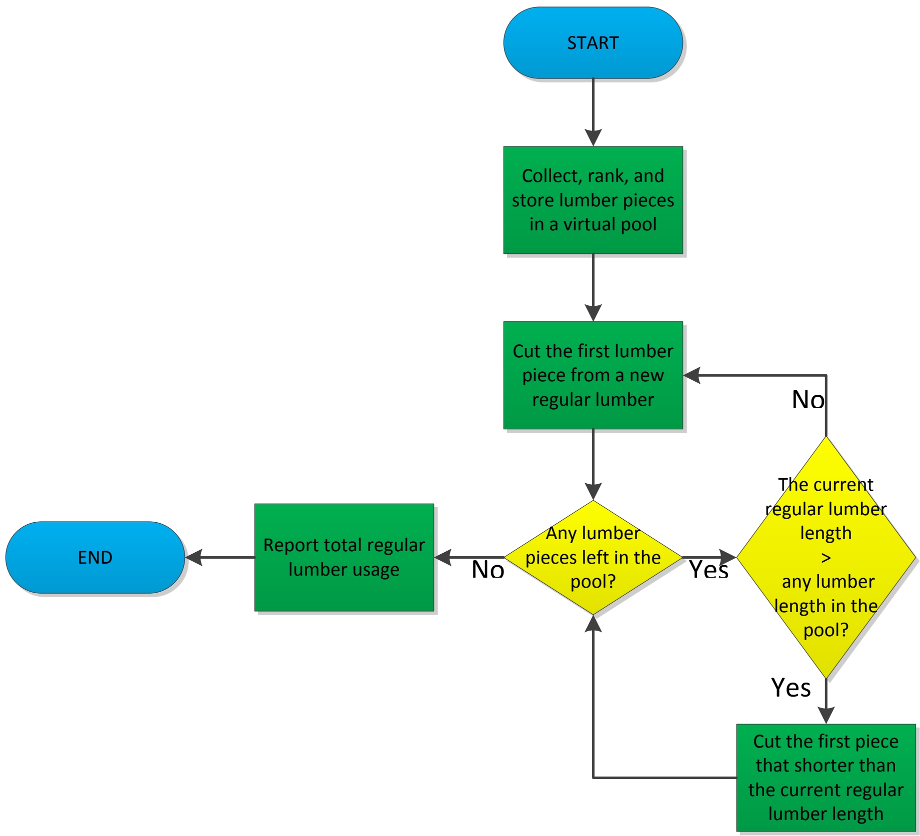


Figure 3.10: Flowchart of lumber cutting process.

The advantages of the greedy algorithm are that (1) independent from external optimizing software; and (2) the processing duration is negligible. The disadvantage, however, is the limited application: only one regular length can be input to optimize each base dimension of lumber. As a result, most generated cutting plans are not ultimately optimized.

3.2.1.2 Simplex Algorithm

Due to the limitation of the greedy algorithm, a more intelligent method is developed based on Simplex algorithm. The benefit of Simplex algorithm is the feasibility of combining multiple regular lengths, which improves the capability of producing an optimized cutting plan. While obtaining multiple regular lengths, the corresponding unit value or cost (v_i) is obligatory to be assigned to each piece of regular lumber, such that the objective is minimizing the sum of each product of lumber quantity and its unit value or cost. After obtaining the regular lengths and the respective values, the stock-cutting problem can be transformed to *Linear Programming Optimization* with matrix representation, which contains an objective function, coefficient matrix, constraints, target array, and decision variables.

The lumber pieces are collected and categorized in the same manner as the greedy algorithm, but where Simplex differs is that the lumber pieces in each lumber pool require further processing. This is achieved by grouping the lumber pieces by length and then ranking the groups in a descending order. The quantity of each lumber piece length is regarded as one element in a *Target Array* (A_T), which is a one-dimensional array containing N elements, and N herein represents the quantity of groups.

$$A_T = [q_1, q_2, q_3 \dots \dots q_{N-1}, q_N]$$

q_i: the quantity of the i^{th} length of lumber piece is demanded in the project

N: the number of tree structure levels or the lumber piece groups

Using the quantities derived from the grouped lumber pool in Figure 3.11, an example Target Array (A_T) is [151, 8, 2, 3, 5, 10, 16, 8, 1, 1, 3, 16].

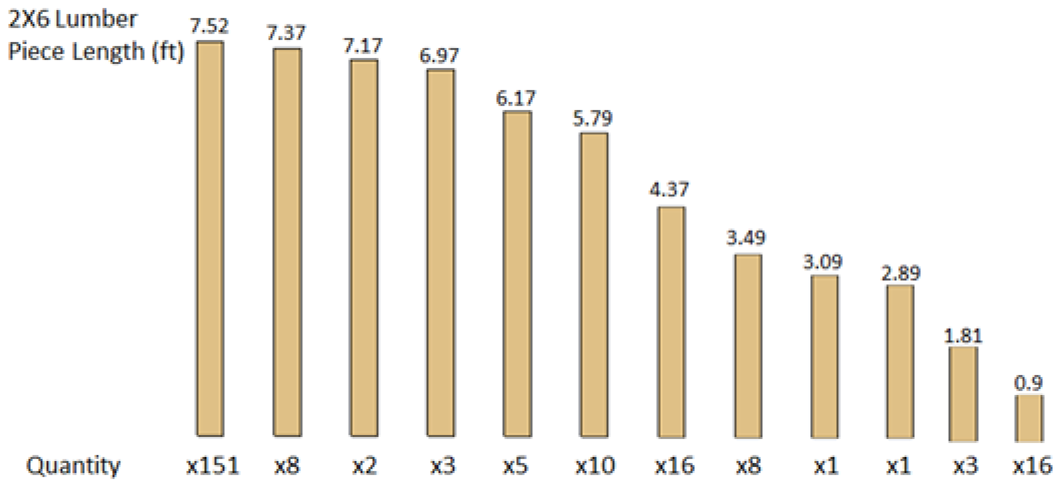


Figure 3.11: Grouped lumber pool (2x6).

Using the established quantities, all the possible cutting patterns need to be enumerated onto each regular length of lumber provided, and different cutting patterns are combined to ensure the quantities of cut pieces equalize or are beyond the corresponding demand of the collected lumber pieces (Target Array). In order to exhaust all the cutting patterns, the tree structure method is implemented (Figure 3.12).

The tree structure has multiple levels of node and branch, and each level holds one lumber piece length (l_i); longer pieces are found higher on the structure level and shorter pieces, proportionately, are found lower on the structure level. Therefore, the number of levels (N) should be equal to the number of lumber groups or the elements in a Target Array. Each tree starts from a top node, which represents a regular length (L_R). Each branch represents the quantity of instances

(n_i) of the lumber piece belonging to this level are cut, and the remaining part of the regular length (L_R) is passed down to the next node. Each node holds a number equals to the remaining length (L_R) of a dimensional lumber after a certain cut from the upper branches. A dimensional lumber may have more than one ($n_i = 0, 1\ldots [\frac{L_R}{l_i}]$) cutting instance at any level, and in this situation, a node can have more than one branch except for the lowest level node, which has only one branch; correspondingly, the remaining portion of regular lumber from the upper level is cut into the shortest length for as many pieces as possible, because the remaining portion after the lowest level is then regarded as waste.

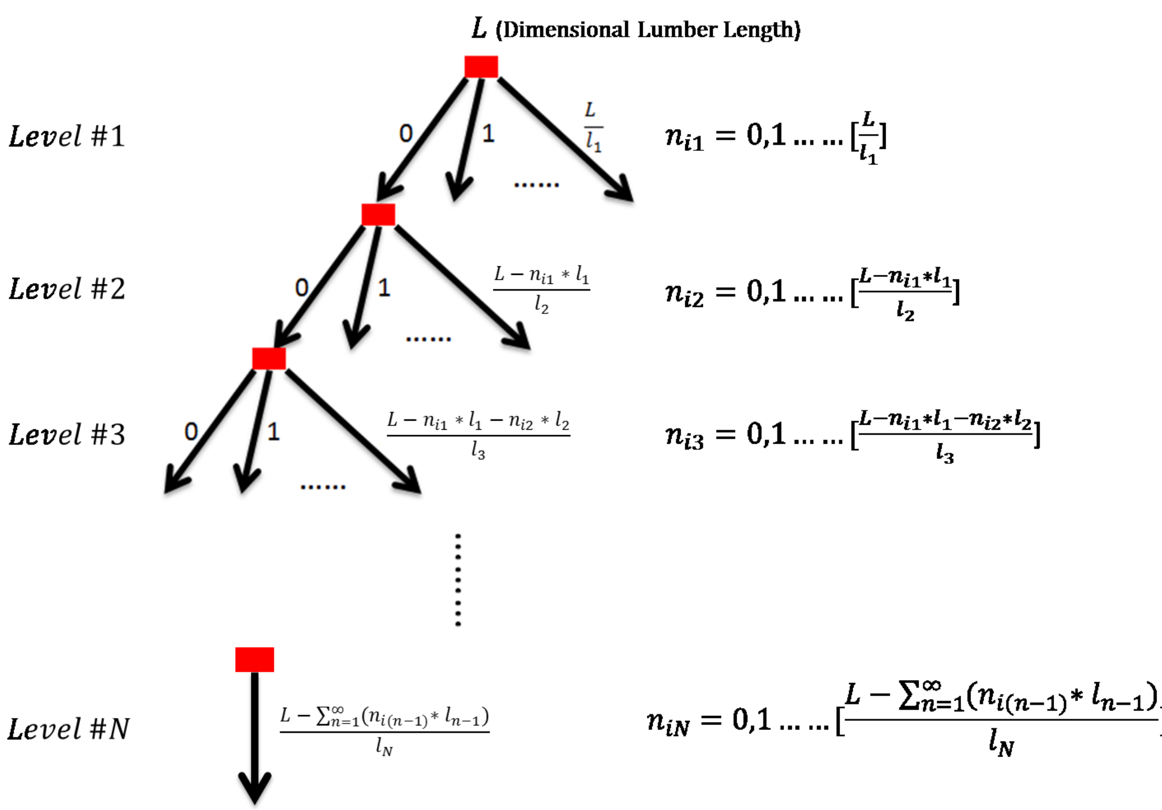


Figure 3.12: Tree structure.

The quantities of instances from each branch are gathered to form one cutting pattern, which is represented as an integer array (A_i)

$$A_i = [n_{i1}, n_{i2}, n_{i3} \dots \dots n_{i(N-1)}, n_{iN}]$$

M: quantity of total cutting pattern

A_i: the i^{th} cutting pattern from tree structure, i = 1, 2, 3……M

n_{ij}: the quantity of j^{th} lumber piece is cut in i^{th} cutting pattern, j = 1, 2, 3…N, i = 1, 2, 3……M

The collection of all the arrays becomes an M by N matrix, M represents the quantity of total cutting patterns, and N represents the quantity of different lumber piece lengths.

$$Array1 = [n_{11}, n_{12}, n_{13}, n_{14} \dots \dots n_{1(N-3)}, n_{1(N-2)}, n_{1(N-1)}, n_{1N}]$$

$$Array2 = [n_{21}, n_{22}, n_{23}, n_{24} \dots \dots n_{2(N-3)}, n_{2(N-2)}, n_{2(N-1)}, n_{2N}]$$

● ● ● ● ● ●

$$ArrayM = [n_{M1}, n_{M2}, n_{M3}, n_{M4} \dots \dots n_{M(N-3)}, n_{M(N-2)}, n_{M(N-1)}, n_{MN}]$$

$$\begin{bmatrix} n_{11} & n_{12} & n_{13} & & n_{1(N-2)} & n_{1(N-1)} & n_{1N} \\ n_{21} & n_{22} & n_{23} & \cdots & n_{2(N-2)} & n_{2(N-1)} & n_{2N} \\ n_{31} & n_{32} & n_{33} & & n_{3(N-2)} & n_{3(N-1)} & n_{3N} \\ & \vdots & & \ddots & & \vdots & \\ n_{(M-2)1} & n_{(M-2)2} & n_{(M-2)3} & & n_{(M-2)(N-2)} & n_{(M-2)(N-1)} & n_{(M-2)N} \\ n_{(M-1)1} & n_{(M-1)2} & n_{(M-1)3} & \cdots & n_{(M-1)(N-2)} & n_{(M-1)(N-1)} & n_{(M-1)M} \\ n_{M1} & n_{M2} & n_{M3} & & n_{M(N-2)} & n_{M(N-1)} & n_{MN} \end{bmatrix}$$

To implement the Simplex method, the *M* by *N* matrix needs to be transposed to an *N* by *M* matrix; in other words, these integer arrays are placed vertically, and the new matrix is called *Coefficient Matrix*. A decision variable is also required to solve the whole problem, and it should be represented by an array with *M* elements. Each element in this array means the quantity of dimensional lumber used to be cut in the corresponding manner.

$$A_d = [x_1, x_2, x_3 \ldots \ldots x_{M-1}, x_M]$$

A_d: Decision Variable Array

In the meantime, a *Coefficient Array* is also formed by the lumber unit value or cost (v_i).

$$A_c = [v_1, v_2, v_3 \ldots \ldots v_{M-1}, v_M]$$

A_c: Coefficient Array

The relation between the *Coefficient Matrix*, *Decision Variable Array* and *Target Array* is shown below.

$$Coefficient\ Matrix \times Decision\ Variable\ Array \geq Target\ Array$$

$$\begin{bmatrix} n_{11} & n_{12} & n_{13} & & n_{1(N-2)} & n_{1(N-1)} & n_{1N} \\ n_{21} & n_{22} & n_{23} & \cdots & n_{2(N-2)} & n_{2(N-1)} & n_{2N} \\ n_{31} & n_{32} & n_{33} & & n_{3(N-2)} & n_{3(N-1)} & n_{3N} \\ & \vdots & & \ddots & & \vdots & \\ n_{(M-2)1} & n_{(M-2)2} & n_{(M-2)3} & & n_{(M-2)(N-2)} & n_{(M-2)(N-1)} & n_{(M-2)N} \\ n_{(M-1)1} & n_{(M-1)2} & n_{(M-1)3} & \cdots & n_{(M-1)(N-2)} & n_{(M-1)(N-1)} & n_{(M-1)M} \\ n_{M1} & n_{M2} & n_{M3} & & n_{M(N-2)} & n_{M(N-1)} & n_{MN} \end{bmatrix}^T \times \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_{M-2} \\ x_{M-1} \\ x_M \end{bmatrix} \geq \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ \vdots \\ q_{N-2} \\ q_{N-1} \\ q_N \end{bmatrix} \quad (3.10)$$

The final goal is to provide an optimized cutting scenario to minimize the total material cost, which is represented by the objective function.

$$Minimizing: x_1 * v_1 + x_2 * v_2 + x_3 * v_3 + \cdots + x_{M-1} * v_{M-1} + x_M * v_M$$

Some piece lengths are longer than the longest dimensional lumber, for example, top and bottom plates are always as long as the modular, which could easily be 72 ft in length. In this optimization, these oversized lumbers are not considered. Based on research's knowledge, different companies have different approaches to obtain these lumbers, and many choose to purchase finger joint lumber or special lumber directly from the supplier without any specific processing in the factory.

3.2.1.3 Algorithm Comparison

The lumber optimization problem can be solved by both of the algorithms, Greedy and Simplex. Greedy will be the primary algorithm to be applied in the industry, since the theory is easily to be implemented by codes compilation and the processing time is negligible. The limitation of Greedy is that only one type of regular lumber is allowed to be applied for cutting process and the most of results are not fully optimized. However, Simplex algorithm can overcome the limitation by integrating multiple types of regular lumbers, and it is capable to provide an exactly optimized solution. Hence it is suitable for scientific purpose. The disadvantage of Simplex is the need of external optimizer, and the processing time becomes unacceptable for large data set (Table 3.1).

Table 3.1 Greedy and Simplex algorithms comparison

	Advantage	Disadvantage
Greedy	1. Easy to compile 2. Negligible processing time	1. Result is not fully optimized 2. Only one type of regular lumber can be considered for cutting
Simplex	1. Fully optimized result 2. Feasible to integrate multiple types of regular lumbers	1. Need of external library 2. Long processing time for large data set

3.2.2 Sheathing Optimization

In wood frame residential construction, sheathing is utilized almost as widely as is lumber. Furthermore, the sheathing cutting process (2D) is more complicated and prone to waste than is lumber cutting (1D). Hence, this research proposes a methodology to facilitate the sheathing cutting process in order to enhance sheathing usage by integrating the BIM software with an optimization algorithm. In this research, the methodology is developed in the environment of Autodesk Revit, which is a widely utilized BIM software for architectural and structural drawing.

However, efforts to optimize sheathing usage face two main obstacles: (1) the Revit 3D model does not have a visible component to represent sheathing, such that the sheathing information is only accessible by further investigating the host element (e.g., wall, floor, and roof) of sheathing; and (2) Revit is configured to regard sheathing and other area materials (such as gypsum board) as whole pieces, where the area of material is equal to the closed area of the host object. This configuration is unable to account for actual construction. Furthermore, the model does not show the seams between two adjacent sheathing pieces, i.e., the sheathing layout on the wall framing.

As Figure 3.13 illustrates, the sheathing pieces are visualized and installed on the wall framing in the model based on the wall configuration and stud locations, and the installed sheathing pieces are collected, reoriented, and ranked. Moreover, the organized sheathing pieces are cut from a certain dimension of regular sheathing by following the greedy and bottom-left heuristic algorithms. As a result, the realistic sheathing usage and optimized cutting plan are exported. A precondition for placing and visualizing sheathing, which is also a requirement for lumber optimization, is that the framing of the walls must be completed in the model prior to carrying out the material optimization. Based on the wall framing, sheathing placement can be achieved.

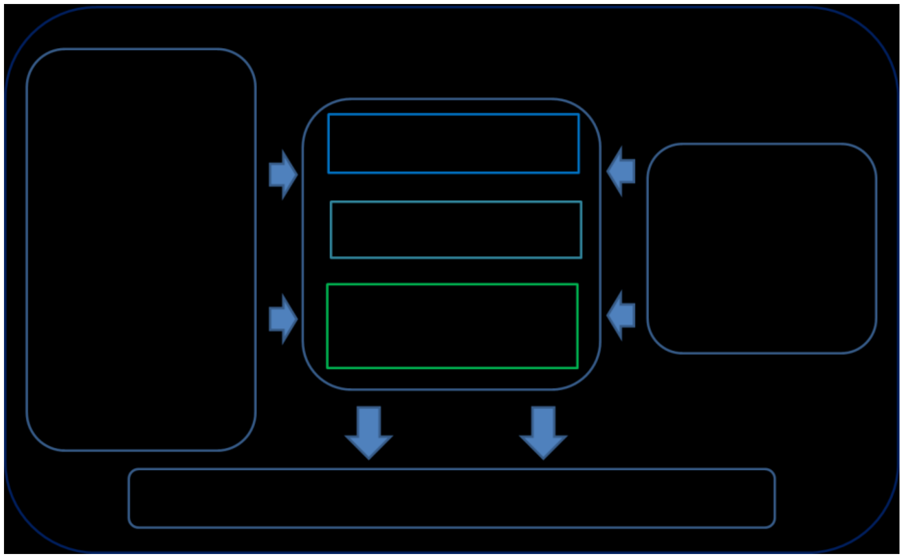


Figure 3.13: Overview of methodology of material optimization.

The following real-life rules are considered in designing the virtual sheathing placement:

- The sheathing is rectangular in shape.
- Space sheathing pieces ⅛-inch apart on all four edges and ⅛-inch away from window and door opening frames.
- The sheathing could be installed vertically or horizontally; in this research, the placing orientation is set to vertical to cover the main body of the wall framing.
- The bottom plates and top plates of wall framing are covered by sheathing.
- Each sheet of sheathing begins at one stud and ends at another stud; in other words, lumber can be nailed in order to fasten on at least two edges of each sheet of sheathing.

To visualize the sheets of sheathing in the model, a new Revit family of *sheathing* is created (Figure 3.14). The sheathing family has five important parameters:

- *Height*: height of sheathing.
- *Length*: length of sheathing.
- *Label*: the label located at the center of sheathing, and is visible from both sides.
- *Locator*: the point on the bottom-inside corner of the sheathing nearer to the framing point, which can be assigned three-dimensional coordinates in order to locate the sheathing on the wall framing.
- *Host*: the wall onto which sheathing is installed.

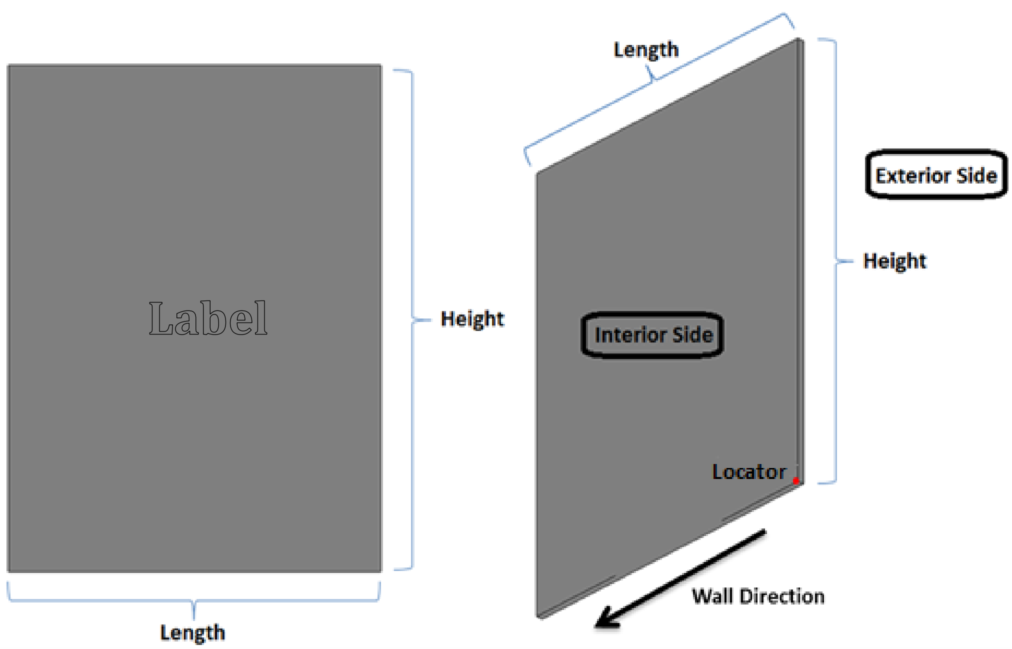


Figure 3.14: Revit family—sheathing.

So far, two sheathing terms are referred to in this research, and both terms need to be specified to avoid ambiguity:

- *Regular Sheathing* (*length*: L_R, *height*: H_R) represents the stocked sheathing with nominal dimensions, and they have not been cut.
- *Sheathing Piece* (*length*: l_i, *height*: h_i) means sheathing framed on the wall. The created Revit sheathing family framed on the wall in the model is the Sheathing Piece.

Since the sheathing is available in the Revit model, the primary task is to determine where to locate it. In space geometry, one point and two vectors are able to locate a 3D object (Figure 3.15), and in this research, the identical principle is applied to locate the sheathing piece.

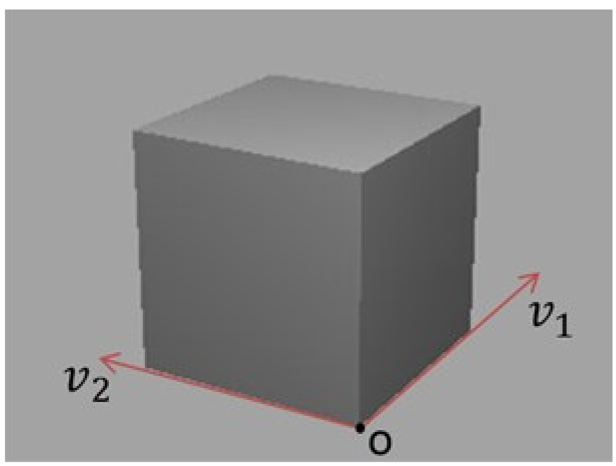


Figure 3.15: A 3D object can be located by one point and two vectors.

The two vectors are apparently the wall direction (horizontal) and the vertical direction (all wall sheathing will be installed vertically, i.e., perpendicular to the floor). Determining the *Start Point*, which is coterminous with *Location*, is the key challenge in locating sheathing. Typically a wall bears more than one sheet of sheathing, so more than one Start Point is present on a wall. The first Start Point is referred to as the *Framing Point*, and it is the most important and difficult to determine. After obtaining the Framing Point, the remaining Start Points can be calculated based on the lengths and heights of the preceding sheathing and the wall direction. In general, the Framing Point is always one of two bottom corners of the outer face of the wall framing, depending on which direction the drafter draws the wall (Figure 3.16).

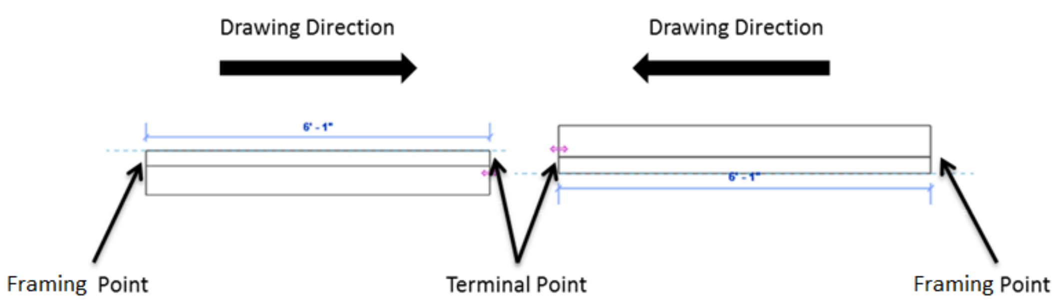


Figure 3.16: Wall direction decided by drawing direction.

For example, if the drafter draws the wall from left to right, the Framing Point of the wall is the left-bottom corner in the front view of the wall, and the *Terminal*, which refers to the end point of the last piece of sheathing on this wall, is the right corner, and vice versa. Figure 3.17 shows two possible Framing Points.

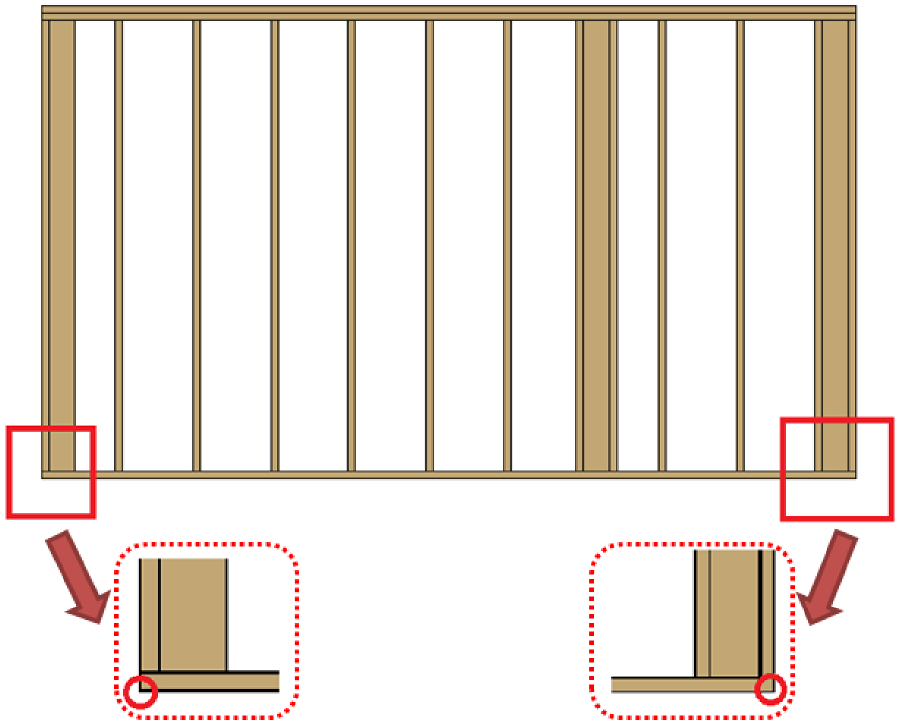


Figure 3.17: Two possible Framing Points of a wall framing.

To determine the Framing Point, wall joint modification is always required. The default wall joint in Revit is *Butt* (Figure 3.18), which means at the intersection of two walls, the wall corner belongs to one of the two walls only, and there is no mutual part between two walls. Although this joint type shows the realistic view, it does not meet the sheathing placement condition. For example, lumber *A* in Figure 3.18 ends at the left side of lumber *B*, but the sheathing on the horizontal wall in reality should stop at the right bottom point of lumber *B*, so the wall joint type should be modified to *Miter*, a joint type where two walls share a corner equally by forming triangular shapes (Figure 3.19).

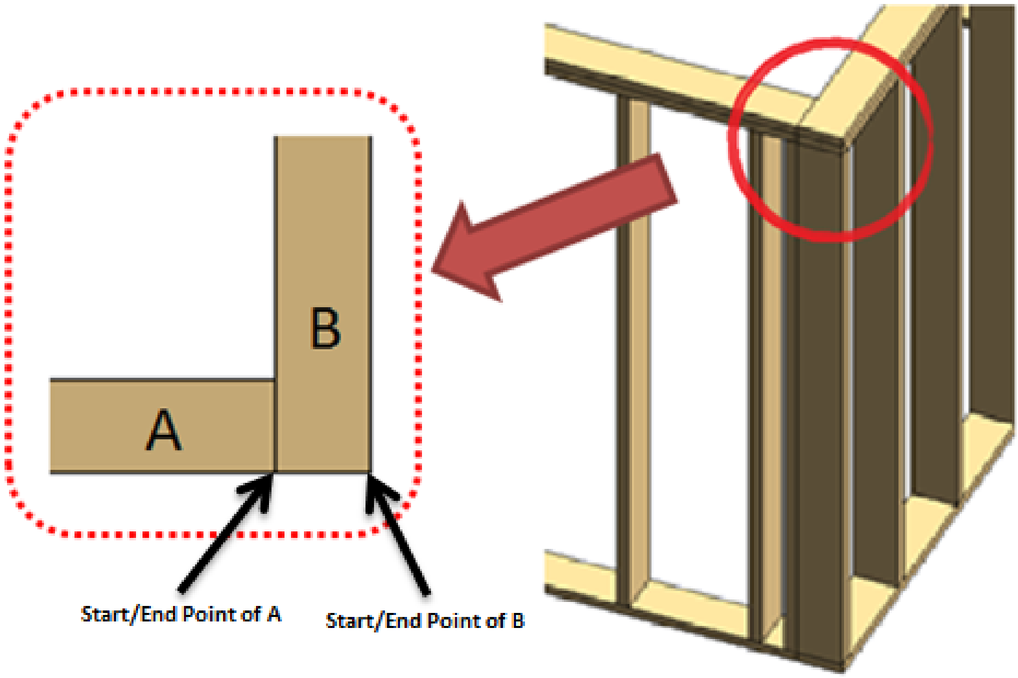


Figure 3.18: *Butt* wall joint type.

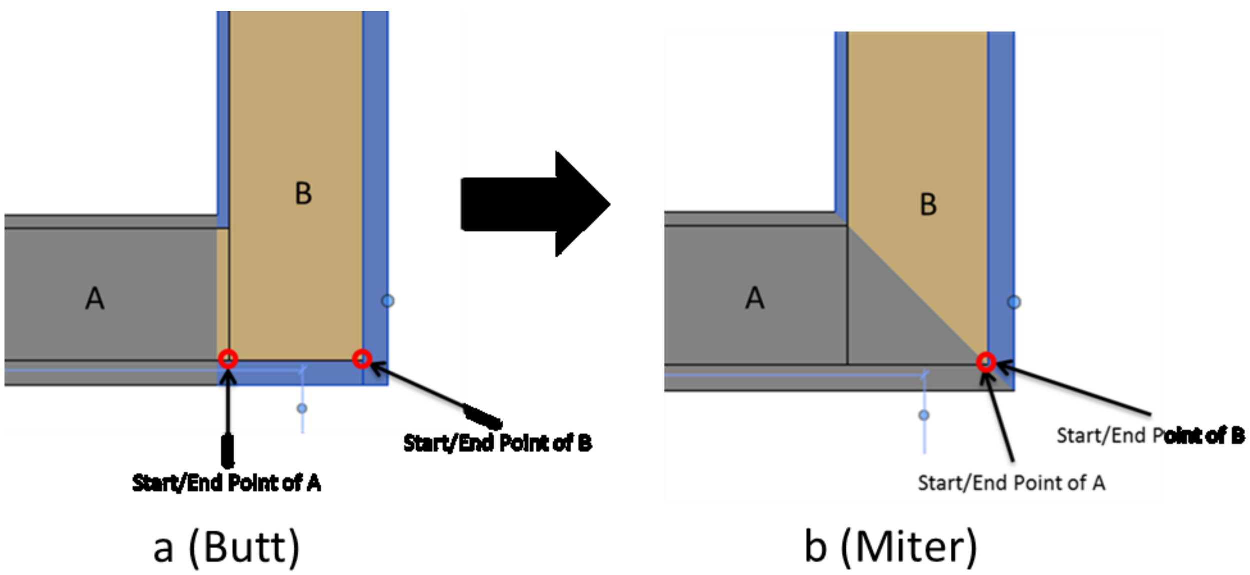


Figure 3.19: Modify *Butt* wall joint to *Miter*.

Even at this step, it is still not practical to obtain the Framing Point directly with Revit functions. However, further investigation shows that the Framing Points of wall and wall framing are perfectly matching after overlapping them (Figure 3.20 and Figure 3.21), and this feature leads to the optimal approach to determine the Framing Point.

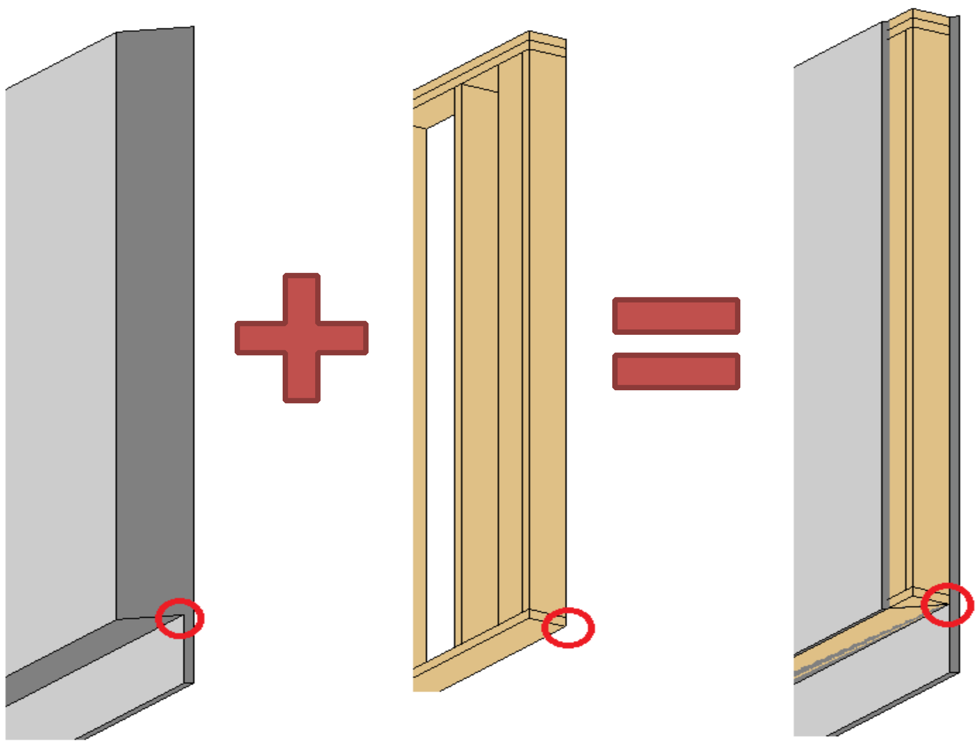


Figure 3.20: The overlap of wall and wall framing; Framing Points are identical and circled in red.

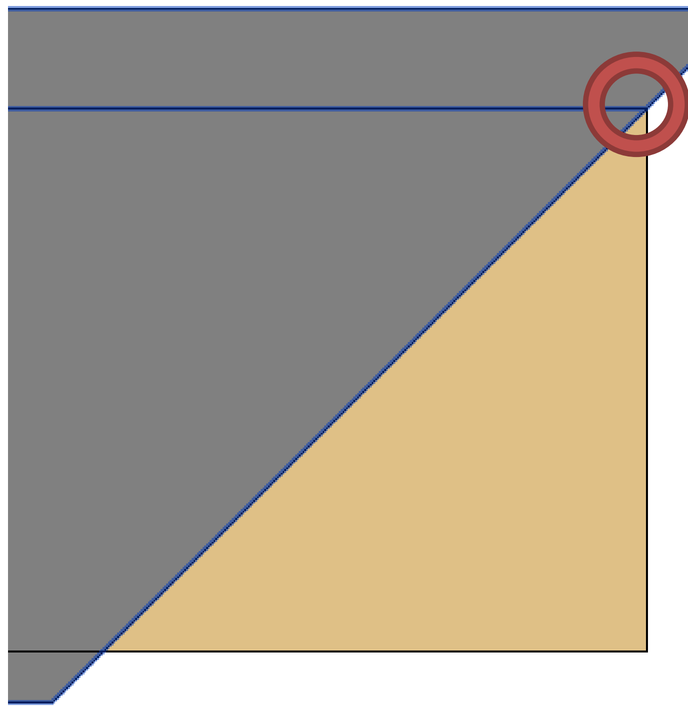


Figure 3.21: Top view of the overlap of wall and wall framing; Framing Point is circled in red.

Some pertinent wall layer relationships are also discovered, and point coordinates (Figure 3.22) and wall layer thicknesses (Figure 3.23) are accessible from Revit. All are essential to derive the three dimensional coordinate of the Framing Point. Based on the gathered information, the Framing Point can be calculated by means of analytically.

- *Mid Point* (M_x, M_y, M_z): Centre point of the bottom intersection line of two walls (accessible from Revit).
- *Exterior Point* (E_x, E_y, E_z): Bottom corner point of exterior face of a wall (accessible from Revit).

- *Interior Point* (I_x, I_y, I_z): Bottom corner point of interior face of a wall (accessible from Revit).

- *Total Layer* (T_t): Total layer thickness (accessible from Revit).

- *Interior Layer* (T_i): Interior layer thickness (Structure layer + Inner side layers of structure layer) (accessible from Revit).

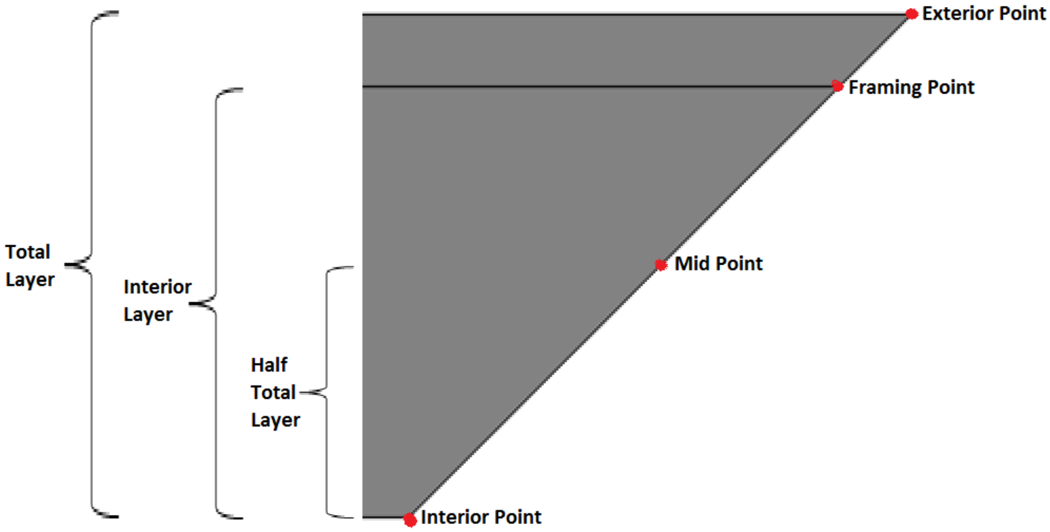
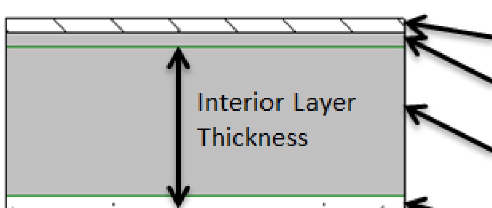


Figure 3.22: Highlight of wall bottom corner.



	Function	Material	Thickness
1	Finish 1 [4]	SIDING - ANITIQUE IVO	0' 0 1/2"
2	Membrane La	Building Wrap	0' 0"
3	Substrate [2]	SHEATHING OSB - 15/3	0' 0 1/2"
4	**Core Boundary**	**Layers Above Wrap**	**0' 0"**
5	Structure [1]	Wood - Stud	0' 5 1/2"
6	**Core Boundary**	**Layers Below Wrap**	**0' 0"**
7	Membrane La	Vapor / Moisture Barrier	0' 0"
8	Finish 2 [5]	Gyproc - Drywall - 1/2"	0' 0 1/2"

Figure 3.23: Wall layers with thicknesses.

Since the placement of sheathing always starts from the floor level, which means the *Z-axis* of all the Framing Points is *0*, only the *X-axis* and *Y-axis* need to be calculated to locate the Framing Point. The required values can be obtained by implementing Revit API functions, and *Triangle Proportionality* is utilized to calculate the coordinates of the Framing Point (F_x, F_y, F_z).

$$F_x = I_x + \frac{2\times(M_x - I_x)}{T_t} \times T_i \tag{3.11}$$

$$F_y = I_y + \frac{2\times(M_y - I_y)}{T_t} \times T_i \tag{3.12}$$

$$F_z = I_z = M_z = 0 \tag{3.13}$$

After obtaining the Framing Point, the succeeding Start Points can be calculated based on this Framing Point and sheathing height, length, and wall direction. In addition, it is imperative to understand the basic components and dimensions of a typical wall framing (Figure. 3.24) in order to further investigate the sheathing placement.

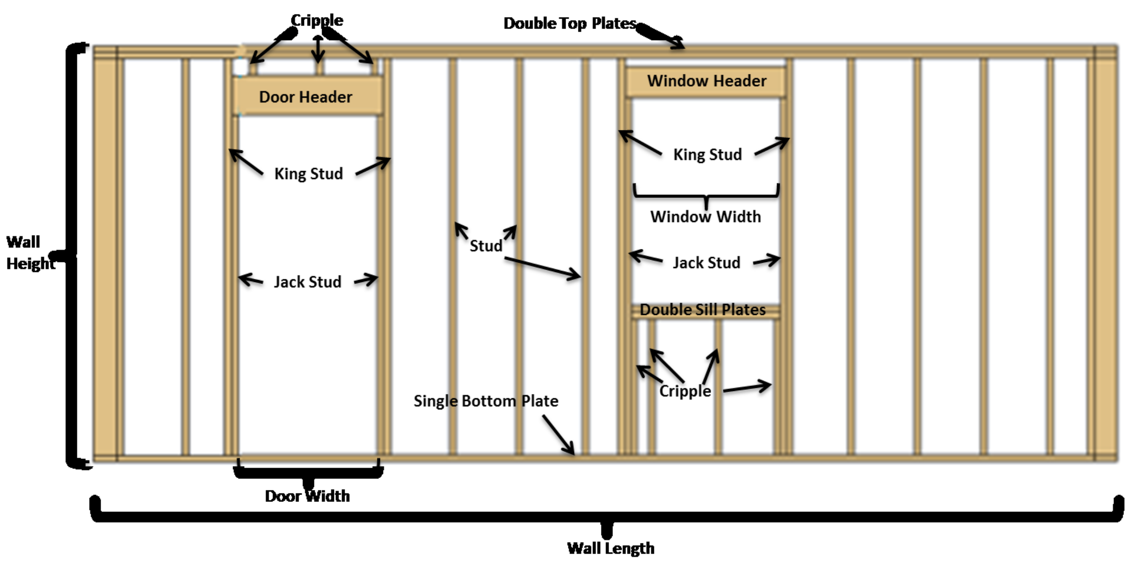


Figure 3.24: Components and dimensions of wall framing.

H_w: $Wall\ Framing\ Height$

L_w: $Wall\ Framing\ Length$

W_{di}: $Width\ of\ ith\ Door\ Framing$

W_{wi}: $Width\ of\ ith\ Window\ Framing$

H_{dji}: $Jack\ Stud\ Height\ of\ ith\ Door\ Framing$

H_{dki}: $King\ Stud\ Height\ of\ ith\ Door\ Framing$

H_{wji}: $Jack\ Stud\ Height\ of\ ith\ Window\ Framing$

H_{kwi}: $King\ Stud\ Height\ of\ ith\ Window\ Framing$

H_{wci}: $Cripple\ Height\ of\ ith\ Window\ Framing$

H_{dci}: $Cripple\ Height\ of\ ith\ Door\ Framing$

T_{dspi}: $Double\ Sill\ Plates\ Thickness\ of\ ith\ Window\ Framing$

T_{sbp}: $Single\ Bottom\ Plate\ Thickness\ of\ Wall\ Framing$

Z: $Bottom\ Face\ Level\ of\ Single\ Bottom\ Plate$ ("0" $for\ all\ single\ storey\ modules$)

To place the sheathing on the wall framing, the window and door framing components are differentiated from the regular wall framing. For the window and door framing, the height of sheathings is set to strictly cover the door's upper framing and window's upper and lower framings (Figure 3.25); the corresponding heights are shown below.

Sheathing height above the ith door: $h_i = H_w - T_{sbp} - H_{dji}$ (3.14)

Sheathing height above the ith window: $h_i = H_w - T_{sbp} - H_{wji}$ (3.15)

Sheathing height below the ith window: $h_i = H_{wci} + T_{sbp} + T_{dspi}$ (3.16)

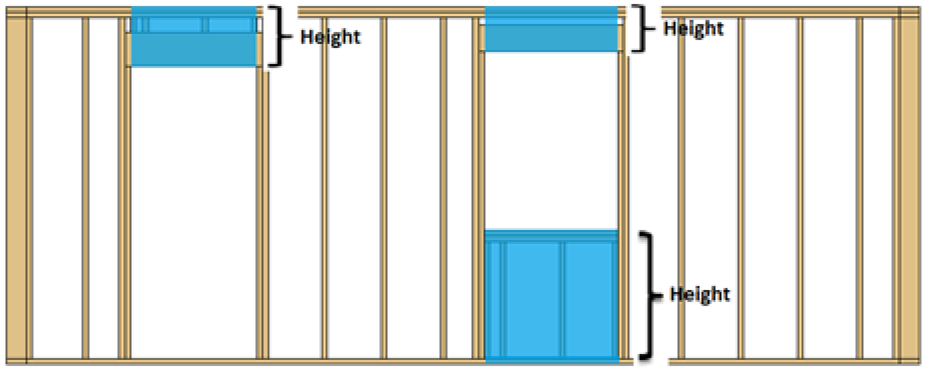


Figure 3.25: Height determination rule (window and door).

After the window and door framing parts are covered by sheathing, the rest of the wall is regarded as the wall without windows or doors, and the height determination rules are shown below.

- If a wall height is lower than the nominal height of regular sheathing, which means only one sheathing can cover the whole height of the wall, the height of the sheathing is the height of the wall (Figure 3.26).

  - Sheathing height: $h_i = H_w$ (if $H_R \geq H_w$) (3.17)

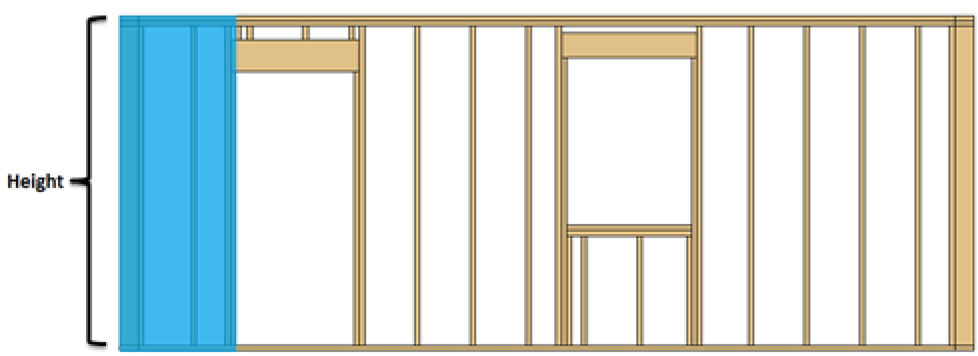


Figure 3.26: Height determination rule (sheathing height is higher than wall height).

- If a wall height is higher than the nominal height of regular sheathing, at least two pieces of sheathing are needed to cover the whole wall height; the lower part is the full height of regular sheathing, and the height of the upper part is the remaining wall height (Figure 3.27).

$$\text{Upper Sheathing height: } h_i = H_w - H_R \text{ (if } H_R < H_w\text{)} \quad (3.18)$$

$$\text{Lower Sheathing height: } h_i = H_R \text{ (if } H_R < H_w\text{)} \quad (3.19)$$

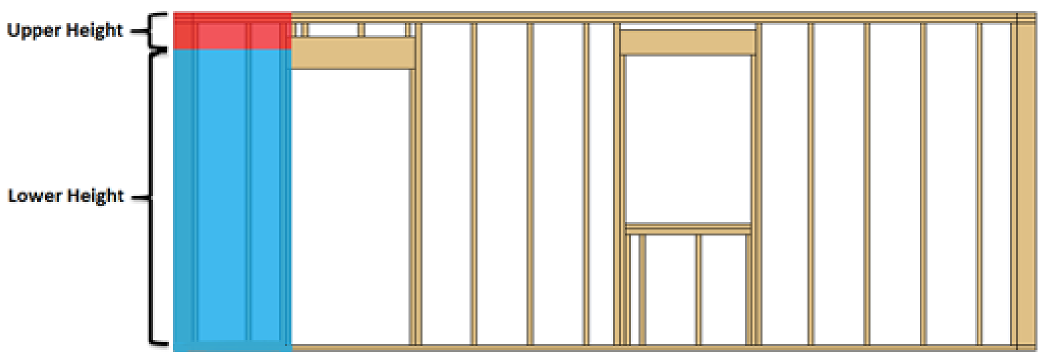


Figure 3.27: Height determination rule (sheathing height is lower than wall height).

Since wall length is most often longer than wall height, the determination of sheathing length is apparently more complicated. In this situation, the sheathing lengths of the framing portions above a door opening and above and below a window opening are determined primarily, which are the respective window and door widths (see SH3, SH4, and SH5 in Figure 3.30). Subsequently, (the distance of) two points are utilized to determine the sheathing length for the main body of the wall framing; one point is Start Point, and the other is *End Point*, which is the location at which the placed sheathing is cut, and the End Point must be at the center or edge of a stud to accommodate nails for fixation. The End Point is also decided by the categories of studs, which is shown below (Figure 3.28).

- *EV*: Two and only two studs at both ends of a wall framing.
- *SV*: The most common studs in a wall framing, and they do not contact any other studs.
- *JSD*: Door jamb studs, locates below door headers.
- *JSW*: Window jamb studs, locates below window headers.
- *SD*: Door king studs.
- *SW*: Window king studs.
- *SJOIN*: A combination of three studs for perpendicular connection with other wall framings, and each is labeled SJOIN (Figure 3.29).

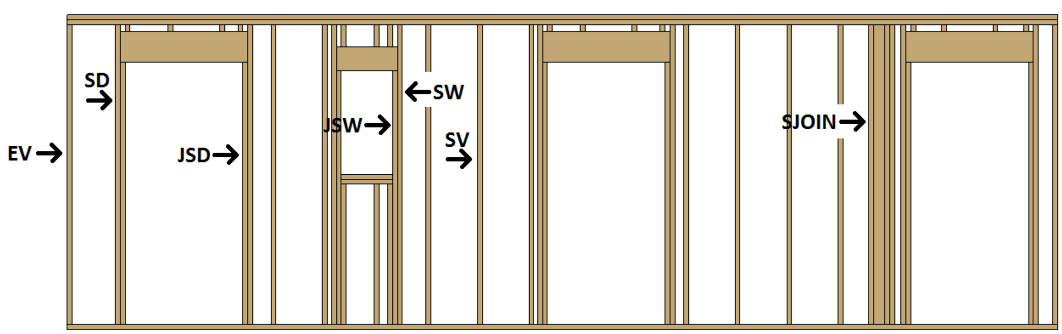


Figure 3.28: Stud categories.

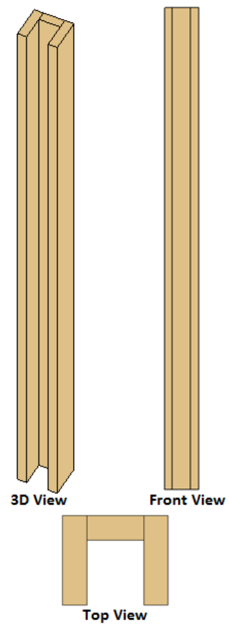


Figure 3.29: Highlight of SJOIN studs.

All the studs are divided into two groups according to the category. *Group 1* incorporates the studs of EV, JSD and JSW, and the End Point of Group 1 is located at the far bottom corner in order to cover the whole width of the stud placed with the sheathing. *Group 2* consists of SV, SD, SW and two parallel SJOIN studs are in the second group. The End Point of Group 2 is located at the center of the studs as the Group 2 stud is invariably shared by two pieces of sheathing on both sides.

The first piece of sheathing starts from the Framing Point and terminates at the next End Point of Group 1 on the occasion that the distance between two points is shorter than the nominal length of regular sheathing. If this condition is not satisfied, this piece of sheathing is shortened to an End Point of Group 2, which results in various possible distances. Among all the distances, the lengths greater than regular sheathing length are filtered out, and the greatest length is selected from the refined distances to be the length of this piece of sheathing.

$$l_i = \begin{cases} D_1, & D_1 \le L_R \\ D_2, & D_1 > L_R \end{cases} \tag{3.20}$$

D_1: Distance between the current Start Point and the closest Group 1 End Point following the wall direction.

D_2: Distance between the current Start Point and the furthest Group 2 End Point following the wall direction, where distance always has a value less than the regular sheathing length.

Under certain circumstances, the wall height is higher than the nominal height of regular sheathing (see SH6, SH7 and SH8 in Figure 3.30), thus another level of sheathing is required to cover the upper part of framing, which is usually more narrow than the regular sheathing f nominal length; consequently, the sheathing is placed horizontally (see SH9, SH10 in Figure 3.30).

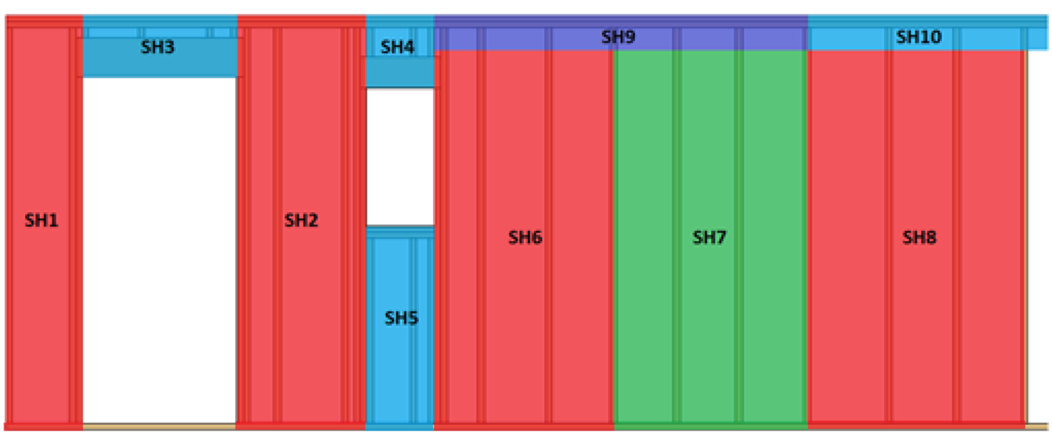


Figure 3.30: Sheathing length determination.

So far, Framing Point, sheathing lengths, and sheathing heights are available, and the information is sufficient to fulfill the placement of the first sheathing on the wall framing. The succeeding sheathing placement always starts from a Start Point (P_x, P_y, P_z), which can be generated from a previous Start Point (p_x, p_y, p_z) and the configuration of the previous sheathing, such as height (h_i) and length (l_i), and the host wall direction (r_x, r_y, r_z). Different approaches are implemented to determine new Start Points dealing with different conditions.

- If sheathing placement does not associate with doors or windows, the new Start Point is always the sheathing bottom corner which locates farther from the Framing Point (Figure 3.31).

$$P_x = L_i * r_x + p_x \tag{3.21}$$

$$P_y = L_i * r_y + p_y \tag{3.22}$$

$$P_z = L_i * r_z + p_z \tag{3.23}$$

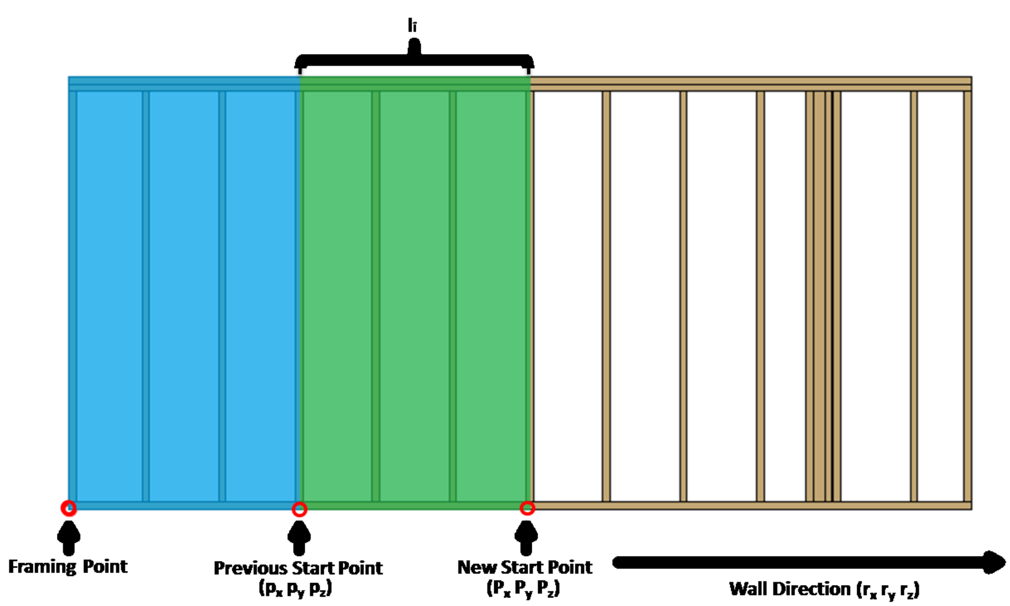


Figure 3.31: Start Point determination (wall without window or door).

- If sheathing is cut off along the edge of a jack stud of a door (JSD), two new Start Points are generated. The *New Start Point 1* (P_x, P_y, P_z) is located below the other JSD with the same *z-coordinate* value ($P_z = p_z$) in order to continue sheathing placement on the main wall framing (Figure 3.32).

$$P_x = (l_i + W_{di}) * r_x + p_x \tag{3.24}$$

$$P_y = (l_i + W_{di}) * r_y + p_y \tag{3.25}$$

$$P_z = (l_i + W_{di}) * r_z + p_z \tag{3.26}$$

The *New Start Point 2* (P_x, P_y, P_z) locates the current JSD tip point, which is farther from the Framing Point (Figure 3.32), and this Start Point commences the sheathing placement above the door opening.

$$P_x = l_i * r_x + p_x \tag{3.21}$$

$$P_y = l_i * r_y + p_y \tag{3.22}$$

$$P_z = l_i * r_z + p_z + H_{dji} \tag{3.27}$$

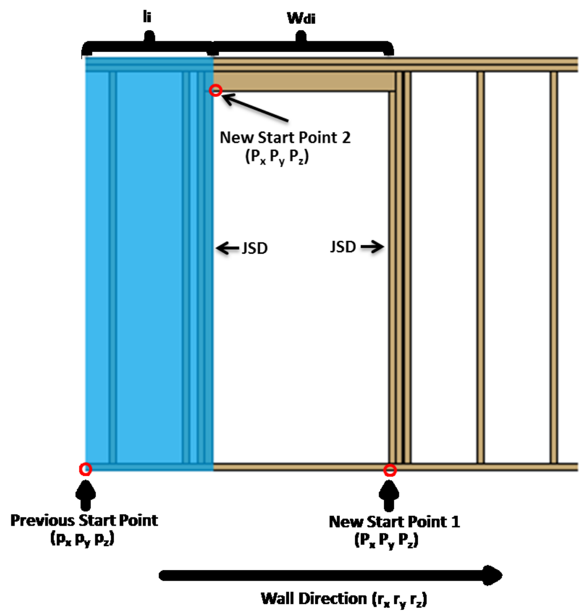


Figure 3.32: Start Point determination (door).

- If sheathing is cut off along the edge of a jack stud of a window (JSW), three new Start Points are generated. The New Start Point 1 (P_x, P_y, P_z) is located to place the sheathing on the opposite side of the window opening.

$$P_x = (l_i + W_{wi}) * r_x + p_x \tag{3.28}$$

$$P_y = (l_i + W_{wi}) * r_y + p_y \tag{3.29}$$

$$P_z = (l_i + W_{wi}) * r_z + p_z \tag{3.30}$$

The New Start Point 2 (P_x, P_y, P_z) is the tip point of a JSW, which is farther from the Framing Point (Figure 3.33).

$$P_x = l_i * r_x + p_x \tag{3.21}$$

$$P_y = l_i * r_y + p_y \tag{3.22}$$

$$P_z = l_i * r_z + p_z + H_{wji} \tag{3.31}$$

The *New Start Point 3* (P_x, P_y, P_z) locates below the current JSD with the same *z-coordinate* value ($P_z = p_z$) in order to place the sheathing below the window opening (Figure 3.33).

$$P_x = l_i * r_x + p_x \tag{3.21}$$

$$P_y = l_i * r_y + p_y \tag{3.22}$$

$$P_z = l_i * r_z + p_z \tag{3.23}$$

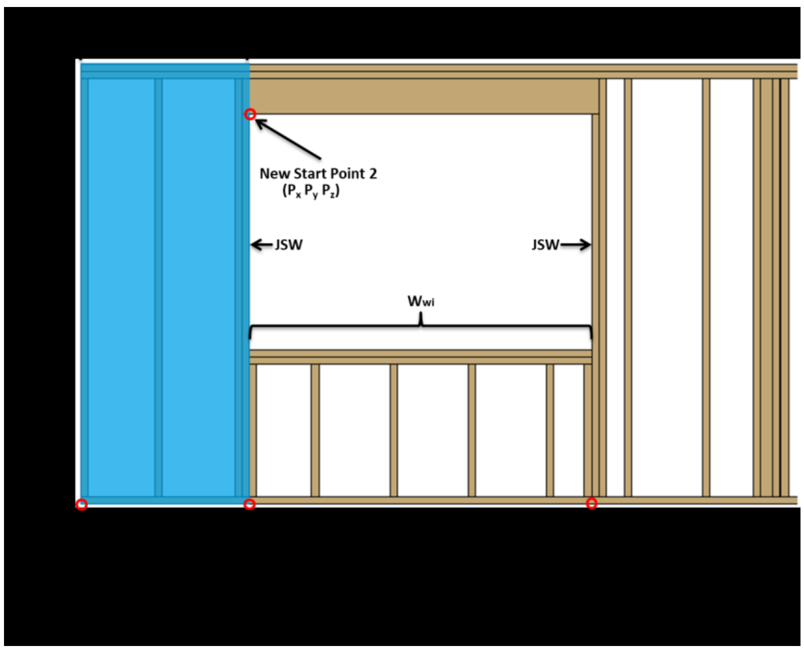


Figure 3.33: Start Point determination (window).

- If a wall height is higher than the nominal height of regular sheathing, another piece of sheathing is required above the current sheathing, so an additional new Start Point (P_x, P_y, P_z) is developed above the current Start Point with an elevation equal to the current piece of sheathing height (Figure 3.34).

$$P_x = p_x \tag{3.32}$$

$$P_y = p_y \tag{3.33}$$

$$P_z = h_i + p_z \tag{3.34}$$

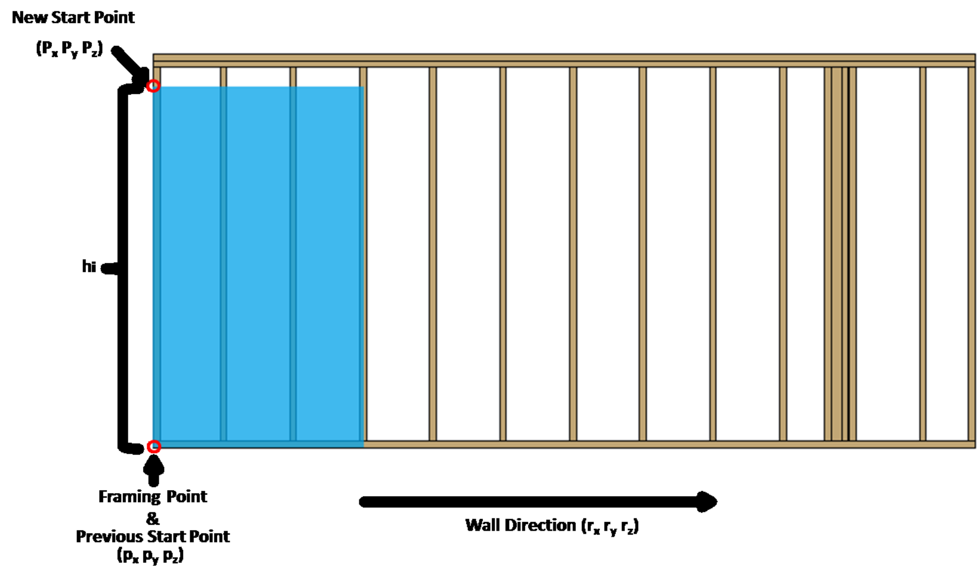


Figure 3.34: Start Point determination (wall height is higher than sheathing height).

Following these principles, the placement of sheathing can be achieved. Each piece of sheathing has a unique label at the centre for differentiation. Generally, the label is combined by the host wall ID and the sheathing ID. For example, if a piece of sheathing locates on an exterior wall "AX4" and the sheathing has an ID of "S27", the label should be "AX4-S27" (Figure 3.35).

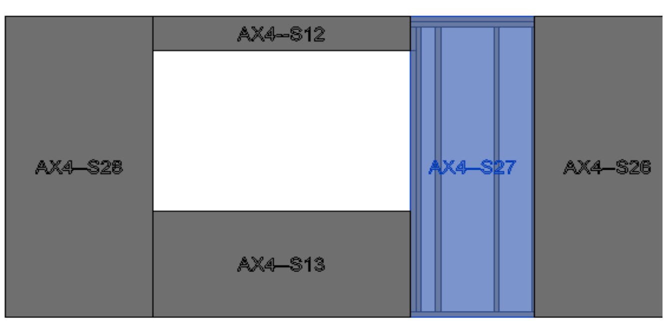


Figure 3.35: Sheathing labels.

3.2.3 Sheathing Optimization

Here, the sheathing pieces are visualized in the model, and their dimensions are able to be extracted. The sheathing optimization thus becomes a traditional *2D Cutting Problem*. To solve this problem, two propositions need to be clarified in advance.

(1) Cut in Guillotine or NonGuillotine pattern?

Guillotine cutting refers to a cutting pattern for rectangular forms where the cutting edge begins at one side and continues towards the opposite side without stopping; it is also called *edge-to-edge* cutting (Aryanezhad et al. 2012). Conversely, the *NonGuillotine* cutting pattern allows the cut tracks to stop anywhere before the edge (Figure 3.36).

Figure 3.36: NonGuillotine and Guillotine cutting pattern (Manrique et al. 2011).

In terms of material saving, NonGuillotine is an optimal pattern; but if considering the efficiency of the cutting process, Guillotine saves considerably more time and does not require the same level of accuracy in measurements or of skill in operators.

(2) Can sheathing be rotated or not?

If the sheathing is set to be rotatable, then it is not necessary for the four sides of a piece of sheathing to be parallel with the edges of regular sheathing. The rotatable cutting pattern has an increased capability of utilizing the regular sheathing sufficiently and accomplishing certain cutting tasks, which are unachievable for orientation-fixed patterns. For example, Figure 3.37 shows that the only way to cut five squares (four 40 x 40 squares and one 28.28 x 28.28 square) from a large square (100 x 100) is rotating the centre square by 45 degrees. However, this cutting pattern has the same disadvantage as the NonGuillotine, which requires additional labour hours, more accurate measurements, and higher skilled operators.

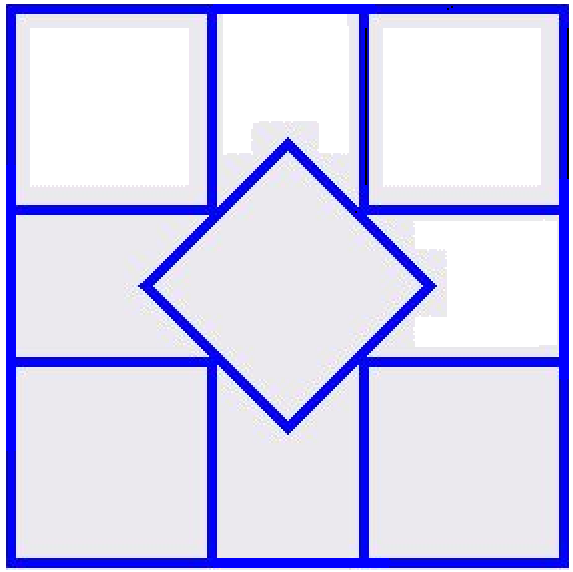
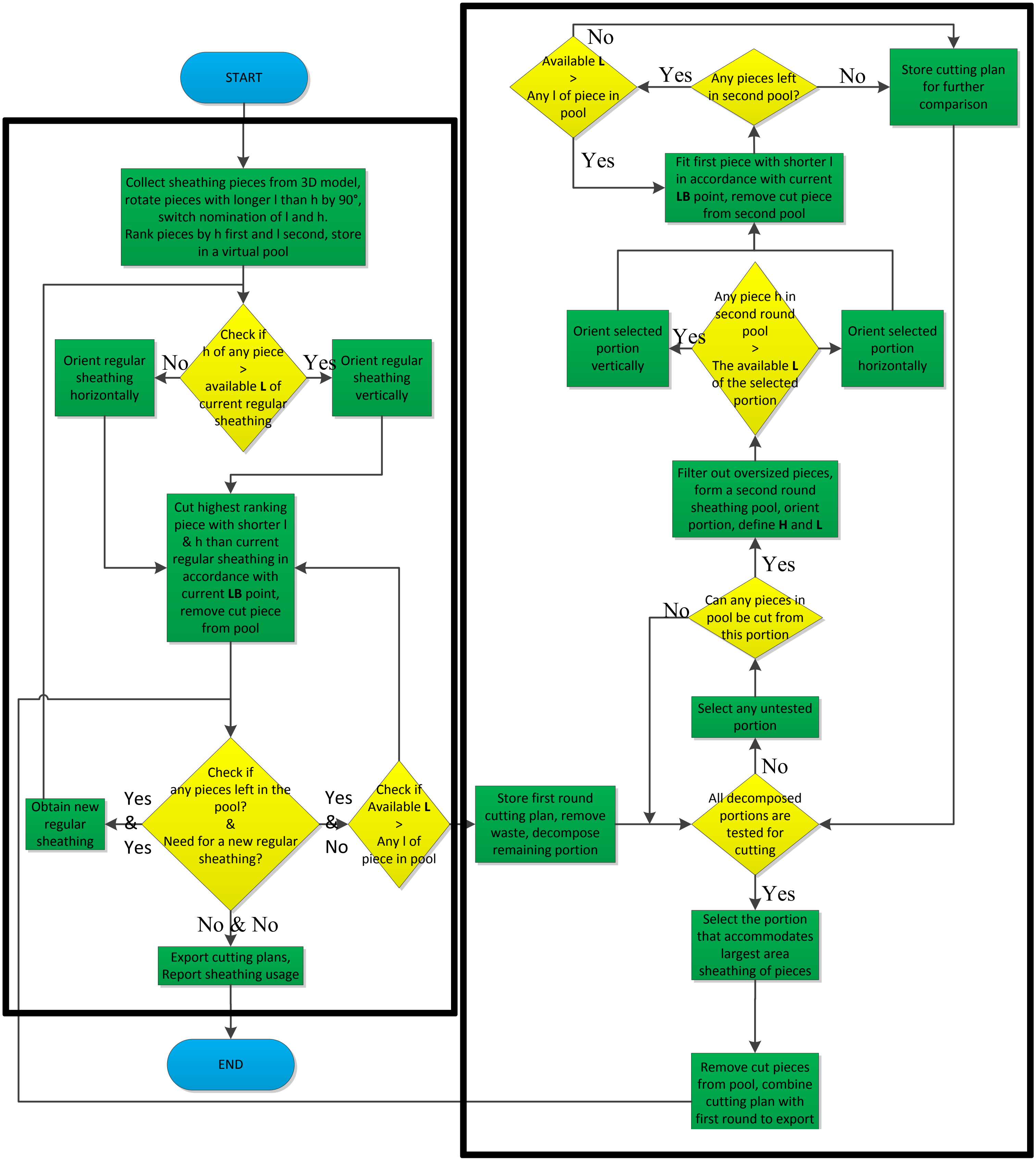


Figure 3.37: The only way to cut five small certain squares in a large square (Solving the 2D Packing Problem 2007).

In Canada, it is sensible to consider the labour saving rather than material saving in view of the high local labour rate, thus the sheathing optimization is implemented based on the Guillotine and orientation-fixed cutting pattern. The following detailed procedure includes two rounds, which are represented by a flowchart shown in Figure 3.38.



First Round **Second Round**

Figure 3.38: Flowchart of sheathing cutting process.

L: Length of the current regular sheathing (or remaining portion of the current regular sheathing)

H: Height of the current regular sheathing (or remaining portion of the current regular sheathing)

l: Length of sheathing piece

h: Height of sheathing piece

BL: Bottom-Left point

First-round cutting:

- Collect the information of sheathing pieces from a Revit model, which includes the height (h_1 to h_n), length (l_1 to l_n), and label, and store the information in a virtual *Sheathing Pool*.
- On the basis of dimensions, rotate the sheathing pieces with longer length than height by 90 degrees, which means two vertical sides are longer than or equal to top and bottom sides of the sheathing piece, and rename the longer side *Height* and the shorter side *Length*. ($h_i \geq l_i$ after rotation) (Figure 3.39).

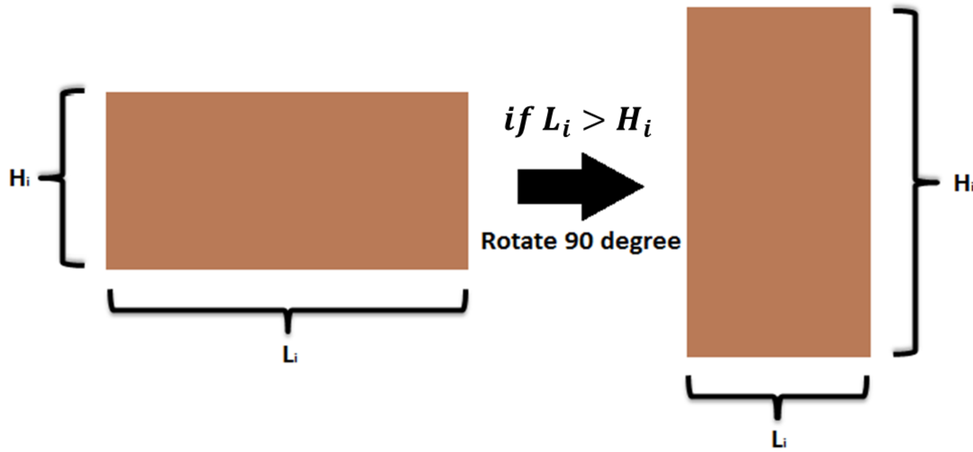


Figure 3.39: Sheathing piece rotation.

- Rank all the sheathing pieces by height and rank the sheathing pieces with the equivalent height by length thereafter. ($h_i \geq h_{i+1}$ after ranking)
- If at least one or the current first sheathing piece's height is longer than the regular sheathing's length, orientate the regular sheathing vertically; If not, orientate the regular sheathing horizontally (Figure 3.40).

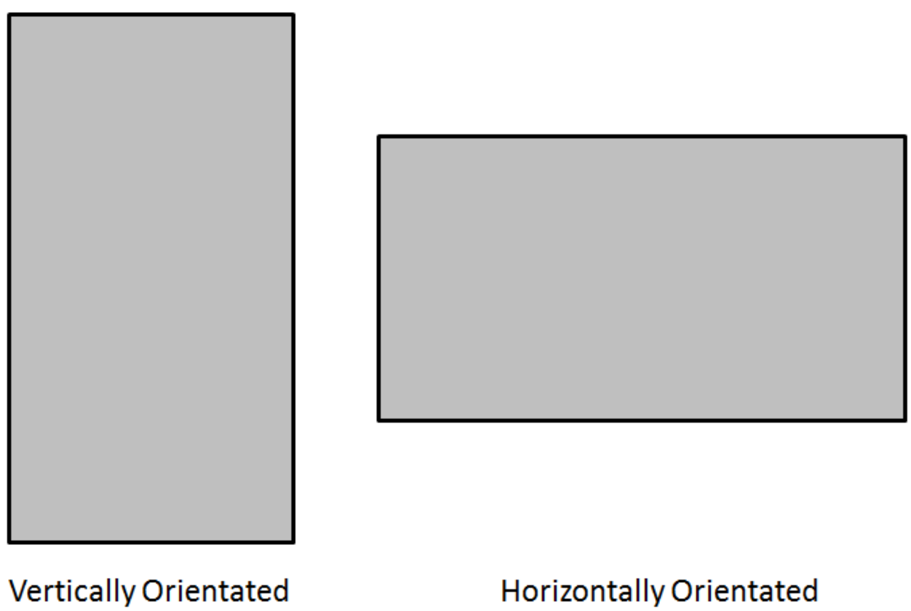


Figure 3.40: Regular sheathing rotation.

- Locate the first sheathing piece at the bottom left point (BL) of the regular sheathing (Figure 3.41), and remove this sheathing piece from the virtual sheathing pool (from now on, the sheathing piece previously in second position becomes the current first sheathing piece); then, check the remaining length (L_r) (Figure 3.42).

$$L_r = L_R - L_i \tag{3.35}$$

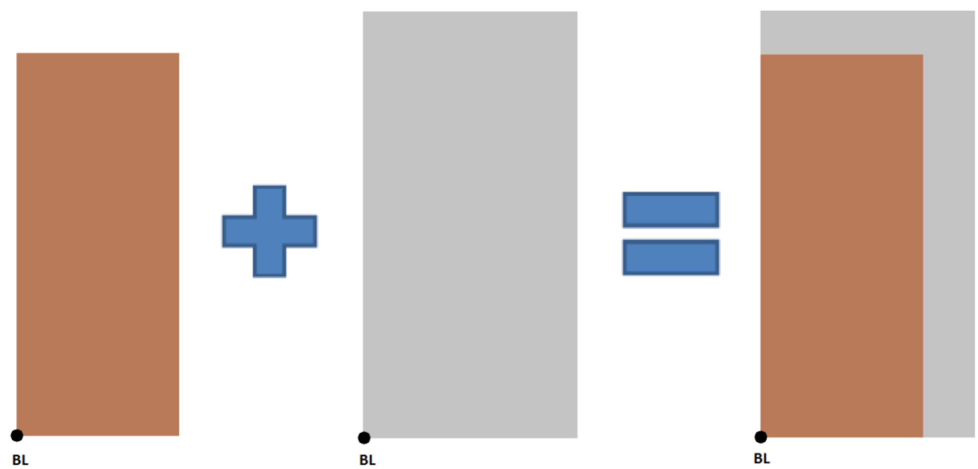


Figure 3.41: Sheathing piece fits on a regular sheathing.

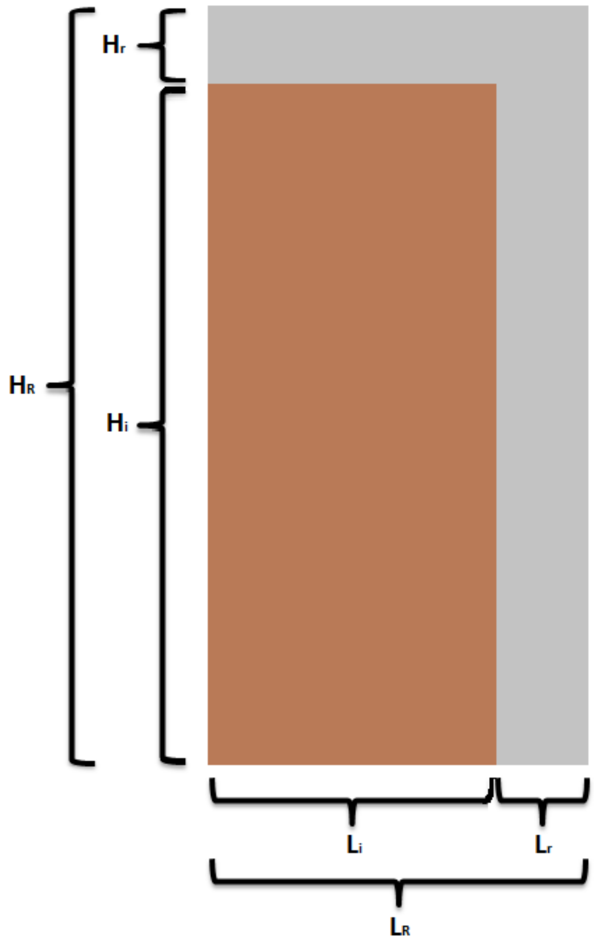


Figure 3.42: Dimensions after fitting piece on a regular sheathing.

- If the remaining length (L_r) is longer than any length of the sheathing pieces ($L_r = L_R - L_1 \geq$ any L_i) in the virtual pool, the bottom left point (BL) moves to the bottom right point of the fitted sheathing piece, and fit the first sheathing piece (blue in Figure 3.43) whose length is more narrow than L_r (Figure 3.43).

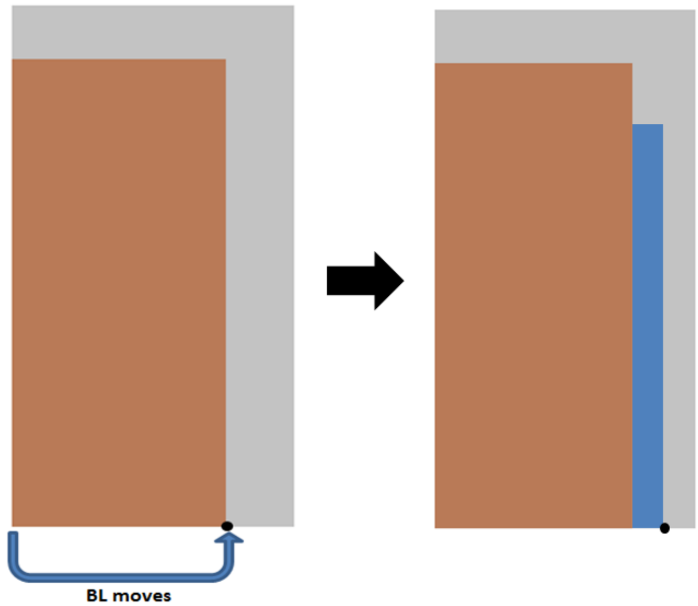


Figure 3.43: Bottom Left point moves to fit more sheathing pieces.

- The process is repeated until the remaining length (L_r) is smaller than any remaining sheathing piece's lengths (l_i), and the sheathing strip (yellow in Figure 3.44) on the right edge of the sheathing piece last fitted is treated as waste. Subtracting the cut and waste parts from the regular sheathing creates a *stair shape*, which also has the potential to hold additional small sheathing pieces, so the *stair shape sheathing* is the object of the second-round cutting investigation (Figure 3.44).

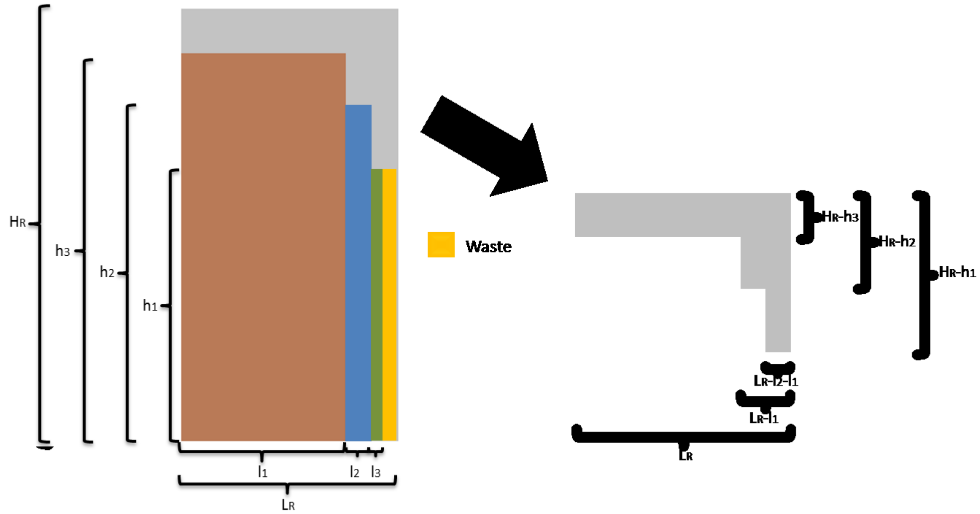


Figure 3.44: *Stair shape sheathing* remaining after first-round fit.

Second-round cutting:

- The stair shape sheathing is decomposed into rectangles, and the number of rectangles is equal to the number of stairs. The decomposing criterion is to obtain the squares with as large an area as possible. Figure 3.45 shows the method to decompose the stair shape sheathing, and the dimensions of three rectangles in this case are also shown.

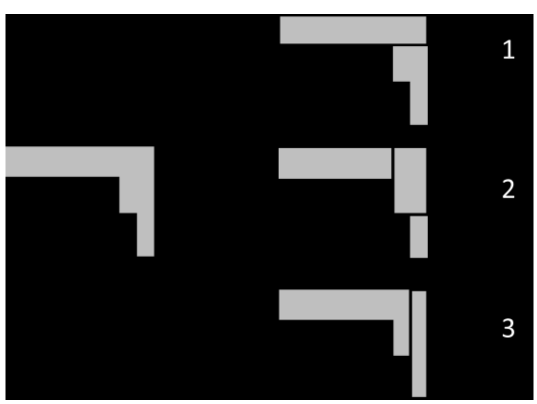


Figure 3.45: Three second-round rectangles.

$$Rectangle\ 1\text{:}\begin{cases} Height = L_R \;\; Length = H_R - h_3,\;\; H_R - h_3 < L_R \\ Height = H_R - h_3 \;\; Length = L_R,\;\; L_R \geq H_R - h_3 \end{cases} \tag{3.36}$$

$$Rectangle\ 2\text{:}\begin{cases} Height = H_R - h_2 \;\; Length = L_R - l_1,\;\; L_R - l_1 < H_R - h_2 \\ Height = L_R - l_1 \;\; Length = H_R - h_2,\;\; L_R - l_1 \geq H_R - h_2 \end{cases} \tag{3.37}$$

$$Rectangle\ 3\text{:}\begin{cases} Height = H_R - h_1 \;\; Length = L_R - l_2 - l_1,\;\; L_R - l_2 - l_1 < H_R - h_1 \\ Height = L_R - l_2 - l_1 \;\; Length = H_R - h_1,\;\; L_R - l_2 - l_1 \geq H_R - h_1 \end{cases} \tag{3.38}$$

- The rectangle with the largest area may not necessarily hold the sheathing pieces with the most or largest area, because the specific shape of the rectangle is also a critical factor. Therefore, the decomposition of each set of rectangles is tested for sheathing piece fitting, and based on the test, the rectangle that holds the largest area within the sheathing piece is selected for cutting, and the rest is wasted. This test is performed to ensure the greatest possible area is always used from each sheathing piece.

- The selected part is regarded as a small regular sheathing, and the identical aforementioned method is applied to fit the remaining sheathing pieces. Figure 3.46 shows three possible cutting scenarios.

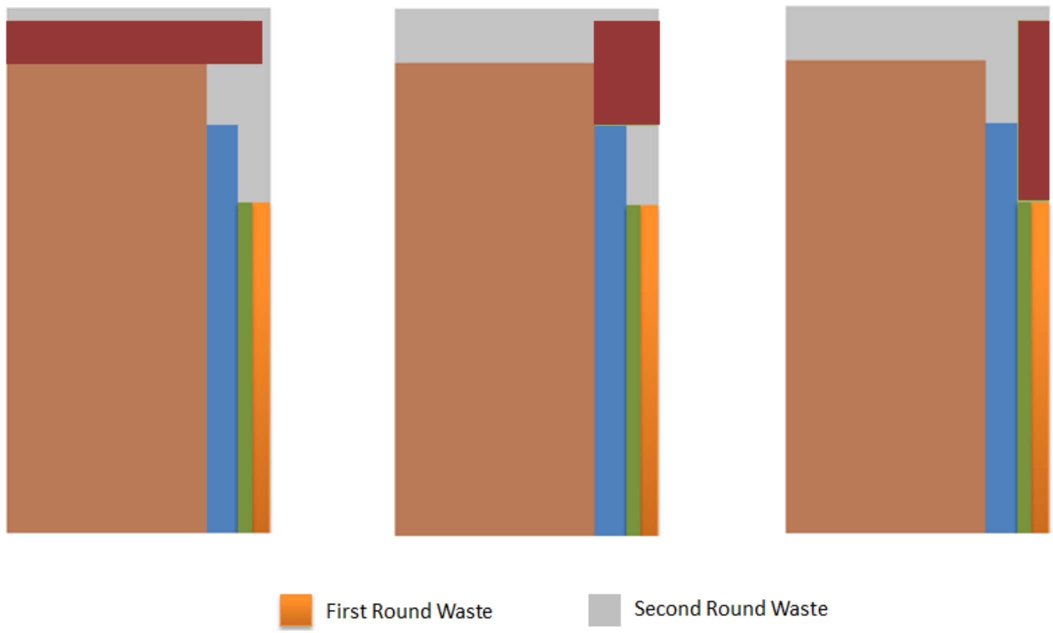


Figure 3.46: Three possible cutting plans on a sheet of regular sheathing.

Chapter 4 Case Study

4.1 Introduction

This section describes the case study implementations of the proposed methodologies. Two in-house add-ons are developed based on Autodesk Revit to perform the automation of quantity takeoff and material optimization. Two Revit models from different companies are employed in the demonstration. First, the material quantity in a model is extracted. Second, the lumber and sheathing usage is optimized on the other model. Finally, the outputs of all work are exported, and the results are analyzed.

4.2 Quantity Takeoff

4.2.1 Background

To illustrate the effectiveness of the proposed methodology, an actual case study is presented. The case study demonstrates how the method is performed to extract the material quantities from a 3D model in Revit, and the quantity takeoff is displayed in the form of an Excel spreadsheet. The 3D model chosen to demonstrate the quantity takeoff add-on is from a manufacturing plant in Edmonton, Canada operated by Civeo (a modular construction manufacturer specializing in modular workforce accommodations and camp logistics). The case study object is a recreation facility 60 ft in length and 24 ft in width, achieved by combining two 60 ft x 12 ft modules, and a common wall between the two modules is removed to obtain a larger open space, and a staircase is installed outside the module in order to provide access (Figure 4.1 and Figure 4.2).

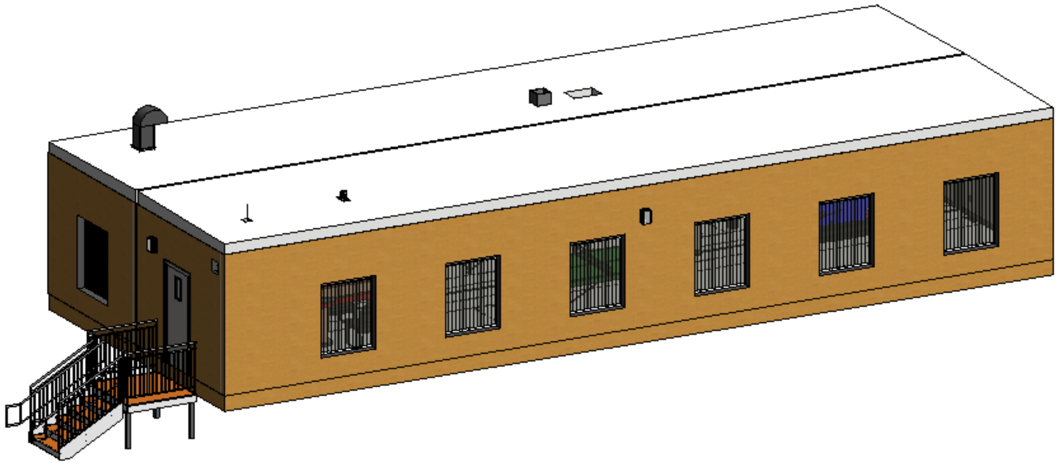


Figure 4.1: 3D view of case study model.

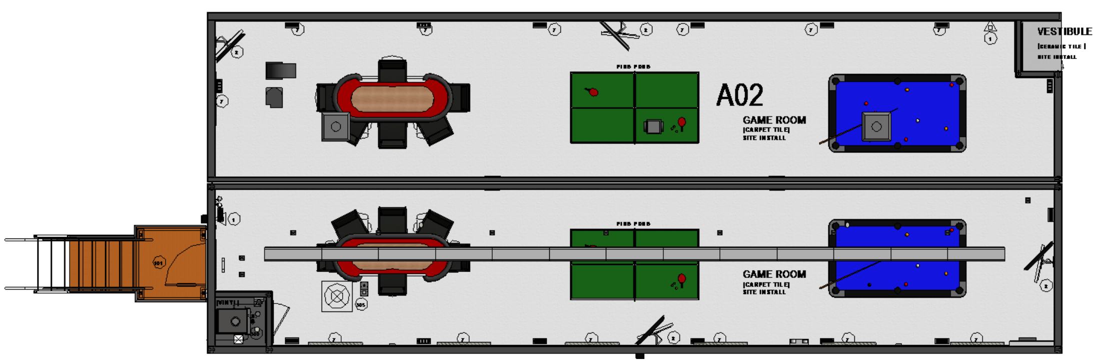


Figure 4.2: Top view of case study model.

4.2.2 Preloading the Revit Model

This Revit model consists of two modules, and each is assigned a distinct Module Number. The upper module in Figure 4.2 is assigned the Module Number *Unit 02*, and the lower module is assigned the Module Number *Unit 01*. The materials belonging to each module have the identical Module Number as the module. Besides the modules, there is a staircase which is shared by the two modules, and the staircase does not belong to any particular module, despite that it connects with the Unit 01 module. The Module Number of the staircase is assigned as *Site Install*. In this scenario, each material in the model has a 6-digit Part Number (called JDE# in Civeo), and Module Number is named *Unit Number*, and the combination of JDE# and Unit Number is the bridge to integrate the Revit model with an Excel template and the key parameter to mirror the quantities onto the Excel template (Figure 4.3).

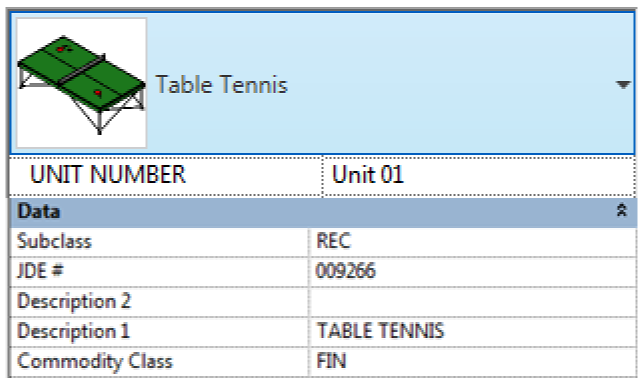


Figure 4.3: Preloaded information in the Revit model.

4.2.3 Standardization of Excel Template

The material properties are transcribed into column headings in the Excel template. This standardized Excel template contains the following columns, *Part_Number*, *Description1*, *Description2*, *Unit*, and *Unit_Number*, which are filled in advance of quantity extraction. Another two columns, *Raw_Quantity* and *Quantity* are left blank to hold quantity extractions from Revit model.

Since three different units (Unit 01, Unit 02, and Site Install) exist in the model, the content in the Excel template is duplicated twice, indicating that there are three identical groups of materials that exist in the template, and Unit 01, Unit 02, and Site Install are assigned to each group under the Unit_Number column (Table 4.1).

Table 4.1: Sample of Excel template (Unit_Number assignment).

Item_Number	Quantity	Unit	Description1	Description2	Unit_Number	Family_Name	Raw_Quantity
009266		EA	TABLE TENNIS		Unit01		
009266		EA	TABLE TENNIS		Unit02		
009266		EA	TABLE TENNIS		Site Install		

4.2.4 Quantity Extraction

The quantity takeoff starts from an activation of the Quantity Takeoff add-on in Revit (Figure 4.4).

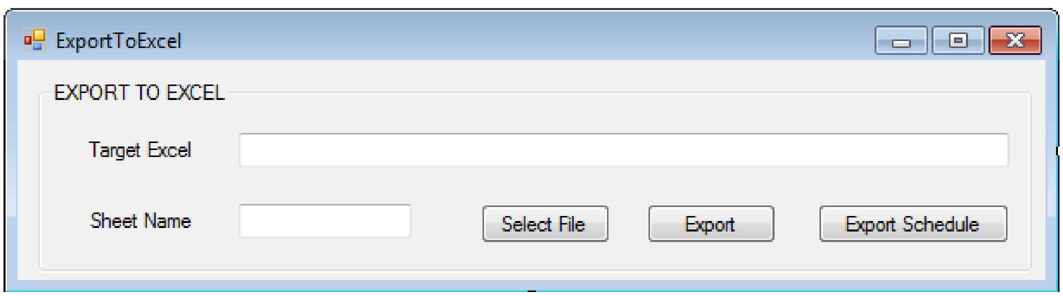


Figure 4.4: Quantity takeoff interface (ExportToExcel).

The Excel template is chosen by clicking “Select File”, and the Excel template file address is shown in the first textbox (Target Excel), and the sheet is selected and the name is shown in the second textbox (Sheet Name). After the textboxes are filled up, clicking the Export button activates the Quantity Takeoff, which extracts the quantities from the Revit model to the Excel template.

In the Revit model, all the material information is collected, which includes the Part Numbers, Unit Numbers, and Quantities. As long as more than one item has the same Part Number and Unit Number, they are grouped with a Quantity of the sum. The prototype automatically searches the entire Excel template to sum up all the cells matching with identical Part Number and Unit Number under the column of Raw_Quantity. Due to the fact that formulas are preloaded into in the Excel template, the column Raw_Quantity is filled with a number. Subsequently, the number is modified by the formula and transported to the cell under the Quantity column in the same row simultaneously. The final quantity takeoff output is shown in Appendix E.

Table 4.2: Sample of extracted quantities.

Item_Number	Quantity	Unit	Description1	Description2	Unit_Number	Raw_Quantity
011830	6	EA	RECP 15A 125V DUPLEX DECORA	LEVITON 5325-W	Unit 01	6
022319	2	EA	SWITCH 15A 120V DECORA 3P	WHITE LEVITON 5603-P2W	Unit 01	2
004971	117.5966	EA	LUM SPF 2X6X10FT	#2&BTR	Unit 01	1069.06
044566	0.594044	EA	TYVEK HOME WRAP	10FT X 150FT	Unit 01	645.7

The first two items (receptacle and switch) in the sample output belong to Category 1, which is counted by *each*. Hence, the directly extracted quantity under the column Raw_Quantity can be transferred to the Quantity column without any processes. The third item (lumber 2x6x10 ft) and last item (Home Wrap) belong to Category 2 and Category 3 respectively, so the formula is required to transform the Raw Quantity.

$$Q = Q_R * f_u * (1 + f_w) * (1 + f_c) \tag{3.7}$$

For Category 2, it is uncontested to assume the extracted lumber length accords with the final lumber length in real construction; as a result, the construction factor f_c is *0*. However, the waste is inevitable due to the cutting process, and the company always issues an extra 10% to 15% of materials for conservative estimate, which leads to the waste factor f_w of 10% for lumber and other Category 2 materials. Moreover, since the unit piece of regular lumber is dimensioned by 10 ft, the unit conversion factor f_u is set to be 1/10 to convert the extracted unit *ft* to inventory unit *Each*. The final value after calculation is shown.

$$Q = 1069.06 * (1/10) * (1 + 10\%) * (1 + 0) \tag{3.7}$$

$$Q = 117.60$$

As described in the previous section, the material waste from home wrap placement on walls with openings is understandable and unavoidable, and the waste causes the material quantity deviation between 3D model and reality; therefore, the construction factor f_c is evaluated to be 20% to eliminate the measurement discrepancy. The stocked home wrap has dimensions of 10 ft x 150 ft (1,500 sq ft), so the unit conversion factor f_u is set to be 1/1,500, and the waste factor $f_w$is assumed to be 15%. Accordingly, the final formula is established below.

$$Q = 645.7 * (1/1{,}500) * (1 + 15\%) * (1 + 20\%) \tag{3.7}$$

$$Q = 0.59$$

Dealing with over 10,000 items causes a high risk of error. Even if only one number is typed incorrectly in the Revit model or Excel template, an unmatched error will occur. To assist the add-on user to look up the incorrect items in a large database, a dialog is designed for prompting errors. In the dialog, the incorrect item types and the part numbers detected from Revit are displayed (Figure 4.5).

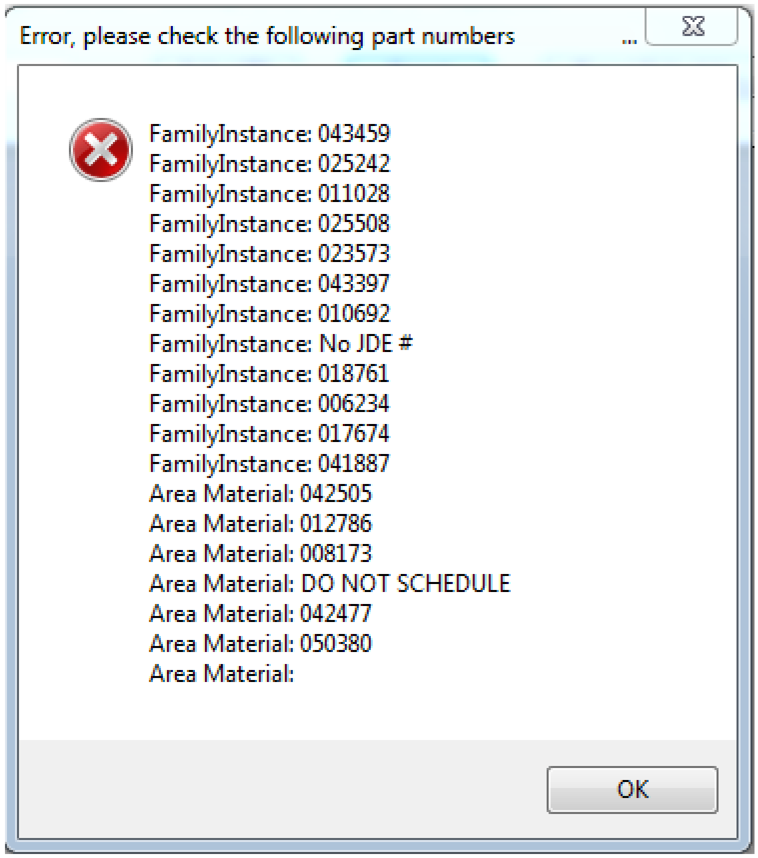


Figure 4.5: Error prompt dialog.

4.3 Material Optimization

4.3.1 Background

The model for material optimization demonstration is from Kent Homes, a home builder based in Bouctouche, New Brunswick, Canada with modular manufacturing operations. The products of Kent Homes include modular homes, mini homes, and commercial modules. Among them, the mini home is a product in high demand (Figure 4.6), and mini home parameters can range from 700 sq ft to over 1,100 sq ft and from 1 bedroom to 3 bedrooms (Kent Homes 2015).

Figure 4.6: A mini home from Kent Homes.

The study object is a rectangular-shaped mini home, with a floor length of 72 ft, floor width of 16 ft, and ceiling height of 7 ft 6 in. This mini home comprises three bedrooms, one bathroom, one living room, and one dining room (Figure 4.7). Six windows and one door are designed on the front side of the house (Figure 4.8), and one patio door is on the back side (Figure 4.9). No openings are present on the remaining two sides.

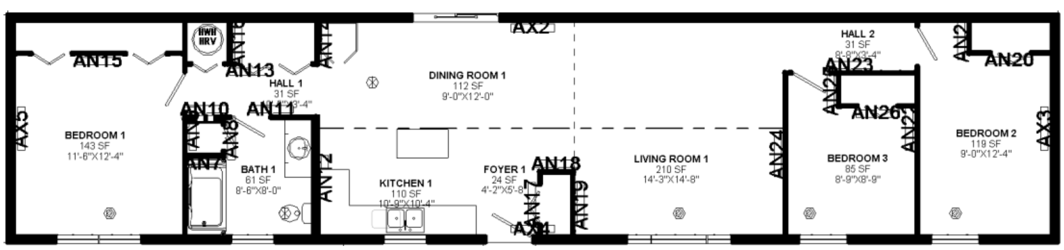


Figure 4.7: Top view of case study model.

Figure 4.8: Front view of case study model.

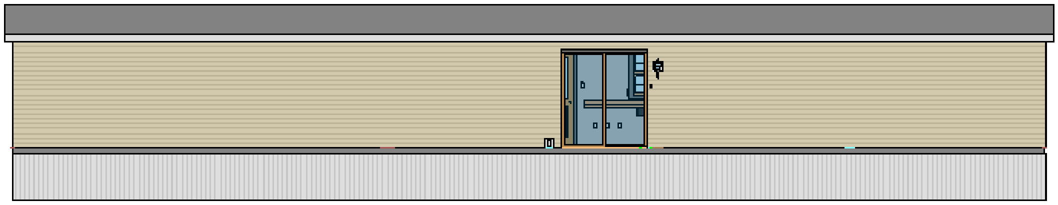


Figure 4.9: Back view of case study model.

4.3.2 Lumber Optimization

The lumber optimization is performed by two algorithms, greedy and Simplex, and both test the same model.

4.3.2.1 Preliminary Work

The precondition to optimize lumber usage is that the BIM model has completed wall framing. However, the current Revit system does not offer a component to represent lumber, so the model is framed by means of an external software called *StrucSoft MWF* (Figure 4.10), developed by StrucSoft Solutions Ltd. StrucSoft MWF is able to automate framing with wood studs in Revit (StrucSoft Solutions 2015). After this process, all the lumber is visible, and the information pertaining to the lumber, such as nominal base dimensions, length, and volume, is also accessible. What is notable is that properties are assigned to the lumber simultaneously: BIMSF_Container, BIMSF_Description, and BIMSF_Label.

BIMSF_Container: the name of the host wall that lumber is framed into.

BIMSF_Description: the lumber type, decided by lumber location.

BIMSF_Label: the lumber name, which is used to distinguish from other lumber belonging to the same host wall.

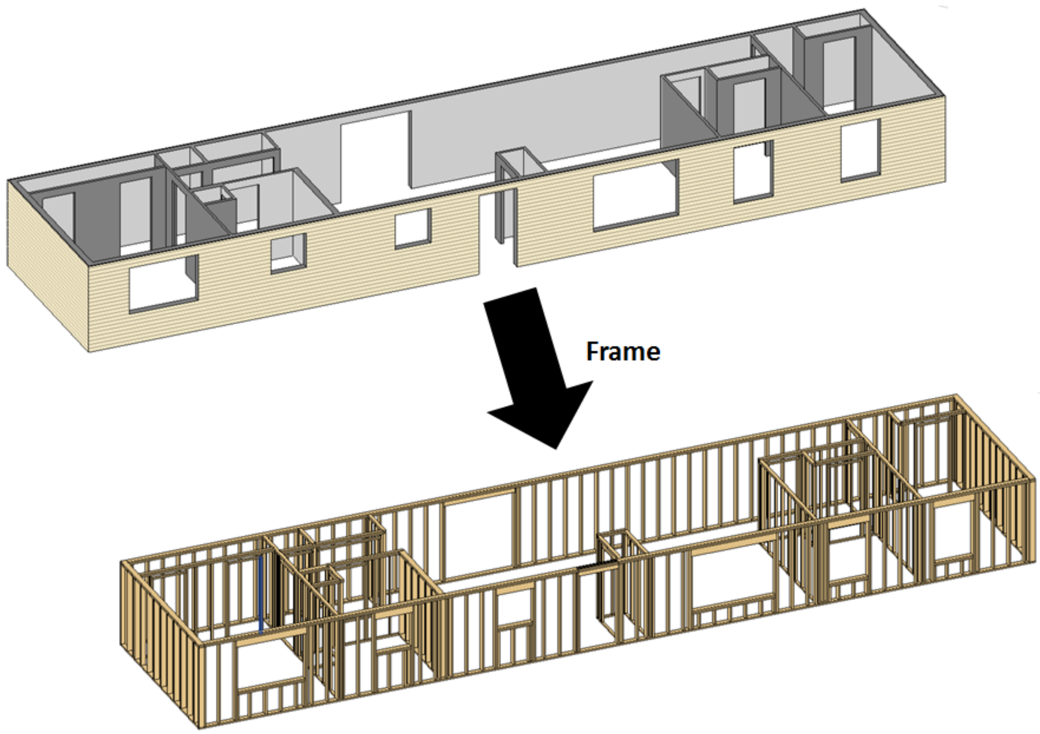


Figure 4.10: Wall framing of case study model.

StrucSoft automatically assigns an ID to each lumber piece, called *BIMSF_Id*. However, this ID is usually too long and complicated to be used for future processes (Figure 4.11). Hence, the combination of BIMSF_Container and BIMSF_Label is used as a unique ID to differentiate lumber throughout the whole model. Figure 4.11 shows some basic information for a selected piece of lumber (in blue) as a sample, and Table 4.3 lists several pertinent properties of a stud.

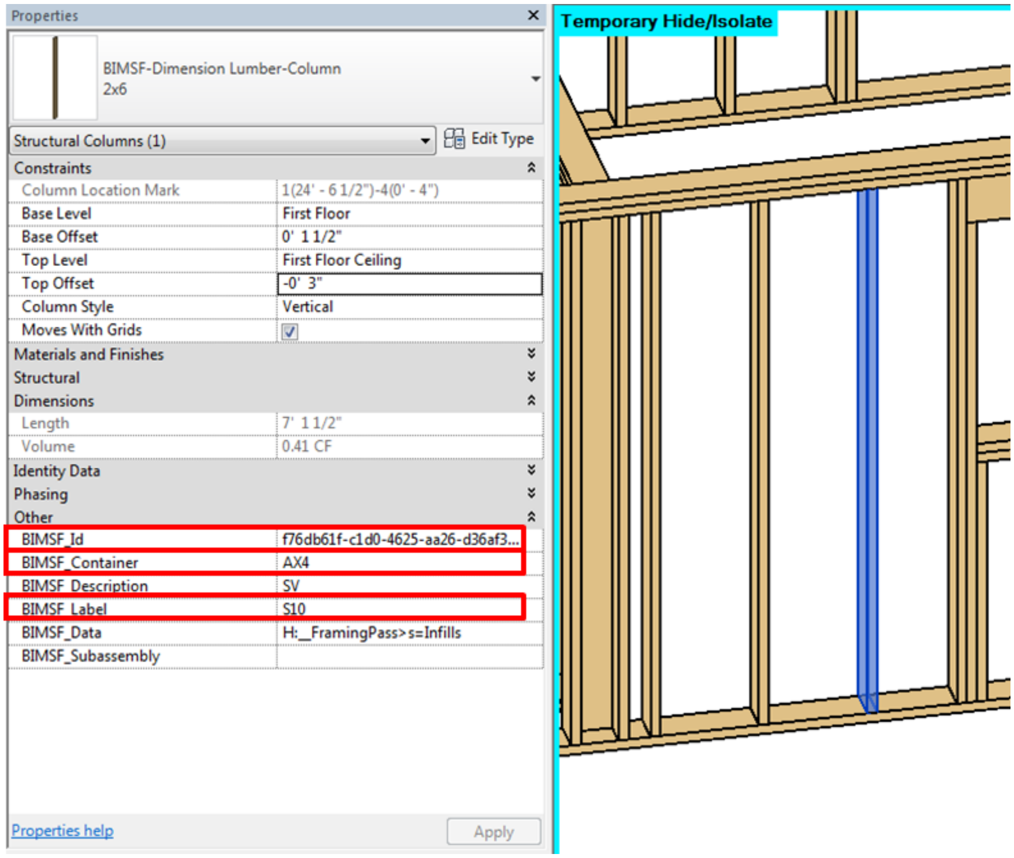


Figure 4.11: Stud properties.

Table 4.3: Stud properties and naming rule.

Nominal Base Dimension	Length	BIMSF_Container	BIMSF_Description	BIMSF_Label	ID
2x6	7 ft 1 ½ in	AX4	SV	S10	AX4-S10

As the precondition of wall framing is satisfied, the optimization commences. All the lumber in the Revit model are collected and separated into different groups by base dimension, and the lumber in each group is ranked by length and stored in a corresponding virtual lumber pool for subsequent processes (see Appendix A, B, C, and D). In this case study, four types of base dimension lumber are extracted: 2x3, 2x4, 2x6, and 2x8 (Table 4.4).

Table 4.4: Studs collection from case study.

Base Dimensions	Quantity (Pieces)
2x3	179
2x4	47
2x6	237
2x8	21

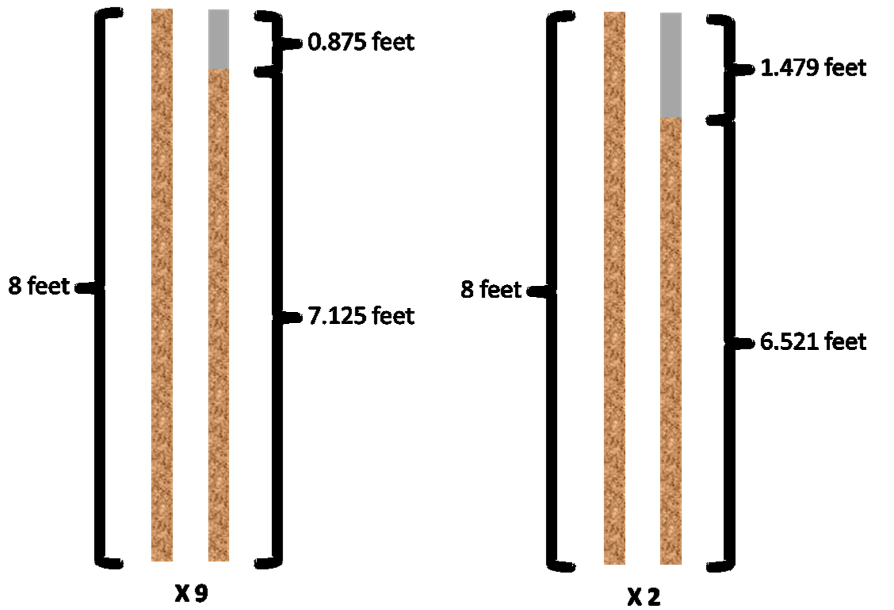
4.3.2.2 Lumber Optimization (Greedy)

To demonstrate the greedy algorithm for optimizing lumber cutting, lumber with base dimensions of 2x4 is selected as it provides proper data volume (47 pieces) for the purpose of demonstrating the concept. At the beginning of the optimization, the user needs to provide the longest regular lumber length for 2x4 studs, and any 2x4 lumber pieces exceeding this length are filtered out. These lumber pieces are reported to the user, and only the satisfactory lumber pieces continue on to the cutting process. In this case study, the longest 2x4 regular length is 8 ft, which leads to rejection of lumber pieces longer than 8 ft from the list (Figure 4.12).

2X4 Lumber Pool			
ID	Length (ft)	ID	Length (ft)
[illegible]	[illegible]	AN20__TTOP2	5.521
[illegible]	[illegible]	AN26__TTOP1	5.187
[illegible]	[illegible]	AN26__TTOP2	5.187
[illegible]	14.75	AN19__TTOP1	4.312
[illegible]	11.583	AN19__TTOP2	4.312
[illegible]	11.583	AN17__TTOP1	4.312
[illegible]	11.104	AN17__TTOP2	4.312
[illegible]	11.104	AN14__TTOP1	3.042
[illegible]	[illegible]	AN14__TTOP2	3.042
[illegible]	[illegible]	AN16__TTOP1	2.833
[illegible]	[illegible]	AN16__TBOT1	2.833
[illegible]	[illegible]	AN16__TTOP2	2.833
AN13__SJOIN3	7.125	AN8__TTOP1	2.708
AN7__E1	7.125	AN8__TTOP2	2.708
AN7__E2	7.125	AN18__TTOP1	2.5
AN7__S1	7.125	AN18__TTOP2	2.5
AN6__SJOIN9	7.125	AN7__TTOP1	2.458
AX2__SJOIN15	7.125	AN7__TBOT1	2.458
AN16__E1	7.125	AN7__TTOP2	2.458
AN16__E2	7.125	AN21__TTOP1	2.292
AN16__S1	7.125	AN21__TTOP2	2.292
AN11__TTOP1	6.521	AN25__TTOP1	2.292
AN11__TTOP2	6.521	AN25__TTOP2	2.292
AN20__TTOP1	5.521		

Figure 4.12: Lumber pool (2x4).

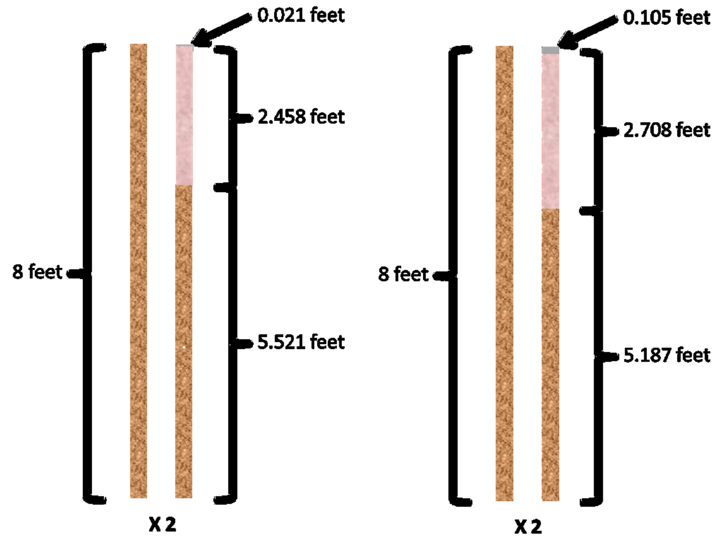
The greedy algorithm starts from the most valuable object; in other words, it assigns the highest priority of cutting to the current longest object. In this case, as shown in Figure 4.12, the AN13__SJOIN3 (with a length of 7.125 ft) is the first length to be cut from the 8 ft regular lumber. After this cut, the remaining portion of the current regular lumber is only 0.875 ft in length, which is much shorter than any pieces left in the pool, so this portion is considered waste. The next longest piece is 7.125 ft in length (AN7__E1), so it is cut in the same pattern as the previous piece (Figure 4.13).



2X4 Lumber Pool	
ID	Length (ft)
AN13__SJOIN3	7.125
AN7__E1	7.125
AN7__E2	7.125
AN7__S1	7.125
AN6__SJOIN9	7.125
AX2__SJOIN15	7.125
AN16__E1	7.125
AN16__E2	7.125
AN16__S1	7.125
AN11__TTOP1	6.521
AN11__TTOP2	6.521
AN20__TTOP1	5.521
AN20__TTOP2	5.521
AN26__TTOP1	5.187
AN26__TTOP2	5.187
AN19__TTOP1	4.312
AN19__TTOP2	4.312
AN17__TTOP1	4.312
AN17__TTOP2	4.312
AN14__TTOP1	3.042
AN14__TTOP2	3.042
AN16__TTOP1	2.833
AN16__TBOT1	2.833
AN16__TTOP2	2.833
AN8__TTOP1	2.708
AN8__TTOP2	2.708
AN18__TTOP1	2.5
AN18__TTOP2	2.5
AN7__TTOP1	2.458
AN7__TBOT1	2.458
AN7__TTOP2	2.458
AN21__TTOP1	2.292
AN21__TTOP2	2.292
AN25__TTOP1	2.292
AN25__TTOP2	2.292

Figure 4.13: Lumber cutting (configuration 1).

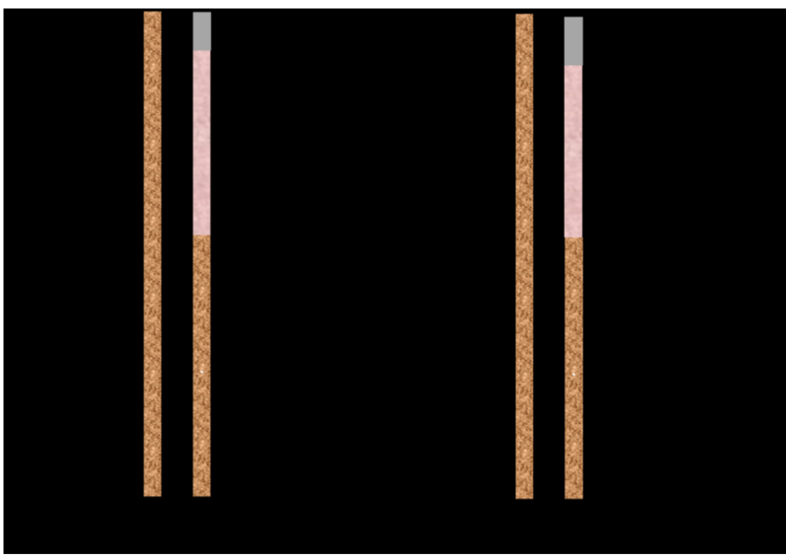
Lumber pieces are cut in the one-piece-cut manner (only one piece cut from a regular lumber) until AN20__TTOP1, which is 5.521 ft in length. After cutting AN20__TTOP1 from the 8 ft regular lumber, the remaining portion is 2.479 ft in length. It can be used to cut the longest remaining piece whose length is less than 2.479 ft, which is AN7__TTOP1 (2.458 ft). Afterwards, the remaining lumber portion is only 0.021 ft in length, which is considered waste (Figure 4.14, left). Two regular lumbers are used for cutting in this manner, and AN26__TTOP1 becomes the greatest length (5.187 ft). After cutting this piece, the remaining 2.813 ft can be used for the next longest piece, which is AN8__TTOP1 (2.708 ft) (Figure 4.14).



2X4 Lumber Pool	
ID	Length (ft)
AN13__SJOIN3	7.125
AN7__E1	7.125
AN7__E2	7.125
AN7__S1	7.125
AN6__SJOIN9	7.125
AX2__SJOIN15	7.125
AN16__E1	7.125
AN16__E2	7.125
AN16__S1	7.125
AN11__TTOP1	6.521
AN11__TTOP2	6.521
AN20__TTOP1	5.521
AN20__TTOP2	5.521
AN26__TTOP1	5.187
AN26__TTOP2	5.187
AN19__TTOP1	4.312
AN19__TTOP2	4.312
AN17__TTOP1	4.312
AN17__TTOP2	4.312
AN14__TTOP1	3.042
AN14__TTOP2	3.042
AN16__TTOP1	2.833
AN16__TBOT1	2.833
AN16__TTOP2	2.833
AN8__TTOP1	2.708
AN8__TTOP2	2.708
AN18__TTOP1	2.5
AN18__TTOP2	2.5
AN7__TTOP1	2.458
AN7__TBOT1	2.458
AN7__TTOP2	2.458
AN21__TTOP1	2.292
AN21__TTOP2	2.292
AN25__TTOP1	2.292
AN25__TTOP2	2.292

Figure 4.14: Lumber cutting (configuration 2).

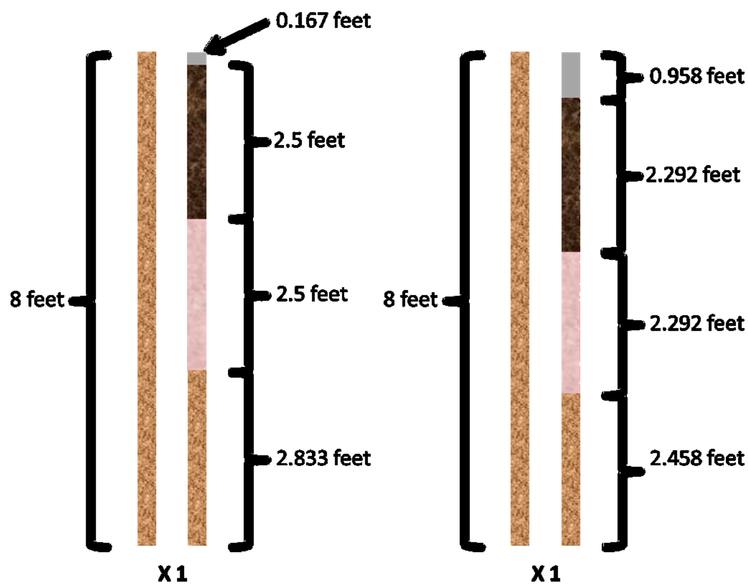
The next two-piece combinations are 4.312 ft + 3.042 ft (0.646 ft waste) (Figure 4.15, left), and 4.312 ft + 2.833 ft (0.855 ft waste) (Figure 4.15, right).



AN13__SJOIN3	7.125
AN7__E1	7.125
AN7__E2	7.125
AN7__S1	7.125
AN6__SJOIN9	7.125
AX2__SJOIN15	7.125
AN16__E1	7.125
AN16__E2	7.125
AN16__S1	7.125
AN11__TTOP1	6.521
AN11__TTOP2	6.521
AN20__TTOP1	5.521
AN20__TTOP2	5.521
AN26__TTOP1	5.187
AN26__TTOP2	5.187
AN19__TTOP1	4.312
AN19__TTOP2	4.312
AN17__TTOP1	4.312
AN17__TTOP2	4.312
AN14__TTOP1	3.042
AN14__TTOP2	3.042
AN16__TTOP1	2.833
AN16__TBOT1	2.833
AN16__TTOP2	2.833
AN8__TTOP1	2.708
AN8__TTOP2	2.708
AN18__TTOP1	2.5
AN18__TTOP2	2.5
AN7__TTOP1	2.458
AN7__TBOT1	2.458
AN7__TTOP2	2.458
AN21__TTOP1	2.292
AN21__TTOP2	2.292
AN25__TTOP1	2.292
AN25__TTOP2	2.292

Figure 4.15: Lumber cutting (configuration 3).

The remaining lumber pieces are all relatively short, so regular lengths of dimensional lumber can be used to cut the three remaining lumber pieces (Figure 4.16).



2X4 Lumber Pool

ID	Length (ft)
AN13__SJOIN3	7.125
AN7__E1	7.125
AN7__E2	7.125
AN7__S1	7.125
AN6__SJOIN9	7.125
AX2__SJOIN15	7.125
AN16__E1	7.125
AN16__E2	7.125
AN16__S1	7.125
AN11__TTOP1	6.521
AN11__TTOP2	6.521
AN20__TTOP1	5.521
AN20__TTOP2	5.521
AN26__TTOP1	5.187
AN26__TTOP2	5.187
AN19__TTOP1	4.312
AN19__TTOP2	4.312
AN17__TTOP1	4.312
AN17__TTOP2	4.312
AN14__TTOP1	3.042
AN14__TTOP2	3.042
AN16__TTOP1	2.833
AN16__TBOT1	2.833
AN16__TTOP2	2.833
AN8__TTOP1	2.708
AN8__TTOP2	2.708
AN18__TTOP1	2.5
AN18__TTOP2	2.5
AN7__TTOP1	2.458
AN7__TBOT1	2.458
AN7__TTOP2	2.458
AN21__TTOP1	2.292
AN21__TTOP2	2.292
AN25__TTOP1	2.292
AN25__TTOP2	2.292

Figure 4.16: Lumber cutting (configuration 4).

The last two lumber pieces are each 2.292 ft in length, so one more regular length of lumber must be consumed, even though 3.416 ft is waste (Figure 4.17).

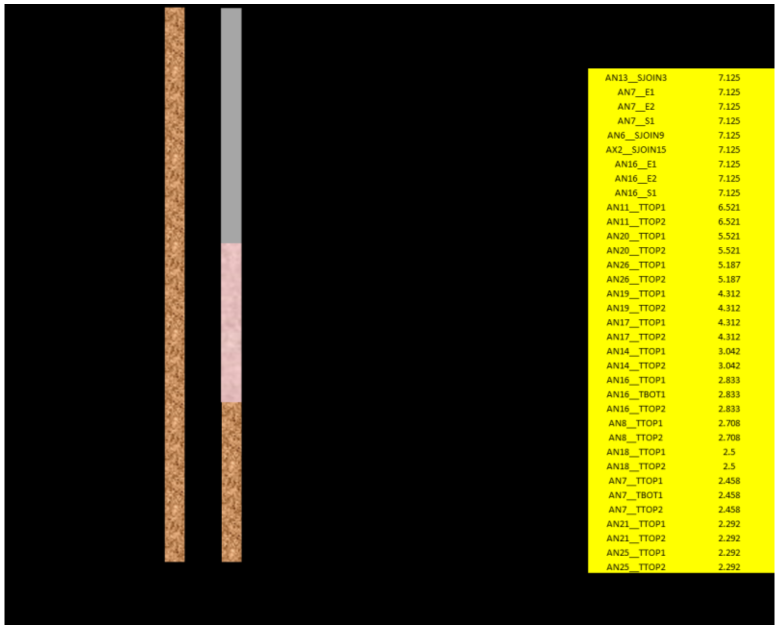
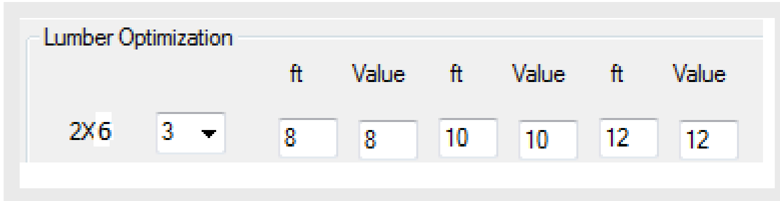


Figure 4.17: Lumber cutting (configuration 5).

4.3.2.3 Lumber Optimization (Simplex)

The Simplex algorithm permits the user to utilize multiple lengths of regular lumber; (in this research, the interface is designed to accept up to three lengths of regular lumber from the end user). For each regular lumber, the user needs to assign a unit value or cost to each regular lumber length. It is not necessary to be a real cost, as the purpose is to create a cost relationship between different regular lumber lengths. To demonstrate the Simplex algorithm, the 2x6 lumber group is tested, and three different lengths of 2x6 regular lumber, 8 ft, 10 ft, and 12 ft, are supplied. The market prices are assumed to be \$8/piece, \$10/piece, and \$12/piece, respectively. In this situation, the value spaces can be filled with 8, 10, 12, or 4, 5, 6 (Figure 4.18).



OR

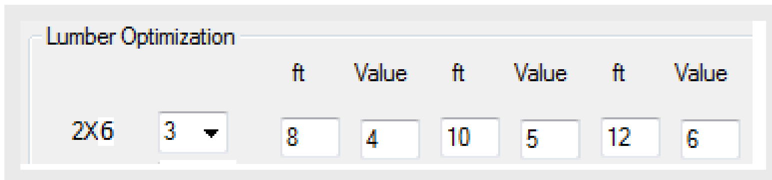


Figure 4.18: Lumber optimization interface (lumber information input).

As mentioned above, the over-dimensioned lumber pieces are filtered out based on the criterion of the longest regular lumber among the provided regular lumber lengths. In this case study, the filter removes the lumber pieces longer than 12 ft. The remaining lumber pieces are grouped by length and ranked in descending order (Table 4.5). The optimization is transformed to a linear program with matrix representation, which contains an objective function, target array, coefficient matrix, coefficient variables, and decision variables.

Table 4.5: Grouped lumber pool (2x6).

2x6 Lumber		
Rank	Length (ft)	Quantity
1	8.062	3
2	7.167	2
3	7.125	159
4	6.771	2
5	6.708	2
6	6.521	12

7	6.188	3
8	5.833	2
9	3.333	4
10	3.25	8
11	3	4
12	2.562	3
13	2.25	6
14	1.333	15

It is easy to obtain the *Target Array*, which is an array that contains the quantities in descending sequence of lumber piece length.

Target Array = [3, 2, 159, 2, 2, 12, 3, 2, 4, 8, 4, 3, 6, 15]

Although the coefficient matrix is complex to build, a feasible approach is the integration of the tree structure and greedy algorithm. In this case study, 14 levels are used in the tree structure ranking, where each level represents a required cut length from a piece of regular lumber. The higher the ranking on the list, the longer the length of the piece to be cut; in other words, the longest piece is located at the highest tree level, and the shortest piece is located at the lowest tree level. The strategy is to obtain the first cutting pattern by cutting the longest piece and then the next longest piece from the list that is shorter than the remaining portion of current regular lumber after the first cut; continue this pattern constantly until the remaining portion of the regular lumber is shorter than any lengths remaining to be cut; this remaining portion is regarded as waste, as it is too short to satisfy any other lengths. Transpose the quantities of lumber pieces to be cut at each level into a corresponding array. After obtaining the first array, the second one can be derived from it. The method is: go through all the elements in the first array; if there is any non-zero element not located at the lowest tree structure level, select the lowest-level element, and reduce the value of the element by one without modifying any elements higher than this level; implement the tree structure again from this level until a full piece of regular lumber is only used to cut the shortest pieces.

In this case study, the first length of regular lumber is 12 ft. The first piece in the 2x6 lumber pool is 8.062 ft in length, so the quantity of 8.062 ft is cut from a 12 ft length of regular lumber and is represented by a value of 1 in the array, which is projected to the first element of the first array. The second lumber length that can be cut from the remaining portion (3.938 ft) is 3.333 ft, which is located at level nine, and the quantity is also given a value of 1, so that the ninth element in the first array is 1. After cutting the 3.333 ft, the regular lumber has only 0.605 ft remaining, which is too short to be used for any other cut. Hence, the first array is:

$$\text{Array}\mathit{1}\ (12\ \text{ft}) = [1, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0]$$

This array signifies that a regular length of lumber (12 ft in length) is used to cut one lumber piece of 8.062 ft in length and another lumber piece of 3.333 ft in length.

After checking all the elements in the first array, the first and ninth elements are found to be non-zero. Since the ninth element is located at a lower level on the tree structure, the value of the element (1) is reduced by 1, which becomes 0. The tree structure method is implemented again starting from this level (level nine) to generate the second array.

Array*2* (12 ft) = [1, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0]

By such analogy, a list of arrays is created, and each array represents one cutting pattern. The last array has only one non-zero element, which is the last level, and once this level is reached, all the cutting patterns have been exhausted.

Array*N* (12 ft) = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 9]

All the cutting patterns (*N* patterns) of a 12 ft regular length of lumber are shown below.

[1, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0]

[1, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0]

●
●
●

[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 7]

[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 9]

The coefficient matrix (14 x *N*) for the regular lumber (12 ft in length):

$$
\begin{bmatrix}
1 & 1 & & & & 0 & 0 \\
0 & 0 & & & & 0 & 0 \\
0 & 0 & & & & 0 & 0 \\
0 & 0 & & & & 0 & 0 \\
0 & 0 & & & & 0 & 0 \\
0 & 0 & & & & 0 & 0 \\
0 & 0 & & & & 0 & 0 \\
0 & 0 & \bullet & \bullet & \bullet & 0 & 0 \\
0 & 0 & & & & 0 & 0 \\
1 & 0 & & & & 0 & 0 \\
0 & 1 & & & & 0 & 0 \\
0 & 0 & & & & 0 & 0 \\
0 & 0 & & & & 1 & 0 \\
0 & 0 & & & & 7 & 9
\end{bmatrix}
$$

Decision Variables Array is an array with N unknowns, and each unknown represents how many 12 ft regular lengths of lumber are used to cut the corresponding certain pattern.

Decision Variable Array = $[n_1, n_2, n_3, n_4, n_5, n_6 \ \dots\dots \ n_{N-2}, n_{N-1}, n_N]$

Coefficient Variable Array is an array with N constants, and these constants are the values read from the user interface. Since the current example is 12 ft regular lumber, all of the N constants are 12 (There is only one regular length in this situation, so the value can be any positive number as long as they are identical).

Coefficient Variable Array = [12, 12, 12, 12 … … 12, 12, 12, 12]

The optimization goal is to minimize the total cost of consumed regular lumber, so the objective function is minimizing the dot product of Decision Variables Array and Coefficient Variable Array.

Minimize: Decision Variables Array * Coefficient Variable Array

Minimize: $12 * n_1 + 12 * n_2 + 12 * n_3 + 12 * n_4 + \cdots + 12 * n_{N-2} + 12 * n_{N-1} + 12 * n_N$

Based on the relationship of

$$
\begin{bmatrix}
1 & 1 & & 0 & 0 \\
0 & 0 & & 0 & 0 \\
0 & 0 & & 0 & 0 \\
0 & 0 & & 0 & 0 \\
0 & 0 & & 0 & 0 \\
0 & 0 & & 0 & 0 \\
0 & 0 & & 0 & 0 \\
0 & 0 & \bullet\bullet\bullet & 0 & 0 \\
0 & 0 & & 0 & 0 \\
1 & 0 & & 0 & 0 \\
0 & 1 & & 0 & 0 \\
0 & 0 & & 0 & 0 \\
0 & 0 & & 1 & 0 \\
0 & 0 & & 7 & 9
\end{bmatrix}
*
\begin{bmatrix}
n_1 \\ n_2 \\ n_3 \\ n_4 \\ n_5 \\ n_6 \\ \vdots \\ \vdots \\ n_{N-5} \\ n_{N-4} \\ n_{N-3} \\ n_{N-2} \\ n_{N-1} \\ n_N
\end{bmatrix}
\geq
\begin{bmatrix}
3 \\ 2 \\ 159 \\ 2 \\ 2 \\ 12 \\ 3 \\ 2 \\ 4 \\ 8 \\ 4 \\ 3 \\ 6 \\ 15
\end{bmatrix}
$$

The results show the optimized cutting layout for 12 ft regular lumber (Table 4.6 and Table 4.7).

Table 4.6: Optimized lumber cutting plan (12 ft only).

Cutting Pattern	Quantity	Scrap (ft/regular lumber)
[1,0,0,0,0,0,0,0,0,0,0,0,0,2]	3	1.272
[0,1,0,0,0,0,0,0,0,0,0,0,2,0]	2	0.333
[0,0,1,0,0,0,0,0,1,0,0,0,0,1]	4	0.209
[0,0,1,0,0,0,0,0,0,1,0,0,0,1]	8	0.292
[0,0,1,0,0,0,0,0,0,0,1,0,0,1]	4	0.542
[0,0,1,0,0,0,0,0,0,2,0,0,0,0]	143	0.375
[0,0,0,1,0,0,0,0,0,0,0,0,2,0]	2	0.729
[0,0,0,0,1,0,0,0,0,0,0,0,2,0]	2	0.792
[0,0,0,0,0,1,0,0,0,0,0,0,2,0]	12	0.979
[0,0,0,0,0,0,1,0,0,0,0,2,0,0]	3	0.688
[0,0,0,0,0,0,0,2,0,0,0,0,0,0]	1	0.334
Total Lumber Usage	184	
Total Cost ($)	2,208	

Table 4.7: Optimized lumber cutting result (12 ft only).

2x6 Lumber (12 ft)			
Rank	Length (ft)	Required Quantity	Actual Quantity
1	8.062	3	3
2	7.167	2	2
3	7.125	159	159
4	6.771	2	2
5	6.708	2	2
6	6.521	12	12
7	6.188	3	3
8	5.833	2	2
9	3.333	4	4
10	3.250	8	8
11	3.000	4	4
12	2.562	3	6
13	2.250	6	22
14	1.333	15	22

By performing the same method, the results of optimized cutting layout for 10 ft regular lumber are shown in Table 4.8 and Table 4.9.

Table 4.8: Optimized lumber cutting plan (10 ft only).

Cutting Pattern	Quantity	Scrap (ft/regular lumber)
[1,0,0,0,0,0,0,0,0,0,0,0,0,1]	3	0.605
[0,1,0,0,0,0,0,0,0,0,0,0,1,0]	2	0.583
[0,0,1,0,0,0,0,0,0,0,0,0,1,0]	153	0.625
[0,0,1,0,0,0,0,0,0,0,0,0,0,2]	6	0.209
[0,0,0,1,0,0,0,0,0,0,0,0,1,0]	2	0.979
[0,0,0,0,1,0,0,0,0,0,0,1,0,0]	2	0.730
[0,0,0,0,0,1,0,0,1,0,0,0,0,0]	2	0.146
[0,0,0,0,0,1,0,0,0,1,0,0,0,0]	6	0.229
[0,0,0,0,0,1,0,0,0,0,1,0,0,0]	4	0.479
[0,0,0,0,0,0,1,0,0,1,0,0,0,0]	2	0.562
[0,0,0,0,0,0,1,0,0,0,0,1,0,0]	1	1.250
[0,0,0,0,0,0,0,1,1,0,0,0,0,0]	2	0.834
Total Lumber Usage	185	
Total Cost ($)	1,850	

Table 4.9: Optimized lumber cutting result (10 ft only).

2x6 Lumber (10 ft)			
Rank	Length (ft)	Required Quantity	Actual Quantity
1	8.062	3	3
2	7.167	2	2
3	7.125	159	159
4	6.771	2	2
5	6.708	2	2
6	6.521	12	12
7	6.188	3	3
8	5.833	2	2
9	3.333	4	4
10	3.250	8	8
11	3.000	4	4
12	2.562	3	3
13	2.250	6	157
14	1.333	15	15

The 8 ft regular lumber is also an option for cutting, but the longest piece length in the 2x6 Lumber Pool is 8.062 ft, which is longer than 8 ft, and is not feasible by using 8 ft regular lumber only. However, if all of the 8.062 ft lumber pieces are ignored and the 8 ft regular lumber is used to produce the lumber pieces with lengths shorter than 8 ft, the result is shown below (Table 4.10 and Table 4.11).

Table 4.10: Optimized lumber cutting plan (8 ft only).

Cutting Pattern	Quantity	Scrap (ft/regular lumber)
[0,1,0,0,0,0,0,0,0,0,0,0,0,0,0]	2	0.833
[0,0,1,0,0,0,0,0,0,0,0,0,0,0,0]	159	0.875
[0,0,0,1,0,0,0,0,0,0,0,0,0,0,0]	2	1.229
[0,0,0,0,1,0,0,0,0,0,0,0,0,0,2]	2	1.292
[0,0,0,0,0,1,0,0,0,0,0,0,0,0,1]	12	0.146
[0,0,0,0,0,0,1,0,0,0,0,0,0,0,1]	3	0.479
[0,0,0,0,0,0,0,1,0,0,0,0,0,0,1]	2	0.834
[0,0,0,0,0,0,0,0,2,0,0,0,0,0,1]	2	0.001
[0,0,0,0,0,0,0,0,1,2,0,0,0,0,0]	3	0.167
[0,0,0,0,0,0,0,0,0,1,0,0,0,2,0]	2	0.250
[0,0,0,0,0,0,0,0,0,0,2,0,0,0,1]	1	0.667
[0,0,0,0,0,0,0,0,0,0,0,1,1,1,0]	3	0.188
Total Lumber Usage	193	
Total Cost ($)	1,544	

Table 4.11: Optimized lumber cutting result (8 ft only).

2x6 Lumber (8 ft)			
Rank	Length (ft)	Required Quantity	Actual Quantity
1	8.062	3	0
2	7.167	2	2
3	7.125	159	159
4	6.771	2	2
5	6.708	2	2
6	6.521	12	12
7	6.188	3	3
8	5.833	2	2
9	3.333	4	4
10	3.250	8	8
11	3.000	4	5
12	2.562	3	3
13	2.250	6	7
14	1.333	15	23

Nevertheless, the most economical way to perform lumber cutting is mixing all lumber lengths. Based on the equivalent lumber value assumptions and optimizing method (Simplex algorithm), the total cost of material is only \$1,542 (Table 4.12), which is considerably lower than any other scenarios; Table 4.13 shows that the final lumber product is extremely close to the lumber pieces demand.

Table 4.12: Optimized lumber cutting plan (mixed).

Cutting Pattern	Quantity	Lumber Length (ft)	Scrap (ft/regular lumber)
[0,1,0,0,0,0,0,0,0,0,0,0,0,0,0]	2	8	0.833
[0,0,1,0,0,0,0,0,0,0,0,0,0,0,0]	148	8	0.875
[0,0,0,0,0,1,0,0,0,0,0,0,0,0,1]	6	8	0.146
[0,0,1,0,0,0,0,0,0,0,0,0,1,0,0]	3	10	0.313
[0,0,1,0,0,0,0,0,0,0,0,0,0,0,2]	5	10	0.209
[0,0,0,1,0,0,0,0,0,0,0,1,0,0,0]	2	10	0.229
[0,0,0,0,1,0,0,0,0,0,1,0,0,0,0]	2	10	0.042
[0,0,0,0,0,1,0,0,0,1,0,0,0,0,0]	3	10	0.146
[0,0,0,0,0,1,0,0,0,0,1,0,0,0,0]	3	10	0.229
[0,0,0,0,0,0,1,0,0,0,1,0,0,0,0]	3	10	0.562
[1,0,0,0,0,0,0,0,0,1,0,0,0,0,0]	1	12	0.605
[1,0,0,0,0,0,0,0,0,0,0,1,0,0,0]	2	12	0.938
[0,0,1,0,0,0,0,0,0,0,0,0,0,2,0]	3	12	0.375
[0,0,0,0,0,0,0,0,2,0,0,0,0,0,0]	1	12	0.334
Total Lumber Usage	156 (8 ft), and 21 (10 ft), and 7 (12 ft)		
Total Cost ($)	1,542		

Table 4.13: Optimized lumber cutting result (mixed).

2x6 Lumber (mixed)			
Rank	Length (ft)	Required Quantity	Actual Quantity
1	8.062	3	3
2	7.167	2	2
3	7.125	159	159
4	6.771	2	2
5	6.708	2	2
6	6.521	12	12
7	6.188	3	3
8	5.833	2	2
9	3.333	4	4
10	3.250	8	8
11	3.000	4	4
12	2.562	3	3
13	2.250	6	6
14	1.333	15	16

The lumber cutting pattern, quantity, and label are all available at this stage, and a framing layout (Figure 4.19) can be exported from Revit, so the lumber cutting and framing processes can easily be connected by lumber labels.

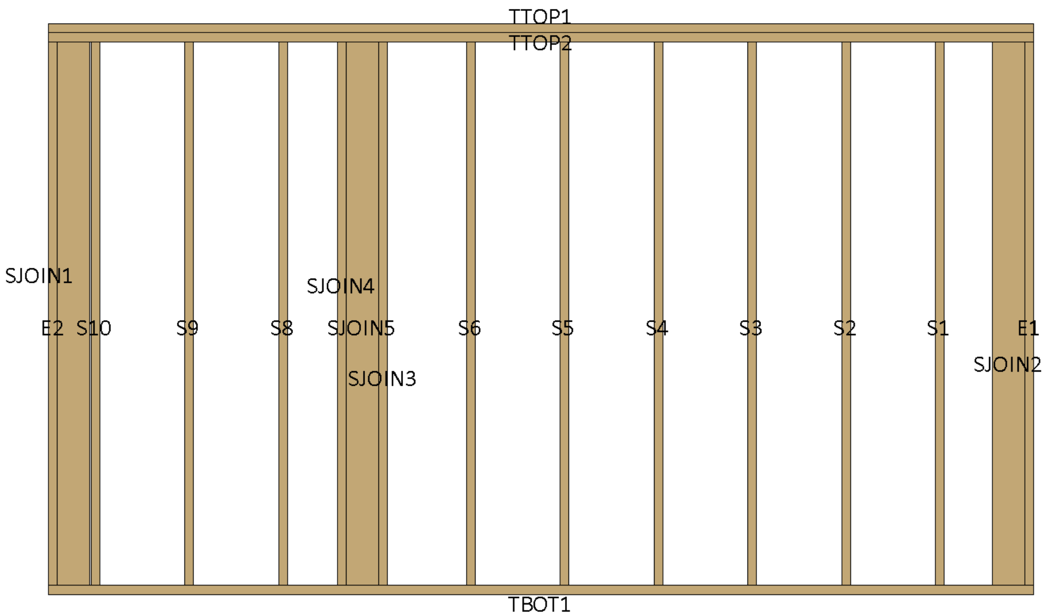


Figure 4.19: Wall framing layout with lumber labels (Exterior Wall AX3).

4.3.3 Sheathing Placement and Optimization

In this section, the sheathing placement and optimization processes are clarified and the optimized cutting layouts are shown.

At the beginning of sheathing placement, the user needs to provide a sheathing nominal size (height and length) and a tolerance in feet by loading known data into the interface (Figure 4.20). The *tolerance* represents the user tolerated accuracy. For example, if the tolerance is filled with 0.01, that means a piece of 4 ft x 3.99 ft sheathing can be used as 4 ft x 4 ft sheathing.

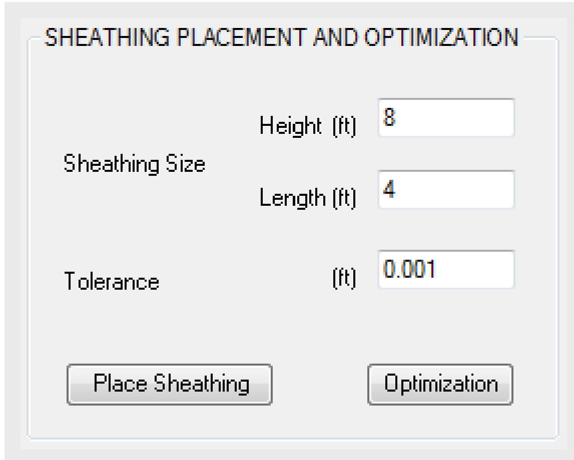


Figure 4.20: Sheathing placement and optimization interface.

4.3.3.1 Sheathing Placement

To demonstrate the sheathing placement function, two sheathing sizes are tested, 4x8 (4 ft in length and 8 ft in height) and 4x7 (4 ft in length and 7 ft in height). The sheathing of 4x8 is higher than the wall height in the case study, which is 7 ft 6 in. The other (4x7) is shorter than the wall height. Six windows and one door are on the house's front wall (wall label: AX4), which is the most complicated face compared to the other 3 wall faces, so the case study focuses on this wall, which is 72 ft in length and 7 ft 6 in in height.

Case 1 (Sheathing size: 4x8)

As mentioned in the methodology, to start placing sheathing on a wall, the first step is to identify the Framing Point (Figure 4.21) based on the wall layer thicknesses (Figure 4.22) and the coordinates of the pertinent points at the corner.

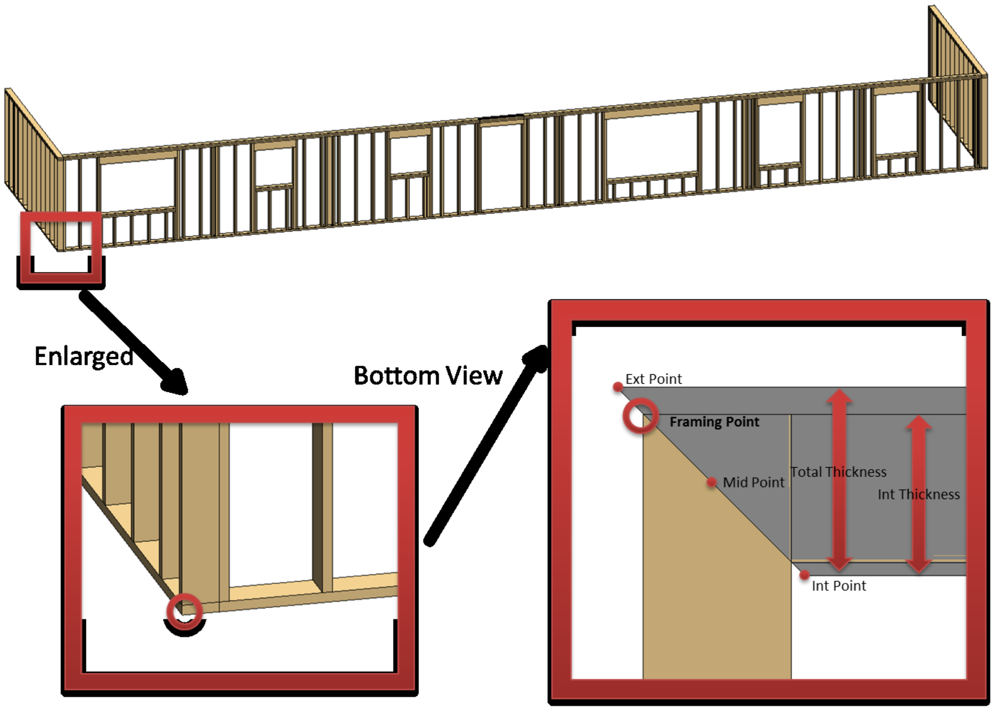
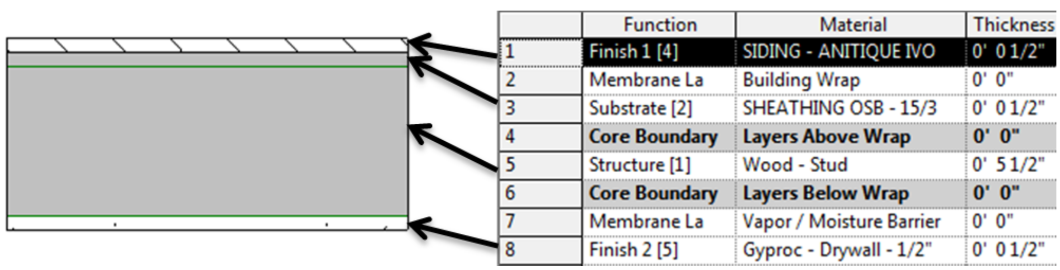


Figure 4.21: Highlight of Framing Point in case study.



	Function	Material	Thickness
1	Finish 1 [4]	SIDING - ANITIQUE IVO	0' 0 1/2"
2	Membrane La	Building Wrap	0' 0"
3	Substrate [2]	SHEATHING OSB - 15/3	0' 0 1/2"
4	**Core Boundary**	**Layers Above Wrap**	**0' 0"**
5	Structure [1]	Wood - Stud	0' 5 1/2"
6	**Core Boundary**	**Layers Below Wrap**	**0' 0"**
7	Membrane La	Vapor / Moisture Barrier	0' 0"
8	Finish 2 [5]	Gyproc - Drywall - 1/2"	0' 0 1/2"

Figure 4.22: Wall layer thicknesses in case study.

Among all the points in Figure 4.21 and layer thicknesses in Figure 4.22, total thickness (T_t), interior thickness (T_i), middle point (M_x, M_y, M_z), and interior point (I_x, I_y, I_z) can be extracted from Revit directly and regarded as known values.

Known values:

$$Total\ Thickness\ T_t = 1/2" + 1/2" + 5\ 1/2" + 1/2" = 7"$$

$$Interior\ Thickness\ \ T_i = 5\ 1/2"{+}1/2"\ \ =\ 6"$$

$$Interior\ Point\ (I_x, I_y, I_z) = (-40'\ \ 5\ 43/128",\qquad 6'\ \ 9\ 39/64",\qquad 0'\ \ 0")$$

$$Middle\ Point\ (M_x, M_y, M_z) = (-40'\ \ 8\ 107/128",\qquad 6'\ \ 6\ 7/64",\qquad 0'\ \ 0")$$

After substituting the known values for the components in the following functions, the result of Framing Point (F_x, F_y, F_z) is accessible.

$$F_x = I_x + \frac{2\times(M_x - I_x)}{T_t} \times T_i \tag{3.11}$$

$$F_y = I_y + \frac{2\times(M_y - I_y)}{T_t} \times T_i \tag{3.12}$$

$$F_z = I_z = M_z = 0 \tag{3.13}$$

$$F_x = -40'\ \ 5\ 43/128" + \frac{2\times(-40'\ \ 8\ 107/128" - (-40'\ \ 5\ 43/128"))}{7"}$$

$$\times\ 6"{=}{-40'}\ \ 11\ 43/128"$$

$$F_y = 6'\ \ 9\ 39/64" + \frac{2\times(6'\ \ 6\ 7/64" - 6'\ \ 9\ 39/64")}{7"} \times 6" = 6'\ \ 3\ 39/64"$$

$$F_z = 0'\ \ 0" = 0'\ \ 0" = 0'\ \ 0"$$

$$Framing\ Point\ (F_x, F_y, F_z) = (-40'\ \ 11\ 43/128",\qquad 6'\ \ 3\ 39/64",\qquad 0'\ \ 0")$$

As the Framing Point is available, the next values to be calculated for sheathing placement are the length and height of sheathing. The sheathing length is determined dealing with two conditions:

$$l_i = \begin{cases} D_1, & D_1 \le L_R \\ D_2, & D_1 > L_R \end{cases} \tag{3.20}$$

D_1: Distance between the current Start Point and the closest Group 1 End Point following the wall direction.

D_2: Distance between the current Start Point and the furthest Group 2 End Point following the wall direction, where distance always has a value less than the regular sheathing length (4 ft).

As the Figure 4.23 shows, D_1 of this wall framing is obviously 2 ft 10 ½ in, which is shorter thanL_R 4 ft. Therefore, the length of the first piece of sheathing (l_1) is 2 ft 10 ½ in.

For the sheathing height, since the regular sheathing size in this case study is 4 by 8 (height (H_R): 8 ft), only one piece of regular sheathing is sufficient to cover the whole wall height (H_w), 7 ft 6 in. Hence the first piece of sheathing height (h_1) is 7 ft 6 in.

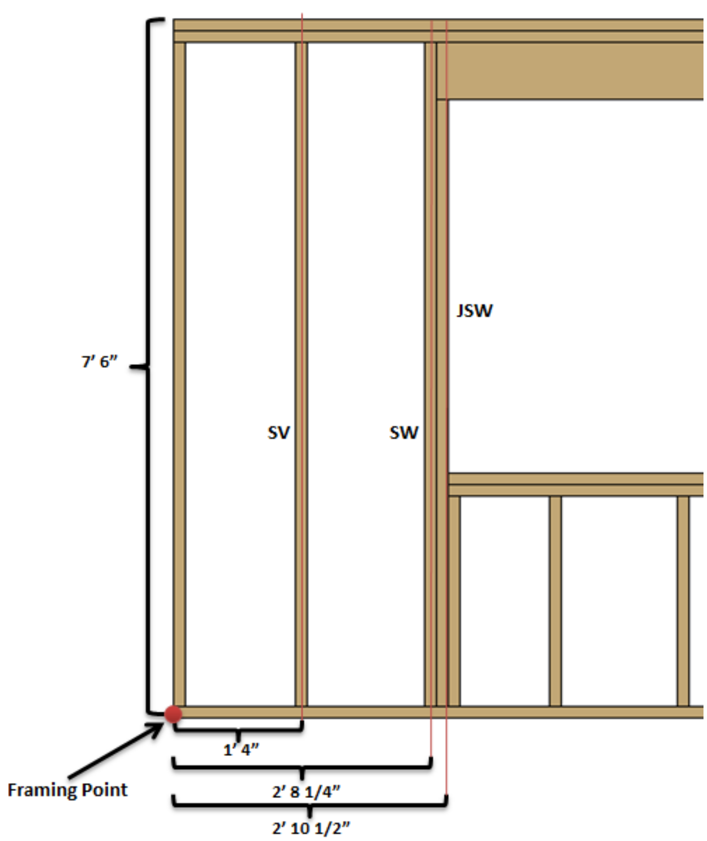


Figure 4.23: Framing Point and three possible sheathing lengths in the wall framing.

As Figure 4.24 illustrates, installation of the first sheathing piece onto the wall generates the Start Points for subsequent pieces above and below the window framing and the piece for full wall-height framing on the other side of the window opening. Both of the sheathing lengths are equal to the width of the window frame (5 ft 10 in), which can be extracted directly from the model, and the heights are equal to the framing above and below the window opening, and the equations to calculate the values are recalled here:

Sheathing height above the i^{th} window:

$$h_i = H_w - T_{sbp} - H_{wji} = 7'6" - 1\ 1/2" - 6'6\ 1/4" = 10\ 1/4"$$

Sheathing height below the i^{th} window:

$$h_i = H_{wci} + T_{sbp} + T_{dspi} = 2'3{+}1\ 1/2 + 3" = 2'7\ 1/2"$$

The bottom sheathing piece has a length of 5 ft 10 in and a height of 2 ft 7½ in, and the top sheathing piece has a length of 5 ft 10 in and a height of 10 ¼ in. To calculate the Start Points, the wall direction is a key value. In this case study, the wall is drawn along the *x-axis* from negative to positive, which generates the wall vector of (1,0,0).

Start Point 1:

$$P_x = (l_i + W_{wi}) * r_x + p_x = (2'10\ 1/2" + 5'10") * 1 + (-40'\ \ 11\ 43/128")$$
$$= -31'\ \ 9\ 43/128"$$

$$P_y = (l_i + W_{wi}) * r_y + p_y = (2'10\ 1/2" + 5'10") * 0 + 6'\ 3\ 39/64"$$

$$= 6'\ 3\ 39/64"$$

$$P_z = (l_i + W_{wi}) * r_z + p_z = (2'10\ 1/2" + 5'10") * 0 + 0' = 0'$$

$$Start\ Point\ 1: (P_x, P_y, P_z) = (-31'\ 9\ 43/128", \quad 6'\ 3\ 39/64", \quad 0'\ 0")$$

Start Point 2:

$$P_x = l_i * r_x + p_x = 2'10\ 1/2" * 1 + (-40'\ 11\ 43/128")$$

$$= -31'\ 0\ 107/128"$$

$$P_y = l_i * r_y + p_y = 2'10\ 1/2" * 0 + 6'\ 3\ 39/64" = 6'\ 3\ 39/64"$$

$$P_z = l_i * r_z + p_z + H_{wji} + T_{sbp} = 2'10\ 1/2" * 0 + 0' + 6'6\ 1/4" + 1\ 1/2"$$

$$= 6'\ 7\ 3/4"$$

$$Start\ Point\ 2: (P_x, P_y, P_z) = (-31'\ 107/128", \quad 6'\ 3\ 39/64", \quad 6'\ 7\ 3/4")$$

Start Point 3:

$$P_x = l_i * r_x + p_x = 2'10\ 1/2" * 1 + (-40'\ 11\ 43/128")$$

$$= -31'\ 0\ 107/128"$$

$$P_y = l_i * r_y + p_y = 2'10\ 1/2" * 0 + 6'\ 3\ 39/64" = 6'\ 3\ 39/64"$$

$$P_z = l_i * r_z + p_z = 2'10\ 1/2" * 0 + 0' = 0'$$

$$Start\ Point\ 3: (P_x, P_y, P_z) = (-31'\ 107/128", \quad 6'\ 3\ 39/64", \quad 0')$$

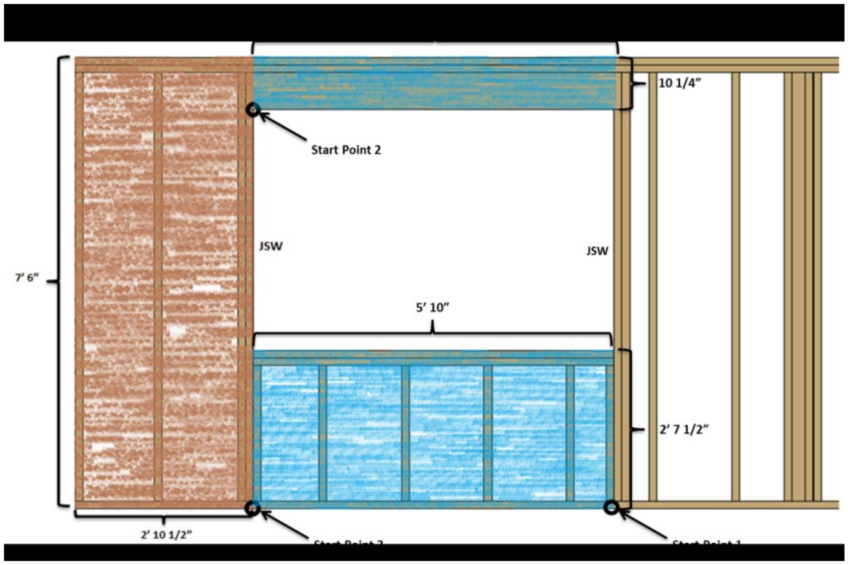


Figure 4.24: Three Start Points are created.

The Start Point at the right bottom corner of the bottom sheathing piece enables the following placements (Figure 4.25). Formula 3.20 is recalled here to determine the lengths of sheathing pieces.

$$l_i = \begin{cases} D_1, & D_1 \leq L_R \\ D_2, & D_1 > L_R \end{cases} \tag{3.20}$$

$D_2 = 6'1\ 1/2"$, which is longer than regular sheathing length($L_R = 4'$), so l_i is equal to $D_1 = 3'3\ 1/2"$ in this situation. The consecutive sheathing piece's length is equal to$D_2 = 2'10"$. Since the wall height is less than the regular sheathing height, both of the heights are the same as the wall height, which is 7’6”.

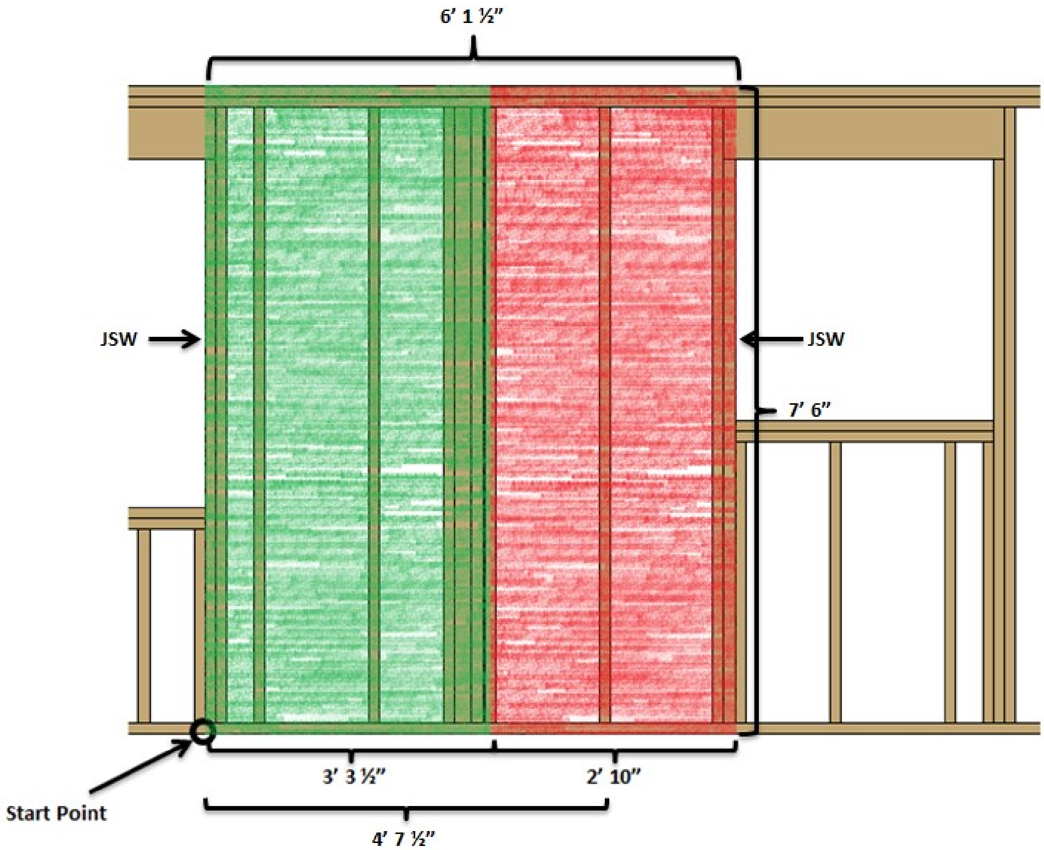


Figure 4.25: Sheathing placements in case study.

With the methodology utilized to place the previous pieces of sheathing, the whole wall panel is framed by sheathing, and Figure 4.26 shows the front view of the external wall (AX4) with completed sheathing placement (4x8 regular sheathing). After the placement, each piece of sheathing has a label assigned at the centre, and the format is the combination of "AX4-S" and sheathing ID, which is a digit.

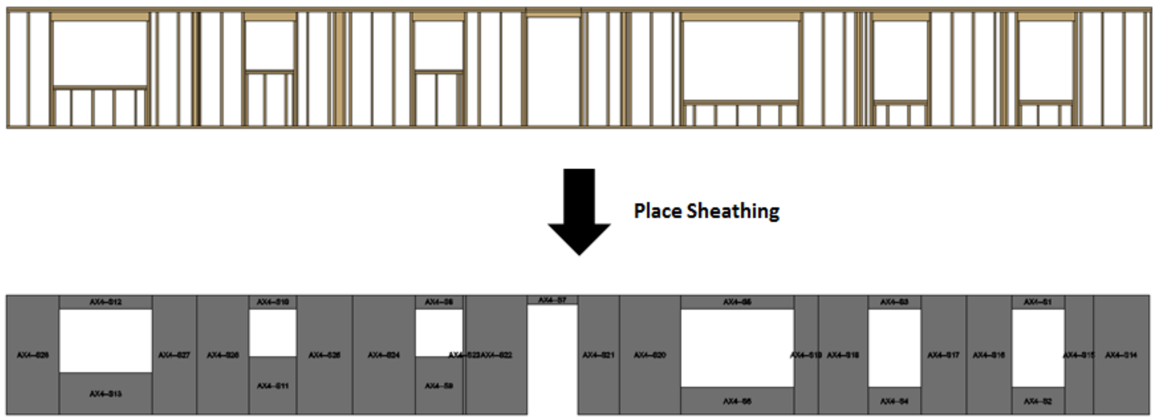


Figure 4.26: Sheathing placement (4x8).

Case 2 (Sheathing size: 4x7)

In this case, the regular sheathing size is adjusted to 7 ft, which is shorter than the wall height, so another layer of sheathing is needed to cover the wall framing.

The sheathing placement begins with the identical Framing Point as Case 1, and after placing the first sheathing piece, there is one more Start Point generated, which locates right above the framing point, and this Start Point is used for placement of sheathing to cover the upper portion of framing.

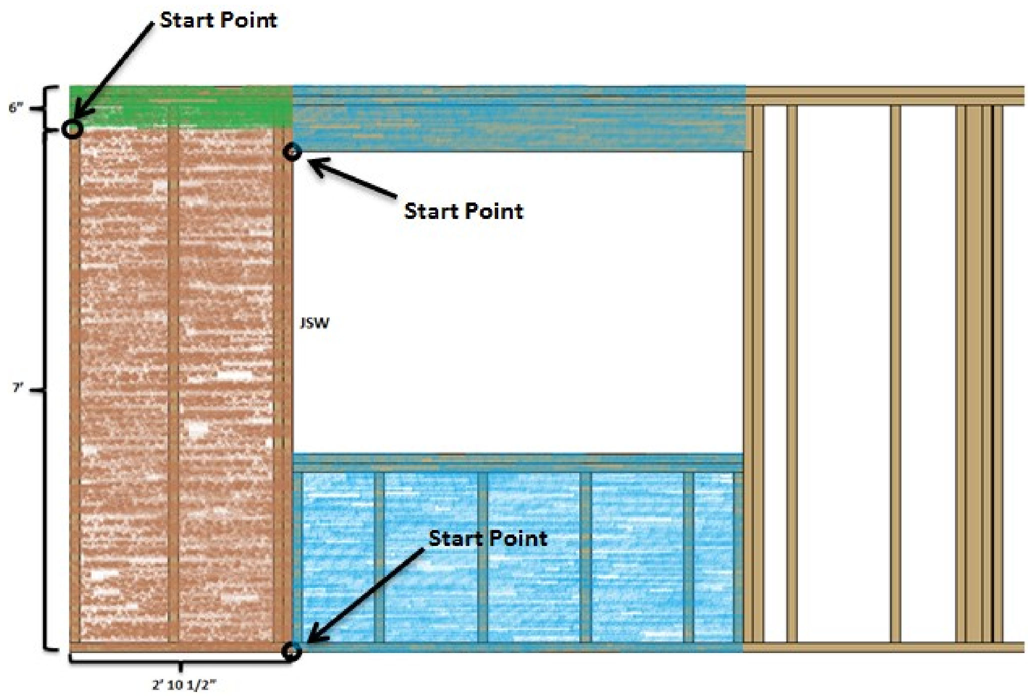


Figure 4.27: Sheathing piece to cover the upper portion of wall (1).

Since the shortened sheathing height does not change the placement of sheathing above and below the window opening, the two pieces of sheathing have the identical size as Case 1. In addition to this, the maximum length to cover the main wall framing is also the regular sheathing length (4 ft), but the maximum length to cover the upper portion of the wall is extended to the regular sheathing height (rotate the regular sheathing by 90 degrees), because the upper portion of framing is generally more narrow than the regular sheathing length (4 ft).

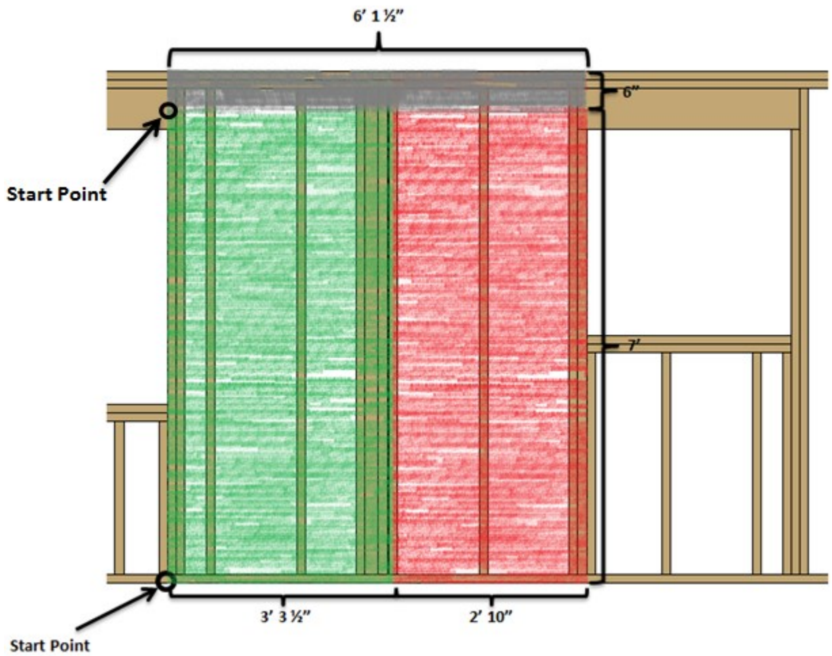


Figure 4.28: Sheathing piece to cover the upper portion of wall (2).

Figure 4.29 shows the front view of the external wall (AX4) with installed sheathing pieces for demonstration.

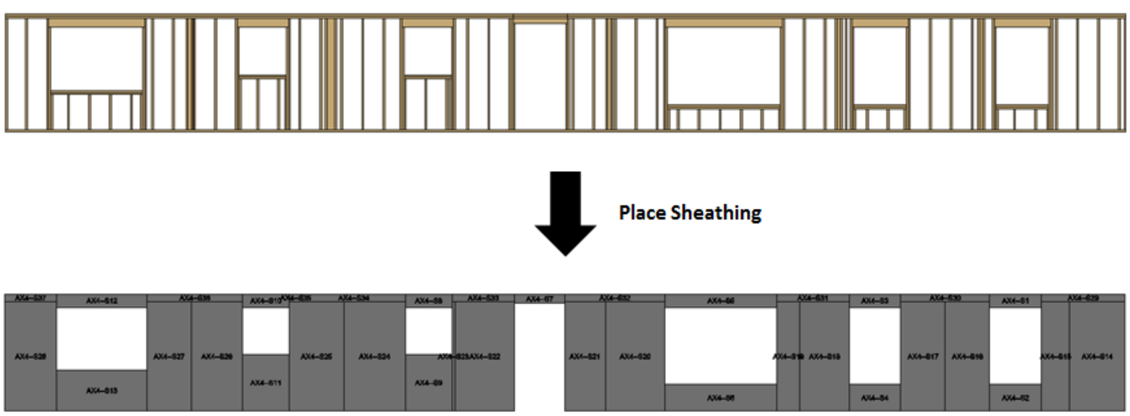


Figure 4.29: Sheathing placement (4x7).

4.3.3.2 Sheathing Optimization

The sheathing pieces in Sheathing Placement Case 1 (sheathing nominal size: height = 8 ft, length = 4 ft) are selected for the sheathing optimization demonstration, and stored in a virtual sheathing pool. The sheathing pieces are assigned different labels and ranked first by height and then by length; a *Sheathing Piece Pool* is formed (Table 4.14).

Table 4.14: Sheathing pieces collection.

Rank	Label	Length (ft)	Height (ft)	Rank	Label	Length (ft)	Height (ft)	Rank	Label	Length (ft)	Height (ft)
1	AX2--S3	4	7.5	19	AX4--S24	3.9384	7.5	37	AX4--S21	2.6042	7.5
2	AX2--S4	4	7.5	20	AX2--S5	3.9166	7.5	38	AX4--S15	1.8126	7.5
3	AX2--S7	4	7.5	21	AX4--S20	3.8556	7.5	39	AX2--S9	1.5536	7.5
4	AX2--S8	4	7.5	22	AX4--S22	3.8528	7.5	40	AX4--S19	1.5	7.5
5	AX2--S11	4	7.5	23	AX3--S1	3.6666	7.5	41	AX4--S23	0.1875	7.5
6	AX2--S12	4	7.5	24	AX5--S1	3.6666	7.5	42	AX4--S6	1.7188	7.1666
7	AX2--S13	4	7.5	25	AX2--S2	3.5402	7.5	43	AX4--S5	0.8542	7.1666
8	AX2--S14	4	7.5	26	AX4--S14	3.5402	7.5	44	AX2--S1	0.6666	5.9376
9	AX2--S15	4	7.5	27	AX4--S25	3.5	7.5	45	AX4--S13	2.6354	5.8334
10	AX2--S16	4	7.5	28	AX4--S28	3.3334	7.5	46	AX4--S12	0.8542	5.8334
11	AX2--S17	4	7.5	29	AX4--S26	3.3126	7.5	47	AX4--S11	3	3.6354
12	AX2--S18	4	7.5	30	AX2--S10	3.1756	7.5	48	AX4--S9	3	3.6354
13	AX3--S2	4	7.5	31	AX4--S18	3.1458	7.5	49	AX4--S2	1.7188	3.3334
14	AX3--S3	4	7.5	32	AX2--S19	3.125	7.5	50	AX4--S4	1.7188	3.3334
15	AX3--S4	4	7.5	33	AX4--S16	2.8542	7.5	51	AX4--S1	0.8542	3.3334
16	AX5--S2	4	7.5	34	AX4--S17	2.8542	7.5	52	AX4--S3	0.8542	3.3334
17	AX5--S3	4	7.5	35	AX4--S27	2.8124	7.5	53	AX4--S7	1.125	3.2084
18	AX5--S4	4	7.5	36	AX2--S6	2.75	7.5	54	AX4--S8	0.8542	3
								55	AX4--S10	0.8542	3

The first step of the sheathing optimization is checking the sheathing in the pool; as long as the current longest piece (7 ft 6 in) is higher than the regular sheathing length (4 ft), the regular sheathing is orientated vertically, otherwise, it is orientated horizontally.

The cutting always starts from the highest ranking piece (AX2—S3) at bottom left corner. Since the length of regular sheathing is fulfilled, after cutting the first piece, only the top portion of sheathing remains, which has 4 ft in height and 0.5 ft in length (Figure 4.30). After going through all the sheathing pieces remaining in the pool, the length of the top portion of remaining sheathing is too narrow to cut any pieces from the pool, so it is considered waste. The next 17 sheathing pieces with the identical dimensions are cut in this manner, and all these sheathing pieces are removed from the pool.

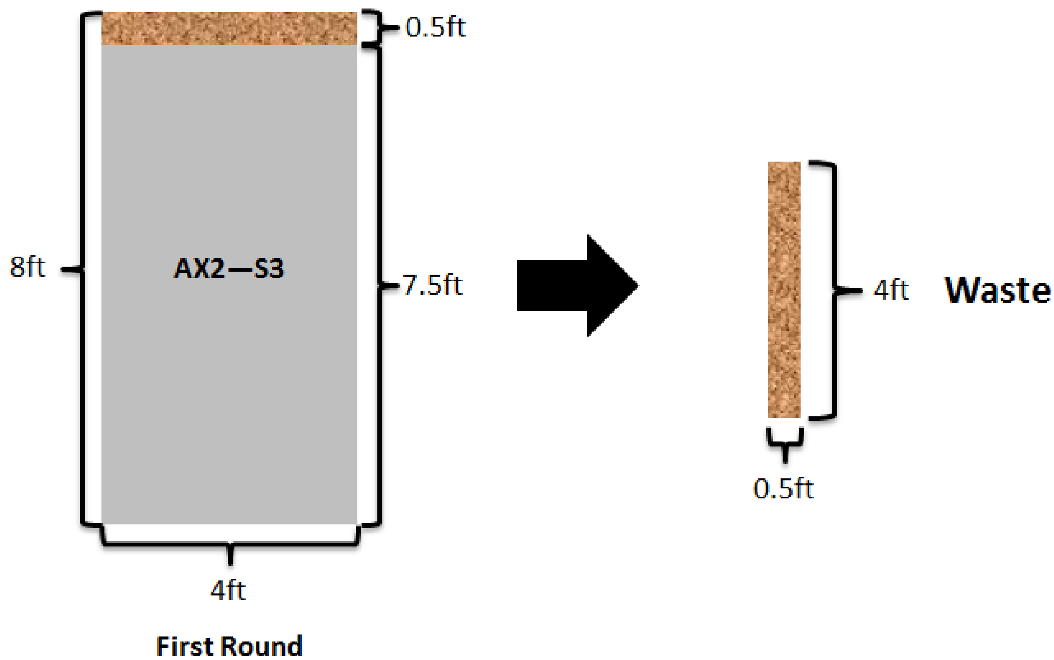


Figure 4.30: Sheathing piece fitting (1).

The next highest one is AX4—S24 (length = 3.9384 ft, height = 7.5 ft), and the available length after cutting is only 0.06 ft, which is much more narrow than any lengths in the pool, so the narrow strip on the right (0.06 ft x 7.5 ft) of AX4—S24 (Figure 4.31) is wasted. Since the other part was tested prior for waste, there is only one piece that can be cut in the regular sheathing.

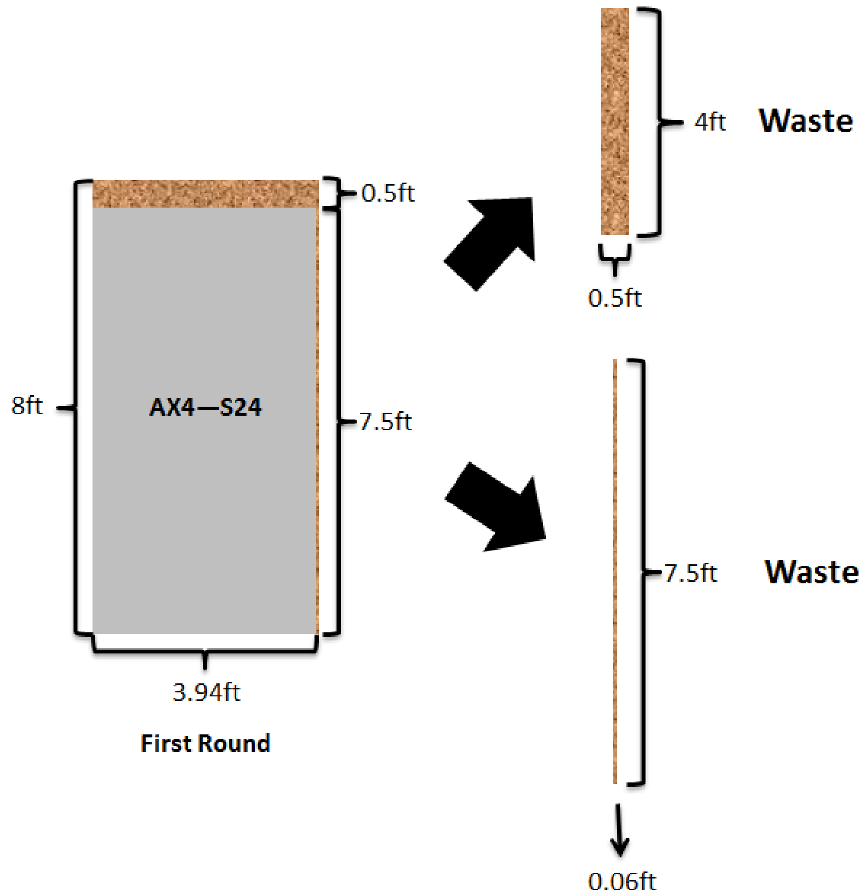


Figure 4.31: Sheathing piece fitting (2).

The same cutting pattern is repeated for the next three pieces until AX3—S1 is reached, because on the right side of AX3—S1, there is sufficient space to fit another piece of sheathing, which is AX4—S23 (Figure 4.32).

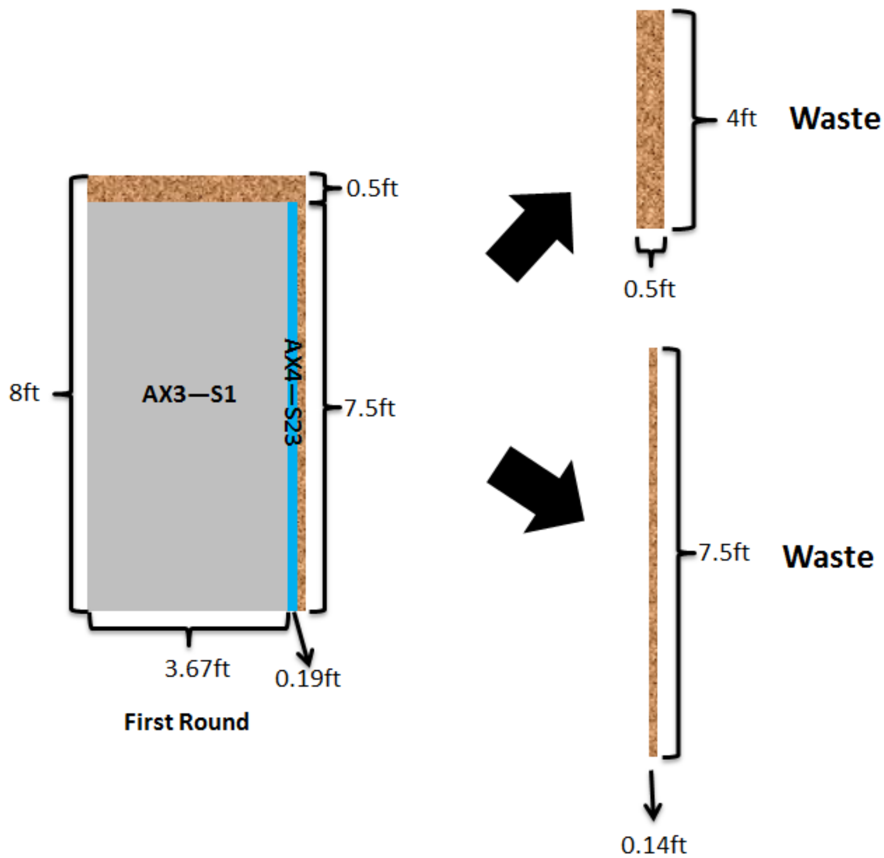


Figure 4.32: Sheathing piece fitting (3).

In this case study, most of the regular sheathing can cut only one or two pieces side by side vertically, as previously shown. In addition, another three cutting patterns are available.

After cutting the piece AX4—S13 from a regular sheathing (Figure 4.33), there are no other pieces that can be cut from the remaining portion on the right side of AX4—S13, so it is waste. Upon testing the upper remaining portion, it is found that it can be used to cut AX4—S2.

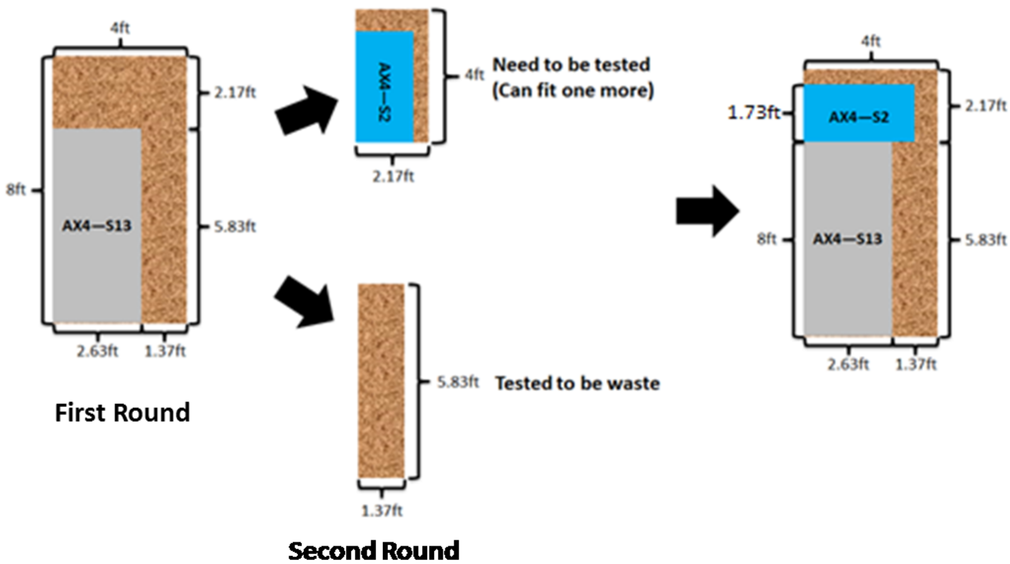


Figure 4.33: Sheathing piece fitting (4).

As shown in Figure 4.34, after cutting two pieces (AX4—S17 and AX4—S1) on a regular sheathing, three rectangular portions remain, and after testing each of them, one rectangular portion can be used to cut AX4—S23.

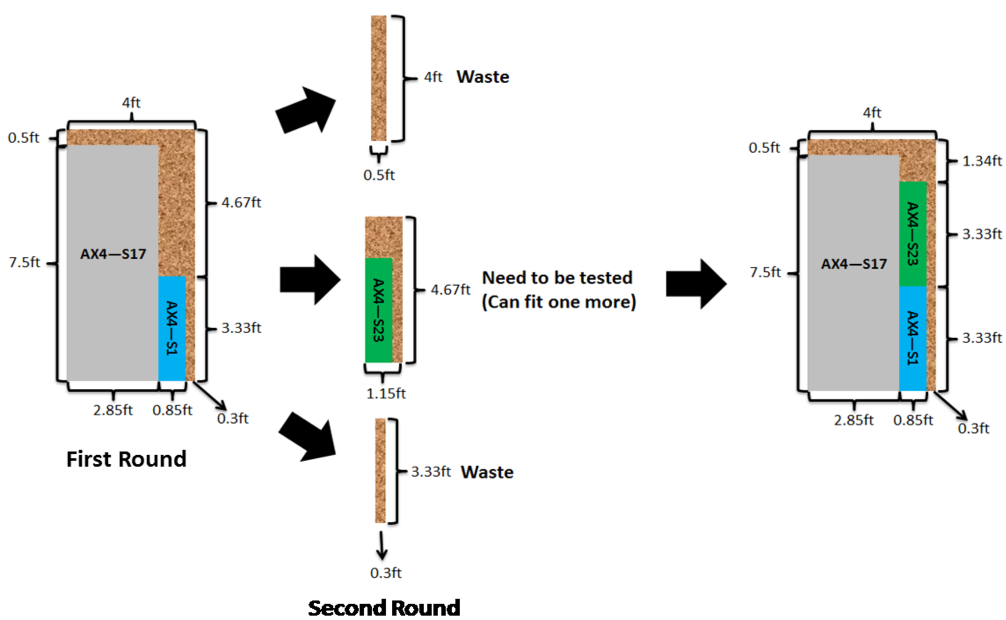


Figure 4.34: Sheathing piece fitting (5).

Following the methodology, the last three pieces left are AX4—S9, AX4—S11 and AX4—S4, and none has a height greater than regular sheathing length (4 ft), which leads to the horizontal orientation of regular sheathing, and the remaining portion is a stair shape. Since there are no remaining pieces in the pool, the stair shape portion is considered waste.

Figure 4.35: Sheathing piece fitting (6).

4.3.3.3 Optimization Export

After the optimization is complete, a developed function (Figure 4.36) can export the cutting plans to a selected folder.

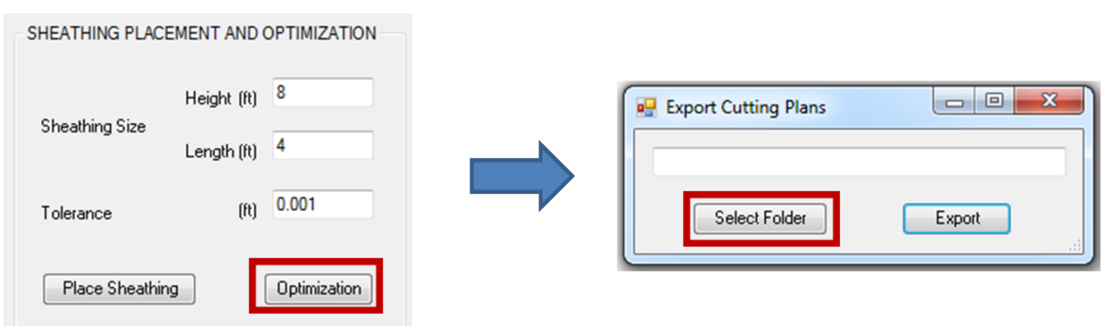


Figure 4.36: Sheathing placement and optimization interface (export cutting plans).

All the cutting plans are created in .jpg type. A regular sheathing is bordered in blue, and all the labeled rectangles inside it represent the cut pieces with corresponding labels and sizes shown beside or below. The horizontal dimension is located ahead of the vertical dimension with the unit of measurement in feet (Figure 4.37).

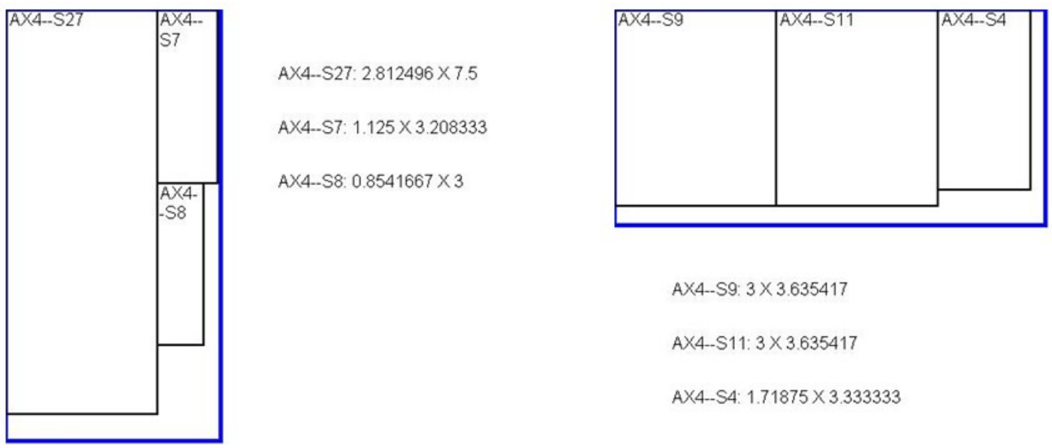


Figure 4.37: Sample sheathing cutting plan.

Chapter 5 Conclusion

5.1 General Conclusion

This thesis presents methodologies for quantity takeoff and material optimization, and they are implemented by two user interfaces developed in the environment of Microsoft Visual C#.NET and embedded into Autodesk Revit.

The task of quantity takeoff is time-consuming and error prone. It currently employs a 2D print-out from a graphical environment, and the main processes, including material counting, measurement, and calculation, are carried out manually rather than by computer. Hence, the research is motivated by the need for an automated quantity takeoff system embedded in Autodesk Revit, which will allow the operation to be performed quickly and accurately, and will limit human error. The final output is an Excel file containing all the necessary quantities.

Material optimization is developed in order to optimize the usage of 1D material (lumber) and 2D material (sheathing). The greedy algorithm and simplex algorithm are applied to optimize lumber, and greedy and Bottom-Left Heuristic algorithms are the main strategies employed for sheathing optimization. The end-user of the add-on need only provide nominal sizes of lumber and sheathing, and the program is able to provide relatively optimized cutting scenarios for the wall sheathing layout to increase workers' productivity and reduce material waste. The final output also provides practical material quantities for inventory.

5.2 Research Contributions

The developed programs in this research, including quantity takeoff and material optimization, can benefit the current modular construction industry in many respects. These benefits are outlined below.

5.2.1 Quantity Takeoff

- The developed quantity takeoff can decrease operation time from approximately 150 minutes to less than 30 seconds, which represents a 99% time savings; this progress can also limit the potential for and effect of human error.

- Since the automated quantity takeoff time is extremely efficient compared to the current manual process, the time requirement to update takeoff due to any unforeseen changes in the construction plan is also decreased significantly.

5.2.2 Material Optimization

- Visualization of sheathing on walls provides a good sense of how the work can be performed efficiently and reduces the experience requirement of sheathing framers to a relatively low level.

- Optimization of materials gives carpenters a clear cutting plan by showing the cutting lengths and quantities; it not only decreases material waste but also increases productivity by eliminating guesswork in the process.

- Cutting plans and lumber/sheathing framing plans are distributed to workers of different trades, but the plans can be connected by labels on each item. Hence the productivity is improved by avoiding errors in communication between different trades.

5.3 Research Limitations

- The precondition of quantity takeoff is that, the Revit model needs to be preloaded with classification system information. For any modular construction company, this is a time-consuming task due to a large amount of input items; even the slightest error in the input process, such as an extra space or an incorrect digit, can greatly affect the outcome.
- The quantity takeoff program cannot offer feasible 1D and 2D material quantities due to limitations of the Revit model, which could not consider the material cutting process, but only read the total length (1D materials) and net area (2D materials).
- The lumber optimization can be performed by the greedy algorithm and Simplex algorithm. Each algorithm has some limitations:
    - For the greedy algorithm, only one length for each nominal size of lumber can be used for cutting; therefore, it will not be the most economical method.

- Simplex algorithm can accommodate multiple lengths of lumber; however, an external library (for example, IBM CPLEX Optimizer) is required.

- Since the greedy algorithm is also applied to sheathing optimization, only one sheathing size can be used for optimization.
- The developed program only allows for one type of sheathing to be used in a given project.

5.4 Future Improvement

These research methodologies can serve as the foundation for quantity takeoff and material optimization, and at least the following three improvements can be implemented in the future:

- Apply multiple sheathing sizes with Simplex algorithm for optimization.
- Apply multiple sheathing types (regular and fire-rated sheathing) for optimization.
- The sheathing placement function currently only works on vertical placement, so the function can be improved to cover other sheathing placement patterns.

References

Aryanezhad, M. B., Fakhim Hashemi, N., Makui, A., and Javanshir, H. (2012). "A simple approach to the two-dimensional guillotine cutting stock problem." *Journal of Industrial Engineering International*, 8(21).

Autodesk (2008). "BIM and API Extensions." Retrieved April 20, 2015, from http://images.autodesk.com/latin_am_main/files/revit_bim_and_api_extensions_mar08.pdf

Autodesk (2013). "Lesson 3: Model-Based Estimating and Quantity Takeoff." Retrieved November 18, 2014, from http://bimcurriculum.autodesk.com/lesson/lesson-3-model-based-estimating-and-quantity-takeoff

Beyond the Paper (2006). "What is quantity takeoff?" Retrieved November 18, 2014, from http://dwf.blogs.com/beyond_the_paper/2006/04/what_is_quantit.html

Build Your Own House (2015). "Laying Concrete Slabs and Framing your House" Retrieved February 26, 2015, from http://buildyourhouse.blog.com/2011/05/30/laying-concrete-slabs-framing-your-house/

Building Information Modeling (2014). Retrieved November 19, 2014, from http://eds.b.ebscohost.com/eds/ebookviewer/ebook/bmxlYmtfXzc2MDc5MV9fQU41?sid=3d7e9e39-e638-479b-aac9-761e5d590298@sessionmgr113andvid=5andformat=EBandrid=2

Costa, F. M. and Sassi R. J. (2012). "Application of an hybrid bio-inspired meta-heuristic in the optimization of two-dimensional guillotine cutting in an glass industry." *Intelligent Data Engineering and Automated Learning - IDEAL 2012* (7435), 802–809.

Firat, C. E., Arditi, D., Hamalainen, J.-P., Stenstrand, J., and Kiiras, J. (2010) "Quantity take-off in model-based systems." *Proceedings of the CIB W78 2010: 27th International Conference, Nov. 16–18.*

Home Innovation Research Labs (2001). "Residential construction waste: From disposal to management." Retrieved January 26, 2015, from http://www.toolbase.org/Best-Practices/Construction-Waste/residential-construction-waste

Insulation Online (2014). "Tyvek Housewrap Breather Membrane." Retrieved February 2, 2015, from http://www.just-insulation.com/002-brands/tyvek-housewrap-breather-membrane-for-walls.html

Kent Homes (2015). "Mini Homes." Retrieved January 30, 2015, from http://www.kenthomes.com/kent-homes-browse-mini-homes.aspx?HomeStyle=Mini%20Homes

Macleod, B. (1993). "An algorithm for the 2D guillotine cutting stock problem." *European Journal of Operational Research*, 68(3), 400-412.

Mah, D. and Al-Hussein, M. (2008). "Residential construction material waste minimization analysis during the framing stage." *Proceedings, Canadian Society for Civil Engineering Annual Conference*, Québec City, QC, Canada, Jun. 10-13, 417-425.

Manrique, J. D., Al-Hussein, M., Bouferguene, A., Safouhi, H., and Nasseri, R. (2011). "Combinatorial algorithm for optimizing wood waste in framing designs." *Journal of Construction Engineering and Management*, 137(3), 188–197.

Manrique, J. D. and Juan, D. (2009). "Automation of design and drafting for wood frame structures and construction waste minimization." *Automation in Construction*, (55), 15-24.

Monteiro, A. and Poças Martins, J. (2013). "A survey on modeling guidelines for quantity takeoff-oriented BIM-based design." *Automation in Construction*, 35, 238–253.

Pekin Hardwood (2015). “Lumber.” Retrieved February 26, 2015, from http://www.pekinhardwood.com/lumber

Sabol, L. (2008). “Challenges in cost estimating with building information modeling.” *Design + Construction Strategy*, 1–16.

StrucSoft Solutions (2015). “MWF.” Retrieved February 19, 2015, from http://strucsoftsolutions.com/products/

Van Nederveen, G. A. and Tolman, F. P. (1992). “Modelling multiple views on buildings.” *Automation in Construction*, 1(3), 215–224.

Appendices

A: 2x3 lumber pool

2X3 Lumber Pool							
ID	Length (ft)	ID	Length (ft)	ID	Length (ft)	ID	Length (ft)
AN22__TBOT1	14.75	AN24_S1	7.125	AN22__SJOIN5	7.125	AN13__JSD-L1-2	6.729
AN6__TBOT1	14.75	AN24_S2	7.125	AN22__SJOIN6	7.125	AN13__JSD-R1-2	6.729
AN15__TBOT1	11.583	AN24_S3	7.125	AN6__SD-L1-1	7.125	AN20__JSD-L1-1	6.729
AN24__TBOT1	11.104	AN24_S4	7.125	AN6_E1	7.125	AN20__JSD-R1-1	6.729
AN23__TBOT1	9.042	AN24_S5	7.125	AN6_E2	7.125	AN26__JSD-L1-1	6.729
AN13__TBOT1	8.875	AN24_S6	7.125	AN6_S1	7.125	AN26__JSD-R1-1	6.729
AN13__SD-L1-1	7.125	AN24_S7	7.125	AN6_S4	7.125	AN23__JSD-L1-1	6.729
AN13__SD-R1-2	7.125	AN24_S8	7.125	AN6_S6	7.125	AN23__JSD-R1-1	6.729
AN13_E1	7.125	AN19_E1	7.125	AN6_S7	7.125	AN8__JSD-L1-1	6.729
AN13__SJOIN1	7.125	AN19_E2	7.125	AN6_S8	7.125	AN8__JSD-R1-1	6.729
AN13__SJOIN2	7.125	AN19_S1	7.125	AN6__SJOIN1	7.125	AN11__JSD-L1-1	6.729
AN14_E1	7.125	AN19_S2	7.125	AN6__SJOIN2	7.125	AN11__JSD-R1-1	6.729
AN14_E2	7.125	AN19_S3	7.125	AN6__SJOIN3	7.125	AN22__JSD-L1-1	6.729
AN14_S1	7.125	AX4__SJOIN3	7.125	AN6__SJOIN4	7.125	AN22__JSD-R1-1	6.729
AN14__SJOIN1	7.125	AX4__SJOIN6	7.125	AN6__SJOIN5	7.125	AN6__JSD-L1-1	6.729
AX3__SJOIN5	7.125	AX4__SJOIN9	7.125	AN6__SJOIN6	7.125	AN6__JSD-R1-1	6.729
AN20__SD-L1-1	7.125	AX4__SJOIN15	7.125	AN6__SJOIN7	7.125	AN15__JSD-L1-1	6.729
AN20__SD-R1-1	7.125	AN8__SD-L1-1	7.125	AN6__SJOIN8	7.125	AN15__JSD-R1-1	6.729
AN20_E1	7.125	AN8_E1	7.125	AN6__SJOIN10	7.125	AN15__JSD-L1-2	6.729
AN20_E2	7.125	AN8_E2	7.125	AN6__SJOIN11	7.125	AN15__JSD-R1-2	6.729
AN20_S1	7.125	AN8__SJOIN1	7.125	AX2__SJOIN3	7.125	AN17__JSD-L1-1	6.729
AN21_E1	7.125	AN10__SJOIN1	7.125	AX2__SJOIN6	7.125	AN17__JSD-R1-1	6.729
AN21_E2	7.125	AN11__SD-R1-1	7.125	AX2__SJOIN9	7.125	AN11__TBOT1	6.521
AN21_S1	7.125	AN11_E1	7.125	AX2__SJOIN12	7.125	AN13__HDD-1-1	5.562
AN21__SJOIN1	7.125	AN11_E2	7.125	AX5__SJOIN5	7.125	AN20__TBOT1	5.521
AN26__SD-L1-1	7.125	AN11_S1	7.125	AN15__SD-L1-1	7.125	AN26__TBOT1	5.187
AN26__SD-R1-1	7.125	AN11_S2	7.125	AN15__SD-R1-1	7.125	AN19__TBOT1	4.312
AN26_E1	7.125	AN11__SJOIN1	7.125	AN15__SD-L1-2	7.125	AN17__TBOT1	4.312
AN26_E2	7.125	AN11__SJOIN2	7.125	AN15__SD-R1-2	7.125	AN23__HDD-1-1	3.062
AN23__SD-L1-1	7.125	AN22__SD-L1-1	7.125	AN15_E1	7.125	AN11__HDD-1-1	3.062
AN23_E1	7.125	AN22__SD-R1-1	7.125	AN15_E2	7.125	AN6__HDD-1-1	3.062
AN23_E2	7.125	AN22_E1	7.125	AN15_S1	7.125	AN14__TBOT1	3.042
AN23_S2	7.125	AN22_E2	7.125	AN15_S2	7.125	AN20__HDD-1-1	2.938
AN23_S3	7.125	AN22_S1	7.125	AN18_E1	7.125	AN26__HDD-1-1	2.938
AN23_S4	7.125	AN22_S2	7.125	AN18_E2	7.125	AN22__HDD-1-1	2.938
AN23__SJOIN1	7.125	AN22_S3	7.125	AN18_S1	7.125	AN15__HDD-1-1	2.938
AN23__SJOIN2	7.125	AN22_S4	7.125	AN18__SJOIN1	7.125	AN15__HDD-1-2	2.938
AN23__SJOIN3	7.125	AN22_S5	7.125	AN18__SJOIN2	7.125	AN17__HDD-1-1	2.938
AN23__SJOIN4	7.125	AN22_S6	7.125	AN17__SD-L1-1	7.125	AN8__TBOT1	2.708
AN25_E1	7.125	AN22_S7	7.125	AN17__SD-R1-1	7.125	AN13__HDD-1-2	2.562
AN25_E2	7.125	AN22_S8	7.125	AN17_E1	7.125	AN18__TBOT1	2.5
AN25_S1	7.125	AN22__SJOIN1	7.125	AN17_E2	7.125	AN21__TBOT1	2.292
AN25__SJOIN1	7.125	AN22__SJOIN2	7.125	AN17_S1	7.125	AN25__TBOT1	2.292
AN24_E1	7.125	AN22__SJOIN3	7.125	AN13__JSD-L1-1	6.729	AN8__HDD-1-1	2.062
AN24_E2	7.125	AN22__SJOIN4	7.125	AN13__JSD-R1-1	6.729		

B: 2x4 lumber pool

2X4 Lumber Pool			
ID	**Length (ft)**	**ID**	**Length (ft)**
AN22_TTOP1	14.75	AN20_TTOP2	5.521
AN22_TTOP2	14.75	AN26_TTOP1	5.167
AN6_TTOP1	14.75	AN26_TTOP2	5.167
AN6_TTOP2	14.75	AN19_TTOP1	4.312
AN15_TTOP1	11.583	AN19_TTOP2	4.312
AN15_TTOP2	11.583	AN17_TTOP1	4.312
AN24_TTOP1	11.104	AN17_TTOP2	4.312
AN24_TTOP2	11.104	AN14_TTOP1	3.042
AN23_TTOP1	9.042	AN14_TTOP2	3.042
AN23_TTOP2	9.042	AN16_TTOP1	2.833
AN13_TTOP1	8.875	AN16_TBOT1	2.833
AN13_TTOP2	8.875	AN16_TTOP2	2.833
AN13_SJOIN8	7.125	AN8_TTOP1	2.708
AN7_E1	7.125	AN8_TTOP2	2.708
AN7_E2	7.125	AN18_TTOP1	2.5
AN7_S1	7.125	AN18_TTOP2	2.5
AN6_SJOIN9	7.125	AN7_TTOP1	2.458
AX2_SJOIN15	7.125	AN7_TBOT1	2.458
AN16_E1	7.125	AN7_TTOP2	2.458
AN16_E2	7.125	AN21_TTOP1	2.292
AN16_S1	7.125	AN21_TTOP2	2.292
AN11_TTOP1	6.521	AN25_TTOP1	2.292
AN11_TTOP2	6.521	AN25_TTOP2	2.292
AN20_TTOP1	5.521		

C: 2x6 lumber pool

2X6 Lumber Pool							
ID	Length (ft)	ID	Length (ft)	ID	Length (ft)	ID	Length (ft)
AX4_TTOP1	71.062	AX4_S11	7.125	AX2_S25	7.125	AX4_JSW-L1-2	6.521
AX4_TBOT1	71.062	AX4_S12	7.125	AX2_S26	7.125	AX4_JSW-R1-2	6.521
AX4_TTOP2	71.062	AX4_S13	7.125	AX2_S27	7.125	AX4_JSW-L1-3	6.521
AX2_TTOP1	71.062	AX4_S14	7.125	AX2_S28	7.125	AX4_JSW-R1-3	6.521
AX2_TBOT1	71.062	AX4_S15	7.125	AX2_S29	7.125	AX4_JSW-L1-4	6.521
AX2_TTOP2	71.062	AX4_S16	7.125	AX2_S30	7.125	AX4_JSW-R1-4	6.521
AX3_TTOP1	15.667	AX4_S17	7.125	AX2_S31	7.125	AX4_JSW-L1-5	6.521
AX3_TBOT1	15.667	AX4_S18	7.125	AX2_S32	7.125	AX4_JSW-R1-5	6.521
AX3_TTOP2	15.667	AX4_S19	7.125	AX2_S33	7.125	AX4_JSW-L1-6	6.521
AX5_TTOP1	15.667	AX4_S20	7.125	AX2_S34	7.125	AX4_JSW-R1-6	6.521
AX5_TBOT1	15.667	AX4_S21	7.125	AX2_S35	7.125	AX4_JSW-L1-7	6.521
AX5_TTOP2	15.667	AX4_S22	7.125	AX2_S36	7.125	AX4_JSW-R1-7	6.521
AN12_TTOP1	8.062	AX4_S23	7.125	AX2_S38	7.125	AX2_HDD-1-1	6.188
AN12_TBOT1	8.062	AX4_S24	7.125	AX2_S39	7.125	AX2_HDD-2-1	6.188
AN12_TTOP2	8.062	AX4_S25	7.125	AX2_S40	7.125	AX2_HDD-3-1	6.188
AX4_STW-1-5	7.167	AX4_S26	7.125	AX2_S41	7.125	AX4_STW-1-2	5.833
AX4_SBW-3-5	7.167	AX4_S27	7.125	AX2_S42	7.125	AX4_SBW-3-2	5.833
AX3_E1	7.125	AX4_S28	7.125	AX2_S43	7.125	AX4_STW-1-6	3.333
AX3_E2	7.125	AX4_SJOIN1	7.125	AX2_S44	7.125	AX4_SBW-3-6	3.333
AX3_S1	7.125	AX4_SJOIN2	7.125	AX2_S45	7.125	AX4_STW-1-7	3.333
AX3_S2	7.125	AX4_SJOIN4	7.125	AX2_S46	7.125	AX4_SBW-3-7	3.333
AX3_S3	7.125	AX4_SJOIN5	7.125	AX2_S47	7.125	AX4_C3	3.25
AX3_S4	7.125	AX4_SJOIN7	7.125	AX2_S48	7.125	AX4_C4	3.25
AX3_S5	7.125	AX4_SJOIN8	7.125	AX2_SJOIN1	7.125	AX4_C5	3.25
AX3_S6	7.125	AX4_SJOIN10	7.125	AX2_SJOIN2	7.125	AX4_C6	3.25
AX3_S7	7.125	AX4_SJOIN11	7.125	AX2_SJOIN4	7.125	AX4_C19	3.25
AX3_S8	7.125	AX4_SJOIN12	7.125	AX2_SJOIN5	7.125	AX4_C20	3.25
AX3_S9	7.125	AX4_SJOIN13	7.125	AX2_SJOIN7	7.125	AX4_C22	3.25
AX3_S10	7.125	AX4_SJOIN14	7.125	AX2_SJOIN8	7.125	AX4_C23	3.25
AX3_S11	7.125	AN10_E1	7.125	AX2_SJOIN10	7.125	AX4_STW-1-3	3
AX3_SJOIN1	7.125	AN10_E2	7.125	AX2_SJOIN11	7.125	AX4_SBW-3-3	3
AX3_SJOIN2	7.125	AN10_S1	7.125	AX2_SJOIN13	7.125	AX4_STW-1-4	3
AX3_SJOIN3	7.125	AN8_SJOIN12	7.125	AX2_SJOIN14	7.125	AX4_SBW-3-4	3
AX3_SJOIN4	7.125	AX2_SD-L1-1	7.125	AX5_E1	7.125	AN10_TTOP1	2.562
AX4_SD-L1-1	7.125	AX2_SD-R1-1	7.125	AX5_E2	7.125	AN10_TBOT1	2.562
AX4_SD-R1-1	7.125	AX2_E1	7.125	AX5_S1	7.125	AN10_TTOP2	2.562
AX4_SW-L1-2	7.125	AX2_E2	7.125	AX5_S3	7.125	AX4_C1	2.25
AX4_SW-R1-2	7.125	AX2_S1	7.125	AX5_S4	7.125	AX4_C2	2.25
AX4_SW-L1-3	7.125	AX2_S2	7.125	AX5_S5	7.125	AX4_C14	2.25
AX4_SW-R1-3	7.125	AX2_S3	7.125	AX5_S6	7.125	AX4_C15	2.25
AX4_SW-L1-4	7.125	AX2_S4	7.125	AX5_S7	7.125	AX4_C16	2.25
AX4_SW-R1-4	7.125	AX2_S5	7.125	AX5_S8	7.125	AX4_C17	2.25
AX4_SW-L1-5	7.125	AX2_S6	7.125	AX5_S9	7.125	AX4_C7	1.333
AX4_SW-R1-5	7.125	AX2_S8	7.125	AX5_S10	7.125	AX4_C8	1.333
AX4_SW-L1-6	7.125	AX2_S9	7.125	AX5_S11	7.125	AX4_C9	1.333
AX4_SW-R1-6	7.125	AX2_S10	7.125	AX5_SJOIN1	7.125	AX4_C10	1.333
AX4_SW-L1-7	7.125	AX2_S11	7.125	AX5_SJOIN2	7.125	AX4_C11	1.333
AX4_SW-R1-7	7.125	AX2_S12	7.125	AX5_SJOIN3	7.125	AX4_C12	1.333
AX4_E1	7.125	AX2_S13	7.125	AX5_SJOIN4	7.125	AX4_C24	1.333
AX4_E2	7.125	AX2_S14	7.125	AN12_E1	7.125	AX4_C25	1.333
AX4_S1	7.125	AX2_S15	7.125	AN12_E2	7.125	AX4_C26	1.333
AX4_S2	7.125	AX2_S16	7.125	AN12_S1	7.125	AX4_C27	1.333
AX4_S3	7.125	AX2_S17	7.125	AN12_S2	7.125	AX4_C28	1.333
AX4_S4	7.125	AX2_S18	7.125	AN12_S3	7.125	AX4_C30	1.333
AX4_S5	7.125	AX2_S19	7.125	AN12_S4	7.125	AX4_C31	1.333
AX4_S6	7.125	AX2_S20	7.125	AN12_S5	7.125	AX4_C34	1.333
AX4_S7	7.125	AX2_S21	7.125	AX4_JSD-L1-1	6.771	AX4_C35	1.333
AX4_S8	7.125	AX2_S22	7.125	AX4_JSD-R1-1	6.771		
AX4_S9	7.125	AX2_S23	7.125	AX2_JSD-L1-1	6.708		
AX4_S10	7.125	AX2_S24	7.125	AX2_JSD-R1-1	6.708		

D: 2x4 lumber pool

2X8 Lumber Pool	
ID	Length (ft)
AX4_HDW-1-5	7.417
AX4_HDW-2-5	7.417
AX4_HDW-3-5	7.417
AX4_HDW-1-2	6.083
AX4_HDW-2-2	6.083
AX4_HDW-3-2	6.083
AX4_HDW-1-6	3.583
AX4_HDW-2-6	3.583
AX4_HDW-3-6	3.583
AX4_HDW-1-7	3.583
AX4_HDW-2-7	3.583
AX4_HDW-3-7	3.583
AX4_HDD-1-1	3.458
AX4_HDD-2-1	3.458
AX4_HDD-3-1	3.458
AX4_HDW-1-3	3.25
AX4_HDW-2-3	3.25
AX4_HDW-3-3	3.25
AX4_HDW-1-4	3.25
AX4_HDW-2-4	3.25
AX4_HDW-3-4	3.25

E: Quantity takeoff report (Case study)

Part_Number	Quantity	Unit	Description1	Description2	Unit_Number	Raw_Quantity
005039	1	EA	ABS BUSH 2"X1-1/2	CANPLAS	Unit 01	1
005050	1	EA	ABS CO LINE 2	CANPLAS	Unit 01	1
005058	1	EA	ABS COUPLING 2	CANPLAS	Unit 01	1
005060	1	EA	ABS COUPLING 3	CANPLAS	Unit 01	1
005062	1	EA	ABS COUPLING 4"X1-1/2	CANPLAS	Unit 01	1
044123	1	EA	ABS DRAIN FLOOR 3	ZURN FD-2240-NT WOOD DECK	Unit 01	1
005090	8.02	LF	ABS PIPE 1-1/2	CANPLAS	Unit 01	8.02
005091	1.56	LF	ABS PIPE 2	CANPLAS	Unit 01	1.56
005092	1.75	LF	ABS PIPE 3	CANPLAS	Unit 01	1.75
005093	1.92	LF	ABS PIPE 4	CANPLAS	Unit 01	1.92
047979	76.61	LF	BASEBOARD RUBBER 4"X120 FT	JOHNSONITE GRIZZLY DC281	Unit 01	76.61
050918	6	EA	BLIND VERT 45-1/2"X57	TAN W/VALANCE GRG JKSN	Unit 01	6
005217	1	EA	BLK 90 1/2		Unit 01	1
005231	1	EA	BLK 90 3/4		Unit 01	1
005171	1	EA	BLK CAP 3/4		Unit 01	1
005295	0.14	LF	BLK PIPE 1/2	SCHED 40	Unit 01	0.14
005298	7.29	LF	BLK PIPE 3/4	SCHED 40	Unit 01	7.29
005395	1	EA	BLK T 3/4"X 1/2"X 3/4		Unit 01	1
005401	1	EA	BLK UNION 1/2		Unit 01	1
003645	2	EA	BOX 1004 3"X2"X3" DEEP 4 KO	TandB CI1004	Unit 01	2
003672	1	EA	BOX FSU 3/4	TandB CIFSU-3/4	Unit 01	1
003663	4	EA	BOX OCTAGON 4"X2-18" DEEP	11 KO TandB BC54171-L	Unit 01	4
003653	11	EA	BOX SINGLE GANG 2-1/4" 4KO	TandB BC1504-LLE	Unit 01	11
003659	10	EA	BOX SQUARE 4"X2-1/8" DEEP	TandB BC52171-K	Unit 01	10
046996	2	EA	BRACKET TV WALL 15" TO 32	BESTMOUNTS BMDA	Unit 01	2
010001	5	EA	BREAKER CH 1P15 BR	PUSH IN CUTLER HAMMER BR115	Unit 01	5
032399	1	EA	BREAKER CH 1P15 GFI 30MLA	PUSH IN CUTLER QPGFEP1015	Unit 01	1
030376	2	EA	BREAKER CH 2P30 BR	PUSH IN CUTLER HAMMER BR230	Unit 01	2
050507	78.57	SY	CARPET TILE SHAWMARK MAKEOVER	STYLE#0A150 SPRUCE UP #50515	Unit 01	707.1
042249	5.915	LF	CASING 2 1/4"X 14 FT	ALBANY MAPLE #3002	Unit 01	82.81
047909	6	EA	CHAIR SLED BASE LEATHER	NO ARMS-TEMPEST 6029 BLK	Unit 01	6
015826	10	EA	COVER PLATE DECORA 1 GANG	WHITE LEVITON 80401-W	Unit 01	10
022369	2	EA	COVER PLATE INSERT TV DECORA	40681-W	Unit 01	2

006780	8	EA	DIFFUSER FLOOR PLASTIC 3"X10	WHITE PRIMEX HR31001	Unit 01	8
031553	1	EA	DOOR HMD 30"X80	PSF 45 MIN FIRE RATED	Unit 01	1
046393	1	EA	DOOR IMD 36"X80"	PSF 10"X18" LITE RHR	Unit 01	1
004813	19.00025	EA	DRYWALL TYPE-X 5/8" 4 X10 FT	PLAIN	Unit 01	760.01
050380	18.685	EA	DRYWALL VC TYPE-X 5/8" 4 X10 FT	FUNARI LINEN SX-36-29	Unit 01	747.4
047719	49.18	LF	DUCT PAN 14-1/4" X2-3/4" 26GA	ASB-HVA-DCT-0016-R0	Unit 01	49.18
047725	59.48	LF	DUCT PAN 19-1/4"X2-3/4" 26GA	ASB-HVA-DUCT-0017-R0	Unit 01	59.48
047721	6	LF	DUCT PAN LID 17" 26GA	ASB-HVA-DCT-0014-R0	Unit 01	6
047722	1	LF	DUCT PAN LID 22" 26GA	ASB-HVA-DCT-0015-R0	Unit 01	1
030761	1	EA	EM LIGHT BP 72W 12V 9W	LUMACELL RG12S722MT9W	Unit 01	1
047697	1	EA	EM LIGHT EXIT UNIVERSAL 3W LE	LUMACELL GRAWUNV3R	Unit 01	1
030763	1	EA	EM LIGHT HEAD DOUBLE 12V 9W	WITH BASE LUMACELL MT212V9W	Unit 01	1
008753	2	EA	FA EDWARDS HEAT DETECT 135 DEG	FIXED EDWARDS 283B-PL	Unit 01	2
004224	1	EA	FA EDWARDS HEAT DETECT 194 DEG	FIXED EDWARDS 284B-PL	Unit 01	1
021105	2	EA	FA EDWARDS HORN STROBE GENESIS	EDWARDS G1R-HDVM	Unit 01	2
004225	1	EA	FA EDWARDS PULL STATION	EDWARDS 270-SPOW	Unit 01	1
011586	1	EA	FA EDWARDS RELAY BASE	FR EDW1451A SD EDWARD	Unit 01	1
044487	1	EA	FA EDWARDS SMOKE DETECTOR HEAD	EDWARDS EC30U-3	Unit 01	1
030831	13	EA	FIXTURE FLUOR T-BAR 1X4	T8 2 LAMP 4 FT	Unit 01	13
007707	2	EA	FIXTURE HPS 70W W/PHOTOCELL	LITHONIA W70SPL 120 M6	Unit 01	2
016775	1	EA	FLAT PLATE 12"X 6"X 1/8	DOUBLE NIPPLE 3/4	Unit 01	1
047858	1	EA	FURNACE 1445 CFM	BRYANT 912SB48100S21	Unit 01	1
043298	2	EA	GRILLE R/A K740 18"X12	WHITE IMPERIAL RG0462	Unit 01	2
008800	739.8	SF	INSUL FG R12 15"X47"X3-1/2		Unit 01	739.8
008799	2062.56	SF	INSUL FG R20 15"X47"X6		Unit 01	2062.56
014055	26	EA	LAMP FLUOR 48" T8 F32T8CW		Unit 01	26
004964	14.283	EA	LUM SPF 2X4X10 FT	#2andBTR	Unit 01	142.83
004971	106.906	EA	LUM SPF 2X6X10 FT	#2andBTR	Unit 01	1069.06
004974	15.17375	EA	LUM SPF 2X6X16 FT	#2andBTR	Unit 01	242.78
044624	43.21	EA	OSB 1/2" 4 X8 FT	SHEATHING	Unit 01	1382.86
044219	1	EA	PANEL CH CPL116 120/240V	125A 16CCT C/W LUGS ONLY	Unit 01	1
047967	1	EA	PLENUM 20X24X16 W/FILTER COLAR	ASB-HVA-DCT-0031-R0	Unit 01	1
045481	22.1	EA	PLYWOOD FIR SELECT 3/4" 4 X8 FT	TandG	Unit 01	707.1
006345	22.18	EA	PLYWOOD FIR SELECT 5/8" 4 X8 FT	TandG	Unit 01	709.82
042476	1355.45	LF	POLY 6 MIL 12 FT ROLL	CGSB	Unit 01	1355.45
042983	5	EA	PVC 90 3/4	SCHED 40	Unit 01	5

012785	6.49	LF	PVC PIPE 3/4	SCHED 40 BELL END	Unit 01	6.49
032474	6	EA	PVC S636 90 3	ULC APPROVED FOR VENTING	Unit 01	6
026886	14.43	LF	PVC S636 PIPE 3		Unit 01	14.43
011830	6	EA	RECP 15A 125V DUPLEX DECORA	LEVITON 5325-W	Unit 01	6
004194	2	EA	RECP 15A 125V DUPLEX GFI	LEVITON N7599-W	Unit 01	2
046993	709.82	EA	ROOF DECTEC R15000 13 FT X 62 FT	EMBOSSED WHITE 806 SF/RL	Unit 01	709.82
051414	1	EA	SLEEVE GALV 24"X12"X4-1/2	W/1" FLANGE ONE END	Unit 01	1
022319	2	EA	SWITCH 15A 120V DECORA 3P	WHITE LEVITON 5603-P2W	Unit 01	2
009275	1	EA	TABLE POOL W/TRI CUE BALL SET	CANADA BILLIARDS 0203	Unit 01	1
009266	1	EA	TABLE TENNIS		Unit 01	1
042841	1	EA	TABLE TEXAS HOLDEM POKER		Unit 01	1
009091	1	EA	TAPIN CIRCULAR GALV 6		Unit 01	1
040653	2	EA	TV 32		Unit 01	2
044566	645.7	LF	TYVEK HOME WRAP	10 FT X 150 FT	Unit 01	645.7
014901	1	EA	VALVE BALL PVC 3/4	SCHED 40 ECONOMY	Unit 01	1
045945	6	EA	WINDOW PVC 47-1/4"X59-3/8	SEALED JAMB 6-3/4	Unit 01	6
Unknown10	1		_PTI FLOOR OPENING	MEP FLOOR OPENING	Unit 01	1
Unknown19	1		48100 furnace assembly	48100 furnace assembly	Unit 01	1
Unknown20	1		COIL AC 4 TON=CNPVP4821ALA	Coil=simplify	Unit 01	1
Unknown21	1		MEP ROOF OPENING	MEP ROOF OPENING	Unit 01	1
Unknown23	4		J152	mwfW_PanelJoin	Unit 01	4
Unknown26	6		PanelParams	PanelParams	Unit 01	6
Unknown27	1		J153	mwfW_PanelJoin	Unit 01	1
Unknown28	1		J163	mwfW_PanelJoin	Unit 01	1
Unknown29	8		2x6	BIMSF-Dimension Lumber	Unit 01	8
Unknown32	1		24x24 - 6x6 Neck	Supply Diffuser - Rectangular Face	Unit 01	1
047979	79.12	LF	BASEBOARD RUBBER 4"X120 FT	JOHNSONITE GRIZZLY DC281	Unit 02	79.12
050918	7	EA	BLIND VERT 45-1/2"X57	TAN W/VALANCE GRG JKSN	Unit 02	7
046996	2	EA	BRACKET TV WALL 15" TO 32	BESTMOUNTS BMDA	Unit 02	2
047808	1	EA	CAP END 19-1/4"X2-3/4" 26GA	ASB-HVA-DCT-0053-R0	Unit 02	1
044754	2	EA	CAP END INSUL 12"X 12		Unit 02	2
050507	78.89	SY	CARPET TILE SHAWMARK MAKEOVER	STYLE#0A150 SPRUCE UP #50515	Unit 02	710
042249	86.32	LF	CASING 2 1/4"X 14 FT	ALBANY MAPLE #3002	Unit 02	86.32

047909	6	EA	CHAIR SLED BASE LEATHER	NO ARMS-TEMPEST 6029 BLK	Unit 02	6
040562	2	EA	DIFFUSER CEILING 8" 24"X24	PRICE 8" 24"X24"/SCD/3C/B12	Unit 02	2
006780	8	EA	DIFFUSER FLOOR PLASTIC 3"X10	WHITE PRIMEX HR31001	Unit 02	8
033058	1	EA	DOOR HMD 36"X80	PSF and 5X20 V LITE GWG 90 MIN	Unit 02	1
004813	17.61975	EA	DRYWALL TYPE-X 5/8" 4 X10 FT	PLAIN	Unit 02	704.79
050380	17.99475	EA	DRYWALL VC TYPE-X 5/8" 4 X10 FT	FUNARI LINEN SX-36-29	Unit 02	719.79
044807	1	LF	DUCT INSUL 12" X 12		Unit 02	1
047783	9.4	LF	DUCT PAN 10-1/4”X2-3/4” 26GA	ASB-HVA-DCT-0019-R0	Unit 02	9.4
047719	51.3	LF	DUCT PAN 14-1/4” X2-3/4” 26GA	ASB-HVA-DCT-0016-R0	Unit 02	51.3
047725	59.76	LF	DUCT PAN 19-1/4”X2-3/4” 26GA	ASB-HVA-DUCT-0017-R0	Unit 02	59.76
047784	2	LF	DUCT PAN LID 13” 26GA	ASB-HVA-DCT-0020-R0	Unit 02	2
047721	6	LF	DUCT PAN LID 17” 26GA	ASB-HVA-DCT-0014-R0	Unit 02	6
047722	1	LF	DUCT PAN LID 22” 26GA	ASB-HVA-DCT-0015-R0	Unit 02	1
008800	744.36	SF	INSUL FG R12 15"X47"X3-1/2		Unit 02	744.36
008799	2020.48	SF	INSUL FG R20 15"X47"X6		Unit 02	2020.48
004964	13.884	EA	LUM SPF 2X4 X 10 FT	#2andBTR	Unit 02	138.84
004971	99.843	EA	LUM SPF 2X6X10 FT	#2andBTR	Unit 02	998.43
004974	13.27	EA	LUM SPF 2X6X16 FT	#2andBTR	Unit 02	212.37
044624	42.35	EA	OSB 1/2" 4 X8 FT	SHEATHING	Unit 02	1355.26
045481	22.1875	EA	PLYWOOD FIR SELECT 3/4" 4X8 FT	TandG	Unit 02	710
006345	22.03	EA	PLYWOOD FIR SELECT 5/8" 4X8 FT	TandG	Unit 02	704.86
042476	1310.48	LF	POLY 6MIL 12 FT ROLL	CGSB	Unit 02	1310.48
046993	704.86	EA	ROOF DECTEC R15000 13 FT X 62 FT	EMBOSSED WHITE 806 SF/RL	Unit 02	704.86
009275	1	EA	TABLE POOL W/TRI CUE BALL SET	CANADA BILLIARDS 0203	Unit 02	1
009266	1	EA	TABLE TENNIS		Unit 02	1
042841	1	EA	TABLE TEXAS HOLDEM POKER		Unit 02	1
020481	2	EA	TAKE OFF SIDE GALV 8		Unit 02	2
040653	2	EA	TV 32		Unit 02	2
044566	605.7	LF	TYVEK HOME WRAP	10 FT X 150 FT	Unit 02	605.7
045945	7	EA	WINDOW PVC 47-1/4"X59-3/8	SEALED JAMB 6-3/4	Unit 02	7
Unknown8	4		OPENING 04	ARCHITECTURAL WALL OPENING	Unit 02	4
Unknown9	2		OPENING 05	ARCHITECTURAL WALL OPENING	Unit 02	2
Unknown11	1		21- ELECTRICAL PANEL CPL116	MEP WALL OPENING	Unit 02	1
Unknown12	1		34-R/A OPENING	MEP WALL OPENING	Unit 02	1
Unknown13	1		32-CONC VENT OPENING	MEP WALL OPENING	Unit 02	1

Unknown14	1		20- ELECTRICAL PANEL CPL116	MEP WALL OPENING	Unit 02	1
Unknown15	1		33-AC LINE OPENING	MEP ROOF OPENING	Unit 02	1
Unknown16	1		35-FAN OPENING	MEP ROOF OPENING	Unit 02	1
Unknown17	1		36-DROP BOX OPENING	MEP ROOF OPENING	Unit 02	1
Unknown18	1		31-F/A OPENING	MEP FLOOR OPENING	Unit 02	1
Unknown22	1		Exhaust Fan Broan 502N Ceiling Mount	Exhaust Fan Broan 502N Ceiling	Unit 02	1
Unknown24	5		PanelParams	PanelParams	Unit 02	5
Unknown25	2		J152	mwfW_PanelJoin	Unit 02	2
Unknown30	1		J153	mwfW_PanelJoin	Unit 02	1
Unknown31	6		2x6	BIMSF-Dimension Lumber	Unit 02	6
050486	1329.9	SF	CEILING TILE ARMST 3/4"X 2 X 2 FT	LEDGES #8013	Site Install	1329.9
051415	1	EA	GOOSENECK 12"X12	W/4" BASE DAMPER and BUG SCREEN	Site Install	1
045899	12.98	SF	TILE CERAMIC BUCKWOLD AVAIRE	SONOMA #21-018-02-01	Site Install	12.98