University of Alberta

Automation of Design and Drafting for Wood Frame Structures and Construction Waste Minimization

by

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A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
in
Construction Engineering and Management

Hole School of Construction Engineering and Management
Department of Civil and Environmental Engineering

Fall 2009
Edmonton, Alberta

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Dedication

This thesis is dedicated to my wife Lindsay, who makes me happy every single day of my life.

Abstract

With the creation and continuous enhancement of Computer Aided Design (CAD) software, innovations in the area of computer modeling for the construction industry have brought numerous benefits in terms of precision, operability, extensibility, and time-cost savings, among others. Nevertheless, the construction industry is one which continually demands innovation and efficiency in design, leading to the introduction of newer modeling approaches to satisfy client needs. The central thinking behind this research, then, has to do with the automation and generation of construction drawings for the home building industry based on 3D and parametric modeling techniques, and the utilization of the best practice for the platform-frame method. Homebuilders in Canada often build without construction drawings due to the high cost and extensive time expenditure associated with their production; instead, the industry relies on trades personnel to build from architectural model designs. This poor practice contributes to the accumulation of material waste and other construction quality issues. The underlying basis for this research is the notion of adding structure to information, both by incorporating intelligence into a set of operational commands and by adding innovation to the construction process. These topics have been incorporated into a 3D CAD solid model to demonstrate the importance of communicating information from consultants to trades and contractors. 3D and parametric modeling provide the foundation for this complex analysis, which focuses on the generation of panelized and site-built dwellings. The minimization of construction wood materials through the use of mathematical models and a search for best combinations of nominal lumber, sheathing and drywall has been added to this research as an aim to become more

efficient. Mathematical optimization models are used to verify the concept for efficient cutting layouts for one- and two-dimensional elements.

This research sets out to demonstrate, by underscoring the present shortcomings, the manner in which 3D and parametric modeling will provide a solution for practitioners and researchers who wish to reduce drafting time and material waste production; to incorporate intelligence to CAD models; and to provide a better use of primary resources by generating guidelines for construction practice.

Acknowledgements

This research was funded by the Canadian research network of Mathematics of Information Technology and Complex Systems (MITACS 2007), the Landmark Group of Builders, Edmonton, Canada, the Natural Science and Engineering Research Council of Canada (NSERC)-CRD Grant (CRDPJ 350089-06) and by the University of Alberta, Construction Engineering and Management Group.

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Nomenclature

P = Array of vertices for wall object in a 3D coordinate system

P_i = Vertex *i* in a wall object with coordinates *xi, yi, zi*

B1 = Top vertices for wall object in a 3D coordinate system

B2 = Bottom vertices for wall object in a 3D coordinate system

D1 = Door top vertices in a 3D coordinate system

D2 = Door bottom vertices in a 3D coordinate system

W1 = Window top vertices in a 3D coordinate system

W2 = Window bottom vertices in a 3D coordinate system

A = Matrix of object vertices for a 3D architectural model

x= Column vector for the linear transformation of 3D coordinates onto a 2D coordinate system

T = Linear transformation for the matrix A

Rij = Rotation along the ij^{th} vector, with 0=**X**, 1=**Y** and 2=**Z** axis

Ti = Translation on the i^{th} axis, with 0=**X**, 1=**Y** and 2=**Z** axis

Ai= Total area of the stock needed to be cut for sheathing

L = Stud Length

L_n = Remaining length of the stud after generating n-1 cuts

$\mathbf{L}_{\mathbf{N}\times 13}$ = Matrix holding the basic cutting patterns

L_p = Length of required studs for the project

n_p = number of instances of length L_p that are produced at level p

S_m = Waste or stud leftover after generating the required cuts

S_p = Waste generated at a given p scenario

S_i = Waste corresponding to the cutting pattern i for sheathing

x_p = Multiplicity of each basic cutting layout

λ_j^n = j^{th} cutting pattern associated with the n^{th} set of patterns of the second stage of cutting

$M^{(m')}$ = represents the first m' and last m rows of the matrix M, which contains all possible cutting patters at the various cutting stages.

$\bar{\lambda}$ = Cutting pattern vector

W = Waste associated with the cutting procedure for drywall and sheathing

Chapter 1: Introduction

1.1 Motivation

Automation in construction has been a landmark for researchers seeking to minimize costs and reduce labor-intensive tasks while simultaneously enhancing the decision-making process. As many engineers and researchers have found, construction methods for the home building industry have not developed to the extent one might expect. One of the reasons for this has been the general lack of new methodologies to bolster the construction engineering discipline, both at the construction site and at the office. For example, a stick-built approach to residential construction has been popular since the early 1900s, whereas few construction companies in Canada have applied the concepts of panelization and modular construction in order to construct a better and less expensive product. As reported by the Canada Mortgage and Housing Corporation (CMHC), more than 227,000 new homes were constructed during 2007, but more than double that number (over 500,000) were resold during the same year in Canada. These numbers reflect the potential market for prefabrication and modular construction.

From 2005-2008, Western Canada saw high housing costs partly due to the shortage of knowledgeable trades personnel. This fact made the cost of materials cheaper than that of man-hours and, hence, materials were not used efficiently. To date, little effort has been invested upfront to optimize the use of primary materials. As a consequence, materials are misused, generating high volumes of waste and decrementing vital resources such as sawn lumber and gypsum. Another distressing consequence of high home building prices is the negative impact on low-income families and their ability to purchase new homes. A lack of affordable housing in the City of Edmonton is prompting the Province, the City, and non-governmental organizations to seek solutions, such as external funding for first-time buyers.

These solutions support the front end of the entire construction process, but not many attempts have focused on the design end in an effort to reduce waste and minimize costs more significantly. Define set of construction drawings, for instance, can substantially increase labor productivity at the construction site or at manufacturing shops, reduce material costs, and transportation due to its explicitly. This lack of innovation at the design end, moreover, has much to do with a lack of standards for construction practice in the home building industry, whereby work strategies vary from trade to trade and from company to company. For example, due to the lack of detail in construction drawings for single-family dwellings, material waste varies based on the discretion and skill of the trades people. Construction standards for material installation must emerge which can drive the housing market in place of the tacit knowledge transferred from trade to trade. The automotive industry, since the introduction of manufacturing processes, has evolved to the point that any ordinary person can afford a vehicle; the home building industry must similarly reduce the breach between hand crafted homes and manufacturing of building components to become more price-accessible to the common consumer.

One should note that not only is waste generated by misusing materials at construction sites cause for concern, but the energy involved and consequently the carbon footprint produced during the production, transportation, and material landfill of wastes throughout the construction cycle is distressing. In today's market, there is a need to implement sustainable practices to protect the environment. Indeed, principles of sustainability should be every builder's concern during the planning and design, construction, turnover, and life cycle of any particular home.

To this point, the need to automate construction designs has become evident. There exists a general lack of interoperability and communication within the Architectural, Engineering and Construction (AEC) industry that must be mitigated. On the other hand, integration between design and construction can maximize profit, quality, and decision making efficiency. The development of an intelligent system that can combine all aspects of cost estimating, scheduling, and construction design, moreover, will provide the means to success.

1.2 Research Goals and Objectives

The aim of this research is the development of an intelligent design management system for the North-American home building industry with regard to wood framing design, construction drawings, and the better utilization of primary materials. The incorporation of Knowledge Based Systems (KBS) and the utilization of the ($\boldsymbol{i}^3$) concept in the proposed methodology show that knowledge transfer and innovation can be easily achieved. In order to realize these goals, the following objectives have been attained:

- Familiarize with construction procedures within the home building industry.

  The following approach describes the steps followed in this regard:

- Observe construction trades and acquired relevant knowledge in wood framing by understanding the intelligence behind the installation of each building component.
- Conduct field observations and identified the difference between framing at the construction site and framing at the manufacturing shop.
- Study different framing techniques in order to identify weaknesses and strengths during construction.

- Identify shortcomings and possible solutions for current processes in the platform-frame method.

  The following approach describes the steps followed in this regard:

  - Identify common errors encountered during the construction and installation of stick-built walls and panels.
  - Determine, design, and quantify repetitive components which can be utilized during the installation of wood framing panels in order to decrease construction time.

- Utilize Building Information Modeling (BIM) techniques as a basis for incorporating the best practice of the platform-frame method into a programmatic language.

  The following approach describes the steps followed in this regard:

  - Analyze different programmatic languages and determine which software to use in the development of construction drawings.
  - Research the inner characteristics of BIM.
  - Generate a list of requirements to create a BIM system.

- Make use of 3D and parametric modeling to automatically represent framing and drywall components in construction and shop drawings.

  The following approach describes the steps followed in this regard:

  - Generate an add-on within a CAD environment for framing design based on 3D modeling principles and parametric algorithms.
  - Decompose knowledge gathered from framing design to automate construction drawings within a CAD environment.
  - Create a list of design variables required by end-users in order to promote versatility in final construction.
  - Incorporate the ($\boldsymbol{i}^3$) concept from the proposed methodology into generic algorithms for building design.

- Analyze different optimization techniques for cutting one-dimensional and two-dimensional materials.

  The following approach describes the step followed in this regard:

  - Identify different optimization techniques and applied the most convenient and feasible approach for material utilization.
  - Develop a cutting procedure for framing trades in order to allow them to reduce waste by combining different cuts from nominal or commercially available materials.

- Provide drafting standards for the home building industry.

  The following approach describes the steps followed in this regard:

  - Analyze different types of construction drawings, including the manner in which information is presented to the end-user.

- Investigate the International Standards Organization (ISO) regulations for drafting design in order to incorporate them into the automated construction drawings to be built.
- Generate construction and shop drawings with ISO Standards.

- Reduce the knowledge barrier between design and construction by developing an intelligent management system.

  The following approach describes the steps followed in this regard:

  - Document the framing and drywall design process into simplistic rules for construction and installation of materials.
  - Create a software add-on in a CAD environment to reproduce findings based on architectural 3D models.
  - Link takeoff lists of materials from construction and shop drawings to numerical spreadsheets in order to facilitate the cost estimate process and to enhance procurement practices.
  - Utilize 3D modeling to guide mechanical, electrical and plumbing contractors in their efforts to minimize rework during material installation.

1.3 Scope of Work

The primary task of this research is to automate wood framing construction drawings for the home building industry by developing an information management system that functions as an intelligent repository. It focuses on the application of 3D and parametric modeling to support the development of repetitive drafting tasks which can, in turn, facilitate the generation of construction drawings for wood framing, sheathing, and interior drywall. The innovation and intelligence incorporated into the repository model provide a means to generate take-off lists of materials, a construction methodology, and improved accuracy for the drafting of design drawings based on the framing platform method, as well as the integration of drafting standards. This research also encompasses the minimization of construction sawn lumber, sheathing, and drywall waste by incorporating a mathematical analysis to generate cutting lists of materials. In a broad sense, this research has a positive impact on the environment by decreasing the use of primary materials from the construction of a stick-built dwelling. The system developed in this research has been applied to the construction of panelized dwellings in Edmonton, Canada, by one of the major housing developers in Alberta, the Landmark Group of Builders. The system has also been tested for multi-family buildings involving four to five story structures for the Becker Group, Canada.

1.4 Thesis organization

This thesis is composed of five chapters. Chapter One discusses the need for the implementation of an information management system for the home building industry. The chapter then presents the general goal, objectives, and scope of the research. Chapter Two describes the particular requirements of wood framing for residential construction as well as the weaknesses and strengths of this methodology. The second part of Chapter Two focuses on research related to CAD modeling in various fields of civil engineering, describing its applications, weaknesses, and strengths. The third portion of Chapter Two reports on research into Building Information Models (BIMs) and parametric modeling. The fourth section of Chapter Two describes the different techniques related to material optimization from a mathematical perspective, where the cutting stock problem is the primary focus of the approach. The fifth part of this chapter describes the utilization of drywall in the home building industry, the techniques required for its installation, and its direct impact on the environment. The sixth part of Chapter Two quantifies the CO_2 contributions during the construction of residential facilities. Chapter Three outlines the proposed methodology and objectives. This chapter summarizes the use of architectural 3D Modeling within a CAD environment for further analyses with the (i^3) concept and parametric algorithms. The application of the best practice for framing design is presented based on the development of the parametric algorithm, FRAMEX, which mimics construction rules and displays results in a graphic interface (construction drawings). This chapter also describes the methodology followed by the algorithm, DRY-X, for drywall layouts for interior finishing. Furthermore, this chapter describes the use of mathematical algorithms for material optimization with specific regard to how a graphical tool combines the use of combinatorial analysis and take-off lists of materials (CUTEX). Chapter Four describes the case study applied at the collaborating company and the future steps to be taken by researchers and builders. Chapter Five provides a summary report of activities performed up to the present time, as well as the research risks, errors, and constraints encountered during the development of the proposed methodology and a set of the conclusions drawn and contributions made by this Ph.D. research. Suggested future research is also recommended.

Chapter 2: State-of-the-Art Literature Review

2.1 Research in Wood Framing

Automation in framing design has been well developed in northern European countries, where computer numerical controlled (CNC) machines are fed with nominal lumber, sheathing, and drywall. Wall panels are thus constructed with few workers, with better precision, and hence are of a better quality (Fazio and Poliquin 2000). Yet few attempts have been made in this regard in North-America, which ought to stand as motivation for further investigation and increased application within the home building industry. The public-private Partnership for Advancing Technology in Housing (PATH) is one of only a few North-American organizations which conduct research in housing technology (PATH 2008).

In order to develop standards for best practice in stick-built construction, constructability issues must be considered. The information rendered here generates the core of this research, in which tacit knowledge must be mimicked by a computer algorithm[1]. The advantage of relying on the development of an automated information management system is the efficacy and efficiency of applied knowledge into programmatic rules. Such a system can produce and verify the production of construction drawings for stick framing and reduce the amount of drafting and experienced labor needed.

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[1] A version of this chapter has been submitted for publication, Journal of Construction Engineering and Management, American Society of Civil Engineers (ASCE) 2009.

2.1.1 Wood Framing Design

In North-America, there are two basic stick-built construction methodologies: the balloon-frame method, and the platform-frame method. Both have strengths and weaknesses, and both offer a speedy on-site erecting process. Nevertheless, the platform method has been preferred due to the ease of material transportation, the smaller number of laborers required for assembly, and the potential advantage of utilizing wall section prefabricates.

The balloon-frame method was introduced to the market for the construction of low-income dwellings in 1833 in Chicago (Waterford Connection 2005), thus transcending the complicated and expensive construction methodologies of earlier centuries. The balloon method uses vertical studs which extend through the wall's full height, starting from a slab on grade or on top of a wood floor. Some of the limitations of this construction methodology are the need for lengthy and straight wood elements, longer trucks to transport the material to construction sites, and scaffolding for work on upper floor-levels, and a lack of fire stops from floor to floor. Another inconvenient aspect of this methodology is the relative difficulty of installation. The vertical wood elements used are lengthy, necessitating that workers build full-height walls on-site. Thus the maximum wall height which can be constructed is 20ft. The advantage of this method is that houses will settle more uniformly than with any other conventional method. In the early 1920s, the platform-frame method rose in prominence because of its ability to eliminate the problems encountered in the balloon frame method. Since then, the platform method has been utilized for most stick-built dwellings constructed in North-America.

The platform-frame method consists of single-height walls running from floor to floor, composed of 2x4 or 2x6 studs. In this method, walls include bottom and top plates which secure the vertical wood elements (studs), as well as a very top plate which fastens adjacent or intersecting walls (see Figure 1). The Platform-frame method has been popular among North-American construction companies due to its ease of assembly, minimal requirements in terms of natural resources and specialized skilled labor, easy material transportation, and low erecting costs. The stud spacing is designed to match current nominal sizes for sheathing, drywall, and rigid insulation in order to minimize material waste, with the first two material types commonly available in 4x8, 4x10 and 4x12ft. sheets, and the latter adjustable to the given stud spacing—generally between 16 and 24 inches.

2.1.2 Panelized Constructions

Several modifications have been made to the platform-frame method since its introduction in the early 1900s. Stick-built dwellings are now commonly erected in one of three ways: on-site construction, panelized construction, or modular construction. The latter two methodologies, in which a controlled environment drives the quality, performance and final cost of building a house, are quickly becoming the future of stick-built framing.

Unfortunately, customers are reluctant to purchase prefabricated homes. In the United States, for example, only 0.2 percent of expenditures in new housing are on homes built from panelized systems. Meanwhile, the homebuilding industry accounts for 4 percent of the nation's economic activity (NAHB 2002a).

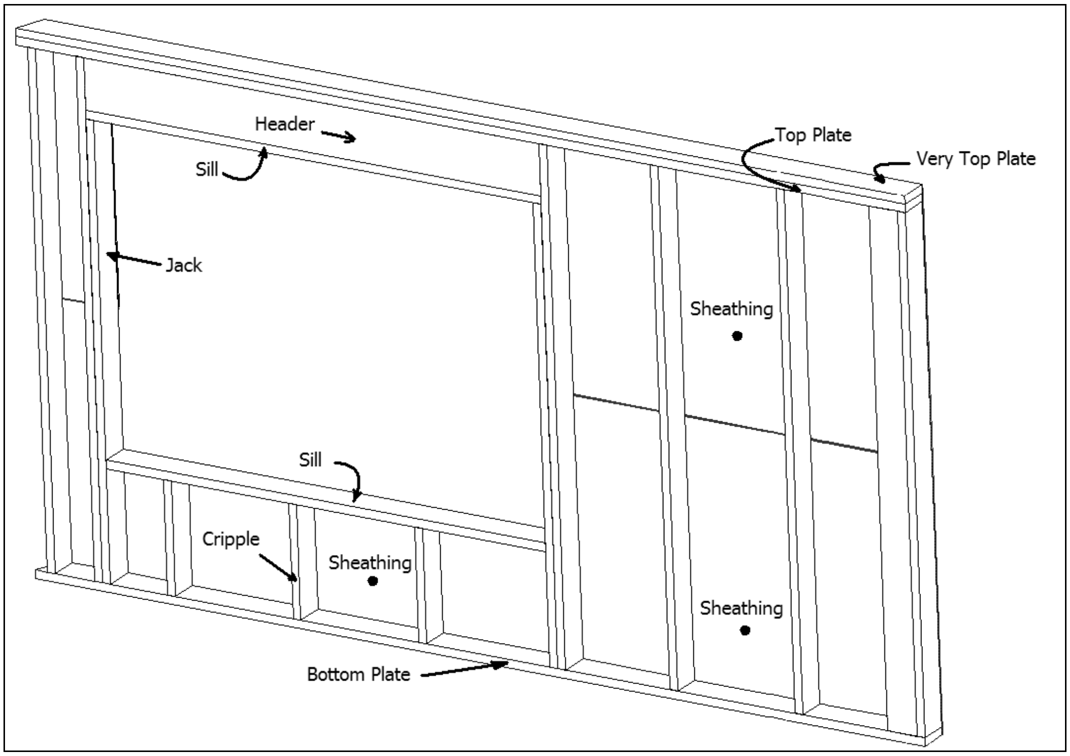


Figure 1. Wall panel composition

There are particular reasons why panelized and modular construction have not yet been fully embraced, such as customer skepticism about the methodology; lack of training for code officials; sensitivity to damage during transportation and handling; transportation fees; and expensive equipment and initial investments (NAHB 2002a). On the other hand, prefabrication of dwelling components can standardize the industry while lowering construction costs through the introduction of mass production, the ability to work year-round in a controlled environment, better quality control over finished products, material waste minimization, ease of assembly, workers safety, etc. (NAHB 2002b).

This research focuses in particular on on-site and panelized systems—the techniques most commonly applied in North-America. It is important to note that panelized construction is performed by a relatively small sector within the North-American construction industry. The collaborating company seeks to pioneer and introduce broadly the practice of prefabricating wall panels in the construction of wood dwellings in order to deliver a more affordable and higher quality product to the customer. Nevertheless, this industry has not yet exploited the benefits of panelized and modular construction. The introduction and further development of automated systems for the homebuilding industry must emerge to counteract the increasingly high construction costs associated with labor and materials.

The first step in the development of on-site and panelized construction is the improvement of automated construction drawings for homebuilding design. This research employs CAD modeling, parametric algorithms, and material optimization techniques to feed the upfront of both construction methods in order both to guarantee the optimum use of materials and labor and to incorporate standards.

2.1.3 Framing Characteristics

The platform-frame design for walls can be broken down into wall types, wall connections, and wall components. As mentioned above, for the purpose of this research the primary focus is on automating and optimizing wall panels for stick-built dwellings; automation and optimization for floor layout and design can be expected as future research. In the current residential construction practice, floor and roof systems are engineered. Depending on the manufacturer, depths, spans, connections and other intrinsic characteristics vary based on the materials used and the structural solicitations applied to them.

For the development of this research, it was necessary to understand the basic principles of the platform-frame method: types of materials involved, modes of installation, material requirements and constraints. During the earliest stages of the research, the collaborating company supplied the means and methods for best construction practices.

The characteristics and requirements for light-framed construction are presented in Tables 1, 2 and 3. In order to gather this information, it was necessary to shadow trades people at construction sites and framers at the manufacturing shop in order to gain a better understanding of the platform-frame construction method.

2.1.4 Lumber characteristics

In order to guarantee the quality of wood used for stick-built construction, dimensional lumber must be grade-stamped. The grade represents the characteristics and standards of the component, such as lumber size, intent of use, quality, and wood species. Given these characteristics, one can infer information as to the strength and quality of the component. Most of the lumber used in Canada comes from a group of lumber species collectively referred to as Spruce Pine Fir (SPF). With regard to the quality rating, it might simply be stated that the higher the grade, the stronger the piece of wood. In Canada, lumber for home building construction is typically graded as either No. 1 or No. 2. (e.g., No. 1 SPF). Grade No. 3 is primarily used for wood storage crating boxes and bracing materials (AFPA 2008). Every mill must thus specify the quality of the lumber by stamping its characteristics on the item itself. For example, The Alberta Forest Products Association (AFPA) is the entity in charge of verifying lumber standards in the production of construction lumber. The National Lumber

Grades Authority (NLGA) has defined the standards for lumber grading, as well as the rules required for lumber production in Canada. Entities such as the AFPA are responsible to check that lumber standards are met.

Figure 2 shows an example of a lumber grade stamp, where (1) is the registered symbol of the given agency; (2) is the mill identification number; (3) is the species special group (see above), (4) is the seasoned condition, and (5) is the grade name or number (ASPF 2008).

Figure 2. Lumber grade stamp

Dimensional lumber for use in construction should not have a moisture content exceeding 19 percent. If the moisture content exceeds this rate, it may precipitate dimensional errors during installation; i.e., once the lumber dries, the piece will shrink. The seasoned condition in Figure 2 (4) describes the moister content of the dimensional lumber. The acronym "KD-HT" stands for "kiln-dried and heat treated", meaning that the wood has a moisture content of 19 percent. Synonymous terms are KD-19 or KD-15 (when a 15 percent moisture content threshold is at play). For manufacturing purposes, vertical studs should have a moisture content of 5 percent or less in order to avoid any shrinkage after installation. Plates and sills can have higher moisture content since a change of dimensions would not affect the final product. Table 4 shows the common characteristics and uses of lumber (American Forest & Paper Association 2001).

Table 1. Wall Components

Table 1: Wall Components

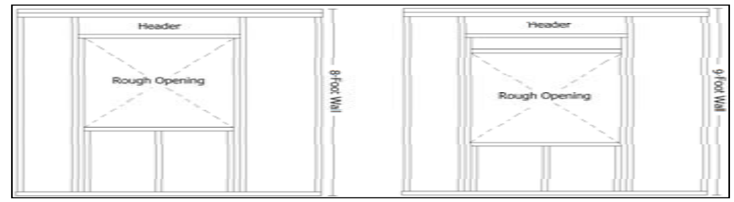
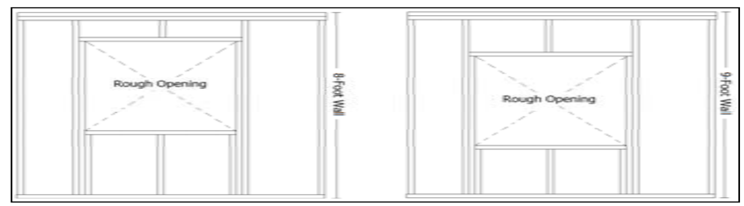
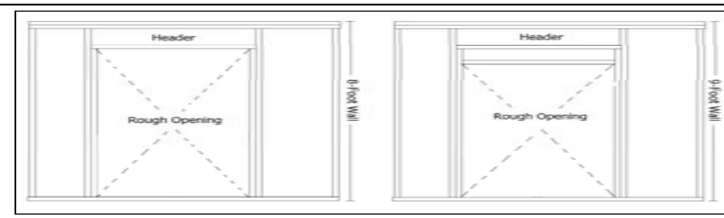
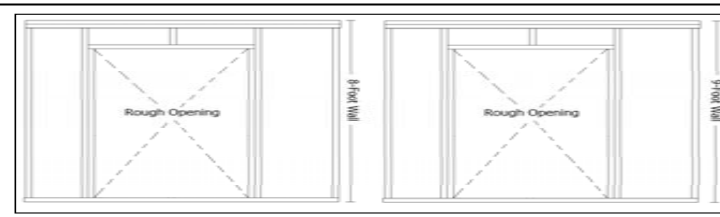
Windows	**Bearing Walls:** windows in bearing walls must be structurally designed to avoid floor failures and deflections. When joists are resting on top of the window, an engineered header has to transfer the load coming from the joist to the levels below. A window is composed of jacks which support the engineered header or lintel, cripples which support the bottom portion of the window, and studs adjacent to the jacks which provide a better anchor to the wall and which function to transfer the loads more uniformly. For a rough opening greater than 60 inches, it is recommended to have double jacks on both ends of the engineered header to provide a better bonding between the two components. The engineered header has a depth of 9.5 inches, and, depending upon the carried load, two to three headers joined against each other are also required. For walls with heights exceeding nine feet, the header is usually fixed just beneath the top plate, but it is left to the discretion of the framer to follow this practice (See Appendix A).	
	Non-Bearing Walls: There is no need to utilize engineered headers for these type of windows since there is no load needing to be transferred from the floor system through the wall. In this case, there is only cripples above the top of the window sill to provide support to the rough opening (See Appendix B)	
Doors	**Bearing Walls:** The same principles from windows in bearing walls apply to doors in bearing walls. The only notable difference is that doors do not include a bottom sill plate. For manufacturing purposes, the bottom plate extends from end to end in the wall, and once the panel arrives on site, the section of bottom plate in the door is cut out. This method prevents wall deflections during transportation.	
	Non-Bearing Walls: These doors follow the same principles as windows in non-bearing walls.	

Table 2. Wall Components

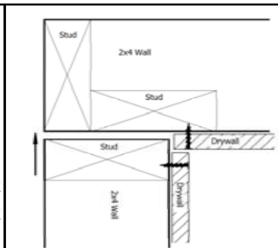
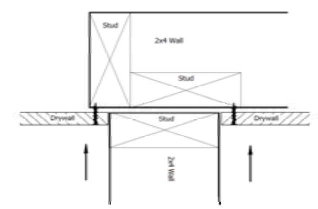
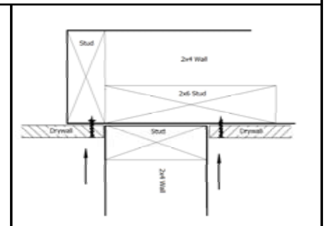
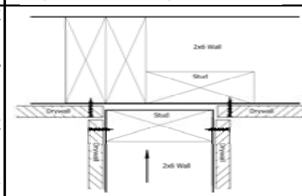
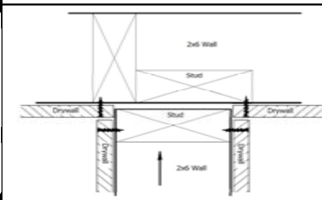
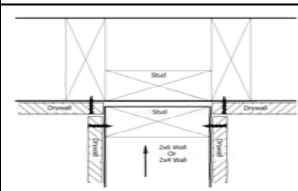
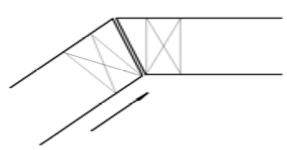
General Description	These types of connections are the most common for any stick-built dwelling design. 90-degree connections are commonly used at building corners and wall intersections. The advantage of this connection is that it provides a stronger bond between walls, and also provides space for sheathing and drywall to be screwed to the studs. The intersecting wall caps the intersected wall with the very top plate, which is fastened to both walls on top.			
Types	**L-Connection:** This connection occurs when two 2x4 walls are connected. At corners, the L-Connection is composed of two 2x4 studs. For a wall which intersects another, there are two options. The first is to use an L-connection comprised of a 2x4 and a 2x6 stud, providing space for drywall to be screwed; the second option uses an L-connection composed of two 2x4 studs. This second connection provides less space for drywall to be screwed against the stud, so greater precision is required. The advantage is that less material is consumed.			
	2bl L-Connection: This connection provides a stronger support for walls. It is used when two 2x6 walls intersect one another. There is also a possible modification to this connection: For interior walls intersecting exterior walls, a simple L-connection composed of two 2x6 studs can be used to save material, but precision must be emphasized when placing this connection due to the relatively limited amount of space left for drywall installation .			
	U-Connection: As show in Appendix E, the U-Connection places two studs in between the intersecting wall. The U-Connection requires more material than the L and 2bl L-Connections and, due to this fact, is not practical. This method also has the inconvenience of blocking the access for insulating inside the U-Connection. This connection is only effective for interior wall connections.			
	Other-Degree Connections: These connection types do not have a strong support. Although the very top plate fastens the connection on top, the angle formed between these two walls does not provide the strength which 90-degree wall connections offer. These wall connections are primarily used where no shear requirements are needed in the structure.			

Table 3. Wall types

Exterior Bearing Walls	These types of walls carry out the loads coming from roof and floors down to the foundation walls. It is normal practice to have stud spacing between 16 and 19.2 inches on centers, but this spacing may vary according to structural solicitations and floor spans. Starting from the exterior side of the wall and progressing toward the interior side, the composite materials are: siding, building paper, sheathing, 2x6 studs, rigid insulation, vapor barrier, drywall.
Exterior Non-Bearing Walls	These walls run along the joist layout of the dwelling, and hence these walls provide the structure with a higher shear capacity. The normal stud spacing here is 19.2 to 24 inches on centers, but this too may vary according to the given structural requirements. These walls can be constructed with 2x4 studs, but due to temperature requirements 2x6 studs are usually used. The composite materials used for these walls are the same as for any exterior bearing wall.
Interior Bearing Walls	The general function of these walls is to support floor joists and reduce the span length between exterior walls. These walls have a stud spacing between 16 and 19.2 inches on center, but again this may vary according to the structural requirements. These walls consist of a series of half-inch drywall on both sides, and 2x4 or 2x6 studs in between (depending on the loading).
Interior Non-Bearing Walls	The primary use of these walls is to separate areas within the house. There is no structural support from these walls, and the stud spacing in most cases is 24 inches on center. Again, the wall is comprised of half-inch drywall on both sides, and 2x4 studs in between.
Interior Mechanical Walls	The function of these walls is to carry plumbing pipes/ heating ducts from floor to floor. The stud spacing has to match the joist layout in order to avoid spatial conflicts between the studs, the floor joists, and the plumbing pipes/ducts. These walls are composed of 5/8-inch drywall on both sides and 2x6 studs in between. For cases for which there are no mechanical ducts passing through the mechanical walls, a half-inch drywall may be used for both sides of the wall. Each pipe/duct must be fire-caulked to eliminate fire hazards.
Party Walls	Party walls have the property of providing sound insulation and also increasing the fire rating between two adjacent houses (i.e., townhouses). These walls are doubled-framed, having studs staggered between panels in order to minimize sound transmission. The sound transmission class (S.T.C.) based on the requirements of the Alberta Building Code must be above 54.

Table 4. Lumber uses and Characteristics

Use	Grade	Comment
Light framing	Construction, Standard, Utility	For use where high strength is not required (studs, plates, sills, cripples, blocking)
Studs (2x2 to 4x6) up to 10 ft.	Stud, Standard or Better	All-purpose grade for lumber 10 ft. or shorter in length. Stud grade suited for all stud uses, including load-bearing walls
Structural - Light framing (2x2 to 4x4)	Select structural, No. 1, No. 2, and No. 3	Grades for higher bending strength ratios. Typically for trusses and concrete pier wall forms
Structural – Joists and planks (to 4x16)	Select structural, No. 1, No. 2, and No. 3	Used primarily as floor/ceiling joists and roof rafters. First three grades commonly sold as "No. 2 & Better."

2.2 Research in 3D Modeling

The foundation for this research is the use of 3D models to graphically present a wood structure prior to construction, such that decision making can occur at the office rather than the construction site. The author of this research underscores the importance of designing accurate 3D models which can effectively represent reality. To do so, the need for computer knowledge is required in order to overcome design and productivity issues in the drafting of models. Analyze previous research approaches in 3D Modeling.

2.2.1 3D Modeling Applications in the Construction Industry

In recent years, with the enhancement of CAD software, researchers and practitioners have encountered a renewed impetus to model building components in a 3D environment. Technology is emerging which integrates all disciplines and aspects of the construction industry. Architectural, Engineering and Construction (AEC) disciplines can now interact with one another at the design stage to enhance coordination and prevent the emergence of constructability issues. Nevertheless, the automation of construction designs based on 3D modeling has not yet reached an adequate level. VR tools, which serve to illustrate how building components appear prior to construction, are driving the software market. In today's industry, most of the models developed lack vital information and are difficult to update. Song et al. (2005) has shown the importance of developing and using rich 3D building models for a uniform visual representation method, thus allowing project managers to assess performance, identify problems, make decisions more efficiently, and communicate effectively with other project participants.

CAD software has evolved considerably to facilitate integration. Nevertheless, the tools included in these CAD programs lack the specific user components needed for design. The end-user must either develop programmatic codes to bolster his drafting productivity or spend long drafting hours. Another issue which emerges when modeling 3D objects in a CAD environment is the lack of guidelines outlining the requirements involved in applying modeling tools in real-time on actual construction projects (Staub-French and Khanzode 2007).

Extensive research in construction engineering has been based upon the utilization of 3D modeling techniques to visually present the development of future projects prior to construction. 3D modeling has been applied in particular for constructability purposes, as in the case presented by Manrique et al. (2007). In this case, the need for accuracy demanded the location of building constraints from a virtual reality model, as well as the use of computational animations to eliminate errors in the installation of 108 concrete panels with the use of a crawler crane and tilt-up panels. Sacks and Barak (2005) have stressed the issue of enhancing work productivity for structural engineering designs, as well as the manner in which measuring methods based on 3D modeling can improve modeling time, drafting accuracy, and cost reductions. Teizer et al. (2007) have focused on the use of automated 3D sensing at construction sites to detect and track project resources.

In general, two different approaches have been formulated since the introduction of CAD modeling as a drafting solution to support end-users: entity-based modeling and object-based modeling. Entity-based modeling began as a solution to assist CAD designers in drafting elements. However, these elements or "entities" do not have relationships with one another. Parameters for drafting an entity are provided by the modeler but are not recorded, so this information is lost. Consequently, any new changes must be made manually. Many building models have been designed based on the entity-based approach, and the whole building model, therefore, is simply represented by raw graphic entities or primitives (e.g., lines and arcs) which fail to provide rich semantic meaning about the building (Tse et al. 2005).

Object-based modeling has been introduced into the field in order to achieve better drafting performance by creating a history that describes how an object was created or modified. This method is known in industry as parametric modeling. New software approaches, disseminated under the name Building Information Modeling (BIM), exploit the principles of parametric modeling to generate changes by making use of object relationships, such that modelers need not look after any of the current modifications. Companies such as Graphisoft and Autodesk, to mention a few, are adding innovation to their CAD packages by incorporating an intelligent repository into a CAD model. Information generated by the model is classified according to its attributes, such that multi-aspects from the Mechanical, Electrical and Plumbing (MEP) and AEC disciplines can be linked at each stage of the lifecycle of the building facility: scheduling, costing, sustainability, maintainability, acoustics, and energy simulation (Aouad et al. 2005).

2.2.2 Generic Algorithms – Programming Language

As defined by the Microsoft Developer Network (MSDN 2008), Visual Basic (VB) is a tool designed for productively building type-safe and object-oriented applications. Researchers have applied the use of this programmatic language for the development of civil engineering applications. From modeling optimizations (Easa 2008) to Generic Algorithms (GAs) and integer programming (Salem 2008), VB has provided an ample capacity for automating repetitive and complicated processes.

Further utilizations of VB for modeling design have figured in the development of GAs to solve mathematically challenged processes requiring an optimal solution to a given problem. Manrique et al. (2007) have developed a GA to graphically locate a crawler crane around a construction site for the purpose of optimizing the power of the equipment and displacing it in the least amount of time possible in order to enhance the lifting sequence for pre-cast panels. Salem et al. (2007) have developed a

GA capable of minimizing the production of 1D material waste by utilizing VB, the principles of the cutting stock problem, and neural networks. Kandil and El-Reyes (2006) have created a multi-objective GA to enable an efficient and effective optimization of resource utilization in large-scale construction projects.

Most of the GAs developed at present seek the optimization of complicated problems for which possible solutions are not evident (Hegazy and Petzold 2003). The utilization of VB and other programmatic languages make possible the development of iterative routines that can be handled with the basic power of personal computers. This Ph.D. research involves in particular the use of GAs developed under VB for the generation of building components in a 3D environment in which lengthy and repetitive routines will eliminate the use of extensive drafting hours. The process of identifying model constraints and iterating the final location of wall components can serve to optimize the development of framing designs for residential facilities, having a positive trade-off in the elimination of drafting errors and man-hour costs.

2.3 Building Information Modeling (BIM) – Parametric Modeling

New CAD technology is driving the design market toward self-sufficiency and the ability to manage extensive and comprehensive amounts of data. This research seeks in specific the integration of modeling design, manufacturing principles for panelized processes, and cost estimating for building materials under an intelligent management system, similar to the framework followed by BIM and parametric modeling systems.

2.3.1 Research in BIM and Parametric Modeling

As defined by the National Institute of Building Sciences (WBDG, 2009), a Building Information Model is a "digital representation of physical and functional characteristics of a facility. As such, it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle from inception onward. A basic premise of Building Information Modeling is collaboration by different stakeholders at different phases of the life-cycle of a facility to insert, extract, update or modify information in the Model to support and reflect the roles of that stakeholder. The Model is a shared digital representation founded on open standards for interoperability". In essence, BIM covers the entire lifecycle of a construction project, from design and planning stages to project turn over by facilitating the use of data. This research adds up to this premise by providing more information in regards to construction drawings and by linking optimization models to a building manufacturing technique: Wood-frame Panelization.

BIM, introduced by Autodesk, targets the development of Object-Oriented Programming (OOP) to its full extent. OOP is based upon such techniques as encapsulation, modularity, polymorphism and inheritance (Taylor 1992), thus providing meaningful information to any object represented in a programmatic language. Through the development of CAD software in recent years, it has become more evident that the inclusion of more information in the CAD model can provide end-users with a more comprehensive understanding of the designed model. One of the notable aspects of BIM is the graphical communication between designer and CAD model, which includes the capacity to show building conflicts resulting from the inherited intelligence given to the model's object components. The ability to track changes and on-time updates is a powerful characteristic included in most BIM software which serves to prevent design errors during conceptual stages. BIM allows for changes to be made to the design of a project at any time without any laborious re-coordination or manual checking (McFarland 2007).

With the advancement in building information modeling (BIM) software, it is possible for end-users to create an efficient analysis for building processes, types, sizes, materials effects and coordinate complex MEP systems (Korman et al. 2008). Through the utilization of intelligent data repositories, any 3D model can be frontloaded with complex information pertaining to construction materials, crew types and sizes, and equipment transportation and installation (Vilkner et al. 2007).

Most of the implementation to date with respect to BIM has occurred at the design stage, but little has been done to provide construction trades with this rich information. Accurate models have been developed by some consultant companies in North-America, but they have not yet been adopted in practice (Sacks and Barak 2005). There is a need to connect both sectors of this industry in order to fully utilize the benefits from rendered models.

BIM looks beyond graphical design by mingling together multiple disciplines from the AEC industry, and has the advantage of decreasing time and costs for design and construction. In the case of the construction of the Kamppi Center Project, located in Helsinki-Finland, for instance, the use of BIM helped to keep construction under budget and on-time (SRV Group 2007). Benefits related to risk minimization, optimized schedules, and accurate construction drawings have also been obtained through the use of powerful CAD tools with rich model information. The most significant impact on building construction is that BIM facilitates the management of multiple tasks under one intelligent database system.

CAD software has evolved to the extent that simplicity and functionality drive the drafting market. However, it seems that North-American researchers and practitioners have focused on the use and development of Autodesk® products such as Revit® and AutoCAD® software. In Europe, the major CAD distributor is not Autodesk®; instead, there are a number of CAD software applications, such as ArchiCAD® by Graphisoft®, and CATIA by Dassault Systems, which share the market. Most of the European software developed to date has been C++-based, whereas most of the software developed in North-America is Visual Basic-based.

The market has also seen the arrival of experimental software which advances the development of BIM constructs such as IDEA+ (Boeykens and Neuckermans 2006), looking towards the integration of Building Modeling and Construction Engineering techniques. Most of the research presented to date has focused on the use of BIM, its characteristics, weaknesses, and strengths. A number of surveys have been conducted to gather more information from the end-user, so that better software can be developed subsequently (Suermann and Issa 2007; Faulkner 2007; Ibrahim et al. 2003; Panushev and Pollalis 2006).

In the context of this research, the purpose of analyzing BIM has been to include its systematic approach to gathering and sharing information related to building designs. The platform-frame method has been modeled using Visual Basic, mimicking the construction process followed by experienced framers. By following the principles of BIM, the proposed methodology will incorporate as much information as possible for framing design, such as panel dimensions; visual representations; material take-offs; and cutting lists for dimensional lumber, sheathing, drywall, and thermal insulation.

2.4 Material Waste and Material Optimization in Construction

Material waste of any kind creates issues for cities and municipalities dealing with disposable and non-disposable material, material classification, landfills, and material treatment. This thesis looks toward the elimination/reduction of material waste in a specific niche—the residential construction industry. Mathematical techniques have been utilized in order to generate a creative approach that assists managers in the decision making processes related to material usage, storage, transportation and final disposal.

2.4.1 Research in material waste and optimization

Through the introduction of the platform-frame method in North-America, it has become possible to encounter advantages in terms of material utilization, transportation, and installation over previous construction methodologies (Miller et al. 2004). Nevertheless, the platform-frame method has undergone only minimal changes since having been introduced in the early 1900s, as mentioned above.

Structural Insulated Panels (SIPs) and other prefabricated construction solutions have served to facilitate the construction of residential facilities by enhancing the utilization of construction materials under controlled environments. Due to the use of manufacturing processes, the utilization of labor and materials has become more efficient than with conventional practices. Admittedly, however, there are numerous unknowns which homebuilders must address on a daily basis in order to maintain business operations in today's market, making the introduction of new construction techniques and materials difficult to accept by the general public. As described by Mullens and Arif (2006), the buying perception in the construction market for residential facilities can fluctuate due to market conditions, materials utilized for construction, and innovative construction techniques. As an immediate consequence, and given the high demand for housing in large urban communities, many construction companies fail to minimize the use of primary materials on site, thereby generating large amounts of material waste. One of the crises contributing to this condition is the relatively high cost of labor and the shortage of experienced trades personnel.

Mah (2007) has shown the substantial difference between skilled and non-skilled labor when constructing stick-built houses using the platform-frame method. Mah has investigated this issue by quantifying current waste at construction sites for the same house model but different framing crews. As a result, for the construction of a Catalina II model by the collaborating company (approx 1700 sq. ft. in area), the average (linear) amount of wood waste was determined to be 974 kg. The issue relates to the range of material waste (low: 751 kg, high: 1350 kg), where almost 600 kg of material waste can be accounted for based on factors such as material damage, theft, and workmanship.

Laquatra and Pierce (2004) have found that the North-American construction industry produces up to 24 percent of all municipal solid waste, 80 percent of it being recyclable. In residential homebuilding, between two and four tons of debris are produced in the construction of a single-family dwelling. Overall, researchers have concluded that the wood waste produced in the construction of a single-family dwelling accounts for close to 50 percent of total waste (Sustainable Communities Network 2000).

Most of the research performed up to this point has focused on the quantification of material waste (see, for example, Formoso et al. 2002), but few studies have addressed the matter of reducing construction material waste from the design end. In residential construction, materials are available in nominal sizes, and the best practice in building design should consider these dimensions in particular in order to arrive at an optimum construction methodology without jeopardizing the building esthetics. Extensive research has been carried out in the area of material optimization—on how to cut and arrange pieces with minimal waste, but an amalgamation between design optimization and CAD is essentially an untouched area of research. The principles behind material optimization originated in the early 20th century with the coupling of combinatorial analysis and linear programming, a phenomenon known in the mathematical field as the cutting-stock problem. Another approach studied in the field has to do with 2D optimizations based on the guillotine and non-guillotine cutting-stock problems. Linear programming and combinatorial analysis had had little success by the early 1950s, given the considerable number of constraints involved and the extensive array of possible operations and solutions that could satisfy the demanding requirements of a problem (Gilmore and Gomory 1961). But since computational systems were beginning to become more sophisticated, the gap between mathematical modeling and its solutions soon disappeared. Since most of the mathematical theory for modeling optimization has already been formulated in previous work, researchers are currently applying these concepts and theories through the use of computational software.

Although the theory behind the cutting-stock problem is well known, the effort required to re-implement an algorithm from its published description is nontrivial due to the well-acknowledged gap between the abstract theoretical explanation of an algorithm and its software implementation (Ladanyi et al. 2005). Different approaches have been conceived of by researchers to the optimization of solutions to the cutting-stock problem (Trkman and Gradisar 2007; Song et al. 2007; Diegel et al. 2006; and others), all of which demonstrate the importance of adapting new math in order to extract the most nontrivial solutions for any 1D matter. With regard to area or 2D optimizations, the guillotine and non-guillotine cutting-stock problems correspond to the optimization of materials which require cuts in two orthogonal axes. For example, MacLeod et al. (1993) analyzed the guillotine cutting-stock problem where rectangular shapes needed to be extracted from a stock piece with a maximum total value (minimum waste) by seeking approximated solutions. Beasly (2004) focused on optimizing the cutting-stock problem based on a non-guillotine approach by utilizing a population heuristic algorithm in order to maximize the value of pieces from a single sheet.

By implementing such mathematical theories to real cases, benefits in terms of material optimization and labor productivity can be expected, along with a decrease in fixed and variable costs due to the better use of material and resources. Construction material waste can be reduced substantially by integrating CAD modeling techniques with material optimization algorithms. This research thus focuses specifically on the utilization of these techniques in order to fully integrate scientific theory with modeling design.

2.5 Drywall layout and automation of drafting design

The misuse of drywall at construction sites is one of the main causes for material waste in residential construction in North-America. The residential construction industry can thus benefit from this research through the application of the developed algorithms to automate layout designs. The development and further utilization of GAs for the design of accurate construction drawings can provide ample benefits in terms of the optimization of the use of primary materials. The capabilities of parametric modeling have been fully exploited through the development of a GA that utilizes spatial analysis and repetitive design rules for the layout design of drywall sheets for stick-built dwellings. The algorithm, DRY-X, has been developed to mimic the installation of on-site and panelized constructions under the platform-frame approach. Nevertheless, procedures for applying the proposed methodology can be found to be greatly beneficial by virtue of the associated material savings.

2.5.1 Research in Drywall

From 2004 to 2008, many regions of Canada experienced significant economic growth. This was especially true of the construction industry, where more than CAD $72 billion were invested in 2008 alone (Statistics Canada 2008). These numbers denote the significant contribution in terms of the generation and utilization of primary materials, accounting material waste disposed of at landfills. During 2006 in Canada alone, more than 27 million tons of construction material waste were disposed of (Statistics Canada 2006). Notably, some materials can be used much more efficiently in order to mitigate the problems mentioned above. Drywall waste, for example, which accounts for a significant share of material waste, is generated from new construction (64 percent), demolition (14 percent), manufacturing (12 percent), and renovation (10 percent) (California Integrated Waste Management Board 2007). This accounts for 10 percent of the total construction waste generated in cities and municipalities (Alberta Innovation and Science 2006) (see Figure 3). During the installation of drywall sheets, an average of 12 percent of material waste is generated as a result of design and workmanship inefficiencies (California Integrated Waste Management Board 2007).

Figure 3. Drywall waste in residential constructions

Drywall is the most utilized material in North-America for finishing interior walls and fire-rating partitions, ceilings, and structural members. The utilization of drywall in the residential and commercial industries has been successful due to its fast installation and relatively low cost (US \$3.12/m^2 12.7 mm thick, R.S. Means 2008). Nevertheless, during the production of drywall, the embodied energy required to make these sheets is high (approx 8.64 MJ/kg, Chen et al. 2001), as are the associated Green House Gas

(GHG) emissions (approx 24 kg. of CO_2/kg. of drywall, Clapham 2008). It should be noted that energy is used not only to produce primary materials but to transport goods to their final location. In this case, for drywall, the demanded energy in transportation is in the range of 3.36 MJ/kg-Km (Chen et al. 2001). Furthermore, in the province of Alberta, Canada, 61,100 tons of drywall waste is deposited in landfills annually (Alberta Innovation and Science 2006). With the rapid growth of green building practices in both the public and private sectors, the lack of solutions to waste management and other environmental issues is becoming problematic. Commitments by private institutions; the federal, provincial and municipal governments; and developers to using strict measurement tools, such as the Leadership in Energy and Environmental Design (LEED®) and Built Green™ Alberta, speak to the urgent need to provide solutions. In today's construction practice, the production of drywall accounts for one percent of the total GHG emissions on the planet per year (Green Energy News 2008). Leftovers from construction are used for soil compost, and no harm to the biosphere as a result of this process has been documented to date (Alberta Innovation and Science 2006). Nevertheless, the need to optimize the use of drywall has become evident—either by creating optimum layout designs and enhancing current construction drawings, by providing incentives to trades and contractors to reduce material waste, or by optimizing the cutting of drywall in effective ways.

The precise amount of material waste is a function of the expertise of trades personnel the amount of planning during pre-construction stages, and the availability/lack of construction drawings.

2.5.2 Drywall Layout and design rules

In order to reproduce accurate sets of construction drawings for drywall layouts, it became necessary to follow the design principles for boarding stick-built dwellings as presented in Tables 5 and 6. The design principles in both tables denote the best practice for boarding interior walls and partitions. For both manufacturing and on-site installations, there is a need to reduce the amount of taping required, as well as to utilize the sheets of drywall in the most suitable way. One should note that the dwelling layout determined by the architects cannot be modified to suit the best material utilization from a waste point of view. Nevertheless, design principles enhance the usage of drywall by pointing out all possible cases for boarding and taping.

Table 5. Design principles for boarding wood-stick dwellings, Exterior Walls

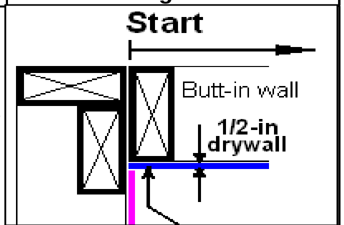
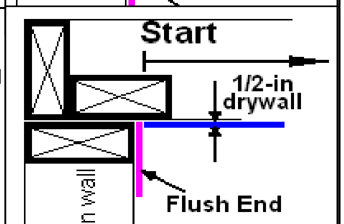
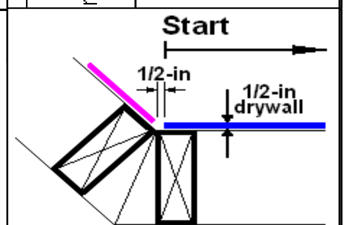
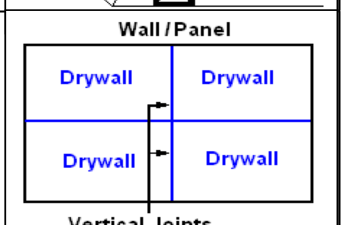
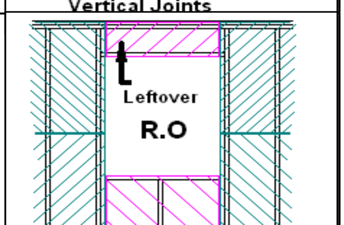
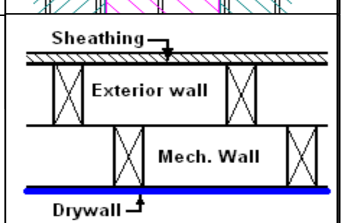
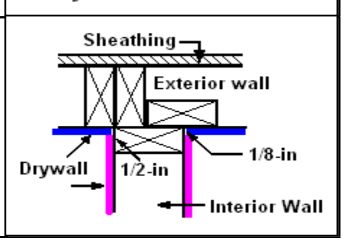
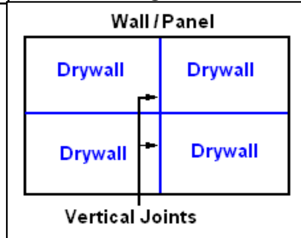
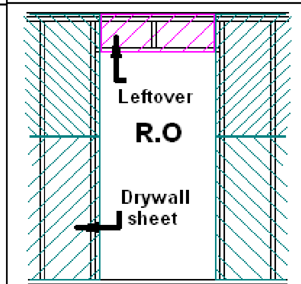
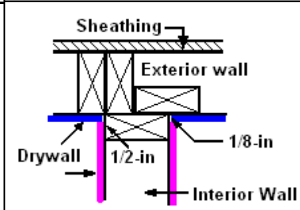
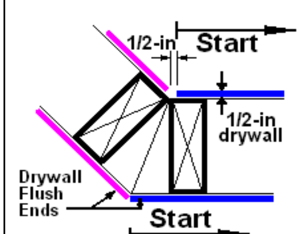
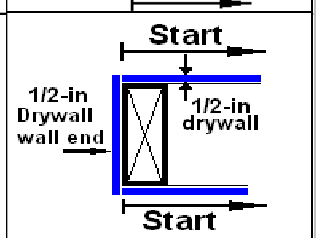
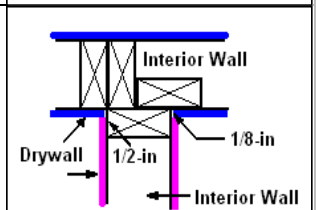
Item #	Description	Figure
Design Principle 1: Start/End point	When there is a 90-degree connection, the drywall sheet for the butt-in wall will start flush with the first stud of the panel. By doing so, the flush end can be easily screwed against the stud. The drywall on the butt-out wall will have to be ressesed 1/2-in.	
Design Principle 2: Start/End point	When there is a 90-degree connection, the drywall sheet for the butt-out wall will start half-inch after the Butt-in wall. The principle is the same as in the previous case. Same rule applies for the end of the panel/wall	
Design Principle 3: Start/End point	When the connection between walls/panels is not at 90 degrees, the drywall sheet for the interior corner will start 1/2-in after the corner. The same rule applies for the end of the panel/wall	
Design Principle 4: Drywall joints	Drywall joints do not have to run staggered between horizontal and vertical rows. This will allow tapers to finish the walls with higher quality and less touch-up work.	
Design Principle 5: Wall Openings	When there is an opening, the drywall sheet ends/starts flush at the beginning/end of the rough opening. Use left overs to cover bottom and top of windows, and top of doors.	
Design Principle 6: Mechanical walls	If a mechanical wall happens to run parallel to an exterior wall, do not drywall in between both walls, unless there is a fire-rating requirement.	
Design Principle 7: Connections with interior wall	The installation of the drywall sheet on a exterior wall when an interior wall connects to it should end/start 1/8-in before/after the interior wall frame. The drywall sheet for the interior wall should end/start 1/2-in before/after the last/first stud.	

Table 6. Design principles for boarding wood-stick dwellings, Interior Walls

Item #	Description	Figure
Design Principle 8: Drywall joints	Drywall joints do not have to run staggered between horizontal and vertical rows. This will allow tapers to finish the walls with higher quality and less touch-up work. The installation of drywall sheets should go on both sides of the interior wall unless the interior wall encloses a space with no access, such as closets, fireplaces, etc...	
Design Principle 9: Wall Openings	When there is an opening, end the drywall sheet flush at the beginning of the rough opening. Install the next drywall sheet right after the end of the rough opening. Use left overs to cover bottom and top of windows, and top of doors.	
Design Principle 10: Connections with interior wall	The installation of the drywall sheet on an exterior wall when an interior wall connects to it should end/start 1/8-in before/after the interior wall frame. The drywall sheet for the interior wall should end/start 1/2-in before/after the last/first stud.	
Design Principle 11: Start/End point	When the connection between walls/panels is not at 90 degrees, the drywall sheet for the interior corner will start 1/2-in after the first stud. The sheets of drywall should finish flush on the exterior corners.	
Design Principle 12: Wall Ends	Drywall the end of any interior wall that is not merging or connecting to any other wall	
Design Principle 13: Connections interior wall to interior wall	The installation of the drywall sheets for the merging/connecting interior wall should start/finish 1/2-in before the connection on both sides of the wall. The connected interior wall should start/end the sheets of drywall 1/8-in after/before the connection	

2.6 Carbon Footprint in Residential Constructions

Only limited research has been conducted which aims at quantifying the CO_2 emissions incurred directly through the construction process, although Nassen et al. (2007) have highlighted the need to address the issue of CO_2 emissions resulting from house production. The need to deliver vital information on-time to residential constructors thus constitutes the keystone of this research. The supply of accurate information can be provided by information technologies that can connect real-life, complex, long-term processes with information management repository databases. The utilization of BIM for the quantification of CO_2 emissions due to construction processes can provide the vital information needed by decision makers working to enhance current practices. With the use of an intelligent repository, many flaws in the construction of residential dwellings can be identified and corrected before construction starts. The quantification of GHG emissions from the current residential construction process can be automatically obtained from the analysis of rich 3D models and comprehensive lists of construction methods.

2.6.1 Research in CO_2 emissions in the residential industry

The significance of this research to housing is noteworthy, especially considering the contribution of the housing industry to Canada's GDP. Furthermore, the relationship between housing construction and CO_2 emissions has been made evident: the residential sector is the third largest energy user in Canada, accounting for 17 percent of secondary energy and 16 percent of GHG emissions or 77 megatons (NRC 2006). A recent project funded through the Canadian Mortgage and Housing Corporation

(CMHC) on Net Zero Housing has provided the impetus for this application through its goals of reducing environmental impact and encouraging sustainable construction. More broadly, all citizens and companies must contribute to mitigating climate change while providing value to society (Yu et al. 2008).

Previous findings have shown that CO_2 emissions during the conventional framing of a dwelling amounted to more than 45 tons of CO_2 (Gonzalez and Garcia Navarro 2006). In Alberta alone during 2007, the nearly 50,000 residential units constructed would have released more than two million tons of CO_2. These numbers demonstrate the economic and environmental impacts of building construction and their relationship to CO_2 emissions within the context of current construction practices. Furthermore, the building sector alone is the third-largest energy user, after the industrial and transportation sectors, accounting for 17 percent of secondary energy use in Canada and 16 percent of related GHG emissions (77 megatons).

Research has shown the possibility of a 30 percent reduction in CO_2 emissions from the selection of low-environmental impact materials (Gonzalez and Garcia Navarro 2006). Other studies by researchers have highlighted the relationship between construction materials and CO_2 emissions in terms of life cycle, ranging from manufacturing to construction to operation and finally demolition (Seo and Hwang 2001). As well, there is a body of literature which provides CO_2 emissions rates based on embodied energy from different materials (Upton et al. 2008).

The rapid increase in the concentration of GHG emissions is widely acknowledged as the major cause of climate change. Based on data provided by Natural Resources Canada (NRC 2006), total Canadian GHG emissions are estimated to have been 758 megatons in 2004; of this, 67 percent resulted from secondary energy use. Based on a survey conducted by researchers at the University of Alberta, the direct CO_2 emissions (i.e., material transportation, workforce travel, and construction equipment) in stick-built house construction in the Edmonton area, from stake-out to drywall completion, amounted to 10.6 tons per dwelling (Yu et al. 2008). The GHG emissions from the operation of a new home, on the other hand, have been reduced by 20 percent—about three tons per household per year due to the enhancement of the National Building Code(NRC 2006).

Process documentation for construction activities and its relationship to cost estimates, construction schedules, quantity take-offs and, in this case, CO_2 emissions can be easily incorporated, manipulated, updated and depicted through the use of BIM (Goedert and Meadati 2008).

With BIM, homebuilders have eased the process of gathering relevant information in order to reduce the economic impact of home construction while enabling themselves to produce higher-quality homes. Nevertheless, solutions for fostering sustainable residential construction are required in order to address environmental concerns such as CO_2 emissions and energy efficiency. The need to address sustainable development has become ostensible as the demand for resources and energy requirements has grown. There are many approaches that could be followed to meet the need for action in this regard. For instance, many new products, processes, and regulations have emerged in the marketplace and have enjoyed some success. The justification for sustainable construction is now well-established in our society, and sustainable facilities are becoming an increasingly favorable prospect for many forward-thinking organizations (Buchanan 2007).

Chapter 3: Proposed Research Methodology

This Ph.D. research has focused on the development of a Knowledge Based System (KBS) to fully automate the construction design for framing components in the residential industry by utilizing the (i^3) concept. Figure 4 shows the input and criteria required by the KBS in order to generate the necessary construction drawings, take-off and cutting lists of materials, 3D model for framing design, and an inventory control that operates as a repository for information analysis and cost estimating. Implementation of the KBS rests on two of three pillars of the (i^3) concept : information, and intelligence (i^2), innovation is left to the end user in order to produce a better product or process[2].

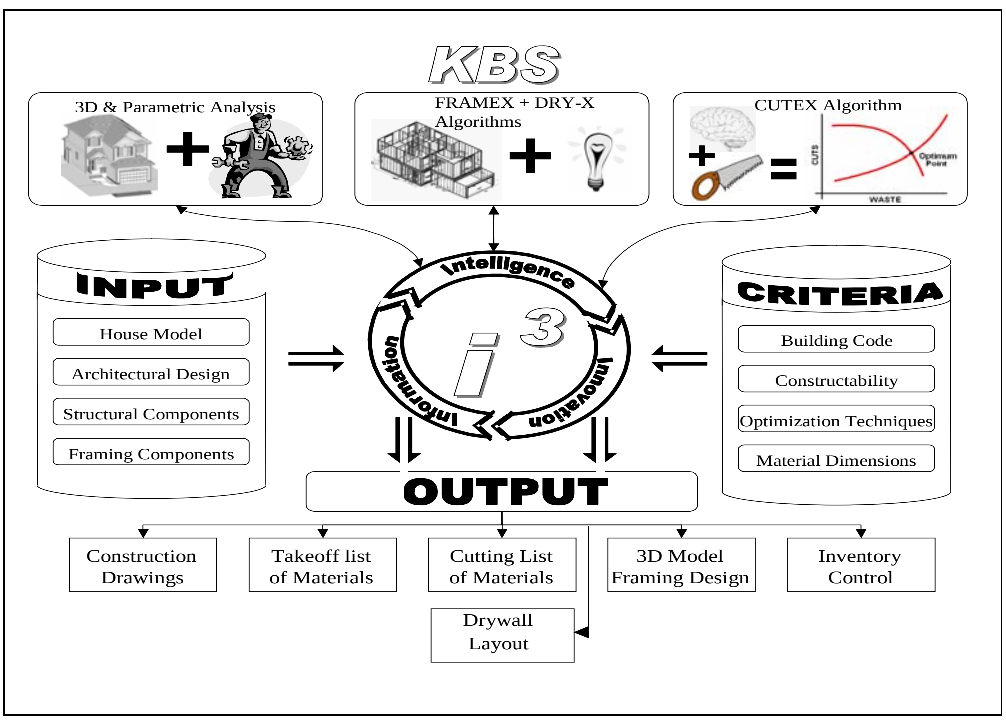


Figure 4. Knowledge Based System based on i^3

[2] A version of this chapter has been submitted for publication, Journal of Construction Engineering and Management, American Society of Civil Engineers (ASCE) 2009.

The KBS is based on the knowledge presented in the literature for stick-built design and drywall rules. This research acknowledges the necessity of incorporating the automation of mechanical and electrical components for residential facilities to provide a complete picture of construction design. By filling this need, the repository model becomes a live entity from which better analyses of information can be retrieved. It is suggested the integration of the National Building Code of Canada to the information technology generated in this research as a means of fully analyzing residential construction models.

The KBS begins by utilizing the information related to the residential construction model, such as the architectural, structural and MEP drawings. One should note that these drawings are the final representation of the client's needs. This information is subject to city bylaws and regulations such as building orientation, amount of openings, setbacks, and so forth. Materials also play an important role when constructing residential facilities in North-America. Most of the materials available on the market for building construction to date are predefined by size; a smart design should consider these intrinsic characteristics in order to minimize material waste, installation time, and, hence, cost.

The KBS uses the mathematical algorithms, FRAMEX (platform-frame design), DRY-X (drywall boarding layout), and CUTEX (mathematical optimization algorithm for 1D and 2D materials). The algorithms are bridged with the (i^2) concept (in this case with information and intelligence); these algorithms are fully explained in the following chapters. In general terms, (i^2) will provide to the end-user a knowledge-based repository model from which construction drawings and material optimization models can be extracted.

As a consequence, it becomes possible through the use of the (i^3) concept to automate construction drawings based on user needs and parameters. The automated construction drawings provide to trades personnel and framers accurate information for wood framing design and drywall layouts through the generation of take-off and cutting lists of materials. Another accomplishment produced by the KBS is its versatility in simplifying the visualization process through the generation of 3D models that can be easily converted to computer animations. In addition, an inventory control provides the final boost by linking quantity take-offs complete with cost estimates that enhance the procurement process for construction companies that desire to know in advance the total cost of a particular designed model.

3.1 The (i^3) concept: Information, Innovation and Intelligence

The platform-frame method described in Tables 1-3 has been mimicked in the (i^3) framework in terms of (1) information knowledge management through the use of the best practice for panelized and on-site framing construction methods and (2) intelligence through the use of mathematical algorithms that can understand the final shape of a 3D architectural drawing and model construction components within the scope of user requirements and specifications. The innovation (3) is a byproduct of the information and intelligence applied to the process. As mentioned before, the innovation is carried out by the end user to obtain better results to the current practice and continuously enhance it through construction management techniques such as lean thinking, value engineering, earn value analysis, etc. Optimal solutions for the minimization of wood material waste and drywall are a derivate from this application.

Figure 5 illustrates the proposed concept, where the 3D model is front-loaded with useful project information. The success of this research results from the information integration between various disciplines, thus reducing the bridge between discipline-specific designs. (i^3) is defined in this thesis as a registry comprised of two distinct components (information and intelligence, see Figure 5). At each node of the registry, practitioners assess project information (i_1) (traditional graphic and project planning); the registry or KBS provides the intelligence (i_2) needed to evaluate material and process waste. These two components promote and help decision makers to seek for potential innovations (i_3) in terms of alternative materials, methods of construction and the application of techniques to measure and control processes more efficiently. By utilizing mathematical algorithms, it assesses the proposed construction method with respect to efficiency, cost, schedule, and environmental impact (CO_2 analysis). Most of this information is expected to be added to the 3D-Solid model during the design stage and throughout the progression of the project (during construction and commissioning). (i^3) remains active and open for innovation, making the 3D-model a dynamic intelligent repository of project information. The implementation of the (i^3) concept is not expected to be free of logistical and technical challenges. Algorithms cannot model innovation, instead, the development of these generic algorithms can support decision makers to come up with better solution. The proposed 3D model functions as an active virtual model throughout the lifecycle of the project, this concept is in alignment with the principles of BIM. The (i^3) concept serves as a registry attached to each activity, each process, and each link between activities throughout the various construction stages.

As illustrated in Figure 5, architects can develop a project using the 3D-CAD model, which represents a set of predefined objects. Object definition is performed through the integrated internal database, and each object added to the drawing is described by all levels of the hierarchy. The properties of these objects represent the model database schema. Construction engineers will receive an intelligent virtual repository model which can be used at all stages of the project, as all necessary information is contained within the model, including floor plans, details, sections, elevations, materials, and assemblies. A walk-through, and even virtual reality scenes can be generated in or added to the ($\boldsymbol{i}^3$) registry. This research, however, is challenged with the task of object definition and with setting the limits of detail such that the model is comprehensive yet simple. The other challenge has to do with the utilization of ($\boldsymbol{i}^3$), identifying potential innovations in order to apply lean construction concepts and value engineering.

To better facilitate visualization of the automation process, this thesis illustrates the design and assists in the construction of residential building models. (Figure 6 depicts four steps within the ($\boldsymbol{i}^3$) approach.) 3D modeling for residential facilities has incorporated many architectural aspects in representing the final product to be constructed; nevertheless, this information has not yet been exhausted to its full potential, and the need to add intelligence to these models cannot be ignored. The BIM acts as a repository database to transform a 3D model with certain architectural features into an intelligent parametric management system. This system is organized by sets of rules and a structured hierarchy using parent-child relationships, allowing the end-user to automatically design the project based on the best practice of construction methods—in this case, for framing design and drywall layout. The ($\boldsymbol{i}^3$) process is then utilized to analyze each step in terms of object definition, construction design, material optimization and elimination of waste, material take-offs, and cutting lists. 3D modeling add-ons (FRAMEX & DRY-X) under a parametric modeling technique (see Part 2, Figure 6) engender the concept of framing design and drywall layout, organizing each wall object (parent) by location and functionality. The parametric algorithm follows logical sets of rules for windows, doors, columns, panels, etc. (children), and stores information into a repository database (registry). The (i^2) thinking process assists during the design process and in the reporting of construction drawings and take-off lists of materials. A combinational evolutionary optimization algorithm (CUTEX, see Part 4, Figure 6) is embedded in the reporting process in order to determine the optimum material cutting solution that minimizes the total number of cuts as well as total material waste.

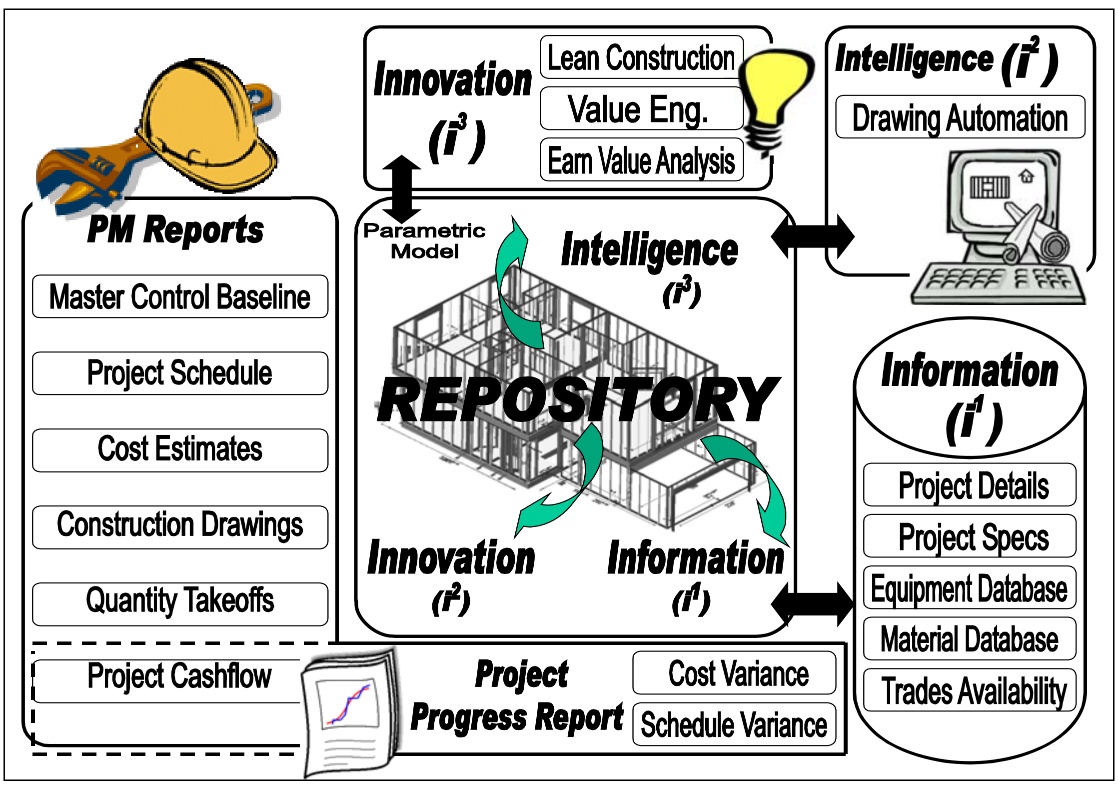


Figure 5. Research Overview

Items of information such as nominal material dimensions are fed into the algorithm so that the combinational analysis can also determine the optimal purchase of lumber available according to the market information input as a parameter by the end-user. For instance, one framer interviewed during the development of the automation model for shop drawings indicated that testing the increase of floor height (from 8’ to 10’) in increments of one foot could result in substantial savings in labor and materials, given that linear dimensional lumber is available on the market in nominal sizes of 8’, 9’, 10’, 12’,14’ and 16’ sheets of sheathing while drywall are available in (4 x 8), (4 x 10), and so on. One can judge the size of one wall/panel based on its length and size. However, without the use of advanced tools incorporating combinational evolutionary optimization algorithms, it is not possible to assess the effect of this innovative message on the construction of the entire house. (*i^3*) thus serves to reduce the risks associated with material allocation, cost estimation, and transportation, and benefits trades through the production of effective designs.

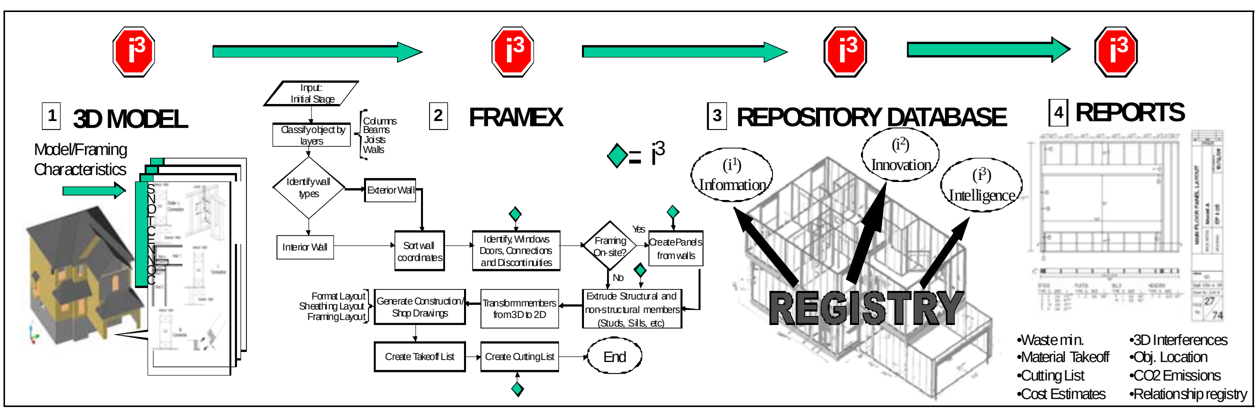


Figure 6. Proposed Concept for Residential Construction

Once the product has been specified, the operations are evaluated in order to build the product and define which resources need to be mobilized for manufacturing or erecting on-site. The (i^3) registry is continually populated using the lean-production concept, including information related to productivity, resource utilization, and bottlenecks in the system, in addition to the proposed model's effect on the project objectives. The next step looks at applying 3D visualization. The design and future construction of a residential facility is thus controlled at the office and not by trades at the construction site.

3.2 Utilization of 3D and Parametric Modeling

An OOP concept of inheritance and encapsulation of data has been developed as the underlying data model for the representation of the construction process and for combining the above-listed areas of information and their interactions. The function of encapsulation is applied in order to set the hierarchy level of operations and processes, and 3D-Solids are proposed to represent the physical objects within the CAD model. Integrating the 3D-Solids with the external data models makes the CAD-model an intelligent repository which can be manipulated in the actual building of the design and construction processes. 3D-Solids are thus a superior alternative for object handling when utilized as a medium of analysis, experimentation, and communication.

In order to analyze an architectural structure for future framing design and drywall layouts, it is necessary to develop a 3D model containing exact information about all types of dimensions of the house, i.e., rough openings for windows and doors, wall lengths and heights, locations of objects within the walls, wall composite sections and dimensions, and so on. To generate a reliable set of construction drawings within a CAD environment, it became necessary to acquire types of information from different sources: architectural components, structural components, structural requirements, and the 3D model. Each wall object to be framed has been classified based on its functionality under different layer names using BIM. This classification is made according to the wall structural behavior with respect to five different types of walls: Exterior Bearing walls (EB), Exterior Non-Bearing walls (ENB), Interior Bearing walls (IB), Interior Non-Bearing walls (INB) and Mechanical walls (M) (see Figure 7).

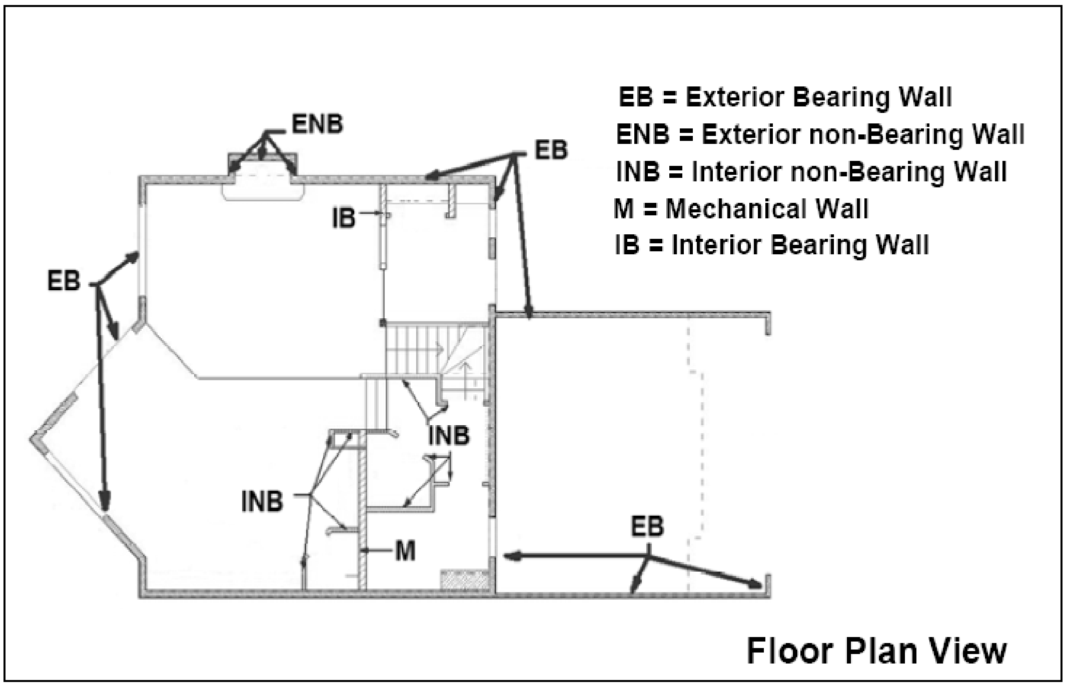


Figure 7. Wall Classification

3.2.1 FRAMEX

The parametric algorithm, FRAMEX, has been designed to automatically generate construction drawings for two different construction processes which utilize the platform-frame method: (1) on-site framing of residential facilities and (2) framing of residential facilities at the shop. Through the use of a generative process planning system (Chang and Wisk 1985; Salim And Bernold 1995), the construction drawings can be generated without reference to existing plans in a database.

Figure 8 shows the proposed methodology used for defining the working roadmap for FRAMEX.

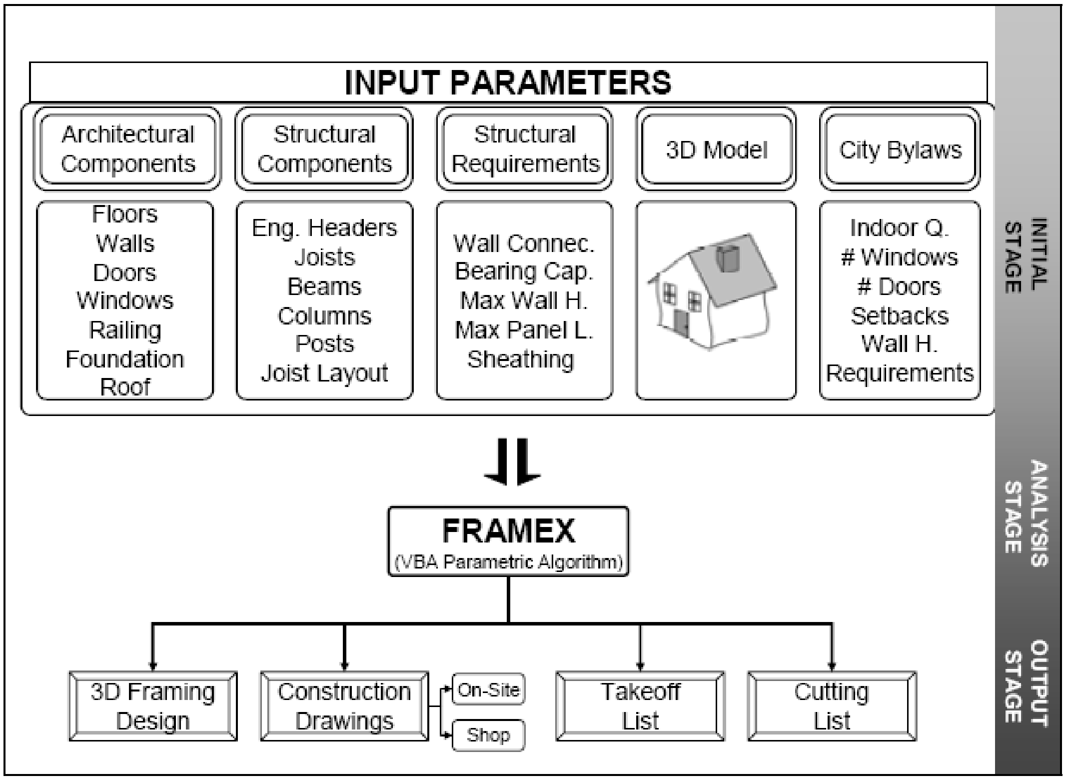


Figure 8. Proposed Methodology

The input parameters, similar to the ones required for the KBS, relate to the design components for the residential facility to be framed. The 3D model becomes the core component from which FRAMEX drives a spatial analysis to add the required framing members for each wall or panel. The input parameters are added at the initial stage of analysis where architectural and structural components are classified by layer names.

Figure 9 shows the dialog box utilized under a CAD environment to simulate the framing design at the shop. The information required from the end-user has been divided into five main boxes.

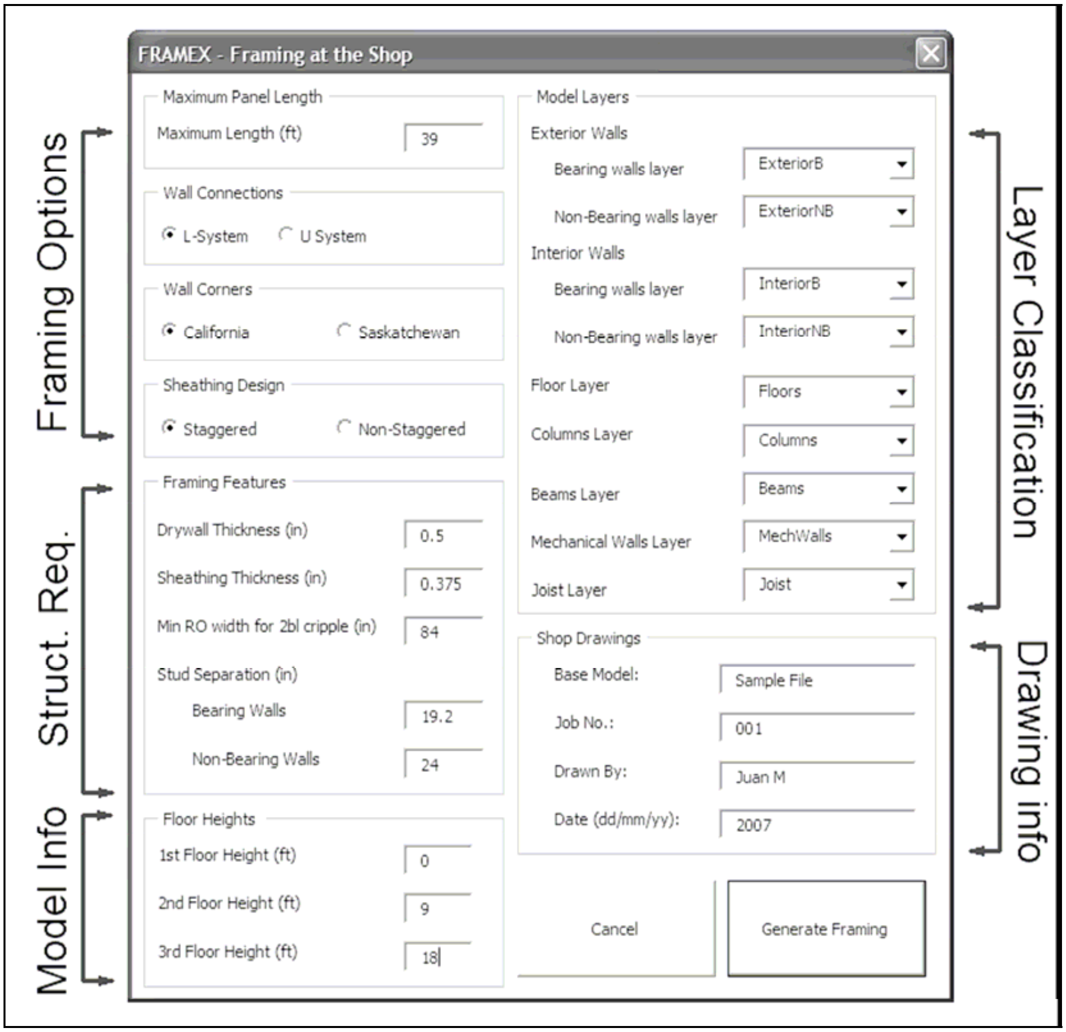


Figure 9. VB Dialog box - FRAMEX

In regards to the framing options, the end-user can specify how long the panels can be built at the manufacturing shop. The range can vary from 2.44 m to 12.2 m (8ft to 40ft) based on the type of crane on site, the sizes of trailers available for transportation purposes, as well as the type of framing table used. Two different types of wall connections can be selected through the algorithm: the ladder connection, (which can utilize stud scraps but is more time-consuming), or the L-connection, (which utilizes full-length studs as shown in Figure 10 and as described in Table 2).

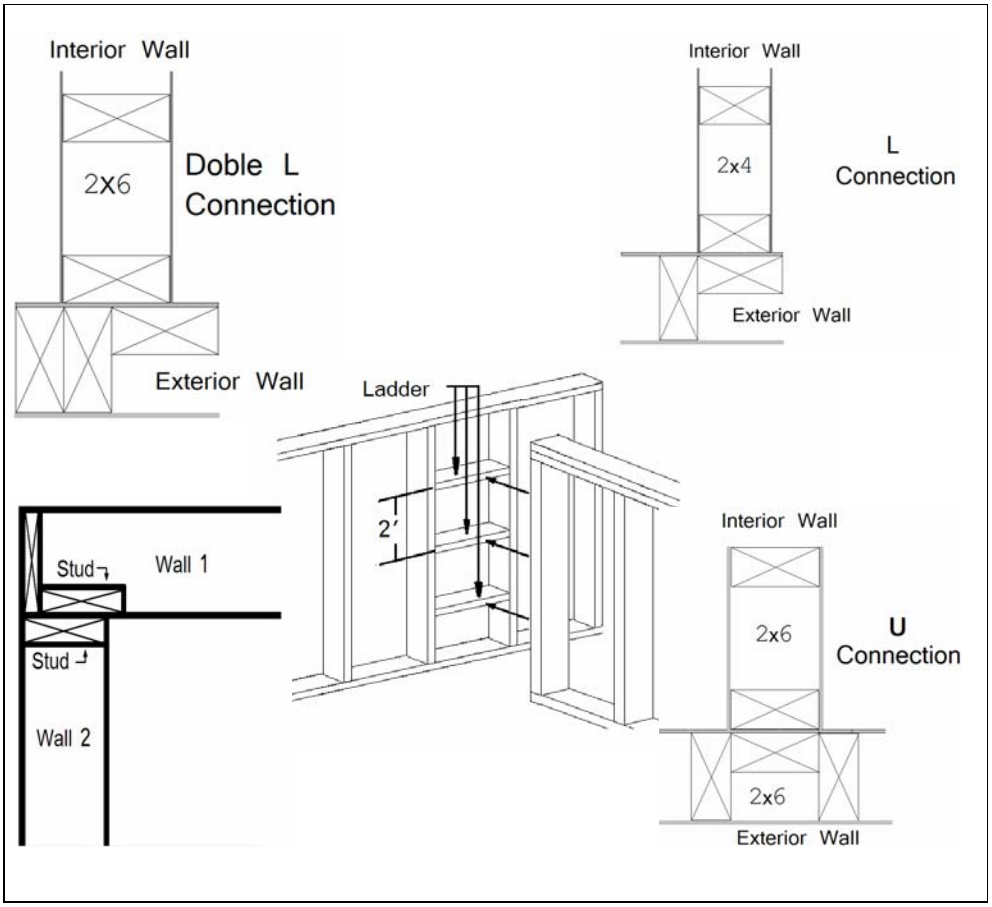


Figure 10. Wall Connections

The end-user can choose between Californian and Saskatchewan corners for exterior walls. The difference between the two types has to do with how the exterior sheathing finishes: it can end flush with the connecting wall (Saskatchewan) or protrude 9.52 mm (3/8-in) beyond the connecting wall. Another option that can be selected is the staggering of the exterior sheathing. The algorithm will run the layout of the sheathing on the panel along its larger size and will avoid having two rows of sheathing ending along the same seam.

With respect to the structural requirements for load and non-load bearing walls, the end-user can specify the stud spacing according to the structural requirements. The material thicknesses are also included under this floating dialog box. The layer classification will assist the algorithm in determining the type of structural conditions the walls have in the dwelling, as well as whether or not special wood columns and beams (engineered members) will be required to support the floor system. Table 7 summarizes the end-user parameters in FRAMEX's main dialog box.

Once these options are added by the end-user, the algorithm begins analyzing the 3D model by defining wall boundaries, wall connections, window and door dimensions, and locations (see Figure 11). By reading the characteristics included in the 3D model, FRAMEX then generates a database for the purpose of further analysis. Once the structure has been analyzed, the algorithm extrudes rectangular shapes to represent studs, sills, plates, headers, beams, columns, and sheathing according to the wall components, structural requirements, and the parametric options already selected.

Table 7. Shop Framing dialog box attributes

Parameter	Functionality
Maximum Panel Length	This parameter allows the user to define the maximum panel length that can be constructed at the shop
Wall Connections	As shown in Figure 10, two types of connections can be constructed: the L-System, which utilizes two joined studs parallel to the merging wall and one plate perpendicular to the merging wall, and the U system, which uses two studs parallel to the merging wall, both nailed at the ends of the plate.
Wall Corners	Two types of wall corners can be constructed: Californian corners, for which one of the wall ends has a sheathing overhang that connects the corner to the next butt-out panel, and Saskatchewan corners, which lack a sheathing overhang.
Sheathing Design	The user can select the design for staggered sheathing, based on the given structural design.
Framing features	The user is prompted to indicate structural requirements for bearing and non-bearing walls as well as stud separations and material thickness for drywall and sheathing.
Floor Heights	The information input here will come from the 3D model, and allows the parametric model to identify and classify wall components according to their floor locations.
Model Layers	Layer information for bearing and non-bearing, interior, exterior, and mechanical walls is required of the user, as well as layer information for floors, columns, beams, and joists.
Shop Drawings label information	The answer to these parameters will be printed with each shop drawing as basic information for the job, including Base model, Job Number, Drawn By, and Date of drawing.

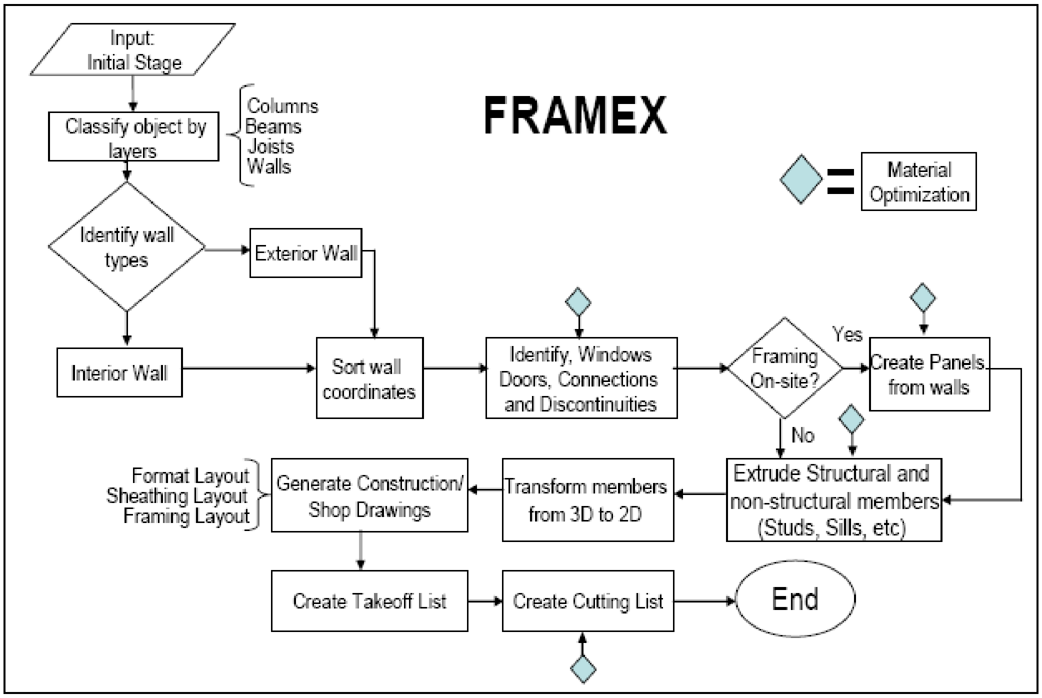


Figure 11. FRAMEX flow chart

FRAMEX includes a pre-defined set of logic-decision rules which serve to interpret the X, Y, and Z coordinates from every vertex of every wall component. As shown in Figures 12 and 13, this logical sequence is broken down into the following procedure prioritization: (1) wall boundaries, (2) doors, (3) windows, and (4) wall connections.

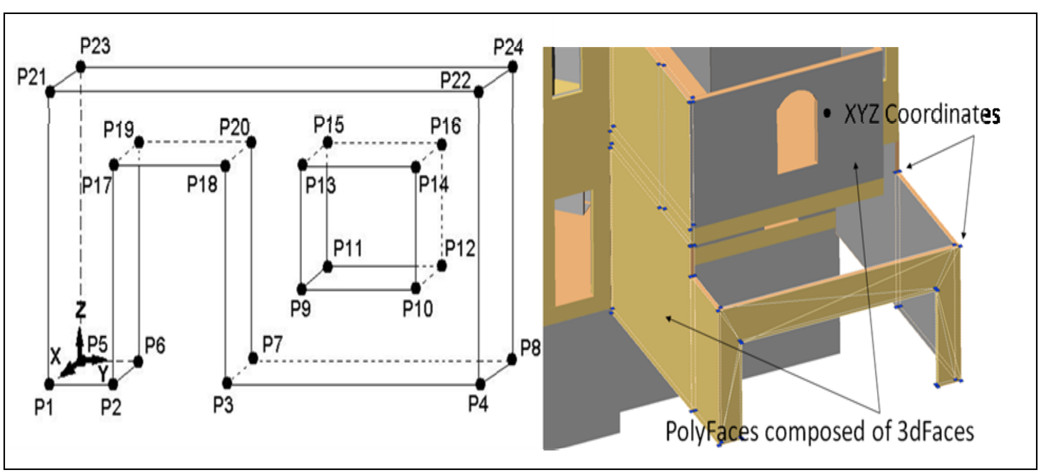


Figure 12. X-Y-Z Coordinate points in a 3D wall

In order to analyze any type of wall in terms of object space, location and dimensions, the following procedure has been incorporated into a programmatic code using VB (see Figure 12 and Figure 13). The first step followed by the algorithm is to determine the vertex with the highest **Z** value. By doing so, the vertices on the top of the wall/panel can be classified (**B1** = P21, P22, P23 and P24, see Figure 13). The following step is to find the vertices with the lowest Z value that match with the same XY coordinates from **B1** (**B2** = P1, P4, P5 and P8). The aforementioned procedure follows this sequence due to the fact that there are no more than 4 vertices on the top of a wall/panel; opposite case happens for the bottom of each wall/panel. After finding these wall boundaries, the wall height and thickness can be found by doing simple math. The following step is to determine the amount of doors per panel/wall. One should notice that every door in the panel has 8 vertices, four on the bottom of the panel, and the other four at any height within the wall boundaries. In order to identify a door, the algorithm finds the vertices with the lowest Z values within the wall boundaries, excluding the vertices in **B2** (in this case, **D1** = P2, P3, P6 and P7). In order to find the top points of the door, the algorithm will find the match in XY coordinates from **D1** but with different Z values (**D2** = P17, P18, P19 and P20). The remaining points will become window points (**W1**= P9, P10, P11, P12, P13, P14, P15 and P16).

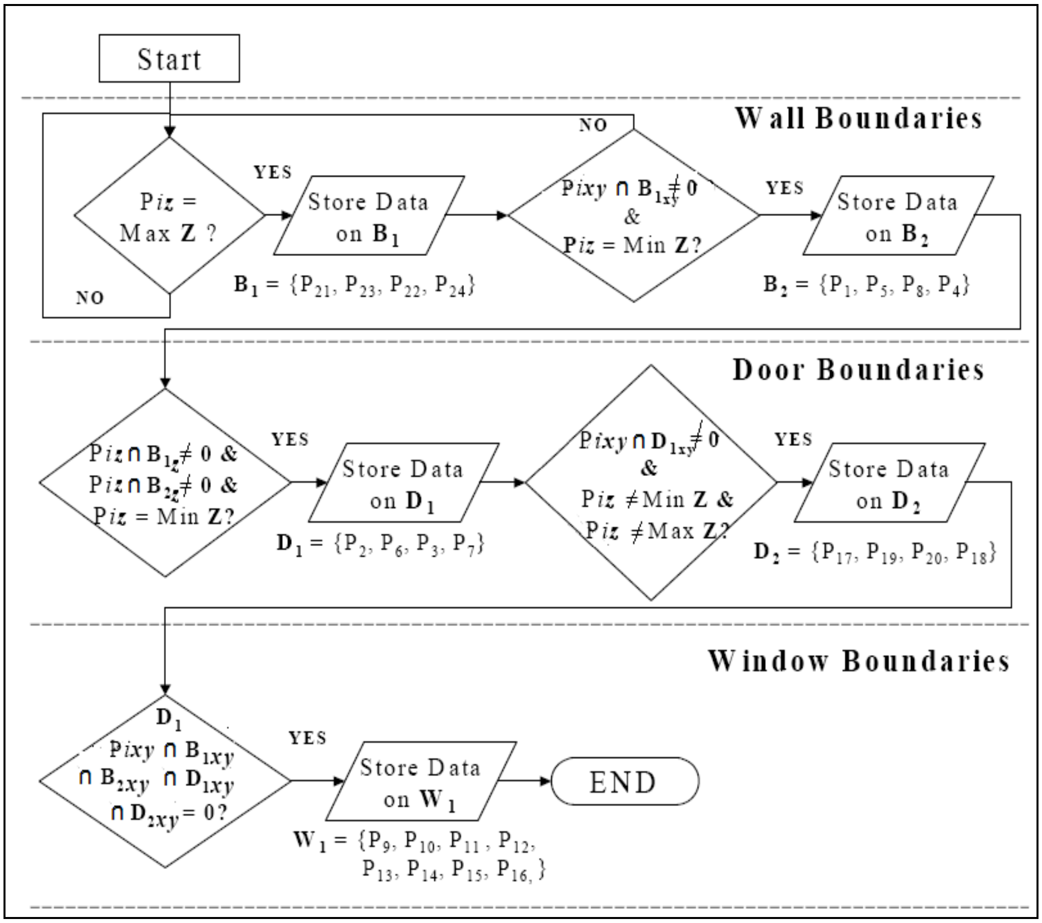


Figure 13. KBS for framing design

1) Wall Boundaries:

P = {P1, P2, … P24}

a) Upper boundaries: **B1** = Pi ∈ **P** ∀ **Piz**= Max Z (1)

⇒ **B1**= {P21, P22, P23, P24}

b) Lower boundaries: **B2** = Pi ∈ **P** ∀ **B1xy** ∩ **Pixy** ≠ 0 ∧ Piz = Min Z (2)

⇒ **B2**= {P1, P4, P5, P8}

2) Door Boundaries:

a) Upper boundaries: $\mathbf{D1} = \text{Pi} \in \mathbf{P} \ \forall \ \mathbf{B1} \cap \mathbf{P} = 0 \wedge \mathbf{B2} \cap \mathbf{P} = 0 \wedge \text{Piz} = \text{Min Z}$ (3)

$\mathbf{D1} = \{P2, P3, P6, P7\}$

b) Lower boundaries: $\mathbf{D2} = \text{Pi} \in \mathbf{P} \ \forall \ \mathbf{D1xy} \cap \mathbf{Pixy} \neq 0 \wedge \text{Piz} \neq \text{Max Z} \wedge \text{Piz} \neq \text{Min Z}$ (4)

$\mathbf{D2} = \{P17, P18, P19, P20\}$

3) Window Boundaries: $\mathbf{W1} = \text{Pi} \in \mathbf{P} \ \forall \ \mathbf{P} \cap \mathbf{B1} \cap \mathbf{B2} \cap \mathbf{D1} \cap \mathbf{D2} = 0$ (5)

$\mathbf{W1} = \{P9, P10, P11, P12, P13, P14, P15, P16\}$

In order for the shop/construction drawings to be created, the framing information generated in the 3D model must be linearly transformed by means of a 4x4 matrix which follows the syntax expressed in Equation [6]. The purpose of transforming the information from the 3D model to the shop/construction drawings is to generate a parametric relationship. Once the 3D model has been framed, every panel maintains a parent-child relationship, so when changes are generated either at the parent or child level, the information is updated at both instances.

$$T(\boldsymbol{x}) = \mathbf{A}\boldsymbol{x} \quad (6)$$

Where:

T = Linear transformation

$\boldsymbol{x}$ = Column Vector

$\mathbf{A}$ = Transformation matrix of T (see Figure 14)

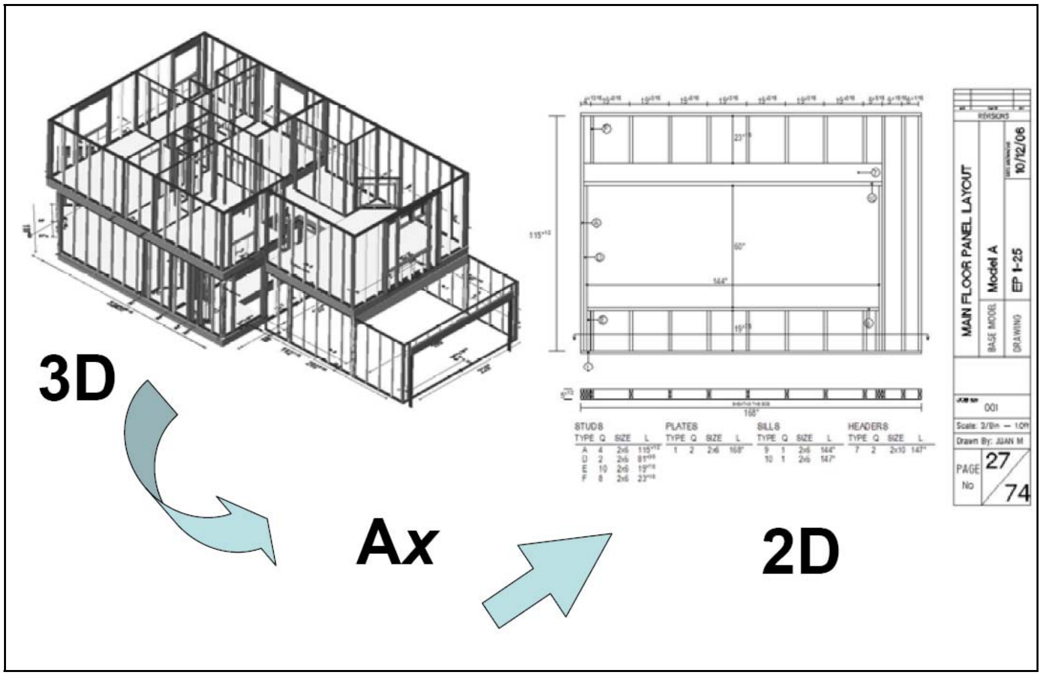


Figure 14. 3D to 2D transformation

The transformation matrix A has the following syntax:

R00	R01	R02	T0
R10	R11	R12	T1
R20	R21	R22	T2
0	0	0	1

Where:

Rij = Rotation along the ij^{th} vector, with 0=**X**, 1=**Y** and 2=**Z** axis

Ti = Translation on the i^{th} axis, with 0=**X**, 1=**Y** and 2=**Z** axis

Once this information has been stored in an intelligent repository, the final design stage takes place. The linear transformation separates every wall design into single construction drawings that are drafted with final dimensions to ease the construction assembly of wood elements.

Figure 15 shows one of the generated construction drawings. The panel shows the layout for studs, sills, plates, headers and sheathing for a 2.44 m (8-foot) ceiling exterior wall. The studs are spread from right to left the distance specified by the end-user from the perspective of a viewer inside the house. For quantification purposes, the materials required for framing each individual panel are listed on each drawing and summarized in a spreadsheet. The benefits of using FRAMEX for both panelized and site-built framing methodologies are listed in Tables 8 and 9.

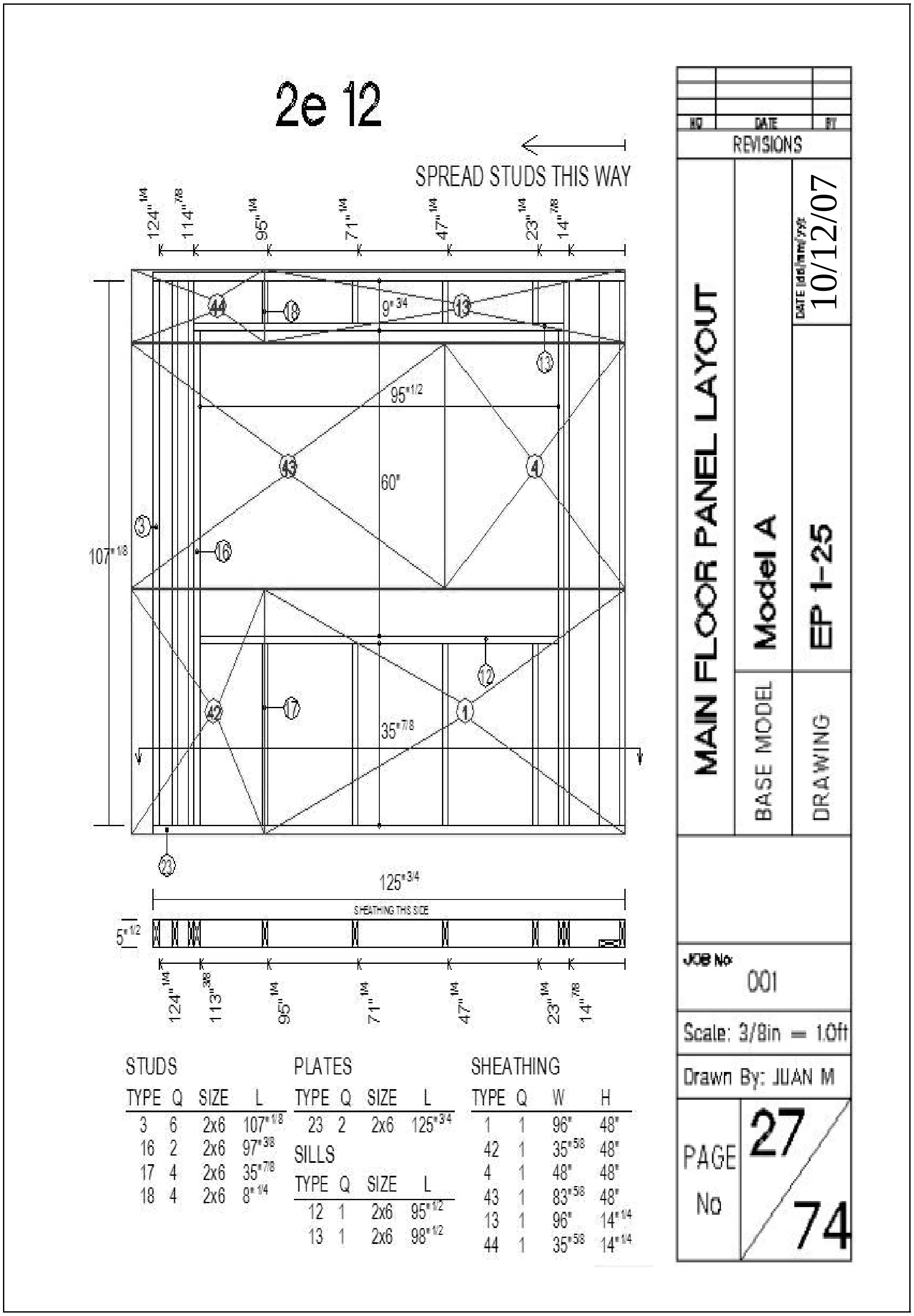


Figure 15. Construction drawings – Stick-built dwellings

Table 8. Benefits – FRAMEX

Item	Benefit
Materials	A thorough list of materials is provided once the wood structure has been analyzed, along with a classification of studs, sills, plates, headers, and sheathing by size and dimensions. By utilizing this take-off list of materials, construction companies and trades will have better control over the material needed for construction in a manufacturing shop, or the required material needed to be delivered to the construction site. By doing so, inventory can be reduced, thus diminishing the likelihood of unnecessary material waste.
Construction process	Two construction processes were mimicked based on the platform-frame method. By automating the framing design for wood houses, the construction process can be improved using the rigorous guideline rendered. Whether the selected construction process takes place at the construction site or at the shop, the productivity rate will be expected to increase due to the elimination of guess-work. The drawings generated as an output can be used by the AEC trades involved in the construction process for future reference.
Transportation	The take-off list of materials and the cutting list provide the optimum amount of lumber needed for construction. Savings in terms of unused materials, double shipping, and extra space for storage can be anticipated.
Labor	The need for highly-skilled labor can be reduced since the construction/shop drawings specify all of the requirements for construction. Productivity rates should increase since guess-work is eliminated completely.
3D Modeling	The 3D model with the framing design will add another dimension to the design process by helping in the communication of the project and easing its understanding. The visual output facilitates the construction process by helping to circumvent guess-work.
Drafting	By virtue of the implementation of parametric modeling into a CAD interface, the need for long drafting hours is eliminated by automating the process. Errors can be detected easily by checking the construction/shop drawings from the architectural model, thus enhancing the quality for drafting design. Also, by automating the design process, an alleviation of environmental burdens linked to the reduction of upstream waste will be encountered.

Table 9. Shop Framing Benefits

Item	Benefit
Work Environment	Weather conditions do not affect the pre-fabrication process. Temperatures can be manipulated inside the facility to provide better conditions for workers
Site organization	By utilizing lean manufacturing, material, equipment, and personnel can by organized to produce a pull system, generating a better flow for the cutting and assembly of wood pieces. The Lean manufacturing 5's system can be implemented to provide better workplace conditions (Hirano 1996)
Material handling	Lumber is stocked in one place and used through a continuous flow within the process. Lumber is not double handled, a condition which serves to eliminate rework between stations. Material waste is minimized by following a final take-off and cutting list of materials.
Construction quality	Inspections are easier to perform during the manufacturing flow process. Each station performs quality checks to verify that pieces are assembled correctly. The final product is a high quality piece, constructed on time and under the stipulated requirements. The shop drawings enhance the inspection process by communicating to the inspector every detail required to construct each panel.
Productivity	Due to the immersion of lean manufacturing techniques, productivity can be controlled and enhanced by allocating the correct amount of resources to different working stations. On-site spatial constraints are eliminated due to the use of a one-level stage working area.
Equipment	The use of stationary equipment and ease of access to electrical outlets within the station/cell generate an added value to the final product. Labor mobilization is minimized as a result of the accessibility of equipment. More precise equipment can be used due to the given working environment.
Work force utilization	By introducing lean manufacturing techniques, the state map layout will take into account the number of cells and labor required to perform at takt time (Tapping et al. 2002). The number of personnel required to frame a facility can be reduced by breaking down the component's structure and leveling the amount of work per cell. A reduction of personnel/hrs/job will be encountered, thus producing an improvement in total hours spent completing the job.

3.2.2 DRY-X

A generic algorithm, DRY-X, has been developed to identify the spatial constraints from any architectural model, as well as to utilize the framing design previously generated by FRAMEX. Figure 16 shows the steps followed by the algorithm to mimic the layout of drywall sheets within a CAD environment. DRY-X uses as input parameters building specifications such as floor-to-ceiling heights, wall dimensions (length, width, openings, connections, etc.) and wall characteristics (exterior load bearing, interior non-load bearing, interior mechanical, etc.). The materials required for boarding any type of wall are also specified (drywall thickness, fire-rating characteristics, available sheet sizes on the market, etc.). The end-user can also select the orientation of the drywall sheets to be installed in the dwelling (horizontally vs. vertically positioned). These essential parameters in combination with (1) the design principles for installation (see Tables 5 and 6); (2) the core of the algorithm (logical rules for design); and (3) the optimization layout procedure will generate a model output for final review. During this design stage, the principles of the (i^3) concept apply to all processes in terms of innovation (through the use of spatial analysis and coding for 3D models), information (material types and installation rates), and intelligence (by optimizing the boarding layout based on material size availability). By automating logical sequences for design, the algorithm, DRY-X, is capable of producing 100 percent accurate construction drawings, a complete take-off list of materials for each panel/wall and the installation sequence for material storage during the cutting process.

By using CUTEX, a 2D combinatorial algorithm that optimizes material usage, the end-user can provide a final cutting list and link it to a database for material costing.

The final repository model will be composed of all materials required for framing (nominal lumber and sheathing), as well as a complete list for interior drywall boarding. The repository model is the summary of a rich parametric model that provides to end-users a well-detailed 3D model, with all its components, within a CAD environment.

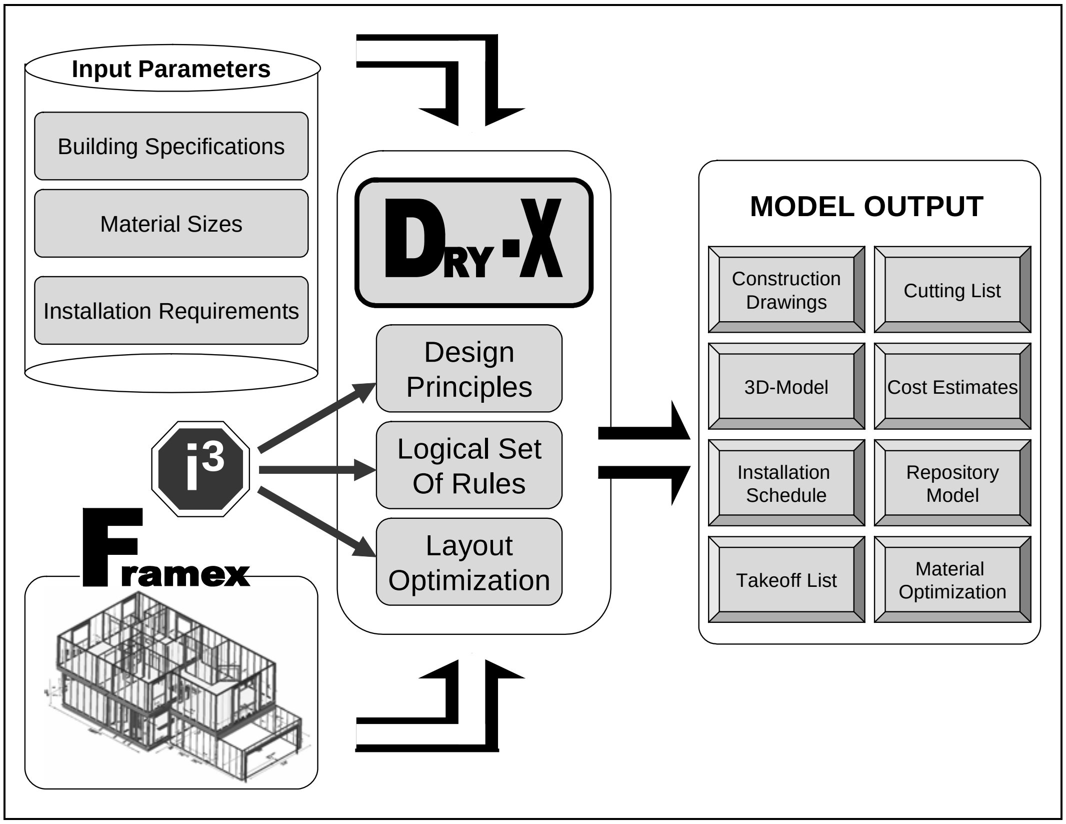


Figure 16. Proposed Methodology for DRY-X

Once the algorithm, DRY-X, is launched in the CAD environment (Autodesk 2009), a dialog box will appear with a series of design questions to be addressed by the end-user (see Figure 17).

Figure 18 shows a flowchart of the logical operations followed by DRY-X for exterior wall boarding. DRY-X identifies the different types and locations for each wall component in the architectural drawing. For instance, with the user having only selected the exterior non-load bearing walls, it determines the wall characteristics and proceeds to lay out the sheets of drywall per panel/wall according to the design principles.

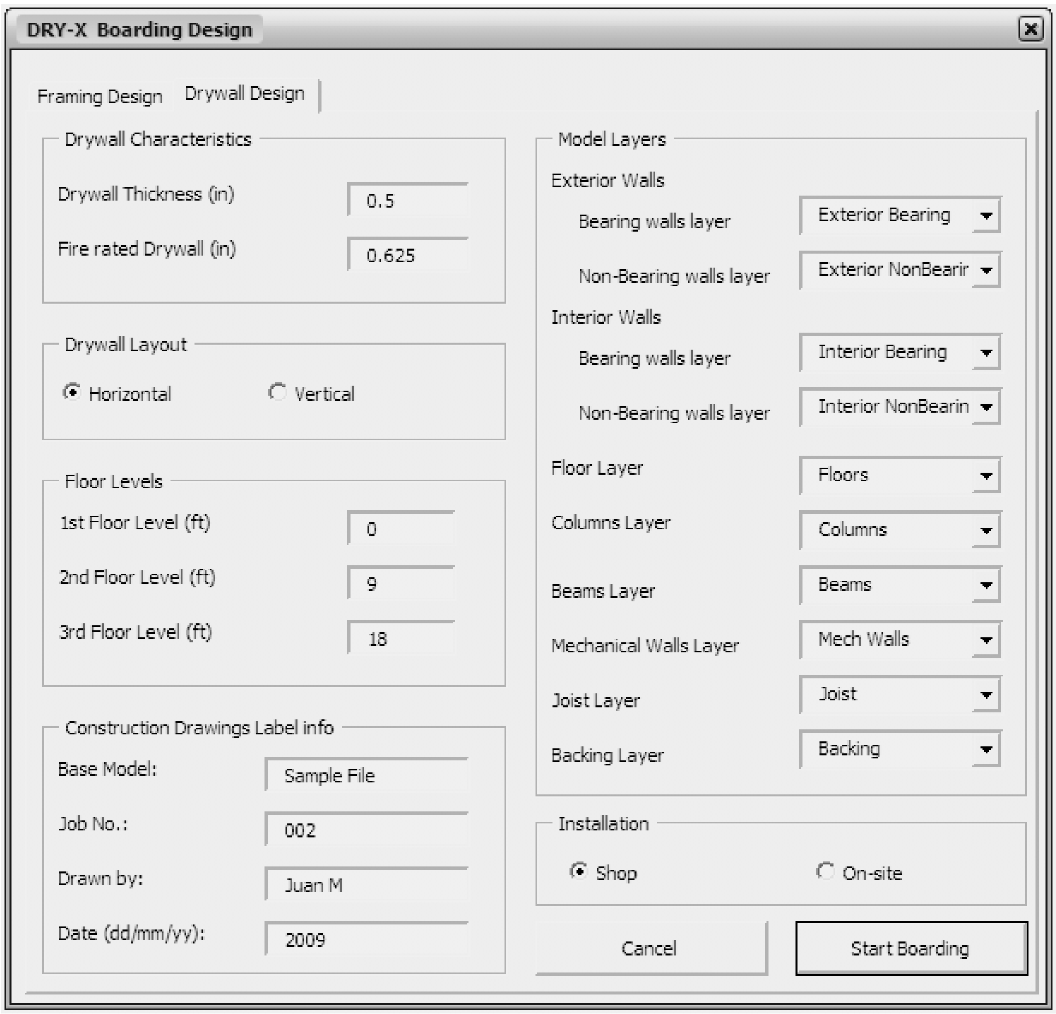


Figure 17. DRY-X Dialog Box

During this process, the layout optimization model determines the design that will create the least amount of material waste. In this way, the optimum utilization of material can be achieved. The model runs under iterative logical loops and records all possible combinations to fit the best cut of drywall on the panel based on material sizes available on the market. For instance, if the panel length is 9ft-3in (2.82 m) by 8ft (2.44 m), the algorithm will choose 2x4x10ft (2x1.22x3.05 m) sheets rather than 2x4x8 or 2x4x9 with an additional strip, (to avoid a configuration which would generate more material leftovers).

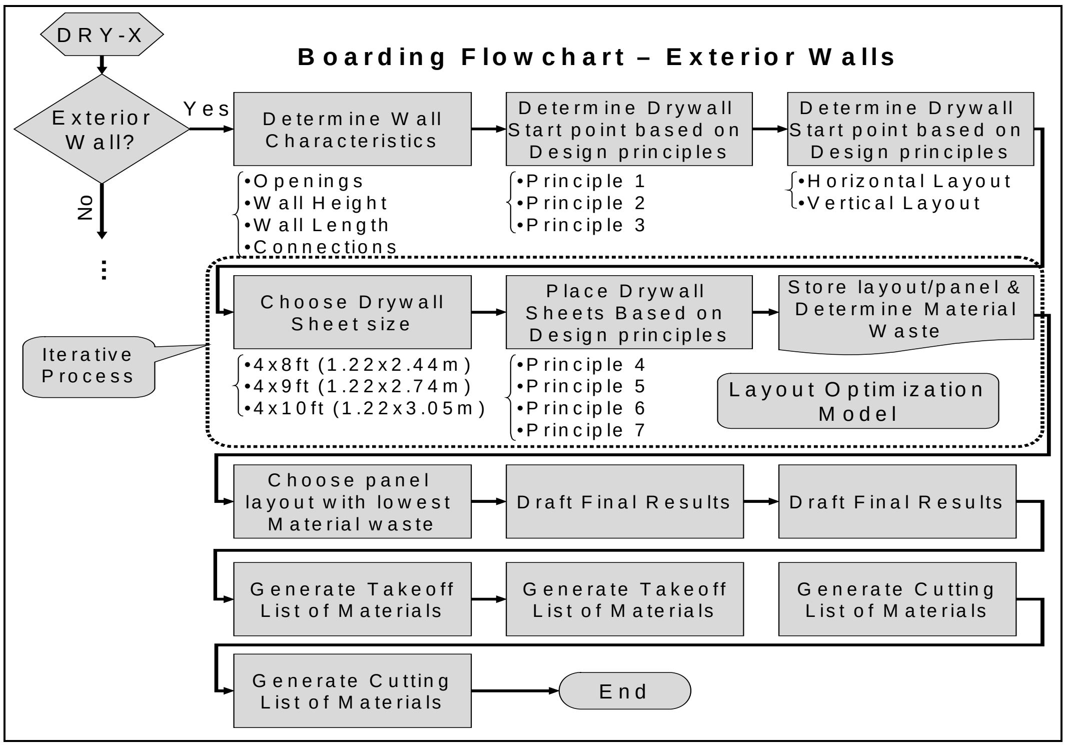


Figure 18. Exterior boarding with DRY-X

The algorithm also accounts for the panel's inner characteristics, such as openings, connections with interior walls, etc. DRY-X also minimizes joints, which is why it may shift sheets from a horizontal to a vertical position. This reduces the amount of extra work required in mudding and taping after installation. Once the layout is determined, the panels are drafted as shown in Figure 19. Final take-off lists of materials for each panel/wall and for the entire home are summarized and exported to the repository model for further cutting analysis and cost estimating. As shown in Figure 19, each sheet is identified by a particular number. Each sheet also has a description of the corresponding size and quantity required. An experiment was conducted in order to determine the amount of hours saved by a CAD operator when drafting the layout design of drywall for a stick-built dwelling.

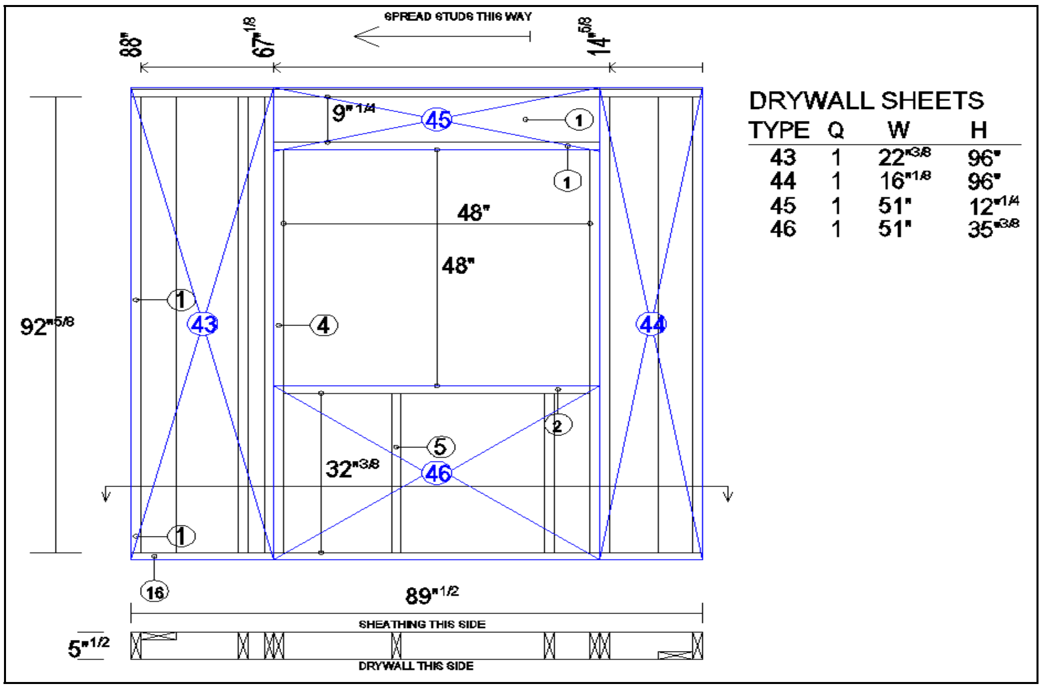


Figure 19. Panel Shop Drawing with Drywall

The findings showed that for an average two-storey home with an area of 157 m^2 (1700 sq. ft.) and a 2.44 m (8ft) floor-to-ceiling height, an experienced drafter would spend 33.5 hours, not to mention the amount of errors that needed to be fixed after generating each layout. When utilizing DRY-X, on the other hand, the drafting of the drywall layout only few seconds. Another advantage of designing with a parametric tool is its ability to adapt to drafting changes generated by the user. For any CAD operator, any change in the design implies checking and redrawing components, a cycle which can be avoided through the use of GAs.

3.3 Utilization of material optimization techniques

For the purpose of this research, the minimization of material waste falls within the scope of the stock-cutting problem (SCP), with respect to which a variety of optimization procedures have been investigated in the literature. Within the construction industry and as illustrated below, there are two types of SCPs: one- (1D-SCP) and two-dimensional (2D-SCP). Since a number of stock sizes are available for studs, the 1D-SCP is more complicated than the simple case in which one stock size is used to generate all the demands. Gilmore and Gomory (1961) have noted that combining different stock sizes, although it helps to achieve better material utilization, presents a case in which it becomes more difficult to find optimum solutions due to the complicated nature of the objective function.

The results presented in the case study confirm this observation. However, the majority of studies published over the past few years in this field have been devoted to solving the simple 1D-SCP case in which there is a single stock size (Scheithauer and Terno 1995, 2001; Vance 1998). As for the cutting of sheathing and drywall, it has become necessary to turn to the methods developed for solving the 2D-SCP. It should be mentioned that in the case of sheathing and, ultimately, for drywall, one may use either 1.22 x 2.44 m (4x8 ft.) or 1.22 x 3.05 m (4x10 ft.) stock sizes, or a combination of both. The SCPs for 1D and 2D elements have thus been incorporated into the GA, CUTEX.

3.3.1 CUTEX

CUTEX has been created under a dynamic OOP language, Python, for the purpose of reading the take-off lists of materials generated by FRAMEX and optimizing the cutting of dimensional lumber, sheathing, and drywall in order to minimize material waste. All possible combinations of cutting layouts for studs, sheathing, and drywall are generated automatically and then analyzed by CUTEX—including 1D (length) and 2D (area) optimization techniques, and, based upon the cutting-stock, guillotine and non-guillotine problems.

3.3.1.1. Stud Optimization

A 1D-SCP optimization model was used for the purpose of utilizing cut-offs of studs, sills, and plates, since the dimensional lumber lengths are used to generate the smaller pieces needed by framers. In the current industry practice, there are three stock lengths which are commonly used: 2.35 m (92 5/8 in.—8-footer), 2.66 m (104 5/8 in.—9-footer) and 2.94 m (115 5/8 in.—10-footer). In order to solve the SCP problem, either of two approaches may be employed, depending on the size of the dataset.

Small Datasets: For small datasets, (i.e., relatively few stock lengths and a small number of different studs to be generated, with no more than 20 different lengths), it is possible to seek integer solutions for the problem. This problem is well known as the Non-Polynomial (NP) hard (similar to the famous traveling salesman), meaning that the time required to solve it does not increase as a power of the size of the problem. Instead, the relationship is exponential. This aspect imposes severe limitations on the size of the problem that can be treated when an integer solution is sought (Degraeve and Schrage 1999; Vanderbeck 1999; and Barnhardt et al. 2000). More precisely, a common feature to all algorithms seeking an integer solution to the stock cutting (or bin packing) problem is the necessity to explore all possible configurations. The number of these configurations, it should be noted, increases extremely quickly with the size of the problem.

When a dataset has more than 20 different lengths, the Gilmore-Gomory heuristic approach (1961) becomes more practical due to the amount of computational calculations required. The time requirement can be kept within reasonable bounds even when a relatively modest desktop computer is used. In this context, the problem is usually solved in two steps:

(1) For a given commercially available stud length, enumerate all the possible manners in which it can be cut in order to generate the combinations of studs required for the project. Each of these scenarios has an associated waste, to be referred to subsequently as S_i.

(2) Once all possible cutting scenarios (or patterns) have been generated along with their corresponding wastes, an objective function is constructed and then optimized in order to minimize waste. The constraint here is the need to generate at least the required number of studs needed for the project.

Tree structure for the elementary cutting scenarios: The generation of a complete list of possible cutting scenarios is an exhaustive search, for which a tree structure must be used. The upper limit of the number of children at each node is determined by calculating the number of instances one can have. This is accomplished by cutting the given commercial length into similar requested lengths. In other words, if the project requires studs of lengths, L_p, then a commercial stud of length, L, can produce at most

$\left\lfloor L/L_p \right\rfloor$ instances of type p (see Figure 20).

Once the maximum number of allowable branches at each node of the tree has been computed, a combinatorial analysis is performed in order to find all possible cutting scenarios along with their corresponding wastes. The algorithm operates as follows:

A commercially available length is dropped at the top of the tree.

At each level, instances of the stud represented by the level are cut from the commercial stud. Whatever remains from the commercial stud is passed to the next level.

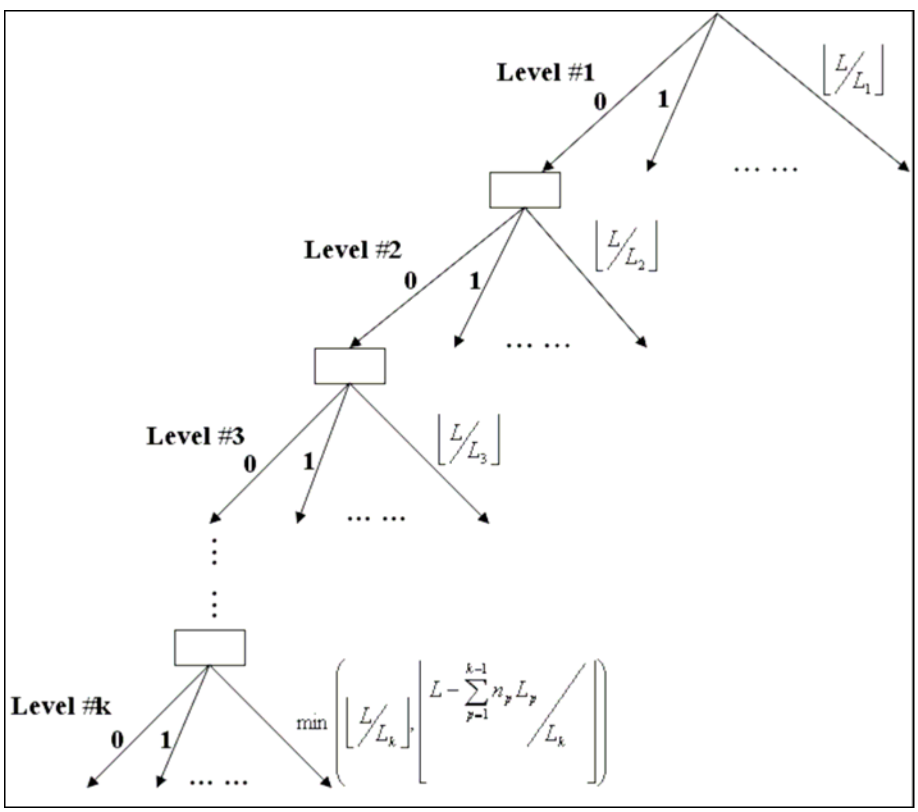


Figure 20. Tree Structure, combinatorial analysis

1) The operation described in Step 2 is repeated. The sum of all instances generated at each level should not exceed the length of the commercially available stud. In essence, the remaining length at the n^{th} level is calculated by satisfying Equation (7),

$$L_n = L - \sum_{p=1}^{n-1} n_p L_p \tag{7}$$

where *np* represents the number of instances of lengths, *Lp*, produced at level *p*. As mentioned above, the cutting is subject to the constraint computed satisfying Equation (8),

$$\sum_{p=1}^{k} n_p L_p \geq L \tag{8}$$

This series of computations entails that the summation of all instances cut from one commercial stud cannot exceed the length of the original stud. As for the waste corresponding to the m^{th} cutting scenario, it is calculated by satisfying Equation (9),

$$S_m = L - \sum_{p=1}^{k} n_p L_p \tag{9}$$

Optimization: At this point, it only remains to establish a cutting procedure that will generate the quantities required with a minimal amount of waste. From a linear programming perspective, this corresponds to an objective function of the form expressed in Equation (10),

$$\min\left[\sum_{p=1}^{N} x_p s_p\right] \tag{10}$$

where s_p represents the waste corresponding to a given cutting scenario and a given commercially available length and *xp* represents the multiplicity of each basic cutting layout that will ensure a minimal objective function. Accordingly, the constraints the numbers of which are equal to the number types required in the final cutting list can be written as expressed in Equation (11),

$$[x_1, x_2, x_3, \cdots, x_N]\, L_{N\times 13} \tag{11}$$

where $L_{N\times 13}$ represents the matrix holding the basic cutting patterns. Theoretically, the optimal result is obtained by searching for a global minimum which can be obtained by using all the cutting layouts as part of the same optimization procedure. Practically speaking, this can be very costly due to the large number of variables to be optimized. This approach, which for small datasets can provide optimal results, can easily become unmanageable when larger systems are addressed.

Large Datasets (Column Generation): As mentioned above, the use of an integer programming which starts with an exhaustive enumeration of all possible cutting patterns becomes extremely time-consuming for problems in which the original stock sizes are large and the variety of required cuts is considerable. As a consequence, in order to maintain the computational effort required for solving the SCP within reasonable bounds, this approach relies on the Gilmore-Gomory procedure (1961). This procedure uses a special column generation technique (Ben Amor and De Carvalho 2005), which does not require complete prior knowledge of the cutting patterns as in the above method. It is worth mentioning that the now classic work of Gilmore and Gomory has been reviewed numerous times (see, for instance, Ben Amor and De Carvalho 2005). Furthermore, numerous variations of the original algorithm have been published (see Haessler 1980; and Dyckhoff 1981).

3.3.1.2. Sheathing and Drywall Optimization

In order to optimize the use of material during the sheathing and drywall operations, one may in theory apply either a guillotine- or a non-guillotine-based cutting procedure. However, according to trade personnel the guillotine method is the most effective from a time standpoint. In this context, the sheets are cut in rectangles as seen in Figure 21 (bottom). As mentioned in the literature review, the guillotine cutting method refers to the procedure in which a planar (2D) sheet is cut in such a way as to obtain two pieces of material. In this context, to generate a set of rectangular (square) elements, the cutting proceeds as a sequence of horizontal/vertical cuts (see Figure 21, top) starting at one edge and finishing at the opposite one. This sequence of cutting patterns has come to be known as the cutting stages, which in turn has led to the terminology "n-stage" guillotine cutting pattern. In contrast, for non-guillotine-based methods (see Figure 21, bottom), the cutting path must switch from horizontal to vertical (or vice versa) at a point that is not along any the boundaries of the 2D panel from which the elements are produced.

Figure 21 shows that once again the problem of generating the areas required for sheathing and drywall is an optimization problem in which the trim waste is minimized. Mathematically speaking, the Gilmore-Gomory model for the 2D cutting problem can be formulated satisfying Equation (12),

$$\min\left(\sum_{j\in J_0}\lambda_j^0\right) \tag{12}$$

Subject to [13, 14, and 15]:

$$M^{(m')}\ \overline{\lambda} = 0 \tag{13}$$

$$M^{(m)}\ \overline{\lambda} \geq D \tag{14}$$

$$\bar{\lambda} \geq 0 \quad (15)$$

Where $\bar{\lambda}$ is a vector whose elements are integers, J_0 is the set of valid cutting patterns during the first stage and λ_j^n is the j^{th} cutting pattern associated with the n^{th} set of patterns of the second stage. $M^{(m')}$ represents the first m' and last m rows of the matrix M, which contains all possible cutting patterns at the various cutting stages. The cutting pattern vector $\bar{\lambda}$ and the demand vector D follow Equations (16) and (17), respectively:

$$\bar{\lambda} = (\lambda_1^0, \cdots, \lambda_1^1, \cdots, \lambda_1^{m'}, \cdots)^T \quad (16)$$

$$D = \left(d_1, d_2, \cdots, d_m\right)^T \quad (17)$$

The optimization of the problem described above can be performed in a variety of ways (including evolutionary algorithms). For this application, the simplest method was chosen by virtue of its wide availability in a large number of mathematical libraries. Practically speaking it is important to mention that although non-guillotine-based patterns may be more efficient in terms of trim waste minimization, the guillotine pattern has been shown to be more productive and preferred by trades personnel

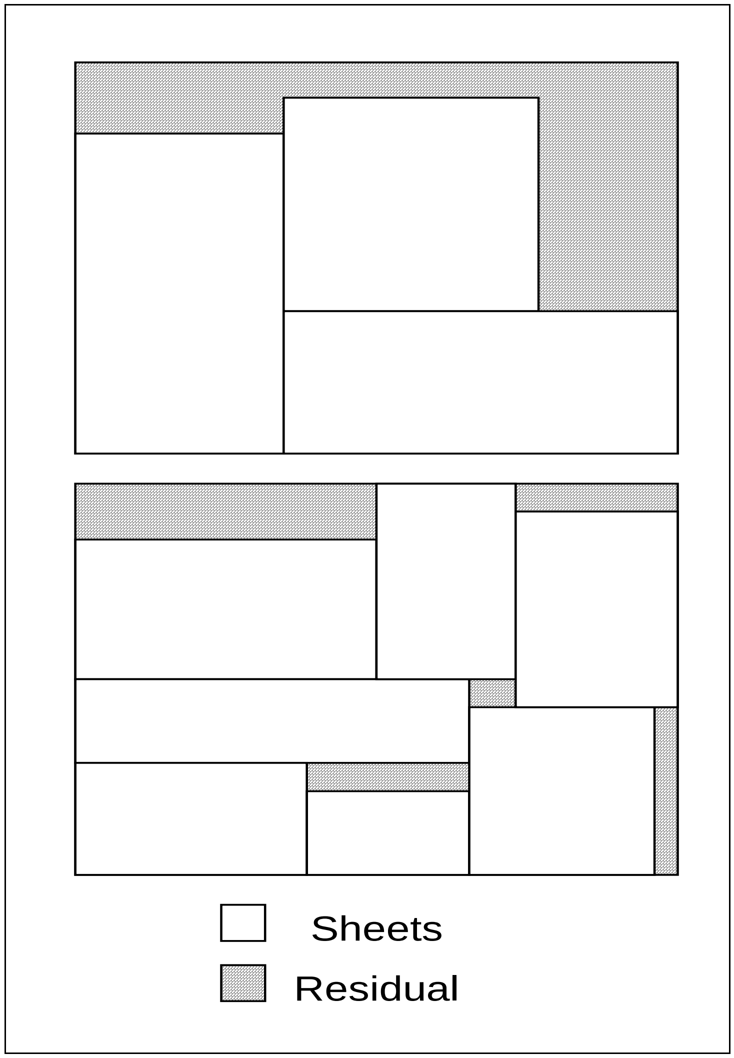


Figure 21. Guillotine and Non-Guillotine cutting

Based on the results provided by Equations (16) and (17), it is possible to find the percentage of wasted material in relation to the original stocks, i.e., from a sheet size of 1.22 x 2.44 m (48x96 in.). The pieces of sheathing or drywall to be used must satisfy Equation (18):

$$W(\%) = \frac{\sum_{i=1}^{23} S_i}{\sum_{i=1}^{23} n_i \ A_i} \qquad (18)$$

where S_i is the scrap corresponding to the cutting pattern, i, and the product, n_i (×) Ai, is the total area of the stock that must be cut in order to generate the appropriate number of instances of the cutting pattern.

Chapter 4: Application of the (i^3) Concept – Case study

Through the utilization of the (i^3) concept and the algorithms FRAMEX, DRY-X, and CUTEX it has become possible to generate construction and shop drawings once an architectural model of a residential facility has been modeled in a 3D environment. After the framing design is complete, FRAMEX proceeds to create each wall panel drawing in separate sheets for easy use and future reference. Each construction and shop drawing is labeled and referenced in the floor plan layout, including the required list of materials (see appendix). The labels in each shop drawing are a fundamental feature in this platform since they facilitate the locating of specific construction drawings from a set of blueprints. On average, between 70 and 90 shop/construction drawings are generated for a single-family dwelling (158 m^2 or 1700 sq. ft. of area, two floor levels). The panels are drafted as if one is located inside the house looking towards the panel, having the sheathing layout beneath the studs. Each stud, sill plate, header, drywall, and sheathing unit is numbered so as to avoid any confusion during construction, as well as for future reference and analysis for the purpose of optimization. Future improvements will encompass the design of mechanical and electrical components.[3]

[3] A version of this chapter has been submitted for publication, Journal of Construction Engineering and Management, American Society of Civil Engineers (ASCE) 2009.

4.1 Analysis of Current Practice

This research began by analyzing one of the largest developers of residential facilities in Edmonton, Canada (the collaborating company). Due to the need to become an industrialized company and continuously enhance construction methodologies, the collaborating company initiated a research program to connect several departments and manage information about their projects and construction processes in a more accurate way.

The first step followed during this research was to map the current practice of the company, from planning and design to construction. The collaborating company is a residential development company having with a number of different target markets: single family homes, townhouses and duplexes, high-end houses, and low- and high-rise multi-family buildings. This research has focused only on the single-family home industry. Figure 22 shows a simple diagram of the collaborating company's practice prior to the beginning of research. According to company practice at that time, the construction process would have begun when the customer had defined the house model, location, interior finishes, and upgrades. This information would have been stored in a network database from where the drafting department would have pulled out and modeled the selected options. Through coordination between the cost estimating department, consultants, and some contractors, the architectural and floor layout drawings would have been generated, as well as labor costs. Some of the problems encountered in this process were related to the coordination between architectural, structural, and mechanical designers. The architectural design would have been performed in-house, as would have been the conceptual design for electrical. The other components of design, such as floor layouts and mechanical and plumbing conceptual drawings, would have been completed by a group of consultants.

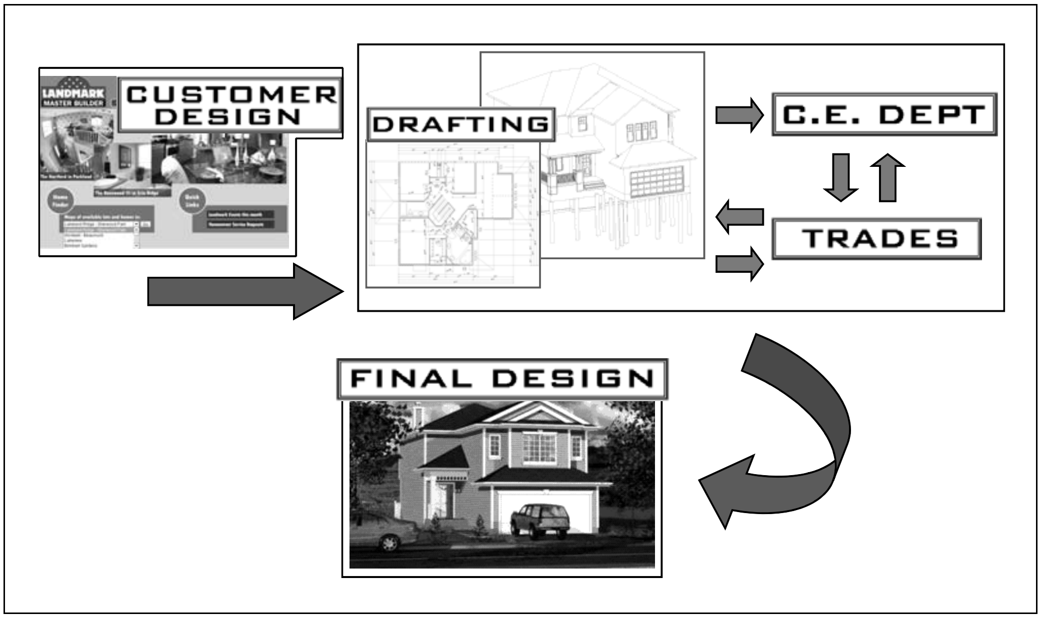


Figure 22. Current Practice

The floor layout design, it should be noted, includes the most important components, such as the joist and beam sizes to be used and the loads to be carried out on certain points by structural vertical elements. Framing shop drawings were not included in the information given to trades personnel for construction. As a consequence, mechanical and electrical shop drawings were not given to the trades personnel, who instead had to rely on their expertise for installation. Most of the problems between different disciplines (architectural, structural, mechanical and plumbing) occurred at the construction site, with trades personnel having to perform rework when interferences were encountered. The lack of shop and construction drawings was the primary source of the problems encountered at construction sites.

Some efforts were made in terms of drafting shop drawings for framing design, but these tasks were found to be very time-consuming—even without taking into account the effort required for generating updates.A proposed methodology to implement the previous process and the design of framing shop drawings is shown in Figure 23.

The process begins with the house model characteristics selected by the customer. Each model takes into account the city bylaws and regulations pertaining to residential construction.

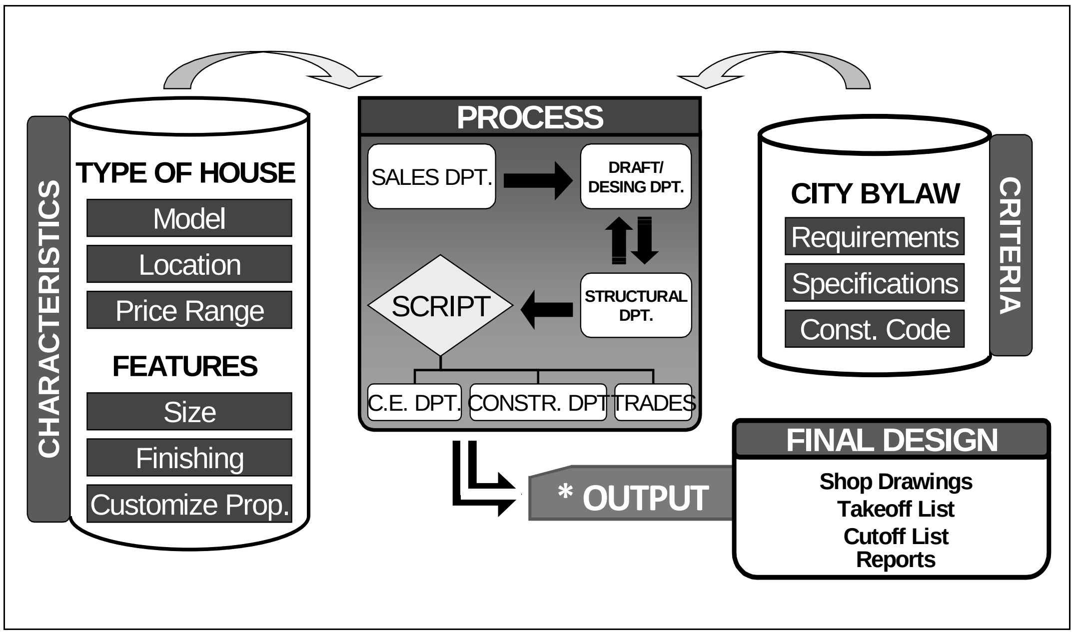


Figure 23. Proposed work process

The information is stored in the network database from where the drafting department models the architectural design in a 3D environment and uses an add-on to generate the required shop drawings for framing design. The floor layout system can then be integrated as well. Once this information is complete and accurate, it is passed on to the cost estimating and construction departments for review, from where trades are selected to begin the construction process. The shop drawings for framing design are sent to the MEP trades, so accurate planning can be made by the various trades before construction crews are ever sent to the site. This benefit is especially pertinent in terms of the location of HVAC systems and plumbing components. Electrical wiring is not of primary concern in terms of installation since the electrical wires are flexible and can be routed around main components.

4.2 Case Study

In order to test the proposed research, the collaborating company provided the architectural designs of five residential facilities (see Figure 24). The five models' areas range from 170 m^2 to 200 m^2 (1830 sq. ft. to 2153 sq. ft.), and their wall heights range between 2.47 m and 2.77 m ($97^{1/8}$ in. and $109^{1/8}$ in.). These houses were framed according to the rules presented in the Canadian Institute of Timber Construction (1993) and the literature described in this research. Although the mechanical and electrical installations have not yet been designed, the current 3D model functions as a guide, allowing trades to identify the optimal path by which to install these services strategically between studs and joists. Research in the areas of mechanical and electrical design for wood dwellings must be performed to enhance the current system.

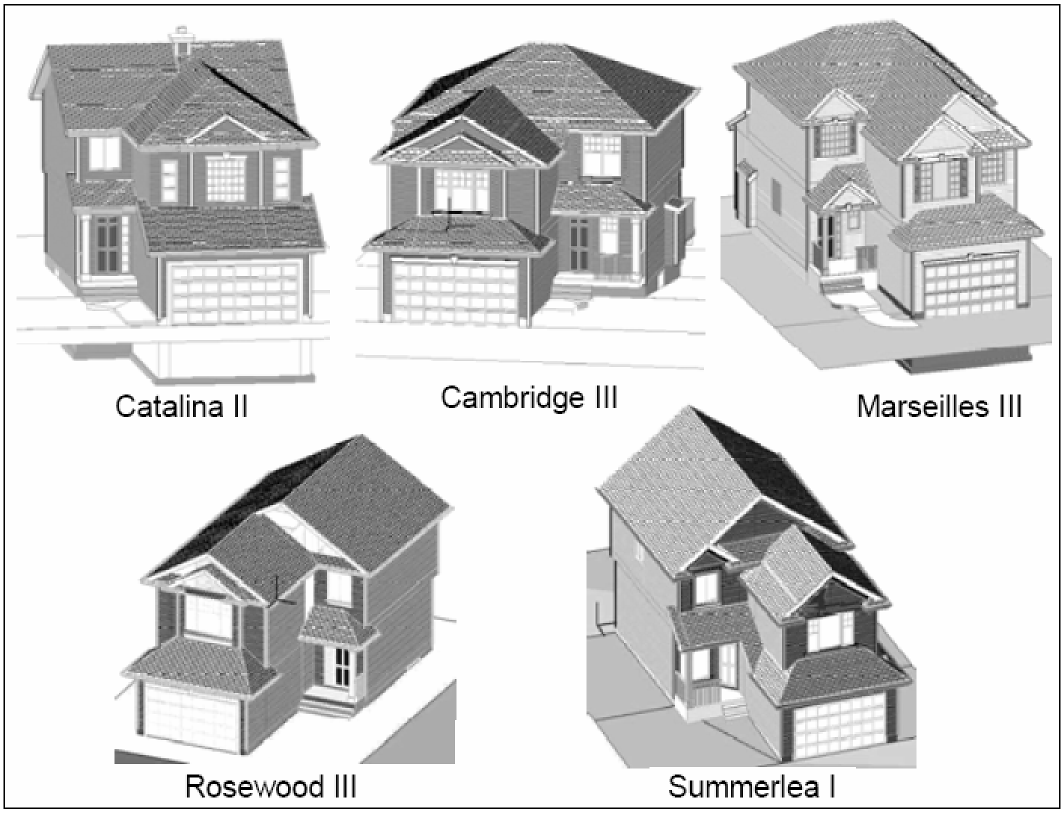


Figure 24. Architectural models – Collaborating Company

4.2.1. Shop drawings

The shop drawings were generated for the aforementioned architectural models, but due to the file size and the amount of blue prints generated by FRAMEX, only one model is shown in the appendix of this document: Catalina II. This 158 m^2 (1696 sq. ft.) house model is a two-storey, single-family dwelling with vinyl siding on exterior walls and pitched roof asphalt shingles. This dwelling comes with three bedrooms and a bonus room on the second floor as well as main amenities on the main floor (kitchen and living areas). The garage is attached to the house with access through the front of the facility. The house sits on a 2.44 m (8-foot) wall-height concrete basement, where the furnace and hot water tank are located. The basement walls are not finished with drywall (this is an optional feature for the customer).

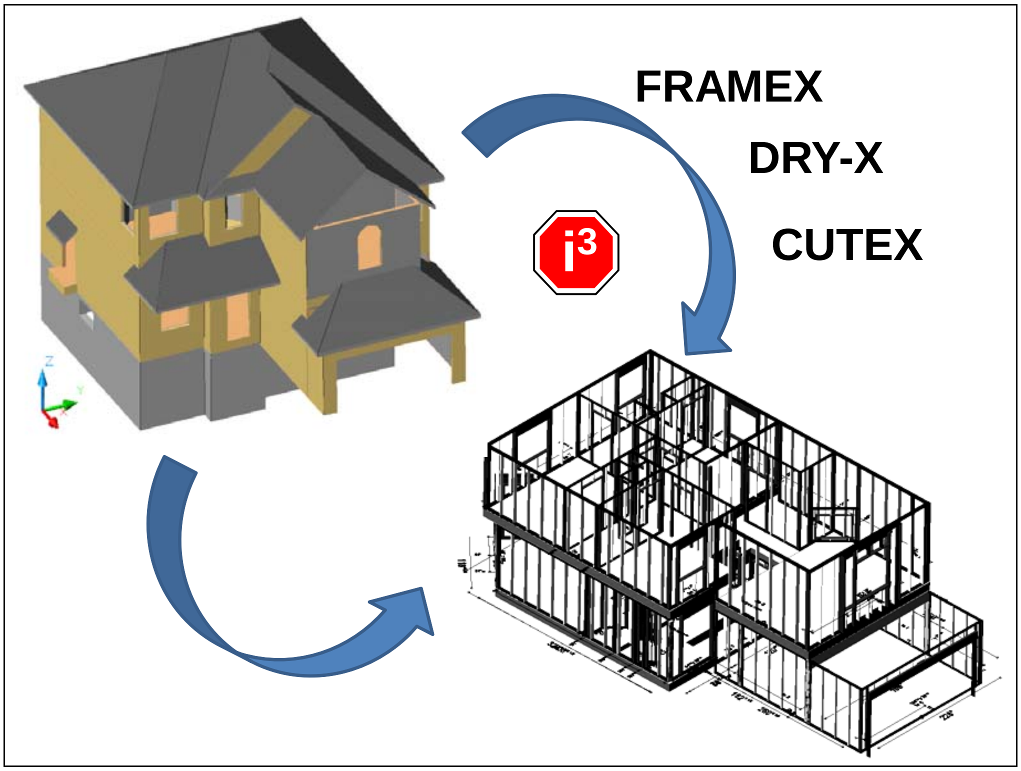


Figure 25. Catalina II Shop framing design

The Catalina II is one of the most sellable models from the collaborating company and it encapsulates the typical north-western Canadian dwelling characteristics valued by middle- and upper-income families. Figure 25 shows the 3D architectural model of Catalina II as well as its 3D framing representation.

Table 10 summarizes the areas and wall ceiling heights for each of the analyzed models. Most of these models have 2.77 m wall ceiling heights in the bonus room (occupying the area above the garage). FRAMEX is capable of identifying these differences between walls and framing the models accordingly.In order to have a common base for FRAMEX to generate any framing design for any stick-built facility, certain rules for drafting design had to be set in place in order to produce accurate results. During this investigation, it was found that every drafter had his or her own rules when using CAD software tools. Precision was thus one of the factors that needed to be improved upon. Most of the structural and architectural elements included in the drafting design were not drafted correctly since the drawings given to the trades were used for reference only.

Table 10. Features of the Architectural Models

Model	Area		Wall Height	
	m^2	sq. ft.	m	in.
Catalina II	182.9	1969	2.47	97 1/8
Cambridge III	172.7	1859	2.47	97 1/8
Marseilles III	196.6	2116	2.77	109 1/8
Rosewood III	166.5	1792	2.47	97 1/8
Summerlea I	181.6	1955	2.47	97 1/8

Table 11 shows a list of requirements (standards for drafting) at play when modeling a dwelling in a 3D CAD environment to be further analyzed by FRAMEX. Figure 26 shows the floor plan layout of the 2nd floor for Catalina II.

Table 11. Rules for 3D drafting design

Item #	Description
1	Create new layers for Columns, Beams, Interior bearing walls, interior non-bearing walls, exterior bearing walls, exterior non-bearing walls, mechanical walls
2	After creating new layers, ensure all layer combinations are correct (Floor plan, electrical, elevations, etc.)
3	Set walls to correct height (8' 1 1/8", 9' 1 1/8", 10' 1 1/8")
4	Check wall heights in drop areas
5	Set window/door RO's at the correct height and correct size
6	Door RO's has to be 2 ½-in taller that door height, 2-in wider than door width. This is for the purpose of leveling and installing the door in the wall.
7	Windows in 9/10-foot walls will be placed according to specs in order to match with windows on main floor areas.
8	If an engineered beam is used as a header for a window in an 8-foot wall, the location of the top of this beam should be at 6'11 1/8" from the floor, else, at 6'11 3/8"
9	Add columns where needed with the right amount of plies, placed at 1 1/2" from

	the bottom of the wall (on top of the bottom plate)
10	If the column runs from bottom to top of the wall, the column height should be the wall height minus 4 1/2" (this is the thickness of one bottom plate plus two top plates).
11	Verify the column heights for special cases (drop beam/column connection)
12	Verify that wall corners and floor corners are merging at the same point
13	Verify that interior walls are not extending into adjoining walls (interior to exterior, interior to interior walls)
14	Verify that walls ends of interior walls are connected to exterior walls
15	Verify that triple-connection walls are done correctly, having a strong 90-degree connection between two walls and the third connecting to a plate
16	Verify wall height for fireplace and check its RO based on the manufacture's specifications
17	Verify that the door RO is exactly 3-in away from the end of the wall or more than 4.5-in
18	Verify floor layout from the model with the joist layout.
19	Verify that wall bottom heights are the same than top of the floor heights. The model needs to be connecting walls with floors; gaps in between are not acceptable
20	Check the composite wall sections for 2x2's 2x4's 2x6's (Sheathing = 3/8", No drywall included in the composite section for interior walls)
21	If a column is at the end of the wall, verify that is placed correctly
22	Verify that the mechanical wall behind washer/dryer area is against the exterior wall
23	Add a simple ply post for the garage, FRAMEX will design the correct column configuration
24	Make sure that the attached window wall in the bonus room is against the exterior wall
25	The engineer headers have a real height dimension ½-in less than the nominal dimension i.e. 10-in header = 9 ½-in
26	The same rule from the point before applies for regular wood headers but with ¾-in less in header height, i.e. 10-in = 9 ¼-in
27	Do not name the layer for interior railing with the same layer name for interior walls
28	Basement concrete walls must have a different layer name than exterior walls on the upper structure
29	Verify floor thickness
35	TJI floor joists are 11 7/8-in + 23/32 for subfloor sheathing
36	Closet in foyer: If there is a wall at 45 degrees on the back of the closet, store it in the layer "NonPrefab", so it can be turned off in the framing program
37	Bring the mechanical wall in the kitchen back to the end of the beam and fix connecting walls.
38	Bring second floor railing back so it is not intersecting with the walls on the bonus room

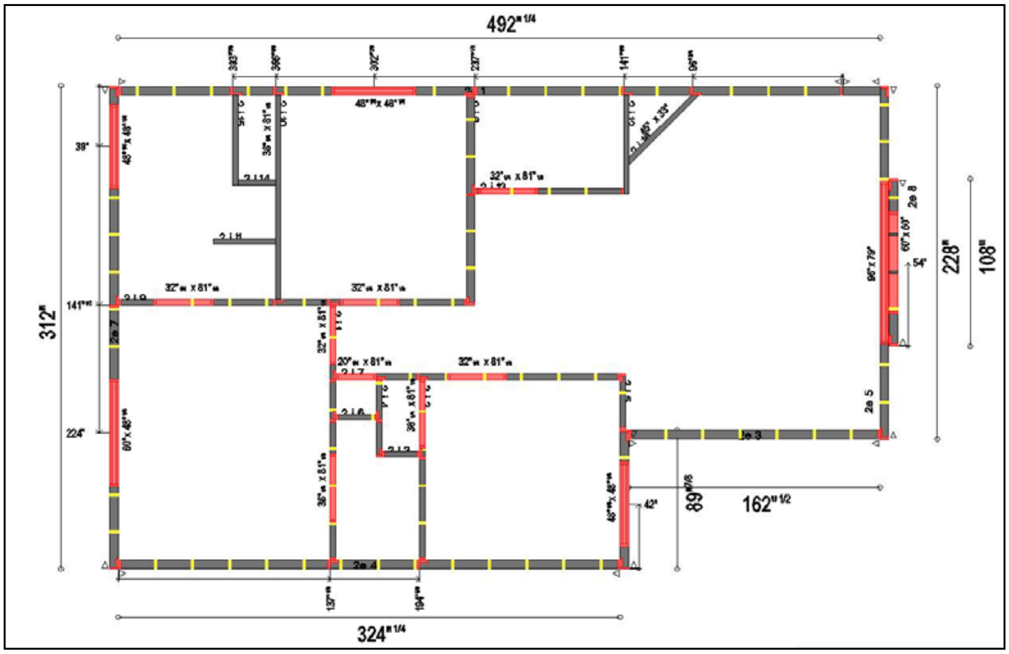


Figure 26. 2nd Floor plan layout – Catalina II

Once the shop drawings (presented in the appendix of this thesis) have been generated, the information related to the take-off list of materials is exported to a Microsoft Excel Spreadsheet.

4.2.2. Takeoff list – Excel

The algorithm, FRAMEX, creates a database with a list of studs, plates, sills, headers, sheathing, and drywall required for each model. One of the advantages of this algorithm is that it has its roots embedded in parametric modeling. Any change generated in the 3D architectural model will be propagated in the framing design, as well as in the database for material take-offs. (Due to the memory sizes of the tables, only the results for Catalina II are shown in this document.)

Table 12 shows the number of studs, cripples and jacks (see literature review for more details) required for framing of the wood panels. It should be noted that this list includes the final lengths required but it does not specify the amount of lumber that must be procured. The list is read by CUTEX and optimized, so the actual amount of lumber is listed in commercially available sizes (2.44 m or *-footers, 2.74 m of 9-footers and 3.04 m or 10-footers).

The material take-off lists for sills, plates, headers, sheathing, and drywall are shown in the appendix. See the reference for consultation.

4.2.3. Stud optimization – CUTEX

In order to illustrate the procedure and equations formulated in the previous chapter, the process begins with the provision of the given cutting patterns based on the most widely-used commercial stock lengths, 2.35 m ($92^{5/8}$ in.) and 2.66 m ($104^{5/8}$ in.), along with their corresponding wastes (see Tables 13 and 14).

In Table 14, each binary list describes a unique cutting layout with its corresponding waste. For instance, the first configuration, [0,0,1,1,0,1,0,0,0,0,0,0,0,0], describes the scenario in which a 2.35-meter ($92^{5/8}$-inch) stud is cut into three pieces with lengths of 23.2 cm ($9^{1/8}$ in.), 183 cm (72 in.), and 29.2 cm ($11^{1/2}$ in).

Table 12. Take-off list of materials for vertical wood elements – Catalina II

TYPE	QUANTITY	SIZE	L (in)	L(m)
1	3	2x2	92.63	2.35
2	3	2x2	88.25	2.24
1	140	2x4	92.63	2.35
2	33	2x4	88.25	2.24
3	11	2x4	115.63	2.94
4	2	2x4	81.88	2.08
7	10	2x4	9.12	0.23
8	6	2x4	72.00	1.83
18	30	2x4	78.50	1.99
19	9	2x4	12.63	0.32
21	3	2x4	8.25	0.21
22	1	2x4	35.63	0.90
23	4	2x4	47.50	1.21
24	2	2x4	39.50	1.00
25	1	2x4	6.50	0.17
26	1	2x4	3.00	0.08
27	3	2x4	88.50	2.25
28	2	2x4	8.50	0.22
1	140	2x6	92.63	2.35
2	9	2x6	88.25	2.24
3	45	2x6	115.63	2.94
4	16	2x6	81.88	2.08
5	8	2x6	32.38	0.82
6	7	2x6	69.62	1.77
9	2	2x6	84.00	2.13
10	12	2x6	83.75	2.13
11	2	2x6	81.00	2.06
12	5	2x6	20.37	0.52
13	4	2x6	104.88	2.66
14	6	2x6	94.50	2.40
15	3	2x6	33.00	0.84
16	3	2x6	8.88	0.23
17	3	2x6	19.63	0.50
20	6	2x6	74.25	1.89

Table 13. Contribution of each type of stud for the total amount of pieces

Studs				Sills			
Q	Length		Contribution	Q	Length		Contributions
	(m)	(in)			(m)	(in)	
133	2.35	92.63	57.33%	1	0.95	37.25	0.43%
29	2.94	115.63	12.50%	6	0.90	35.25	2.59%
10	0.23	9.13	4.30%	1	0.74	29.25	0.43%
6	1.83	72.00	2.59%	1	0.84	33.25	0.43%
26	2.02	79.63	11.21%	1	0.87	34.06	0.43%
12	0.29	11.50	5.17%	3	1.05	41.25	1.29%
3	0.88	34.5	1.29%				

Table 14. Example of cutting patterns generated using two different stock sizes

2.35 m (92 5/8")	S_{92}	2.66 m (104 5/8")	S_{104}
[0,0,1,1,0,1,0,0,0,0,0,0,0]	0	[0,0,1,0,0,2,0,1,1,0,0,0,0]	0
[1,0,0,0,0,0,0,0,0,0,0,0,0]	0	[0,0,7,0,0,1,0,0,0,1,0,0,0]	0
[0,0,0,0,0,0,0,0,0,2,0,1,0]	0.07	[0,0,4,0,0,0,0,0,0,0,0,2,0]	0.01
[0,0,1,0,0,1,1,1,0,0,0,0,0]	0.25	[0,0,0,0,0,0,0,0,0,1,0,1,1]	0.07
[0,0,1,0,0,4,0,1,0,0,0,0,0]	0.25	[0,0,0,0,0,0,0,0,2,0,0,1,0]	0.07
[0,0,5,0,0,1,0,0,1,0,0,0,0]	0.25	[0,0,0,0,0,0,0,1,0,0,1,1,0]	0.07
[0,0,0,0,0,2,0,0,1,0,0,1,0]	0.32	[0,0,2,0,0,2,0,0,0,1,0,1,0]	0.07
[0,0,2,0,0,1,0,0,0,1,1,0,0]	0.38	[0,0,0,0,0,1,1,0,0,2,0,0,0]	0.12
[0,0,0,0,0,2,2,0,0,0,0,0,0]	0.62	[0,0,0,0,0,4,0,0,0,2,0,0,0]	0.12

This configuration yields no scrap since S92 = 0.0; (Figure 27 illustrates this concept). By gathering the information from the required cuts (stud and sill lengths listed in Table 13), each combinatorial configuration will be vector-multiplied with this list to obtain the final amount of waste, *S*.

Based on the most widely-used lengths available on the market—2.35 m ($92^{5/8}$ in.), 2.66 m ($104^{5/8}$ in.), and 2.94 m ($115^{5/8}$ in.), the numbers of the valid cutting patterns similar to those listed above and satisfying the lengths described in Table 13 are 324, 544, and 861. In total, solving this problem using the cutting patterns will necessitate handling 13 constraints involving 1729 variables.

Numerical Results: Before the numerical results are addressed, it should be noted that the data in Table 13 exhibits a special feature in the sense that some of the quantities are at least one order of magnitude larger than the rest. In other words, certain stock sizes contribute very little to the total number of studs.

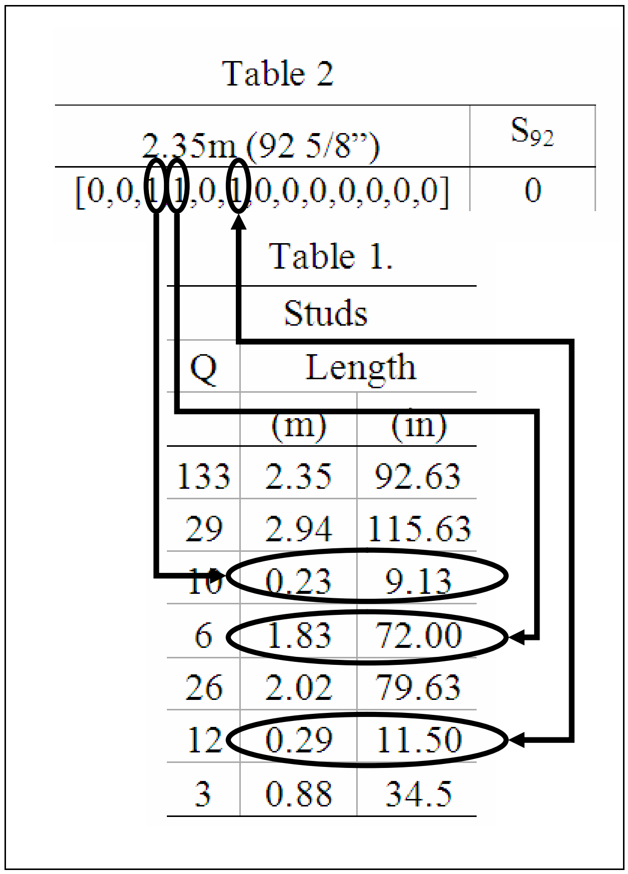


Figure 27. Combinatorial Analysis calculation

This feature is especially significant since the minimization of waste during the cutting process will be highly contingent on whether or not it remains optimal when handling the studs for which large demands are requested. Tables 15, 16, and 17 show the optimized cutting layout produced by utilizing different stud lengths, and Table 18 shows a combination of different length types.

Table 15. Optimized cutting layout for the 2.35 m (92 5/8 in) stud length

Pattern	Q	Scrap
[1,0,0,0,0,0,0,0,0,0,0,0,0]	133	0
[0,0,0,0,1,1,0,0,0,0,0,0,0]	12	18
[0,0,1,0,1,0,0,0,0,0,0,0,0]	10	38.75
[0,0,0,0,1,0,0,0,0,0,0,0,0]	4	52
[0,0,0,1,0,0,0,0,0,0,0,0,0]	6	123.75
[0,0,0,0,0,0,0,0,1,0,0,0,1]	3	48.38
[0,0,0,0,0,0,0,0,2,0,0,0,0]	1	22.13
[0,0,0,0,0,0,0,1,1,0,0,0,0]	1	20.13
[0,0,0,0,0,0,2,0,0,0,0,0,0]	1	23.63
[0,0,0,0,0,0,1,0,0,0,0,1,0]	1	24.07
[0,0,0,0,0,0,0,0,0,1,1,0,0]	1	30.13
Total		
[133,0,10,6,26,12,3,1,6,1,1,1,3]		2.57%

Table 16. Optimized cutting layout for the 2.66 m (104 5/8 in) stud length

Pattern	Num	Scrap
[1,0,0,0,0,0,0,0,0,0,0,0,0,0]	111	1332
[0,0,0,0,1,0,0,0,0,0,0,0,0]	26	650
[1,0,0,0,0,1,0,0,0,0,0,0,0]	12	6
[1,0,1,0,0,0,0,0,0,0,0,0,0]	10	28.75
[0,0,0,1,0,0,0,0,0,0,0,0,0]	5	163.13
[0,0,0,1,0,0,0,0,0,1,0,0,0]	1	3.38
[0,0,0,0,0,0,0,0,0,0,0,0,2]	1	22.13
[0,0,0,0,0,0,2,0,1,0,0,0,0]	1	0.38
[0,0,0,0,0,0,0,1,0,0,0,0,1]	1	26.13
[0,0,0,0,0,0,0,0,2,0,0,1,0]	1	0.07
[0,0,0,0,0,0,0,0,2,0,1,0,0]	1	0.88
[0,0,0,0,0,0,1,0,1,0,0,0,0]	1	34.88
Total		
[133,0,10,6,26,12,3,1,6,1,1,1,3]		14.51%

Table 17. Optimized cutting layout for the 2.94 m (115 $^{5/8}$ in) stud length

Pattern	Q	Scrap
[1,0,0,0,0,0,0,0,0,0,0,0,0]	122	2806
[0,1,0,0,0,0,0,0,0,0,0,0,0]	29	0
[0,0,0,0,1,0,0,0,0,0,0,0,0]	14	504
[1,0,0,0,0,2,0,0,0,0,0,0,0]	6	0
[0,0,0,0,1,0,0,0,1,0,0,0,0]	6	4.5
[1,0,2,0,0,0,0,0,0,0,0,0,0]	5	23.75
[0,0,0,0,1,0,1,0,0,0,0,0,0]	3	4.5
[0,0,0,1,0,0,0,0,0,0,0,0,1]	3	7.13
[0,0,0,1,0,0,0,0,0,0,0,0,0]	2	87.25
[0,0,0,0,1,0,0,0,0,0,0,1,0]	1	1.94
[0,0,0,0,1,0,0,0,0,0,1,0,0]	1	2.75
[0,0,0,0,1,0,0,0,0,1,0,0,0]	1	6.75
[0,0,0,1,0,0,0,1,0,0,0,0,0]	1	6.38
Total		
[133, 29, 10,6,26,12,3,1,6,1,1,1,3]		18.21%

The data under headers 2.35 m (92$^{5/8}$ in.), 2.66 m (104$^{5/8}$ in.) and 2.94 m (115$^{5/8}$ in.) correspond to cuts generated with a single stock size. Calculations using the first two stock sizes were made possible only upon the removal of the second length (2.94 m or 115$^{5/8}$ in.). The results listed in Table 18 clearly show that by merging the basic layouts from three different stock sizes, one may obtain the optimized cutting scheme in which 0.58 percent of waste is generated from the total amount of required dimensional lumber. From a total of 480 m (1580 ft) required in studs, 2.80 m (9 ft) are wasted. As mentioned earlier, the procedure is only usable when the datasets are small, since the computational demand required to generate all the possible cutting patterns grows at a rate beyond exponential (factorial algorithmic complexity).

Table 18. Multi Stock Size Optimization

Pattern	Q	Scrap
[1,0,0,0,0,0,0,0,0,0,0,0,0]	133	0
[0,1,0,0,0,0,0,0,0,0,0,0,0]	29	0
[0,0,0,0,1,1,0,0,0,0,0,0,0]	12	17.76
[0,0,0,0,1,0,0,0,1,0,0,0,0]	6	4.5
[0,0,1,0,1,0,0,0,0,0,0,0,0]	6	23.22
[0,0,0,1,0,0,0,0,0,0,0,0,1]	3	7.05
[0,0,0,0,1,0,1,0,0,0,0,0,0]	2	2.98
[0,0,2,1,0,0,0,0,0,0,0,0,0]	2	4.75
[0,0,0,1,0,0,0,0,0,1,0,0,0]	1	3.37
[0,0,0,0,0,0,1,1,0,0,0,0,0]	1	20.87
[0,0,0,0,0,0,0,0,0,0,1,1,0]	1	25.31
	Total	
[133, 29, 10,6,26,12,3,1,6,1,1,1,3]		0.58%

In such cases, the Gilmore-Gomory approach offers a very pragmatic alternative, although in the case of multi-stock optimization one may end up with a sub-optimal solution. In the present exercise, the Gilmore-Gomory approach was applied using three stock lengths (as described above) and 38 different specified lengths to be generated for studs, sills, and plates. The results are compiled in Table 19.

Table 19. Results of the combinatorial analysis for wood studs

Stud Required		Q	Element Number																																						
(m)	(in)		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	SCRAP
2.35	92.625	133	1																																						0
2.94	115.63	29		1																																					0
2.94	115.63	6					1				1																														4.5
2.35	92.625	6					1	1																																	9
2.35	92.625	5			1	1		1																																	0
2.94	115.63	3					1		1																																4.5
2.66	104.63	2					1																																	1	2
2.66	104.63	1					1																							1											0.5
2.94	115.63	1				1																										1									0.466
2.66	104.63	1			1		1																			1															0.375
2.94	115.63	1						1																							1										1.161
2.94	115.63	1																																			1	1			1.373
2.66	104.63	1			1																		1					1													0.726
2.66	104.63	1					1																											1							1.383
2.35	92.625	1																			1												1								0.104
2.66	104.63	1																						1					1												0.5
2.94	115.63	1			1		1									1																									0.75
2.94	115.63	1			1		1																													1					1.155
2.66	104.63	1													1				1						1																0.018
2.94	115.63	1			1		1											1																							0.875
2.94	115.63	1												1								1													1						0.879
2.66	104.63	1													2												1														0.65
2.94	115.63	1					1										1																								2.059
2.94	115.63	1					1						1																												2.75
2.94	115.63	1																																					1		6.5
2.94	115.63	1					1					1																													6.75
2.66	104.63	1								1										1																					10.875
	TOTAL		133	29	10	6	26	12	3	1	6	1	1	1	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	138.35

4.2.4. Drywall optimization – CUTEX

For the sake of practicality but in order to still show a portion of the obtained results in this section, Table 20 presents just the optimization results, and for the main floor only. One can see that, from the total amount of drywall required, only 2.49 percent is wasted. After running the optimization model, 64 percent of the sheets are 3.048x1.219 (4x10ft), 32 percent are 2.438x1.219 (4x8ft) and less that 4 percent are 2.743x1.219 (4x9ft). Consequently, for the tested architectural model, the waste is determined to be 2.02 percent of the total amount of material required.

Table 20. Results for Drywall Optimization – Catalina II (Main floor only)

Sheet size (m)		Cutting layout (m)		Q	Waste	Sheet size (m)		Cutting layout(m)		Q	Waste
3.048	1.219	2.299	1.219			3.048	1.219	3.048	1.219	12	0.333
		0.722	0.510	2	0.379	3.048	1.219	2.581	1.219	2	0.557
		0.610	0.584					0.406	0.991		
2.438	1.219	2.438	1.200	2	0.094	3.048	1.219	2.489	1.219	2	0.008
2.438	1.219	2.438	1.219	2	0.000			0.406	0.991		
2.438	1.219	2.438	1.181	2	0.184	3.048	1.219	1.324	1.219	2	0.019
2.438	1.219	2.057	1.219	2	0.449			1.721	1.219		
		0.295	0.813			3.048	1.219	1.527	1.219	2	0.021
2.435	1.219	1.969	1.219	2	0.332			1.513	1.219		
		0.406	0.991			3.048	1.219	1.682	1.219	2	0.057
2.438	1.219	2.438	0.610	2	0.032			1.358	1.219		
		2.438	0.603			3.048	1.219	1.497	1.219	2	0.047
2.438	1.219	1.838	1.219	3	0.592			1.527	1.219		
		0.584	0.914			3.048	1.219	1.340	1.219	2	0.101
2.435	1.219	2.143	1.219	2	0.171			1.689	1.219		
		0.295	0.914			3.048	1.219	1.635	1.219	2	0.077
2.438	1.219	2.028	1.219	2	0.195			1.372	1.219		
		0.406	0.991			3.048	1.219	1.683	1.219	2	0.109
2.438	1.219	2.438	1.165	2	0.000			1.334	1.219		
		2.438	0.054			3.048	1.219	1.527	1.219	2	0.340
2.438	1.219	2.438	0.693	2	0.074			1.476	1.219		
		2.438	0.511			3.048	1.219	1.385	1.219	2	0.026
2.438	1.219	2.438	1.016					1.524	1.219		
		2.435	0.102	2	0.001	3.048	1.219	1.602	1.219	2	0.341
		2.435	0.102					1.435	1.219		
2.743	1.219	1.883	1.219			3.048	1.219	1.385	1.219	2	0.341
		0.406	0.914	2	0.612			1.524	1.219		
		0.406	0.914								
						Drywall required (m2)		229.630	Waste (m2)		5.492

It is interesting to note that it will be difficult to determine the amount of sheets and sizes of drywall for a required home without the accuracy of a computer model to minimize the amount of waste and maximize profit.

Once the cutting list of materials has been generated, the information is stored in the repository model. A database for cost estimation of construction materials has been set up internally to reproduce the final costs for materials and installation. The database must be updated on a regular basis in order to match the system to current labor and material prices on the market.

Moreover, the proposed methodology can save up to 370 kg of drywall and almost nine tons of CO_2 per dwelling. The proposed methodology can encounter challenges with regard to the material storage and sheet identification required to dress every wall in the dwelling, however. (In order to address this challenge, manufacturing plants should set up a bin system to store cuts.) This disadvantage can also affect on-site installation because of the lack of space combined with the considerable number of different trades personnel working simultaneously on a facility. Nevertheless, procedures for applying the proposed methodology can be found to offer considerable benefit in terms of material savings.

4.2.5. Sheathing optimization – CUTEX

For this research, the required lengths of sheathing elements were gathered from an analysis of the blueprints. The associated 2D-SCP was optimized, leading to the results listed in Table 21. The element of rank *i* in Table 21 (leftmost column) corresponds to the piece of sheathing of the same rank in Table 22, (which describes the actual pieces that need to be generated for the study).Since the area of all the commercial sheathing elements is standard (1.22 x 2.44 m or 48x96 in.), the term A_i = 2.97 m^2 (4608 $in.^2$) is constant. Consequently, for the tested architectural model, the waste is determined to be 0.03 percent of the total amount of material required.

Table 21. Sheathing cutting optimization

Cutting pattern	Q	Scrap (cm^2)	Scrap (sq. in.)
[1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]	40	0.00	0
[0,0,2,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]	10	0.00	0
[0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]	5	580.64	90
[0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0]	4	465.03	72.08
[0,0,0,0,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]	3	348.77	54.06
[0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0]	2	7432.50	1152.04
[0,0,0,0,1,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]	2	3711.99	575.36
[0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,0,0,0]	1	79.55	12.33
[0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]	1	113.81	17.64
[0,0,0,0,0,0,0,1,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]	1	116.26	18.02
[0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,0,1,0,0,0,0,0,0,0]	1	0.26	0.04
[0,0,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0]	1	0.45	0.07
[0,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]	1	116.13	18
[0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,0,0,1,0,0,0,0,0,0,0,1,0,0]	1	348.32	53.99
[0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0]	1	1974.19	306
[0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]	1	1662.32	257.66
[0,0,0,0,1,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,0,1,0,0,0,0]	1	2289.87	354.93
[0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,1,0]	1	112.13	17.38
[0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,2,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0]	1	1660.00	257.3
[0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1]	1	3830.44	593.72
[0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0]	1	5215.28	808.37
[0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]	1	7432.24	1152
[0,0,0,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]	1	25545.69	3959.59
Total			
[40,5,21,5,8,3,1,1,2,1,1,1,1,1,1,5,4,1,1,1,1,1,1,6,2,1,1,1,1,1,1,1,1]		63035.87	9770.55

Table 22. Sheathing sizes

Rank	Q	Width		Height	
		(m)	(in)	(m)	(in)
1	40	2.44	96.00	1.22	48.00
2	5	1.21	47.63	1.22	48.00
3	21	1.22	48.00	1.22	48.00
4	5	2.43	95.63	1.22	48.00
5	8	1.83	72.00	1.22	48.00
6	3	0.60	23.62	1.22	48.00
7	1	1.97	77.62	1.22	48.00
8	1	0.75	29.62	1.22	48.00
9	2	0.46	18.01	1.22	48.00
10	1	1.68	66.01	1.22	48.00
11	1	2.44	96.00	0.58	22.75
12	1	0.46	18.01	0.58	22.75
13	1	1.51	59.62	1.22	48.00
14	1	1.51	59.62	0.28	10.88
15	1	1.82	71.63	1.22	48.00
16	5	0.61	24.01	1.22	48.00
17	4	0.30	12.00	1.22	48.00
18	1	1.69	66.62	1.22	48.00
19	1	1.08	42.62	1.22	48.00
20	1	1.64	64.63	1.22	48.00
21	1	1.64	64.63	0.64	25.00
22	1	0.92	36.37	1.22	48.00
23	1	0.31	12.37	1.22	48.00
24	6	0.91	36.00	1.22	48.00
25	2	2.13	84.00	1.22	48.00
26	1	1.52	60.00	1.22	48.00
27	1	0.46	18.00	0.28	10.88
28	1	0.45	17.63	1.22	48.00
29	1	0.45	17.63	0.28	10.88
30	1	0.46	18.13	1.22	48.00
31	1	0.45	17.87	1.22	48.00
32	1	0.91	35.63	1.22	48.00
33	1	2.12	83.63	1.22	48.00

Once again, the provided list on Table 21 shows how complex the process is in order to determine the configuration that minimizes material waste. Due to the number of iterations required when finding the local minima, personnel on site will not have the same effectiveness when procuring materials for a typical home if any sort of computer aid is used.

4.2.6. Other models – Results

The following is a summary of the findings for the five aforementioned architectural models. Table 23 shows the material waste per dwelling that would be generated after running the algorithm CUTEX with the take-off lists of materials generated by FRAMEX and DRY-X for wood framing design. The five architectural models shown in Figure 24 have similar characteristics in terms of building size, ceiling heights, and number of storeys (Manrique et al. 2007).

It might be noted that, in the worst case scenario, the amount of material wasted per dwelling can be less than 3 percent of the lumber procured. The difference in material waste per dwelling conforms directly to the fact that most of the wall lengths are not based on commercially available lengths; hence, more cuts and more leftovers are generated. Improvements to minimize the amount of material waste can be introduced if the dimensions in the architectural model are set based on nominal available lengths in local markets. This would include lumber for framing as well as sheathing and drywall. These low percentages are almost negligible compared to the amount of material waste produced in the current practice (Mah 2007).

Table 24 shows the quantity of sheathing waste that is generated after running the optimization model. It is important to note that the percentage of waste is low due to the fact that the studs are spaced to match the commercial length of sheathing (0.6096 m or 24-in on centers).

Due the optimization technique used, it is easy to reuse material leftovers from one panel on another. Leftovers are typically placed on the bottom and/or top of any rough openings (either windows or doors), thus maximizing their use.

Table 23. Wood Framing Waste per model – Proposed Methodology

Model	Wood Framing Waste (%)
Catalina II	0.58
Cambridge III	2.45
Marseilles III	0.89
Rosewood III	1.46
Summerlea I	1.21

Table 24. Sheathing Waste per model – Proposed Methodology

Model	Sheathing Waste (%)
Catalina II	0.03
Cambridge III	0.1
Marseilles III	0.15
Rosewood III	0.09
Summerlea I	0.045

Table 25 shows the drywall waste per model. It should be noted that the amount of drywall waste is high compared to sheathing waste. The area requiring drywall in a house is on average more than three times the amount of sheathing required for the exterior walls. Another reason for having higher waste for drywall is that the studs on the exterior walls are spaced to match with the full length of commercially available sheathing, not drywall. Studs are only spaced to accommodate commercially available drywall dimensions for interior walls. It is also notable that the optimization model makes use of more 2.44 m and 3.05 m (8 and 10 foot-length) drywall sheets than 2.74 m (9-foot-length) sheets.

Table 26 shows the embodied energy and CO_2 emissions that can be saved per model by utilizing the proposed methodology with respect to wood products alone. On average, the supporting company constructs 600 units per year. In the near future, production will increase to 1000 homes as long as the required space for manufacturing building components is secured. On average, 9,200 kg of CO_2 can be saved per model during framing and drywall installation (see Tables 26 and 27). Thinking ahead and based on future construction of homes for the City of Edmonton by the supporting company of this research, more than 9,200 tons of CO_2 could be saved per year. Besides a general reduction in CO_2 emissions, savings can also be encountered in terms of reduced landfill from the misuse of primary materials. More broadly speaking, in the City of Edmonton more than 50,000 single family dwellings are constructed per year, which entails a savings impact of almost half a billion tones of CO_2 per year.

Table 25. Drywall waste per model – Proposed Methodology

Model	Drywall Waste (%)	Sheet Sizes (%)		
		2.44x1.22m	2.74x1.22m	3.05x1.22m
Catalina II	2.02	32	4	64
Cambridge III	4.56	30	18	52
Marseilles III	2.36	45	2	53
Rosewood III	1.56	42	9	49
Summerlea I	2.89	36	6	58

Table 26. Embodied Energy saved in Wood products – Proposed Methodology

Model	Embodied Energy (MJ)	CO2 Kg
Catalina II	2450	327
Cambridge III	4211	562
Marseilles III	3573	477
Rosewood III	2743	366
Summerlea I	3062	409

Table 27. Embodied Energy saved in Drywall per model – Proposed Methodology

Model	Embodied Energy (MJ)	CO2 Kg	Energy in Transportation (MJ/Km)
Catalina II	3202	8895	1245
Cambridge III	2838	7884	1104
Marseilles III	3519	9776	1369
Rosewood III	3201	8892	1245
Summerlea I	3040	8444	1182

4.2.7. Other applications – (i^3) concept

At present, the developed system is able to manage the framing design for two-storey dwellings as well as boxes for modular construction. The system is also able to design 50 percent of the wood framing components required for four-storey buildings. However, more characteristics and logical statements would have to be added to the current process in order to automate the design of partition, corridor, and shear walls for multi-storey buildings.

FRAMEX, DRY-X and CUTEX have been tested in the design of a modular stick-built four-storey building for the Becker Group. Due to financial restrictions tied to the current state of the market, however, the project was postponed.

The proposed methodology can be enhanced and upgraded for steel stud framing and cold form. The analysis and logic to follow is almost identical to the one followed for wood framing design. However, a structural design analysis should also be incorporated in order to verify different conditions and load combinations to be applied to the building to be designed.

Chapter 5: Conclusions

5.1 General Conclusions

Since the introduction of the platform-frame method in the early 1900s, the construction methodology for framing stick-built dwellings has seen few significant changes. In North-America, the homebuilding industry relies primarily on the tacit knowledge acquired by expert framers for the construction of residential facilities and the transfer of this knowledge from trade to trade. The wide-spread use of this methodology is one of the chief causes of the distressing extent of material waste at construction sites. The standardization of framing designs for the homebuilding industry has thus become the solution for top-end construction companies that seek the improvement of their construction methods. This research seeks in particular the standardization and automation of construction drawings for framing design in the residential homebuilding industry. The platform-frame method has been mimicked through the utilization of the (i^3) concept with the introduction of parametric algorithms and a repository database, adding dimensions for information management, innovation, and intelligence within a CAD environment. Alternatively, this research focuses on the utilization of Parametric Modeling and Building Information Modeling to derive rich information from large sets of databases. A knowledge-based system has been created to organize information coming from 3D models and permit further analyses, such as material quantification for procurement and cost estimation, material waste minimization and generation of material cutting lists, and the quantification of carbon foot-prints during construction and operation.[4]

This research enhances the links between building codes, consultants and contractors by improving their current practices and facilitating communication between parties. It also opens a window of opportunity for researchers to add and analyze more information about the architectural, engineering and construction disciplines.

5.2 Research Contributions

Through automation of the framing design of stick-built dwellings, the construction process can be improved using the rigorous guidelines rendered. Whether the selected construction process takes place at the construction site or at a manufacturing shop, the productivity rate can be expected to increase due to the elimination of guesswork. The drawings generated as an output can be used by the AEC parties involved in the construction process for future reference.

This research was initiated at the collaborating company, due to the need to facilitate the prefabrication of wood stud panels in a controlled environment. Shop drawings and a thorough list of materials were required in order to be able to construct, quantify, and cost-estimate production models. The automation of take-off and cutting lists of materials provides the optimum amount of lumber and drywall needed for construction. Savings in terms of unused materials, extra space for storage, avoidance of double shipping, waste, and CO_2 emissions, among others, can be anticipated.

[4] A version of this chapter has been submitted for publication, Journal of Construction Engineering and Management, American Society of Civil Engineers (ASCE) 2009.

As found in this research, by implementing the proposed methodology for the current manufacturing practice, the range of CO_2 savings oscillate between 8,211 Kg (low) to 10,338 Kg (High) per dwelling, as shown in tables 23 through 26. In terms of wood waste, the developed mathematical algorithm generates less than 1 percent of nominal lumber waste (0.58% - Low, 2.45% High). In regards to drywall waste, the optimum solutions are in the range of 1.56 to 2.89 percent of the total amount of sheets required. The total savings of embodied energy per dwelling are in the range of 6,392 MJ to 9,099 MJ. The aforementioned numbers demonstrate the positive impact by utilizing mathematical algorithms in today's construction practices to minimize the amount of building material waste and CO_2 footprint emissions.

The need for highly-skilled labor can be reduced since the construction/shop drawings specify all of the requirements for construction. Productivity rates should increase through the use of fully dimensioned visual tools and blueprints. Based on the current production at the manufacturing shop of the collaborating company, 1.5 houses are manufactured per day, taking 4 to 6 hours to be erected on-site. Stick built on-site takes an average of 12 working days to construct a similar house.

The use of the 3D model in framing design will add another dimension to the design process by assisting in communication for the project and facilitating understanding. The repository has its roots in 3D Modeling, allowing end-users to visualize a walk-through of the structure, and helping them to become more familiar with the final product. By virtue of the implementation of parametric modeling into a CAD interface, the need for long drafting hours is also eliminated through the automation of the process. In regards to the old practice of manually drafting shop drawings, it used to take 32 working days (average) for drafting all the panels required per dwelling (not including sheathing layouts) and 33.5 hours (average) for drafting drywall layout. With the introduction of FRAMEX, it only takes few seconds to generate a parametric solution, in which changes from the 3D model will be automatically reflected in the construction shop drawings, quantity takeoffs and cost estimates. Errors can also be detected easily by checking the construction/shop drawings from the architectural model, thus enhancing the quality for drafting design. Furthermore, through the automation of the design process, an alleviation of the environmental burden linked to the reduction of upstream waste will be encountered.

The results of this investigation were added to an intelligent repository for analyzing construction models for panelized and on-site constructions. Construction companies can benefit from this approach due to the quality of the results and the easiness for retrieving information for decision-making.

Moreover, a state-of-the-art algorithm for optimizing the utilization of primary materials has been developed and introduced to the current practice. It is also worth noting at this juncture that very little research has yet been directed within the residential construction industry toward the reduction of material waste. One of the primary focuses of this research has thus been to apply mathematical algorithms in order to efficiently solve complex problems occurring in the construction engineering discipline. The benefits of applying mathematical algorithms are two-fold. First, it allows for the incorporation of advanced mathematics in the training of engineers, which will bring a new edge to the construction industry through the introduction of lean thinking through efficient mathematical procedures. Second, applying existing tools to practical problems will allow researchers to assess the quality of existing mathematical techniques in terms of algorithmic complexity and numerical stability; in example, the utilization of one and two-dimensional optimization algorithms to minimize construction waste. As demonstrated in this research and based on the results obtained, the manufacturing practice of building components for the residential industry can save up to 10 tonnes of CO_2 emissions per dwelling. This has a great impact in our society; if only 50,000 homes per year are panelized in Canada, half a megaton of CO_2 can be saved from being released to the environment. This research developed an enduring method of framing design for use by North-American, but especially Canadian construction companies and provided them with a thorough plan for the use of construction materials, focusing on the application of engineering techniques and building code requirements. As such, the minimization of material waste should have both an economic and an environmental impact by facilitating sustainability in construction practice through the responsible use of primary resources as demonstrated through the application of the proposed methodology.

At this stage, the research presented herein has developed a system applicable both to two-storey dwellings and to mobile homes. Further development in the areas of mechanical and electrical components can subsequently be incorporated with considerable results. The utilization of BIM and parametric modeling, in conjunction with Gas, provides the missing link between design and construction.

5.3 Research publications

Peer-Reviewed Papers:

- Manrique, J. D., Al-Hussein, M., Bouferguene, A Safouhi, H., and Nasseri, R. (2008). "Automation in Residential Construction Drawings Utilizing 3D CAD and Parametric Modeling." Submitted to the Journal of Construction Engineering and Management, ASCE, Feb., 2008.

- Manrique, J. D., Al-Hussein, M., Bouferguene, A Safouhi, H., and Nasseri, R. (2008)." Combinatorial Algorithm For Optimizing Wood Waste in Framing Designs." Submitted to the Journal of Construction Engineering and Management, ASCE, Feb., 2008.

Conference Papers:

1. Manrique, J.D., Al-Hussein, M., and Bouferguene, A. (2009). "Integrated Design System for the Home Building Industry." *Proceedings of the First International Conference for Construction and Use through Integrated Design Solutions*, Espoo, Finland, June 10-12 2009.
2. Mah, D., Manrique, J. D., Yu, H., Al-Hussein, M., and Nasseri, R. (2009). "Quantification of the CO_2 Footprint in Residential Construction." *Proceedings of the First International Conference for Construction and Use through Integrated Design Solutions*, Espoo, Finland, June 10-12 2009.
3. Manrique, J. D., Al-Hussein, M., Bouferguene, A., Safouhi, H., and Nasseri, R. (2008). "Automation of Construction Drawings and Waste Minimization for Stick-Frame Constructions Based on the (i^2) Concept." *Proceedings of the CSCE 2008 Annual Conference*, Quebec City, Canada, June 10-13, 2008.
4. Manrique, J. D., Mah, D., and Al-Hussein, M. (2008). "Automated Design to Support Sustainable Residential Construction." CCE July, 2008.

5. Manrique, J. D., Al-Hussein, M., Bouferguene, A., and Nasseri, R. (2007). "Shop Drawing Automation and Material Waste Minimization in the Construction of Wood Houses Utilizing 3D-CAD and Optimization Techniques." *Proceedings of the 4th International Structural Engineering and Construction Conference*, Melbourne, Australia, September 26-28, 2007.

5.4 Research risks and mitigations

Due to the particular characteristics of this Ph.D. research, the automation of construction drawings using CAD modeling software and Visual Basic can be highly dependent on software variations. For instance, the current framing modeling system has been designed under the AutoCAD 2006 version, but due to programmatic code changes in more recent Autodesk CAD software, FRAMEX has not been able to operate newer releases of AutoCAD. Research related to the amalgamation of older and newer AutoCAD versions must be conducted in order to keep FRAMEX up-to-date.

Since FRAMEX and the utilization of the ($\boldsymbol{i}^3$) concept are both research-oriented and software-based experimentations, the ultimate utilization of this software is contingent on the participation of the collaborating company for the enhancement of current drafting techniques and drafting standards for panelized construction. The current system requires precise 3D modeling, such that dimensioning of wall components and rough openings for windows and doors must be exact. FRAMEX uses the global coordinates attached to the boundaries of these object-oriented components to deliver the final results. As a consequence, the output may vary based on the drafting expertise of the modeler. In order to mitigate drafting errors, a checklist of building requirements has been written to enhance the modeling design process as shown in the body of this research.

Issues related to code glitches and modeling mistakes will need to be solved in order to eliminate errors in the drafting complicated structures. Since this research aims at the eventual incorporation of mechanical and electrical layouts for home building, FRAMEX will need to be re-structured so that the newly drafted components can become an integral solution to current software problems.

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Appendix

Table 1a, Material quantity takeoff list of headers – Catalina II

TYPE	QUANTITY	SIZE	L (in)	L(m)
1	6	2x10	51.0	1.30
4	2	2x10	55.5	1.41
5	2	2x10	74.9	1.90
6	4	2x10	30.0	0.76
7	4	2x10	63.0	1.60
8	2	2x10	75.5	1.92
9	2	2x10	42.0	1.07
2	1	2x12	15.0	0.38
3	2	2x12	201.0	5.11

Table 2a Material quantity takeoff list of Sills- Catalina II

TYPE	QUANTITY	SIZE	L (in)	L(m)
10	1	2x4	27.00	0.69
11	1	2x4	63.00	1.60
15	5	2x4	39.00	0.99
16	5	2x4	33.00	0.84
17	1	2x4	42.00	1.07
18	1	2x4	21.00	0.53
19	1	2x4	35.00	0.89
20	1	2x4	31.00	0.79
21	1	2x4	40.00	1.02
22	1	2x4	37.00	0.94
1	5	2x6	51.00	1.30
2	3	2x6	48.00	1.22
3	1	2x6	195.00	4.95
4	1	2x6	37.62	0.96
5	1	2x6	55.50	1.41
6	1	2x6	74.87	1.90
7	1	2x6	71.87	1.83
8	2	2x6	24.00	0.61
9	2	2x6	30.00	0.76
10	2	2x6	27.00	0.69
11	3	2x6	63.00	1.60
12	3	2x6	60.00	1.52
13	1	2x6	75.50	1.92
14	2	2x6	72.50	1.84

Table 3a Material quantity takeoff list of Plates- Catalina II

TYPE	QUANTITY	SIZE	L (in)	L(m)	TYPE	QUANTITY	SIZE	L (in)	L(m)
43	1	2x2	32.99	0.84	51	1	2x4	39.11	0.99
48	1	2x2	45.50	1.16	52	1	2x4	36.20	0.92
1	2	2x4	263.62	6.70	53	1	2x4	63.62	1.62
10	1	2x4	220.25	5.59	54	1	2x4	96.13	2.44
21	1	2x4	164.63	4.18	55	1	2x4	58.12	1.48
22	1	2x4	43.15	1.10	56	1	2x4	64.11	1.63
23	1	2x4	24.73	0.63	57	2	2x4	63.13	1.60
24	1	2x4	18.94	0.48	58	1	2x4	43.62	1.11
25	1	2x4	26.13	0.66	2	1	2x6	305.97	7.77
26	1	2x4	116.64	2.96	3	1	2x6	173.62	4.41
28	1	2x4	52.60	1.34	4	1	2x6	126.67	3.22
29	1	2x4	33.94	0.86	5	1	2x6	329.75	8.38
30	1	2x4	18.18	0.46	6	1	2x6	162.50	4.13
31	2	2x4	26.50	0.67	7	1	2x6	267.30	6.79
32	1	2x4	14.30	0.36	8	1	2x6	230.50	5.85
33	2	2x4	24.00	0.61	9	1	2x6	120.51	3.06
34	1	2x4	50.01	1.27	11	1	2x6	107.14	2.72
35	1	2x4	36.14	0.92	12	1	2x6	83.63	2.12
36	1	2x4	17.71	0.45	13	1	2x6	146.06	3.71
37	1	2x4	21.45	0.54	14	1	2x6	65.62	1.67
38	1	2x4	183.63	4.66	15	1	2x6	60.13	1.53
39	1	2x4	44.99	1.14	16	1	2x6	89.50	2.27
40	1	2x4	224.99	5.71	17	1	2x6	305.75	7.77
42	1	2x4	11.87	0.30	18	1	2x6	107.75	2.74
43	1	2x4	32.99	0.84	19	1	2x6	118.27	3.00
45	1	2x4	132.12	3.36	20	1	2x6	115.35	2.93
46	1	2x4	49.00	1.24	27	1	2x6	109.57	2.78
47	1	2x4	21.50	0.55	41	1	2x6	135.62	3.44
49	1	2x4	44.63	1.13	44	1	2x6	132.50	3.37
50	1	2x4	40.00	1.02					

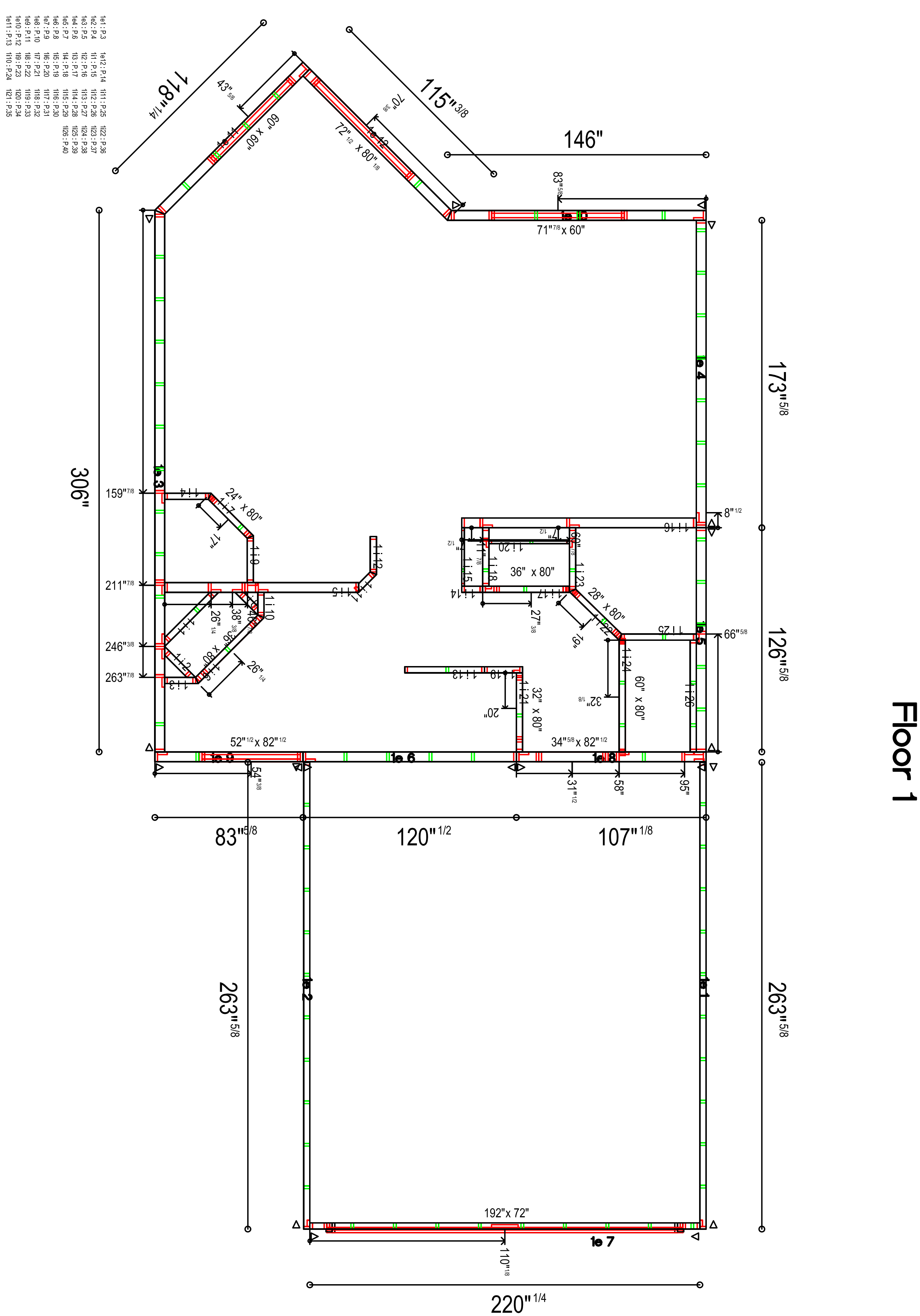
Table 4a Material quantity takeoff list of Sheathing- Catalina II

TYPE	QUANTITY	W (in)	H (in)	W(m)	H(m)	TYPE	QUANTITY	W (in)	H (in)	W(m)	H(m)
1	38	96.00	48.00	2.44	1.22	26	1	75.25	22.75	1.91	0.58
2	3	71.63	48.00	1.82	1.22	27	1	44.37	48.00	1.13	1.22
3	9	48.00	48.00	1.22	1.22	28	1	92.37	48.00	2.35	1.22
4	4	23.63	48.00	0.60	1.22	29	1	24.50	48.00	0.62	1.22
5	1	74.28	48.00	1.89	1.22	30	1	48.00	25.00	1.22	0.63
6	5	72.00	48.00	1.83	1.22	31	1	72.50	25.00	1.84	0.63
7	1	69.57	48.00	1.77	1.22	32	1	41.00	48.00	1.04	1.22
8	1	26.28	48.00	0.67	1.22	33	1	24.00	39.12	0.61	0.99
9	1	93.57	48.00	2.38	1.22	34	1	89.00	39.12	2.26	0.99
10	1	83.50	48.00	2.12	1.22	35	2	83.63	48.00	2.12	1.22
11	1	35.50	48.00	0.90	1.22	36	1	47.78	48.00	1.21	1.22
12	1	30.63	48.00	0.78	1.22	37	2	24.00	48.00	0.61	1.22
13	1	48.00	43.63	1.22	1.11	38	1	23.78	48.00	0.60	1.22
14	1	78.63	43.63	2.00	1.11	39	2	65.62	48.00	1.67	1.22
15	1	47.63	48.00	1.21	1.22	40	1	65.62	22.75	1.67	0.58
16	1	66.13	48.00	1.68	1.22	41	2	66.00	48.00	1.68	1.22
17	1	24.38	48.00	0.62	1.22	42	1	66.00	22.75	1.68	0.58
18	1	18.13	48.00	0.46	1.22	43	2	89.50	48.00	2.27	1.22
19	1	48.38	48.00	1.23	1.22	44	1	11.75	48.00	0.30	1.22
20	1	66.13	22.75	1.68	0.58	45	1	59.75	48.00	1.52	1.22
21	1	72.00	22.75	1.83	0.58	46	1	11.75	22.75	0.30	0.58
22	1	24.38	22.75	0.62	0.58	47	1	22.27	48.00	0.57	1.22
23	1	75.25	48.00	1.91	1.22	48	1	70.27	48.00	1.78	1.22
24	1	27.25	48.00	0.69	1.22	49	1	46.95	48.00	1.19	1.22
25	3	96.00	22.75	2.44	0.58	50	1	94.95	48.00	2.41	1.22

Table 4a Material quantity takeoff list of Drywall- Catalina II

L(m)	H (m)	Q	L(m)	H (m)	Q	L(m)	H (m)	Q	L(m)	H (m)	Q	L(m)	H (m)	Q	L(m)	H (m)	Q
3.05	1.22	12	1.33	1.22	2	0.61	2.44	3	1.60	2.44	2	0.94	2.44	1	0.27	2.44	1
2.97	1.22	2	1.32	1.22	2	0.60	2.44	2	1.60	1.22	2	0.93	2.44	1	0.24	2.44	1
2.58	1.22	2	1.22	0.32	1	0.60	2.44	1	1.53	1.22	4	0.92	2.44	1	0.24	2.44	1
2.49	1.22	2	1.22	0.90	1	0.58	0.61	2	1.53	1.22	2	0.92	2.74	1	0.23	2.44	1
2.44	1.22	2	1.20	2.44	1	0.58	0.91	2	1.52	0.31	1	0.91	0.41	2	0.22	2.44	1
2.30	1.22	2	1.18	2.44	1	0.57	2.44	1	1.52	0.59	1	0.91	0.30	2	0.22	2.44	2
2.14	1.22	2	1.18	2.44	2	0.57	2.44	2	1.52	1.22	2	0.91	0.41	2	0.21	2.44	2
2.06	1.22	2	1.17	2.44	1	0.55	2.44	1	1.52	0.30	2	0.91	2.44	1	0.20	2.44	1
2.03	0.41	2	1.16	2.44	1	0.54	2.44	1	1.52	0.32	1	0.88	2.44	1	0.19	2.44	2
2.03	1.22	2	1.16	2.44	1	0.54	2.44	1	1.52	0.90	1	0.88	2.44	1	0.18	2.44	1
1.97	1.22	2	1.14	2.44	1	0.51	2.44	2	1.52	0.58	1	0.87	2.44	1	0.17	2.44	2
1.91	1.22	2	1.13	2.44	1	0.51	2.44	1	1.52	0.91	1	0.81	0.30	2	0.17	2.44	2
1.88	1.22	2	1.11	2.44	1	0.48	2.44	1	1.51	1.22	2	0.72	0.59	2	0.15	2.44	1
1.84	0.39	1	1.10	2.44	1	0.47	2.44	1	1.50	1.22	2	0.70	2.44	1	0.14	2.44	2
1.84	1.22	2	1.08	2.44	1	0.46	2.44	1	1.48	1.22	2	0.69	2.44	2	0.14	2.44	1
1.83	0.31	1	1.07	2.44	1	0.46	2.44	1	1.44	1.22	2	0.67	2.44	3	0.13	2.44	1
1.73	1.22	2	1.07	2.44	1	0.46	2.44	2	1.38	1.22	2	0.67	2.44	1	0.12	2.44	1
1.72	1.22	2	1.06	2.44	1	0.46	0.41	2	1.37	1.22	2	0.67	2.44	1	0.11	2.44	2
1.69	1.22	2	1.05	4.88	1	0.36	2.44	1	1.37	1.22	2	0.64	2.44	1	0.10	2.44	5
1.68	1.22	2	1.02	2.44	2	0.36	2.44	1	1.36	1.22	2	0.64	2.44	1	0.10	2.44	1
1.68	1.22	2	0.99	0.41	8	0.31	0.59	1	1.34	1.22	2	0.63	2.44	1	0.09	2.44	2
1.64	1.22	2	0.96	2.44	1	0.31	2.44	3	1.33	0.34	1	0.63	2.44	1	0.08	2.44	1
															0.05	2.44	2

Shop Drawings – Catalina II (Landmark Homes, 2008)



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REVISIONS		

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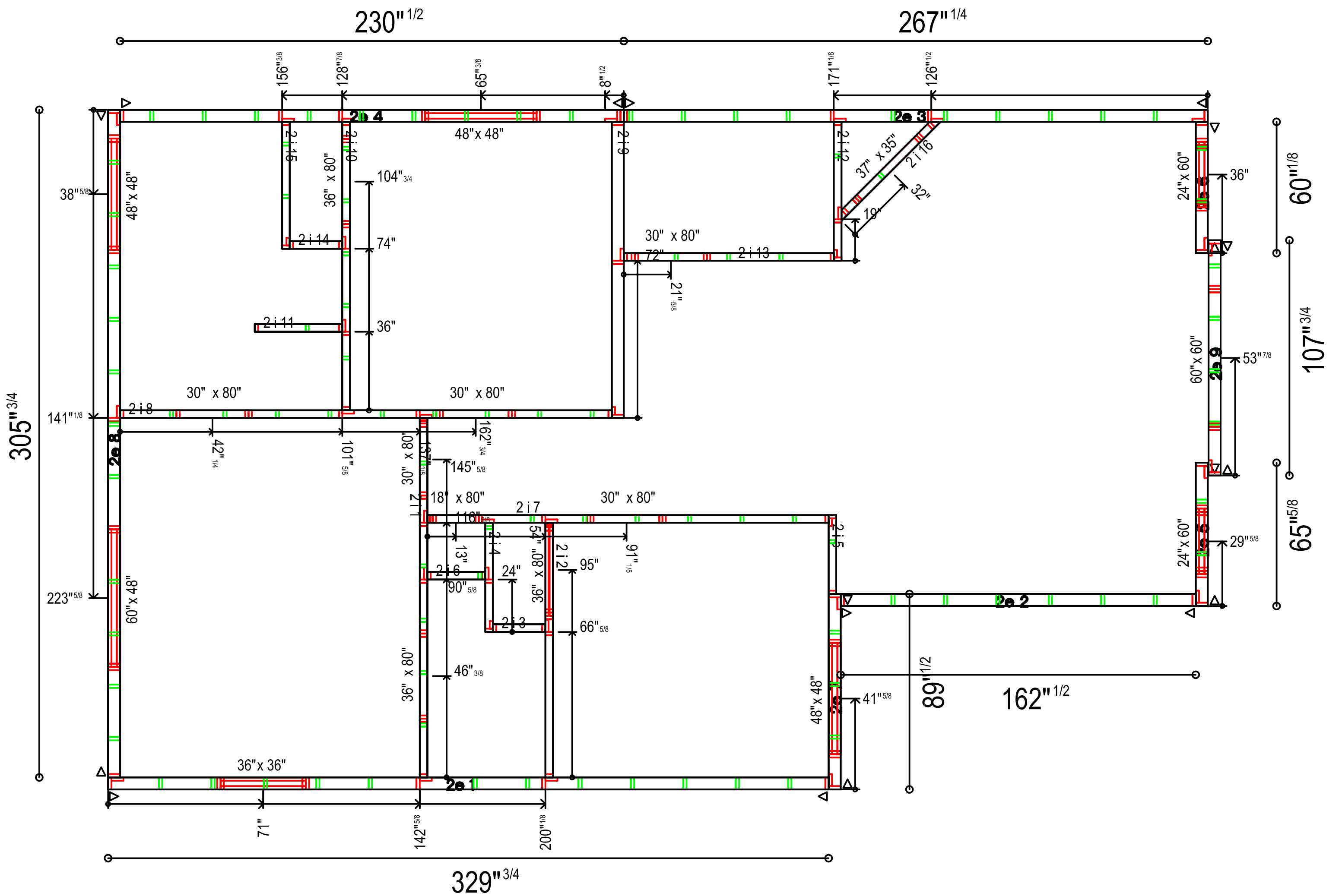

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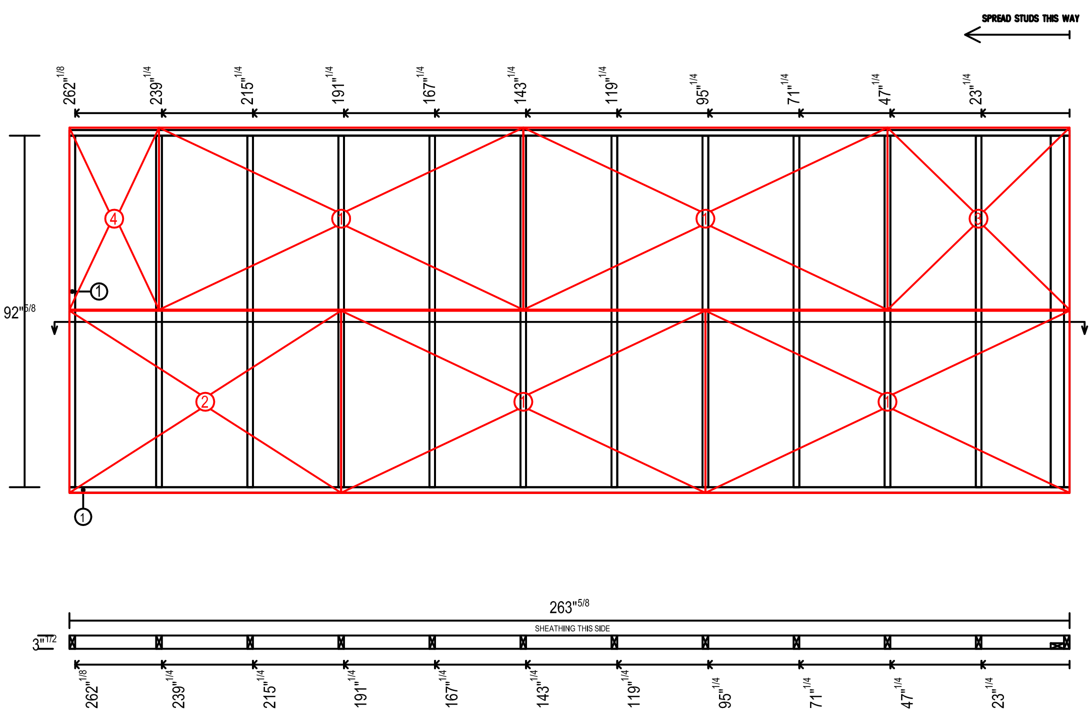

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PLATES

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1	4	96"	48"
2	1	71"5/8	48"
3	1	48"	48"
4	1	23"5/8	48"

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REVISIONS

MAIN FLOOR PANEL LAYOUT

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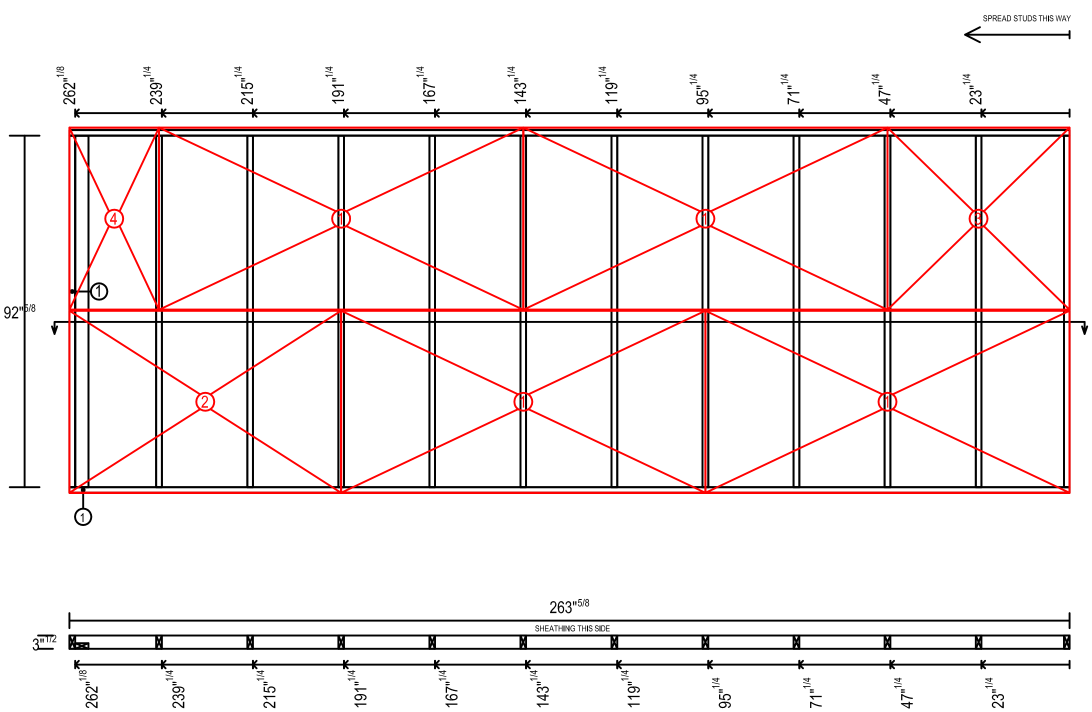

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2	1	71"5/8	48"
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4	1	23"5/8	48"

NO	DATE	BY

REVISIONS

MAIN FLOOR PANEL LAYOUT

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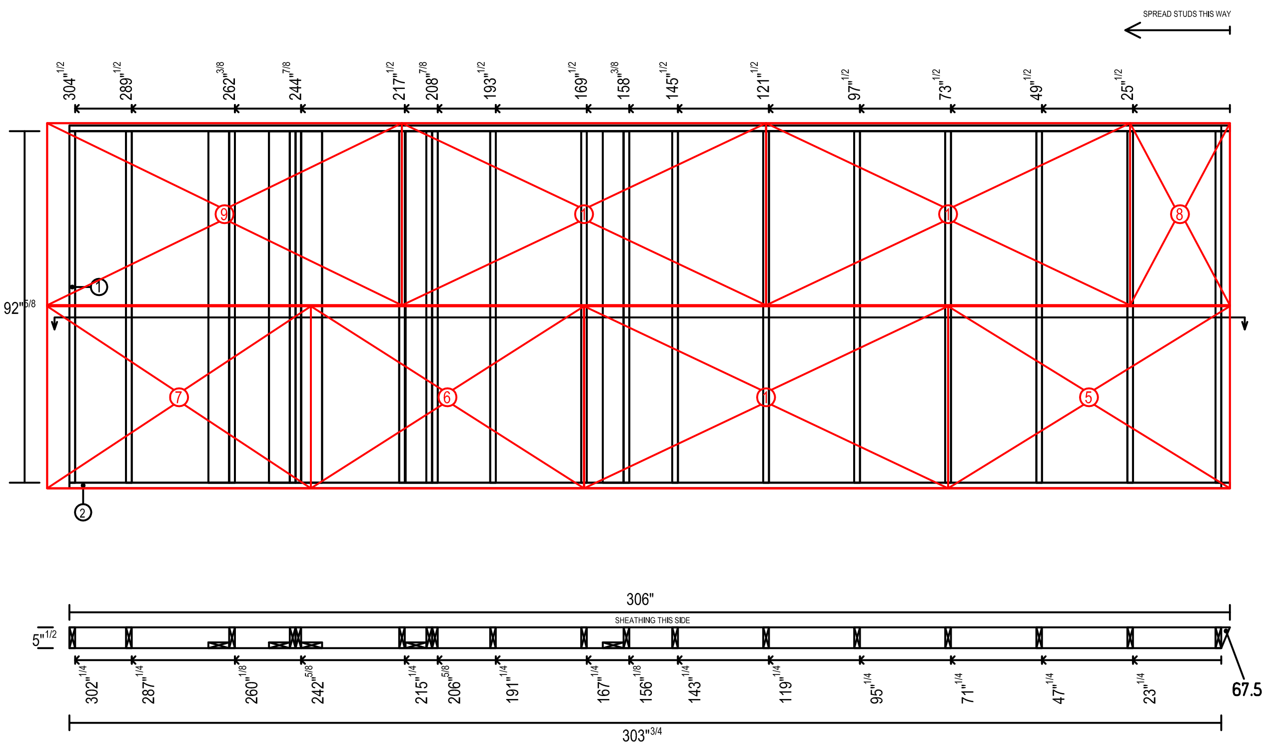

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PLATES

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SHEATHING

TYPE	Q	W	H
5	1	74"1/4	48"
1	3	96"	48"
6	1	72"	48"
7	1	69"5/8	48"
8	1	26"1/4	48"
9	1	93"5/8	48"

NO	DATE	BY

REVISIONS

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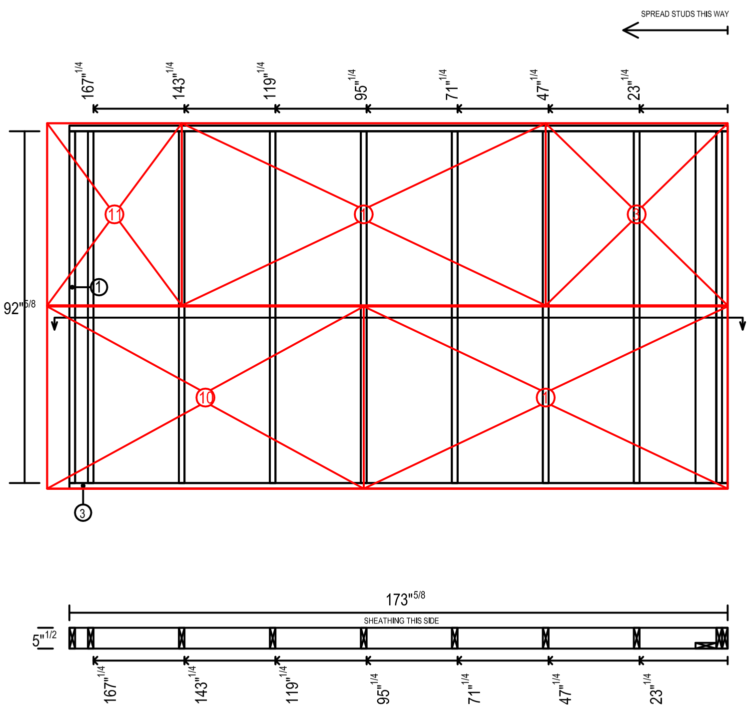

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PLATES

TYPE	Q	SIZE	L
3	2	2x6	173"5/8

SHEATHING

TYPE	Q	W	H
1	2	96"	48"
10	1	83"1/2	48"
3	1	48"	48"
11	1	35"1/2	48"

NO	DATE	BY

REVISIONS

MAIN FLOOR PANEL LAYOUT

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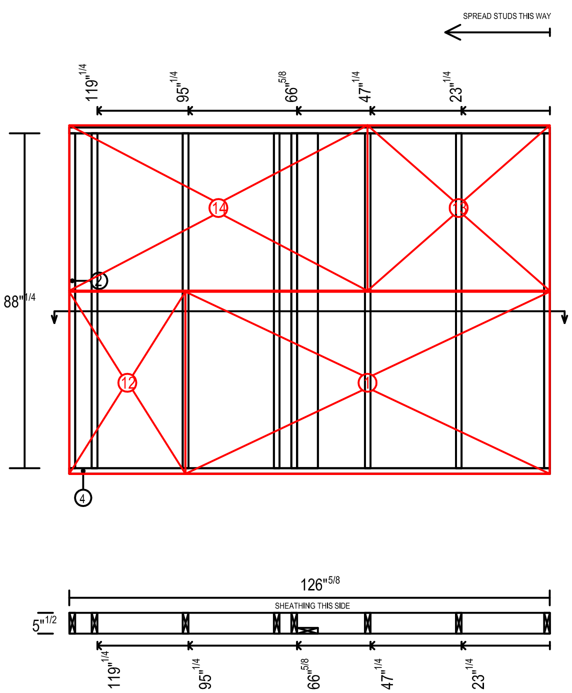

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PLATES

TYPE	Q	SIZE	L
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SHEATHING

TYPE	Q	W	H
1	1	96"	48"
12	1	30"5/8	48"
13	1	48"	43"5/8
14	1	78"5/8	43"5/8

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REVISIONS

MAIN FLOOR PANEL LAYOUT

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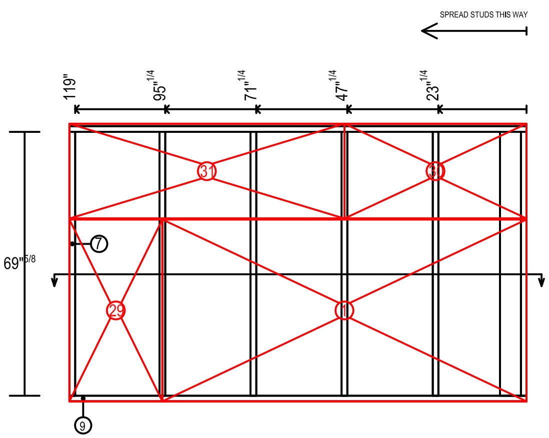

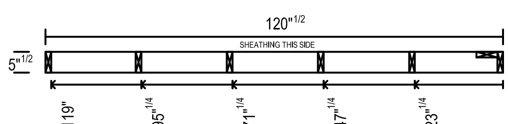

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TYPE	Q	SIZE	L
7	7	2x6	69"5/8

PLATES

TYPE	Q	SIZE	L
9	2	2x6	120"1/2

SHEATHING

TYPE	Q	W	H
1	1	96"	48"
29	1	24"1/2	48"
30	1	48"	25"
31	1	72"1/2	25"

NO	DATE	BY

REVISIONS

MAIN FLOOR PANEL LAYOUT

BASE MODEL **Sample File**

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DATE (dd/mm/yy): **2007**

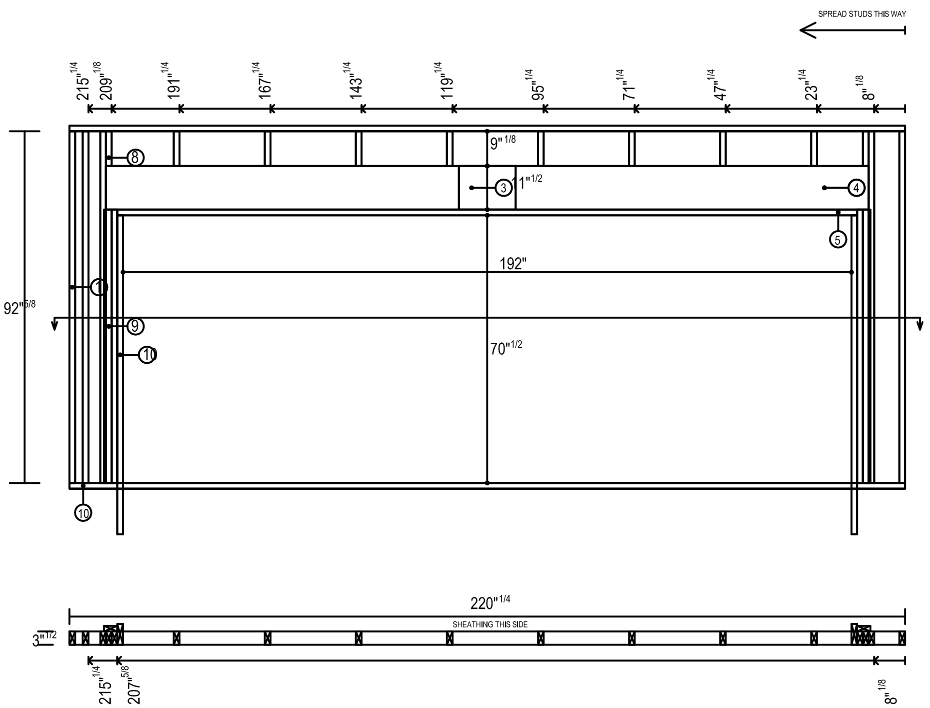
JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

PAGE No **8** / **65**

1e 7



STUDS				PLATES				SILLS				HEADERS				SHEATHING			
TYPE	Q	SIZE	L	TYPE	Q	SIZE	L	TYPE	Q	SIZE	L	TYPE	Q	SIZE	L	TYPE	Q	W	H
1	5	2x4	92"5/8	10	2	2x4	220"1/4	5	1	2x6	195"	3	1	2x12	15"				
8	10	2x4	9"1/8									4	2	2x12	201"				
9	6	2x4	72"																
10	2	2x6	84"																

NO	DATE	BY

REVISIONS

MAIN FLOOR PANEL LAYOUT

BASE MODEL **Sample File**

DRAWING **1e 7**

DATE (dd/mm/yy): **2007**

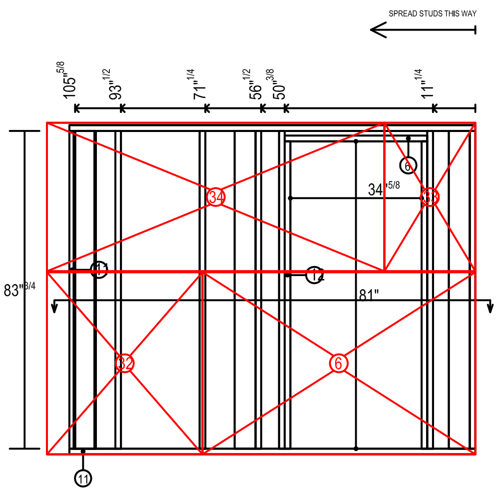
JOB No: 001

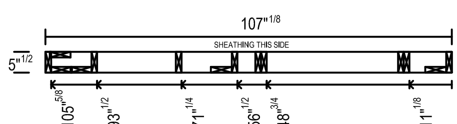
Scale: 3/8in = 1.0ft

Drawn By: Juan M

PAGE No **9** / **65**

1e 8





STUDS

TYPE	Q	SIZE	L
11	12	2x6	83"3/4
12	2	2x6	81"

PLATES

TYPE	Q	SIZE	L
11	2	2x6	107"1/8

SILLS

TYPE	Q	SIZE	L
6	1	2x6	37"5/8

SHEATHING

TYPE	Q	W	H
6	1	72"	48"
32	1	41"	48"
33	1	24"	39"1/8
34	1	89"	39"1/8

NO	DATE	BY

REVISIONS

MAIN FLOOR PANEL LAYOUT

BASE MODEL **Sample File**

DRAWING **1e 8**

DATE (dd/mm/yy): **2007**

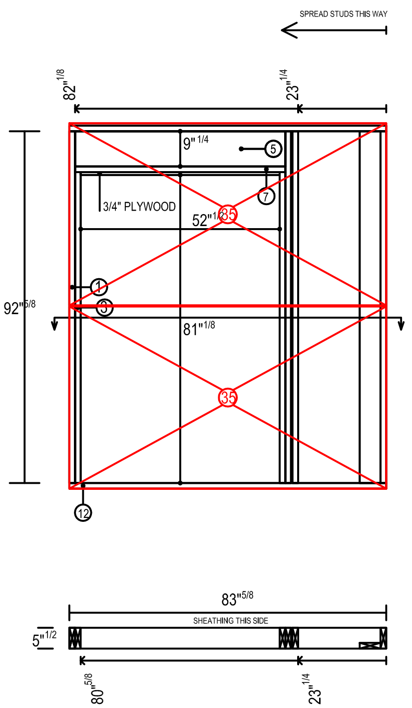
JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

PAGE No **10** / **65**

1e 9



STUDS

TYPE	Q	SIZE	L
1	6	2x6	92"$^{5/8}$
3	2	2x6	81"$^{7/8}$

PLATES

TYPE	Q	SIZE	L
12	2	2x6	83"$^{5/8}$

SILLS

TYPE	Q	SIZE	L
7	1	2x6	55"$^{1/2}$

HEADERS

TYPE	Q	SIZE	L
5	2	2x10	55"$^{1/2}$

SHEATHING

TYPE	Q	W	H
35	2	83"$^{5/8}$	48"

NO	DATE	BY

REVISIONS

MAIN FLOOR PANEL LAYOUT

BASE MODEL **Sample File**

DRAWING **1e 9**

DATE (dd/mm/yy): **2007**

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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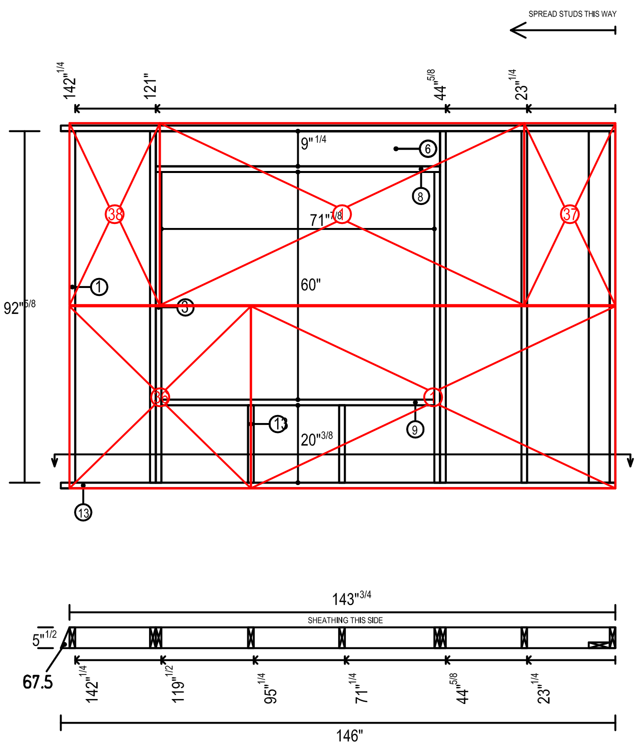
1e 10



STUDS

TYPE	Q	SIZE	L
1	6	2x6	92"5/8
3	2	2x6	81"7/8
13	2	2x6	20"3/8

PLATES

TYPE	Q	SIZE	L
13	2	2x6	146"

SILLS

TYPE	Q	SIZE	L
8	1	2x6	74"7/8
9	1	2x6	71"7/8

HEADERS

TYPE	Q	SIZE	L
6	2	2x10	74"7/8

SHEATHING

TYPE	Q	W	H
1	2	96"	48"
36	1	47"3/4	48"
37	1	24"	48"
38	1	23"3/4	48"

NO	DATE	BY

REVISIONS

MAIN FLOOR PANEL LAYOUT

BASE MODEL: Sample File

DRAWING: 1e 10

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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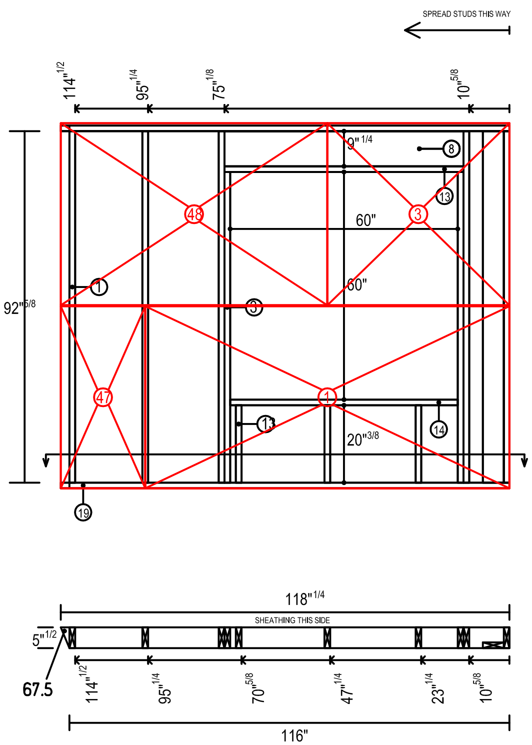
1e 11



STUDS

TYPE	Q	SIZE	L
1	6	2x6	92"5/8
3	2	2x6	81"7/8
13	3	2x6	20"3/8

PLATES

TYPE	Q	SIZE	L
19	2	2x6	118"1/4

SILLS

TYPE	Q	SIZE	L
13	1	2x6	63"
14	1	2x6	60"

HEADERS

TYPE	Q	SIZE	L
8	2	2x10	63"

SHEATHING

TYPE	Q	W	H
1	1	96"	48"
47	1	22"1/4	48"
3	1	48"	48"
48	1	70"1/4	48"

NO	DATE	BY

REVISIONS

MAIN FLOOR PANEL LAYOUT

BASE MODEL **Sample File**

DRAWING **1e 11**

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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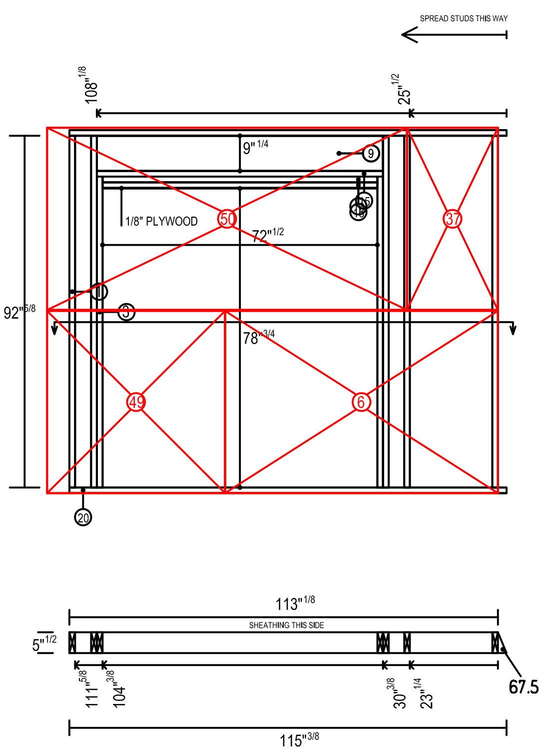
1e 12



STUDS

TYPE	Q	SIZE	L
1	5	2x6	92"5/8
3	2	2x6	81"7/8

PLATES

TYPE	Q	SIZE	L
20	2	2x6	115"3/8

SILLS

TYPE	Q	SIZE	L
15	1	2x6	75"1/2
16	2	2x6	72"1/2

HEADERS

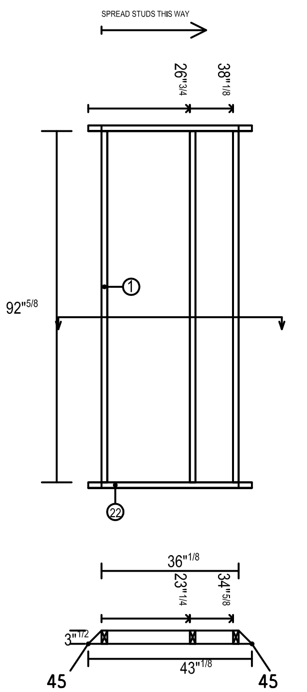
TYPE	Q	SIZE	L
9	2	2x10	75"1/2

SHEATHING

TYPE	Q	W	H
6	1	72"	48"
49	1	47"	48"
37	1	24"	48"
50	1	95"	48"

REVISIONS	NO / DATE / BY
MAIN FLOOR PANEL LAYOUT	
BASE MODEL	Sample File
DRAWING	1e 12
DATE (dd/mm/yy):	2007
JOB No:	001
Scale: 3/8in = 1.0ft	
Drawn By: Juan M	
PAGE No	14 / 65

1i1



STUDS			
TYPE	Q	SIZE	L
1	3	2x4	92"5/8

PLATES			
TYPE	Q	SIZE	L
22	2	2x4	43"1/8

NO	DATE	BY

REVISIONS

MAIN FLOOR INTERIOR WALLS

BASE MODEL: Sample File

DRAWING: 1i1

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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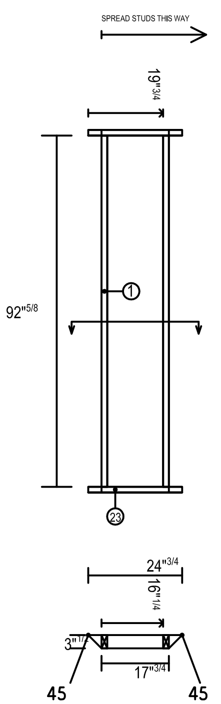
1 i 2



STUDS

TYPE	Q	SIZE	L
1	2	2x4	92"5/8

PLATES

TYPE	Q	SIZE	L
23	2	2x4	24"3/4

MAIN FLOOR INTERIOR WALLS		
BASE MODEL	Sample File	
DRAWING	1 i 2	DATE (dd/mm/yy): 2007

REVISIONS

NO	DATE	BY

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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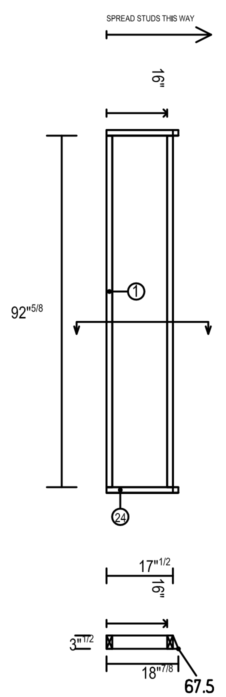
1 i 3



STUDS

TYPE	Q	SIZE	L
1	2	2x4	92"5/8

PLATES

TYPE	Q	SIZE	L
24	2	2x4	18"7/8

NO	DATE	BY

REVISIONS

MAIN FLOOR INTERIOR WALLS

BASE MODEL: Sample File

DRAWING: 1 i 3

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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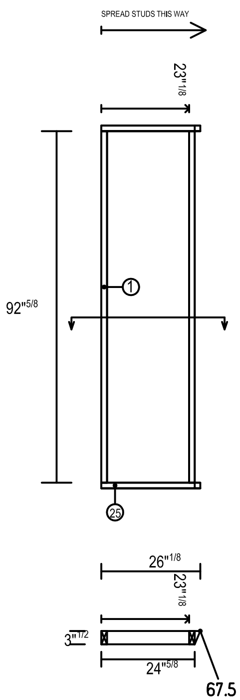
1 i 4



STUDS				PLATES			
TYPE	Q	SIZE	L	TYPE	Q	SIZE	L
1	2	2x4	92"5/8	25	2	2x4	26"1/8

NO	DATE	BY

REVISIONS

MAIN FLOOR INTERIOR WALLS

BASE MODEL: Sample File

DRAWING: 1 i 4

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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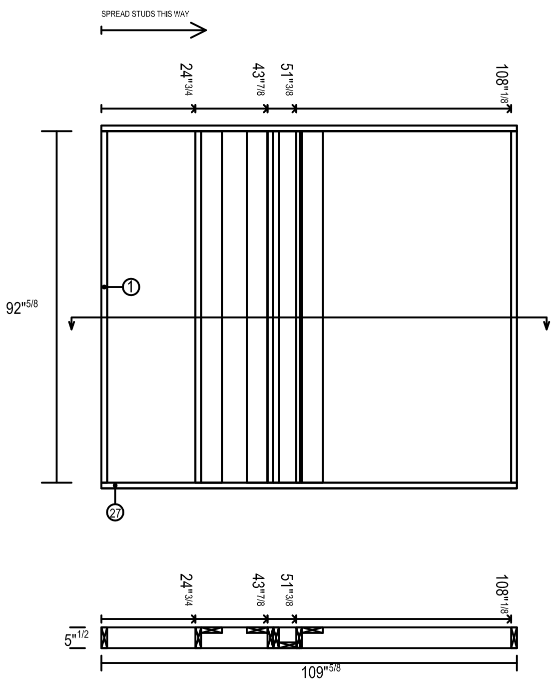
1 i 5



STUDS

TYPE	Q	SIZE	L
1	10	2x6	92"5/8

PLATES

TYPE	Q	SIZE	L
27	2	2x6	109"5/8

NO	DATE	BY

REVISIONS

MAIN FLOOR INTERIOR WALLS

BASE MODEL **Sample File**

DRAWING **1 i 5**

DATE (dd/mm/yy): **2007**

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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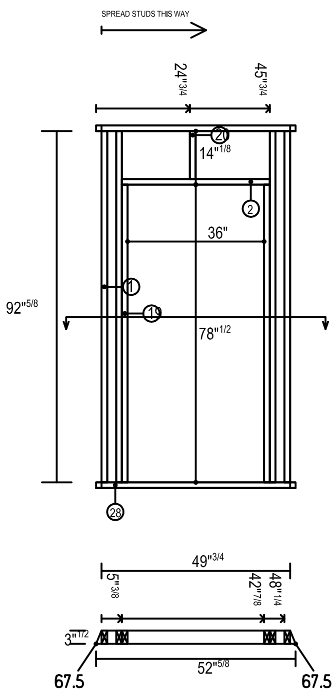
1 i 6



STUDS

TYPE	Q	SIZE	L
1	4	2x4	92"5/8
19	2	2x4	78"1/2
20	1	2x4	12"5/8

PLATES

TYPE	Q	SIZE	L
28	2	2x4	52"5/8

SILLS

TYPE	Q	SIZE	L
2	1	2x4	39"

NO	DATE	BY

REVISIONS

MAIN FLOOR INTERIOR WALLS

BASE MODEL: Sample File

DRAWING: 1 i 6

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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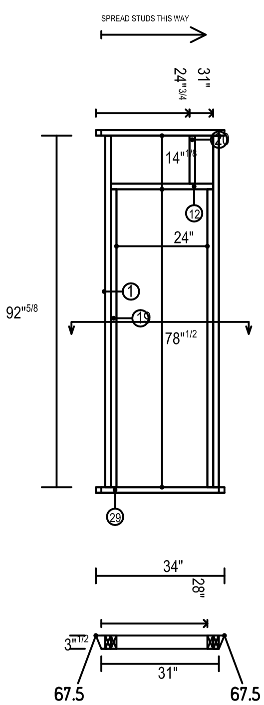
1 i 7



STUDS

TYPE	Q	SIZE	L
1	4	2x4	92"5/8
19	2	2x4	78"1/2
20	1	2x4	12"5/8

PLATES

TYPE	Q	SIZE	L
29	2	2x4	34"

SILLS

TYPE	Q	SIZE	L
12	1	2x4	27"

NO	DATE	BY

REVISIONS

MAIN FLOOR INTERIOR WALLS

BASE MODEL: Sample File

DRAWING: 1 i 7

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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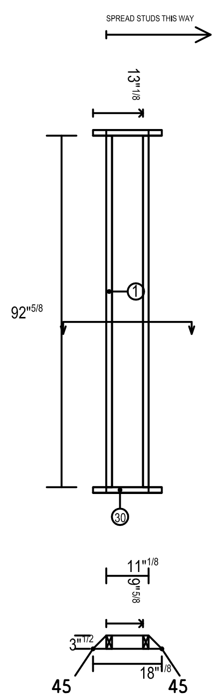
1 i 8



STUDS				PLATES			
TYPE	Q	SIZE	L	TYPE	Q	SIZE	L
1	2	2x4	92"5/8	30	2	2x4	18"1/8

NO	DATE	BY

REVISIONS

MAIN FLOOR INTERIOR WALLS

BASE MODEL: Sample File

DRAWING: 1 i 8

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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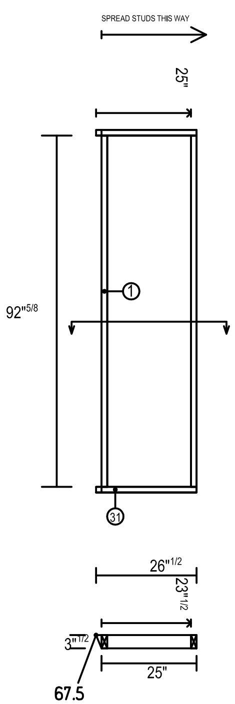
1i9



STUDS				PLATES			
TYPE	Q	SIZE	L	TYPE	Q	SIZE	L
1	2	2x4	92"5/8	31	2	2x4	26"1/2

NO	DATE	BY

REVISIONS

MAIN FLOOR INTERIOR WALLS

BASE MODEL: Sample File

DRAWING: 1i9

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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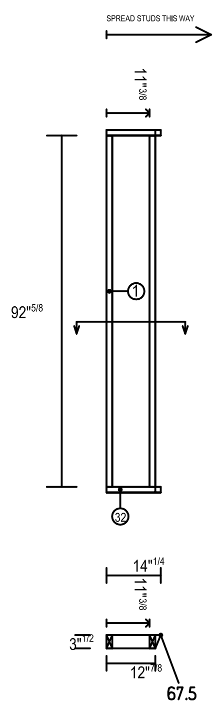
1 i 10



STUDS

TYPE	Q	SIZE	L
1	2	2x4	92"5/8

PLATES

TYPE	Q	SIZE	L
32	2	2x4	14"1/4

NO	DATE	BY

REVISIONS

MAIN FLOOR INTERIOR WALLS

BASE MODEL: Sample File

DRAWING: 1 i 10

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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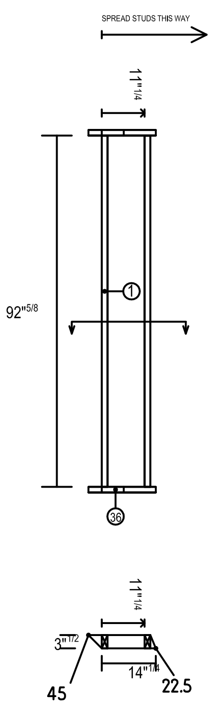
1 i 11



STUDS				PLATES			
TYPE	Q	SIZE	L	TYPE	Q	SIZE	L
1	2	2x4	92"5/8	36	2	2x4	17"3/4

NO	DATE	BY
REVISIONS		

MAIN FLOOR INTERIOR WALLS

BASE MODEL **Sample File**

DRAWING **1 i 11**

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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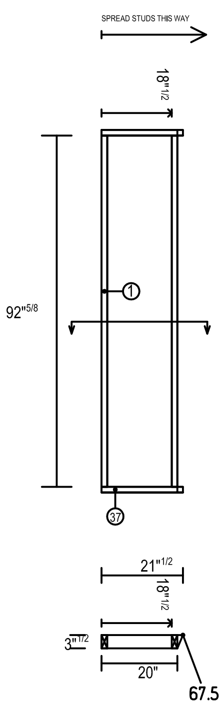
1 i 12



STUDS

TYPE	Q	SIZE	L
1	2	2x4	92"5/8

PLATES

TYPE	Q	SIZE	L
37	2	2x4	21"1/2

NO	DATE	BY

REVISIONS

MAIN FLOOR INTERIOR WALLS

BASE MODEL: Sample File

DRAWING: 1 i 12

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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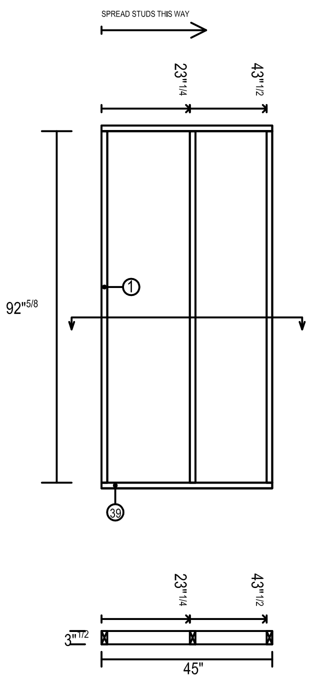
1 i 13



STUDS				PLATES			
TYPE	Q	SIZE	L	TYPE	Q	SIZE	L
1	3	2x4	92"5/8	39	2	2x4	45"

NO	DATE	BY

REVISIONS

MAIN FLOOR INTERIOR WALLS

BASE MODEL: Sample File

DRAWING: 1 i 13

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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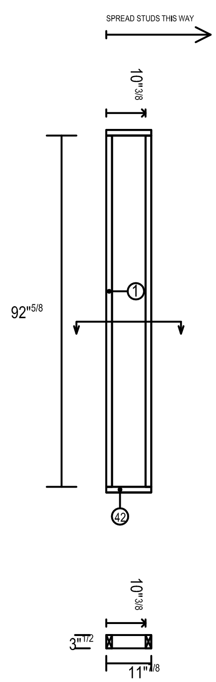
1 i 14



STUDS

TYPE	Q	SIZE	L
1	2	2x4	92"5/8

PLATES

TYPE	Q	SIZE	L
42	2	2x4	11"7/8

NO	DATE	BY

REVISIONS

MAIN FLOOR INTERIOR WALLS

BASE MODEL **Sample File**

DRAWING **1 i 14**

DATE (dd/mm/yy): **2007**

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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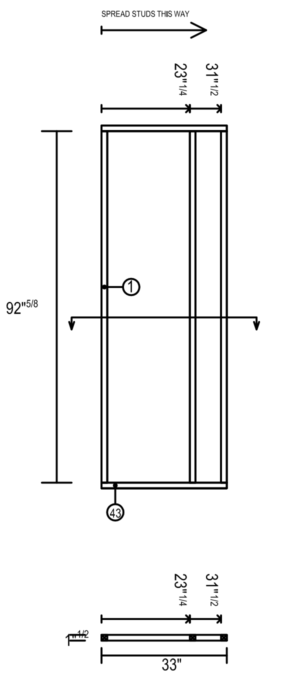
1 i 15



STUDS				PLATES			
TYPE	Q	SIZE	L	TYPE	Q	SIZE	L
1	3	2x2	92"5/8	43	2	2x2	33"

MAIN FLOOR INTERIOR WALLS			
BASE MODEL	Sample File		
DRAWING	1 i 15	DATE (dd/mm/yy):	2007

REVISIONS

NO	DATE	BY

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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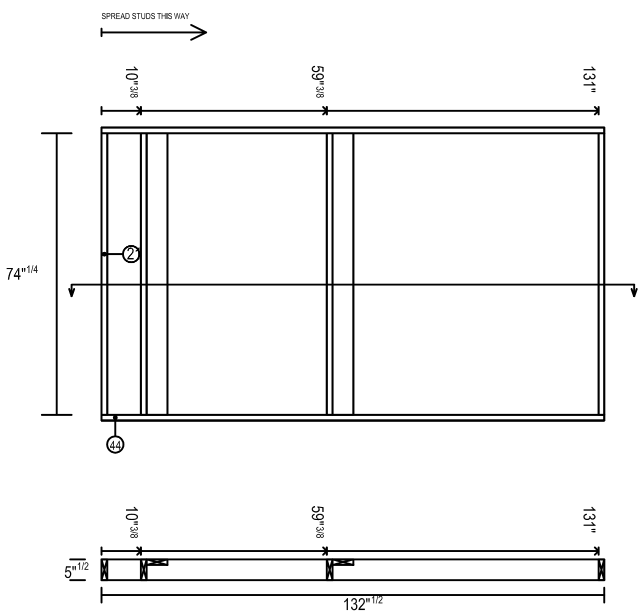
1 i 16



STUDS				PLATES			
TYPE	Q	SIZE	L	TYPE	Q	SIZE	L
21	6	2x6	74"1/4	44	2	2x6	132"1/2

NO	DATE	BY

REVISIONS

MAIN FLOOR INTERIOR WALLS

BASE MODEL **Sample File**

DRAWING **1 i 16**

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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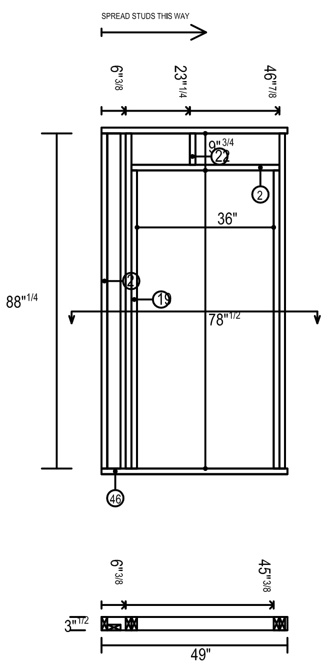
1 i 17



STUDS

TYPE	Q	SIZE	L
2	5	2x4	88"1/4
19	2	2x4	78"1/2
22	1	2x4	8"1/4

PLATES

TYPE	Q	SIZE	L
46	2	2x4	49"

SILLS

TYPE	Q	SIZE	L
2	1	2x4	39"

NO	DATE	BY

REVISIONS

MAIN FLOOR INTERIOR WALLS

BASE MODEL **Sample File**

DRAWING **1 i 17**

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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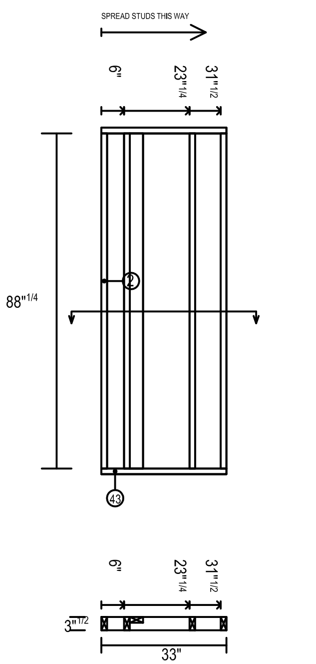
1 i 18



STUDS				PLATES			
TYPE	Q	SIZE	L	TYPE	Q	SIZE	L
2	5	2x4	88"1/4	43	2	2x4	33"

NO	DATE	BY

REVISIONS

MAIN FLOOR INTERIOR WALLS

BASE MODEL: Sample File

DRAWING: 1 i 18

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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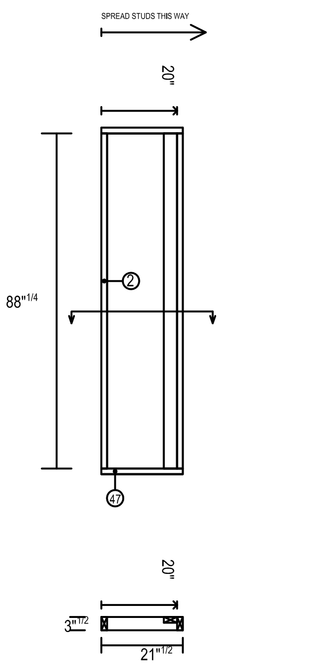
1 i 19



STUDS

TYPE	Q	SIZE	L
2	3	2x4	88"1/4

PLATES

TYPE	Q	SIZE	L
47	2	2x4	21"1/2

NO	DATE	BY

REVISIONS

MAIN FLOOR INTERIOR WALLS

BASE MODEL: Sample File

DRAWING: 1 i 19

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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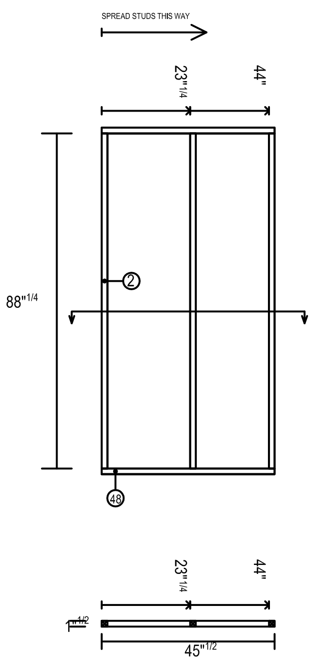
1 i 20



STUDS				PLATES			
TYPE	Q	SIZE	L	TYPE	Q	SIZE	L
2	3	2x2	88"1/4	48	2	2x2	45"1/2

NO	DATE	BY

REVISIONS

MAIN FLOOR INTERIOR WALLS

BASE MODEL: Sample File

DRAWING: 1 i 20

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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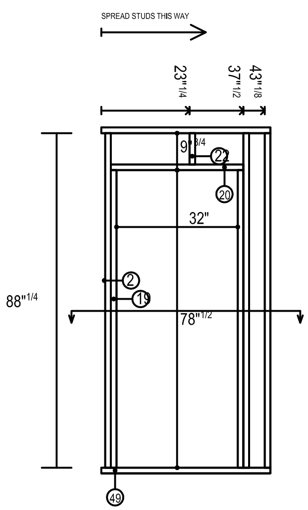
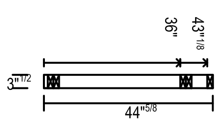
1 i 21





STUDS

TYPE	Q	SIZE	L
2	4	2x4	88"1/4
19	2	2x4	78"1/2
22	1	2x4	8"1/4

PLATES

TYPE	Q	SIZE	L
49	2	2x4	44"5/8

SILLS

TYPE	Q	SIZE	L
20	1	2x4	35"

MAIN FLOOR INTERIOR WALLS	
BASE MODEL	Sample File
DRAWING	1 i 21
DATE (dd/mm/yy):	2007

REVISIONS

NO	DATE	BY

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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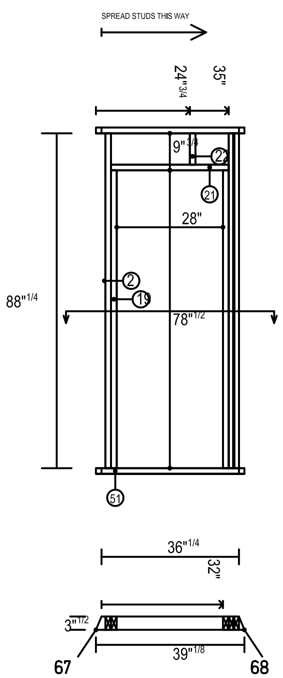
1 i 22



STUDS

TYPE	Q	SIZE	L
2	4	2x4	88"1/4
19	2	2x4	78"1/2
22	1	2x4	8"1/4

PLATES

TYPE	Q	SIZE	L
51	2	2x4	39"1/8

SILLS

TYPE	Q	SIZE	L
21	1	2x4	31"

NO	DATE	BY

REVISIONS

MAIN FLOOR INTERIOR WALLS

BASE MODEL: Sample File

DRAWING: 1 i 22

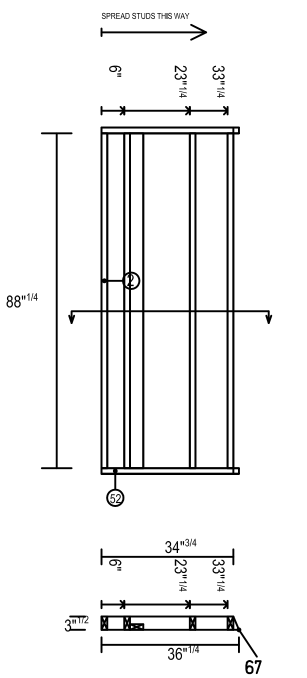
DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

1 i 23



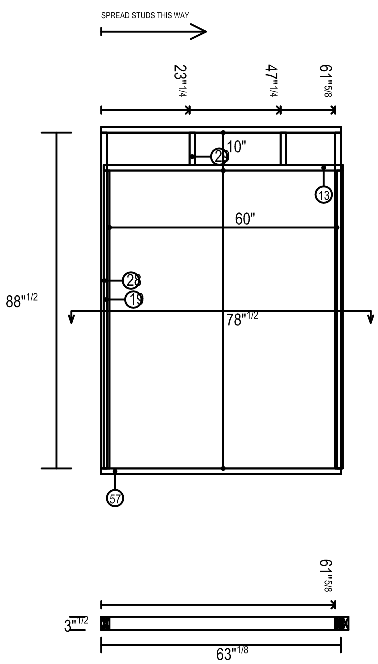
STUDS				PLATES			
TYPE	Q	SIZE	L	TYPE	Q	SIZE	L
2	5	2x4	88"1/4	52	2	2x4	36"1/4

NO	DATE	BY
REVISIONS		

MAIN FLOOR INTERIOR WALLS		
BASE MODEL	Sample File	
DRAWING	1 i 23	DATE (dd/mm/yy): 2007

JOB No:	001
Scale: 3/8in = 1.0ft	
Drawn By: Juan M	
PAGE No	37 / 65

1 i 24



STUDS

TYPE	Q	SIZE	L
28	3	2x4	88"1/2
19	2	2x4	78"1/2
29	2	2x4	8"1/2

PLATES

TYPE	Q	SIZE	L
57	2	2x4	63"1/8

SILLS

TYPE	Q	SIZE	L
13	1	2x4	63"

NO	DATE	BY

REVISIONS

MAIN FLOOR INTERIOR WALLS

BASE MODEL: Sample File

DRAWING: 1 i 24

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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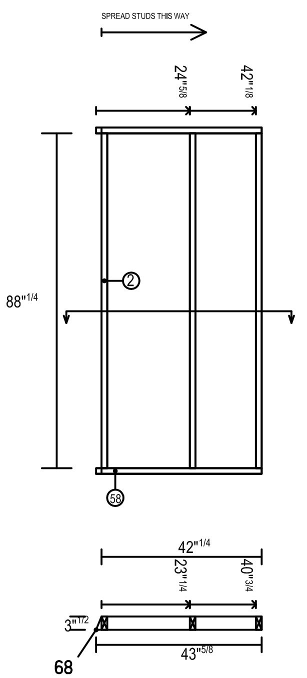
1 i 25



STUDS				PLATES			
TYPE	Q	SIZE	L	TYPE	Q	SIZE	L
2	3	2x4	88"1/4	58	2	2x4	43"5/8

NO	DATE	BY

REVISIONS

MAIN FLOOR INTERIOR WALLS

BASE MODEL: Sample File

DRAWING: 1 i 25

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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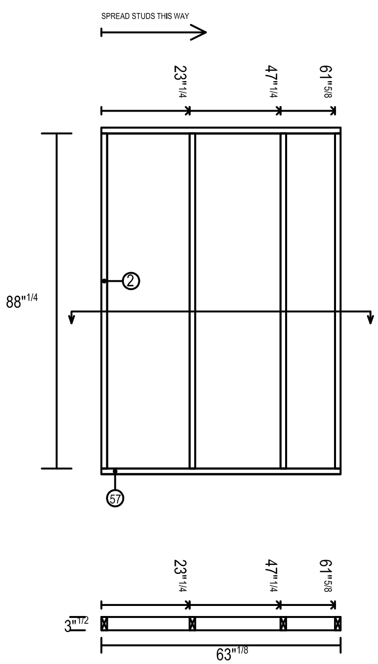
1 i 26



STUDS				PLATES			
TYPE	Q	SIZE	L	TYPE	Q	SIZE	L
2	4	2x4	88"1/4	57	2	2x4	63"1/8

MAIN FLOOR INTERIOR WALLS		
BASE MODEL	Sample File	
DRAWING	1 i 26	DATE (dd/mm/yy): 2007

REVISIONS: NO | DATE | BY

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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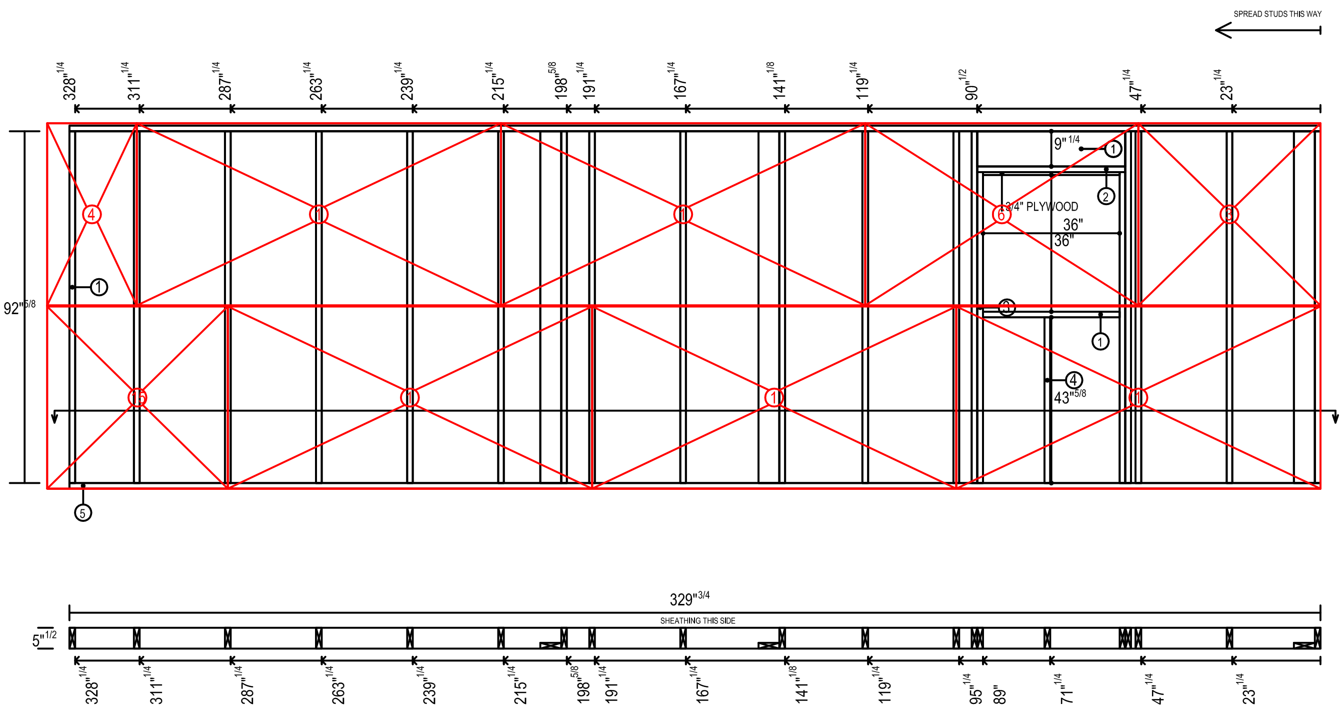
2e 1



STUDS

TYPE	Q	SIZE	L
1	20	2x6	92"5/8
3	2	2x6	81"7/8
4	1	2x6	43"5/8

PLATES

TYPE	Q	SIZE	L
5	2	2x6	329"3/4

SILLS

TYPE	Q	SIZE	L
1	2	2x6	36"
2	1	2x6	39"

HEADERS

TYPE	Q	SIZE	L
1	2	2x10	39"

SHEATHING

TYPE	Q	W	H
1	5	96"	48"
15	1	47"5/8	48"
3	1	48"	48"
6	1	72"	48"
4	1	23"5/8	48"

NO	DATE	BY

REVISIONS

SECOND FLOOR PANEL LAYOUT

BASE MODEL **Sample File**

DRAWING **2e 1**

DATE (dd/mm/yy): **2007**

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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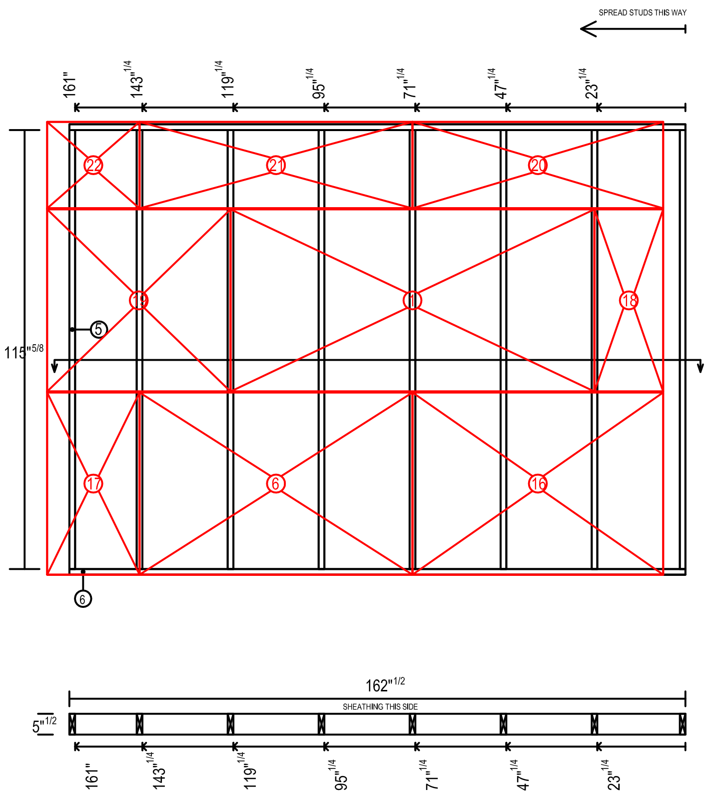
2e 2



STUDS

TYPE	Q	SIZE	L
5	8	2x6	115"5/8

PLATES

TYPE	Q	SIZE	L
6	2	2x6	162"1/2

SHEATHING

TYPE	Q	W	H
16	1	66"1/8	48"
6	1	72"	48"
17	1	24"3/8	48"
18	1	18"1/8	48"
1	1	96"	48"
19	1	48"3/8	48"
20	1	66"1/8	22"3/4
21	1	72"	22"3/4
22	1	24"3/8	22"3/4

NO	DATE	BY

REVISIONS

SECOND FLOOR PANEL LAYOUT

BASE MODEL **Sample File**

DRAWING **2e 2**

DATE (dd/mm/yy): **2007**

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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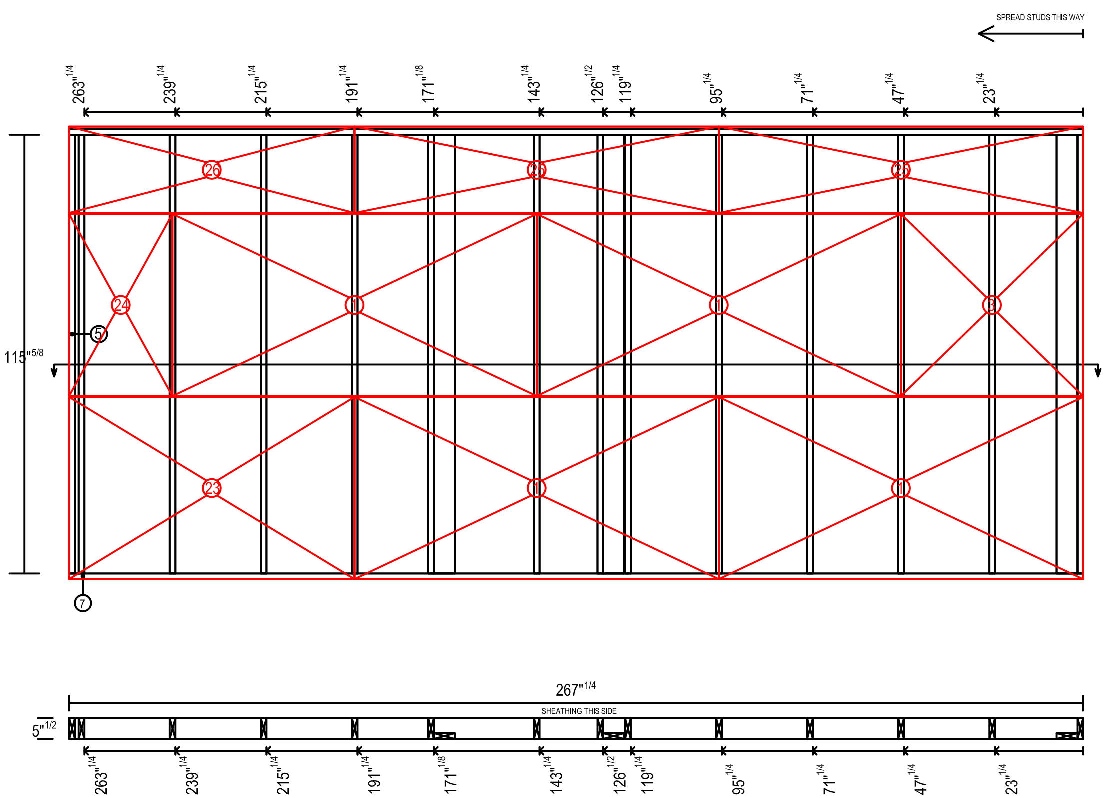
2e 3



STUDS

TYPE	Q	SIZE	L
5	17	2x6	115"5/8

PLATES

TYPE	Q	SIZE	L
7	2	2x6	267"1/4

SHEATHING

TYPE	Q	W	H
1	4	96"	48"
23	1	75"1/4	48"
3	1	48"	48"
24	1	27"1/4	48"
25	2	96"	22"3/4
26	1	75"1/4	22"3/4

SECOND FLOOR PANEL LAYOUT	
BASE MODEL	**Sample File**
DRAWING	**2e 3**
DATE (dd/mm/yy):	2007

REVISIONS

NO	DATE	BY

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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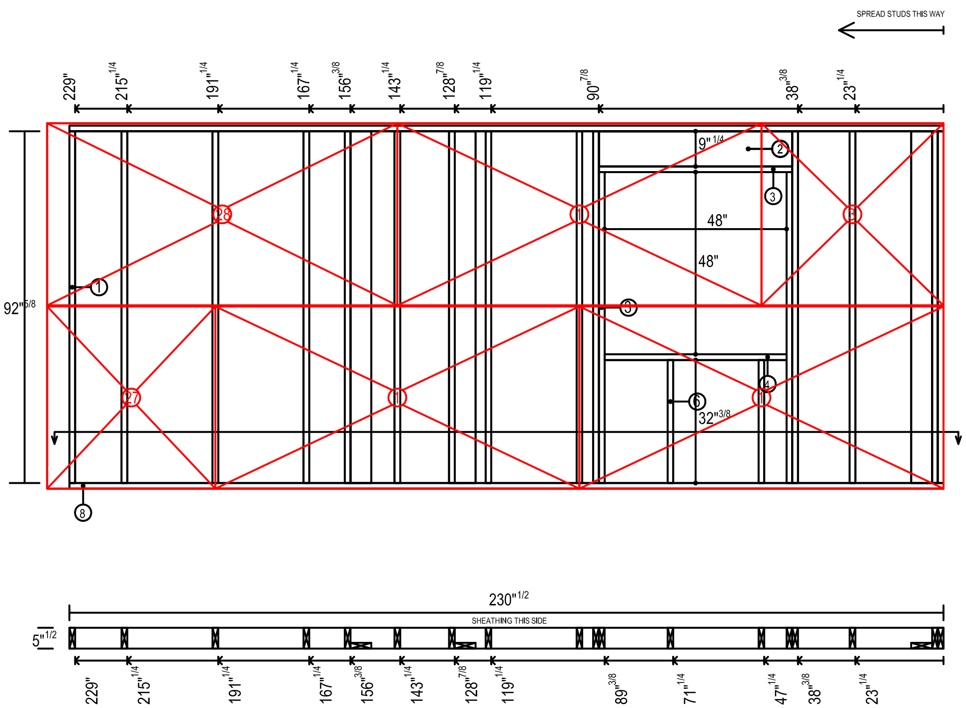
2e 4



STUDS

TYPE	Q	SIZE	L
1	17	2x6	92"5/8
3	2	2x6	81"7/8
6	2	2x6	32"3/8

PLATES

TYPE	Q	SIZE	L
8	2	2x6	230"1/2

SILLS

TYPE	Q	SIZE	L
3	1	2x6	51"
4	1	2x6	48"

HEADERS

TYPE	Q	SIZE	L
2	2	2x10	51"

SHEATHING

TYPE	Q	W	H
1	3	96"	48"
27	1	44"3/8	48"
3	1	48"	48"
28	1	92"3/8	48"

NO	DATE	BY

REVISIONS

SECOND FLOOR PANEL LAYOUT

BASE MODEL: Sample File

DRAWING: 2e 4

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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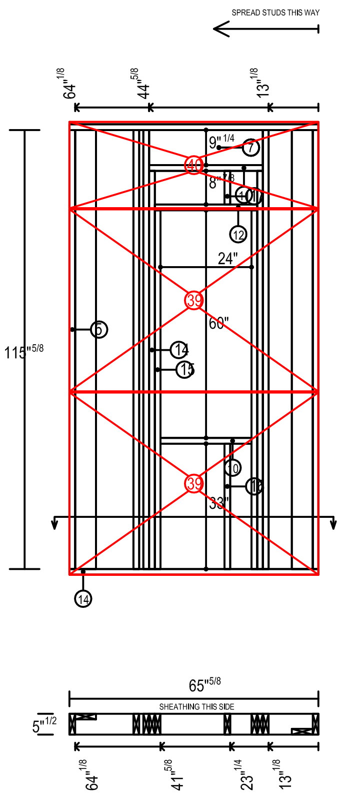
2e 5



STUDS

TYPE	Q	SIZE	L
5	7	2x6	115"5/8
14	2	2x6	104"7/8
15	2	2x6	94"1/2
16	1	2x6	33"
17	1	2x6	8"7/8

PLATES

TYPE	Q	SIZE	L
14	2	2x6	65"5/8

SILLS

TYPE	Q	SIZE	L
10	1	2x6	24"
11	1	2x6	30"
12	1	2x6	27"

HEADERS

TYPE	Q	SIZE	L
7	2	2x10	30"

SHEATHING

TYPE	Q	W	H
39	2	65"5/8	48"
40	1	65"5/8	22"3/4

NO	DATE	BY

REVISIONS

SECOND FLOOR PANEL LAYOUT

BASE MODEL: Sample File

DRAWING: 2e 5

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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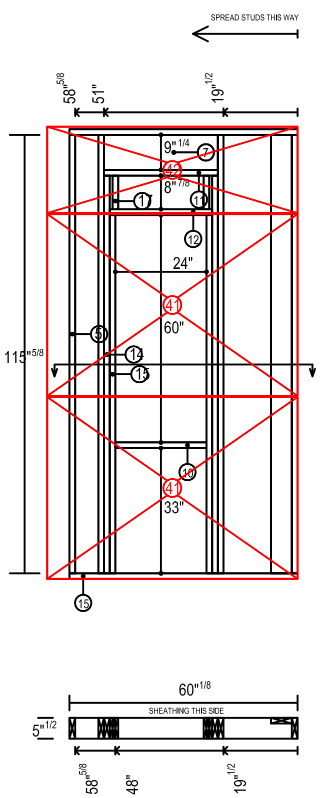
2e 6



STUDS			
TYPE	Q	SIZE	L
5	5	2x6	115"5/8
14	2	2x6	104"7/8
15	2	2x6	94"1/2
17	2	2x6	8"7/8

PLATES			
TYPE	Q	SIZE	L
15	2	2x6	60"1/8

SILLS			
TYPE	Q	SIZE	L
10	1	2x6	24"
11	1	2x6	30"
12	1	2x6	27"

HEADERS			
TYPE	Q	SIZE	L
7	2	2x10	30"

SHEATHING			
TYPE	Q	W	H
41	2	66"	48"
42	1	66"	22"3/4

NO	DATE	BY

REVISIONS

SECOND FLOOR PANEL LAYOUT

BASE MODEL: **Sample File**

DRAWING: **2e 6**

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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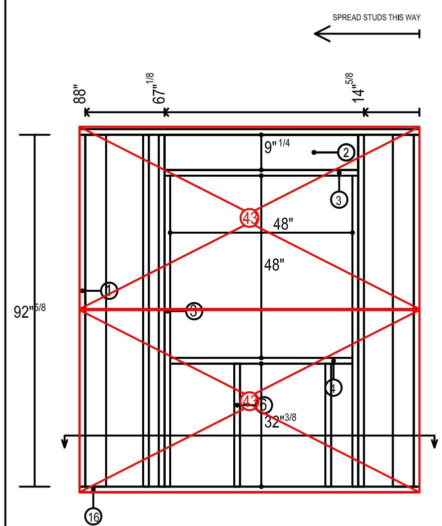
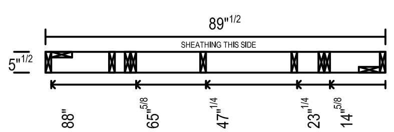
2e 7





STUDS

TYPE	Q	SIZE	L
1	7	2x6	92"5/8
3	2	2x6	81"7/8
6	2	2x6	32"3/8

PLATES

TYPE	Q	SIZE	L
16	2	2x6	89"1/2

SILLS

TYPE	Q	SIZE	L
4	1	2x6	48"
3	1	2x6	51"

HEADERS

TYPE	Q	SIZE	L
2	2	2x10	51"

SHEATHING

TYPE	Q	W	H
43	2	89"1/2	48"

NO	DATE	BY

REVISIONS

SECOND FLOOR PANEL LAYOUT

BASE MODEL: Sample File

DRAWING: 2e 7

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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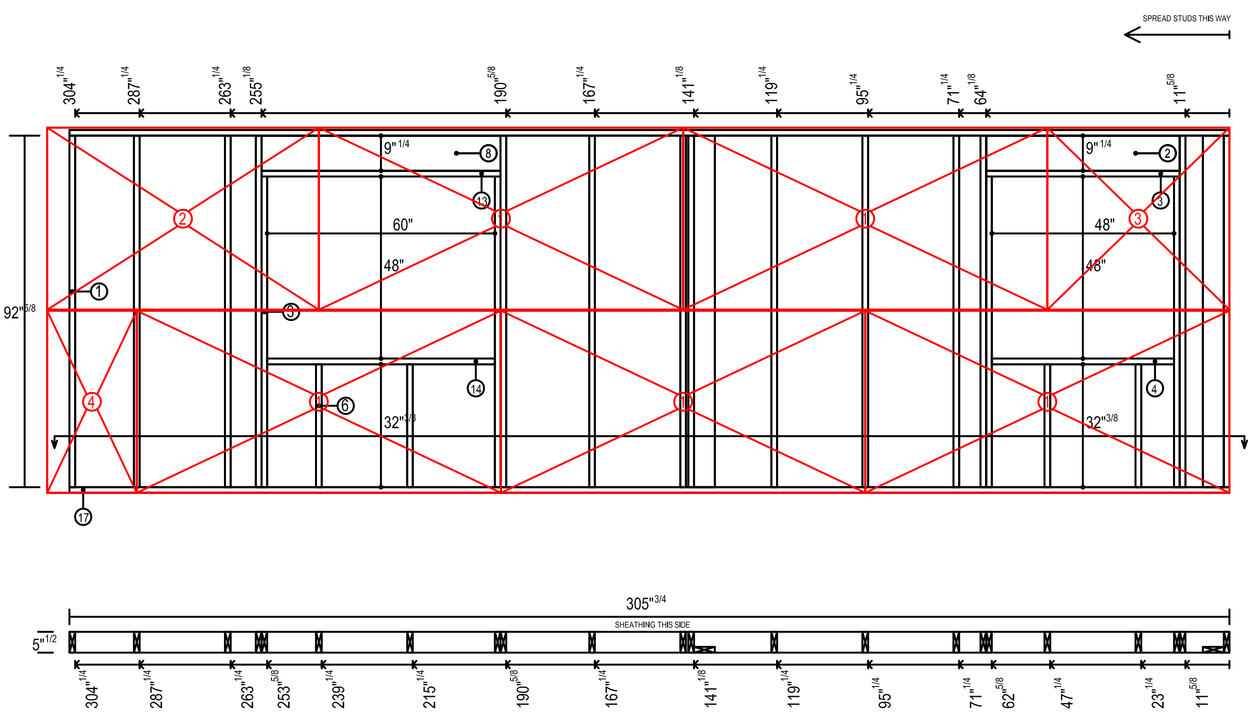
2e 8



STUDS

TYPE	Q	SIZE	L
1	16	2x6	92"5/8
3	4	2x6	81"7/8
6	4	2x6	32"3/8

PLATES

TYPE	Q	SIZE	L
17	2	2x6	305"3/4

SILLS

TYPE	Q	SIZE	L
13	1	2x6	63"
14	1	2x6	60"
3	1	2x6	51"
4	1	2x6	48"

HEADERS

TYPE	Q	SIZE	L
8	2	2x10	63"
2	2	2x10	51"

SHEATHING

TYPE	Q	W	H
1	5	96"	48"
4	1	23"5/8	48"
3	1	48"	48"
2	1	71"5/8	48"

NO | DATE | BY
REVISIONS

SECOND FLOOR PANEL LAYOUT

BASE MODEL: Sample File

DRAWING: 2e 8

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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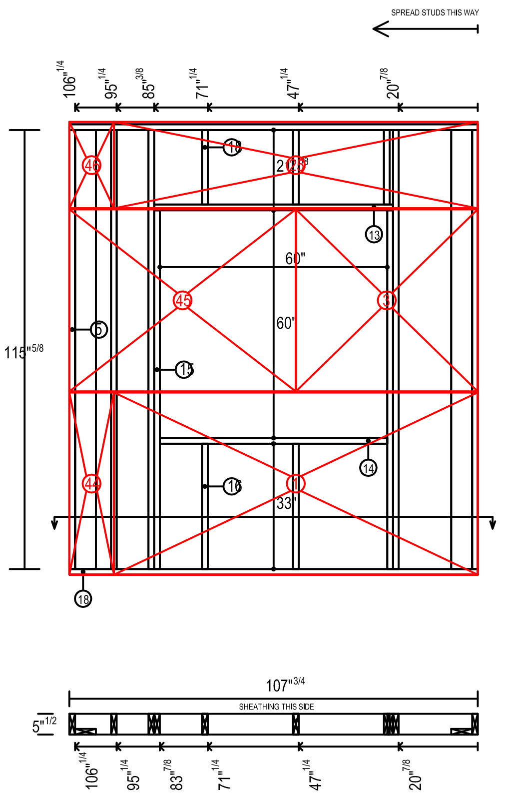
2e 9



STUDS

TYPE	Q	SIZE	L
5	7	2x6	115"5/8
15	2	2x6	94"1/2
16	2	2x6	33"
18	3	2x6	19"5/8

PLATES

TYPE	Q	SIZE	L
18	2	2x6	107"3/4

SILLS

TYPE	Q	SIZE	L
14	1	2x6	60"
13	1	2x6	63"

SHEATHING

TYPE	Q	W	H
1	1	96"	48"
44	1	11"3/4	48"
3	1	48"	48"
45	1	59"3/4	48"
25	1	96"	22"3/4
46	1	11"3/4	22"3/4

NO	DATE	BY

REVISIONS

SECOND FLOOR PANEL LAYOUT

BASE MODEL **Sample File**

DRAWING **2e 9**

DATE (dd/mm/yy): **2007**

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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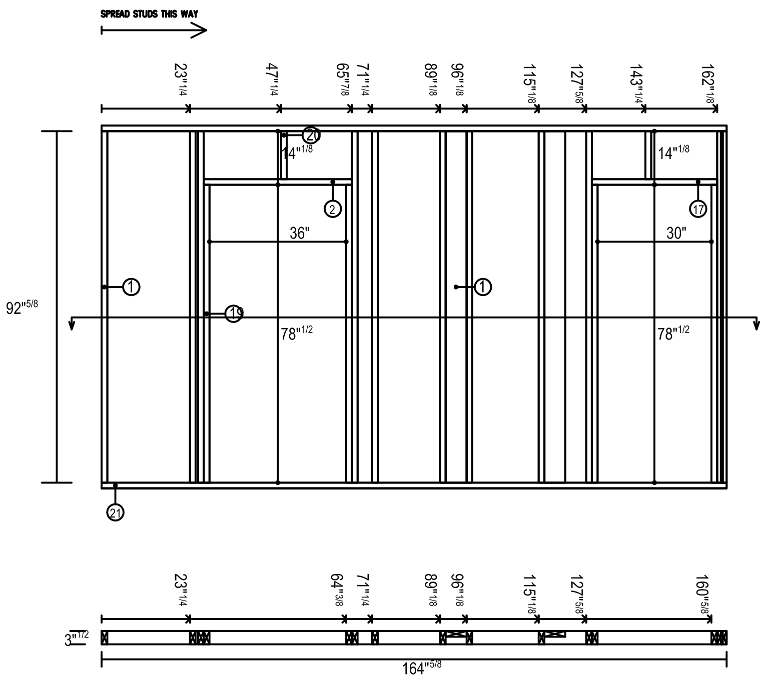
2 i 1



STUDS				PLATES				SILLS			
TYPE	Q	SIZE	L	TYPE	Q	SIZE	L	TYPE	Q	SIZE	L
1	11	2x4	92"5/8	21	2	2x4	164"5/8	2	1	2x4	39"
19	4	2x4	78"1/2					17	1	2x4	33"
20	2	2x4	12"5/8								
1	2	2x6	92"5/8								

NO	DATE	BY

REVISIONS

SECOND FLOOR INTERIOR WALLS

BASE MODEL **Sample File**

DRAWING **2 i 1**

DATE (dd/mm/yy): **2007**

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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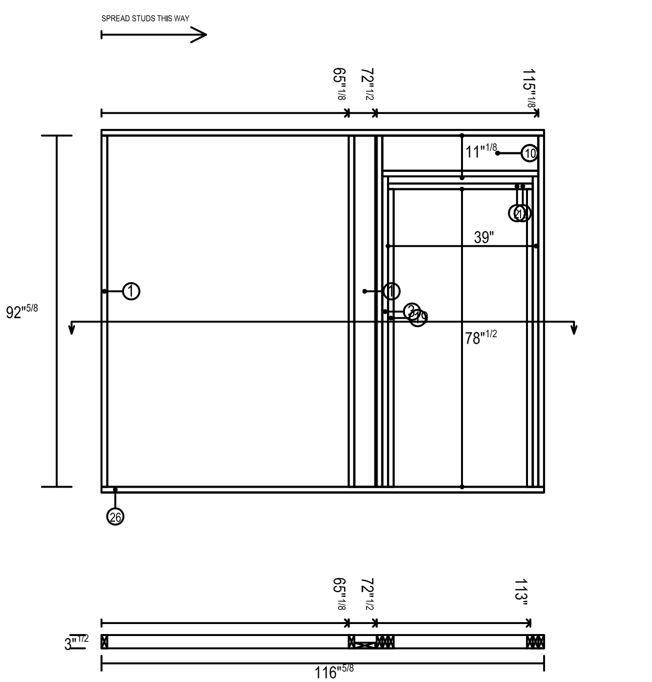
2 i 2



STUDS			
TYPE	Q	SIZE	L
1	5	2x4	92"5/8
1	1	2x6	92"5/8
3	2	2x4	81"7/8
19	2	2x4	78"1/2

PLATES			
TYPE	Q	SIZE	L
26	2	2x4	116"5/8

SILLS			
TYPE	Q	SIZE	L
2	1	2x4	39"
18	1	2x4	42"

HEADERS			
TYPE	Q	SIZE	L
10	2	2x10	42"

NO	DATE	BY

REVISIONS

SECOND FLOOR INTERIOR WALLS

BASE MODEL: Sample File

DRAWING: 2 i 2

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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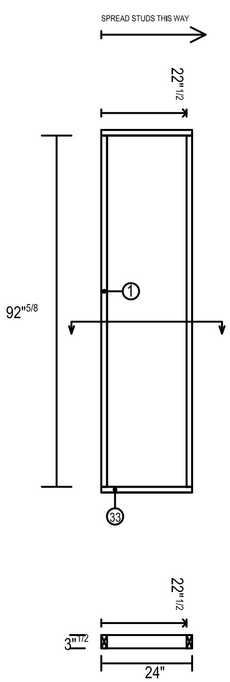
2 i 3



STUDS				PLATES			
TYPE	Q	SIZE	L	TYPE	Q	SIZE	L
1	2	2x4	92"5/8	33	2	2x4	24"

NO	DATE	BY

REVISIONS

SECOND FLOOR INTERIOR WALLS

BASE MODEL **Sample File**

DRAWING **2 i 3**

DATE (dd/mm/yy): **2007**

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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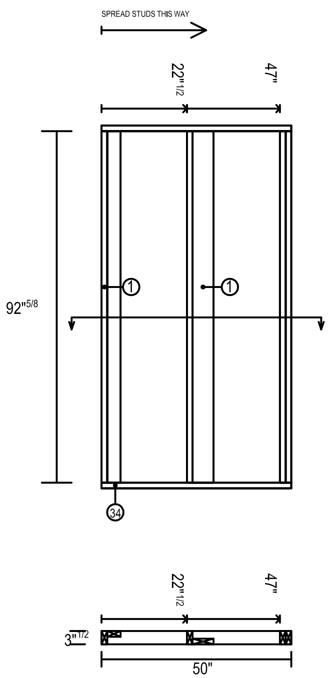
2 i 4



STUDS

TYPE	Q	SIZE	L
1	5	2x4	92"5/8
1	1	2x6	92"5/8

PLATES

TYPE	Q	SIZE	L
34	2	2x4	50"

NO	DATE	BY

REVISIONS

SECOND FLOOR INTERIOR WALLS

BASE MODEL: Sample File

DRAWING: 2 i 4

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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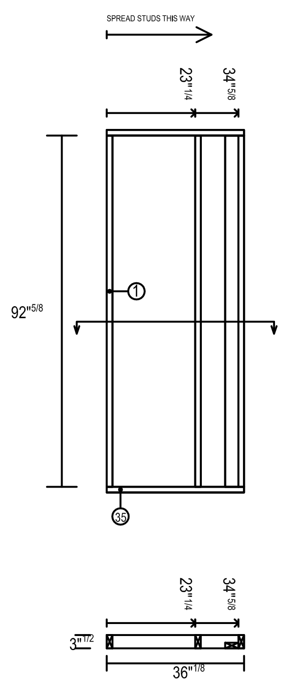
2 i 5



STUDS				PLATES			
TYPE	Q	SIZE	L	TYPE	Q	SIZE	L
1	4	2x4	92"5/8	35	2	2x4	36"1/8

NO	DATE	BY
REVISIONS		

SECOND FLOOR INTERIOR WALLS

BASE MODEL: Sample File

DRAWING: 2 i 5

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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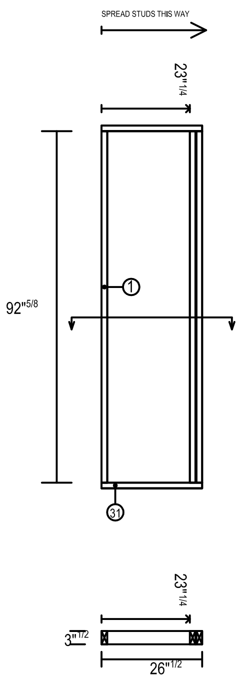
2 i 6



STUDS

TYPE	Q	SIZE	L
1	3	2x4	92"5/8

PLATES

TYPE	Q	SIZE	L
31	2	2x4	26"1/2

NO	DATE	BY

REVISIONS

SECOND FLOOR INTERIOR WALLS

BASE MODEL: Sample File

DRAWING: 2 i 6

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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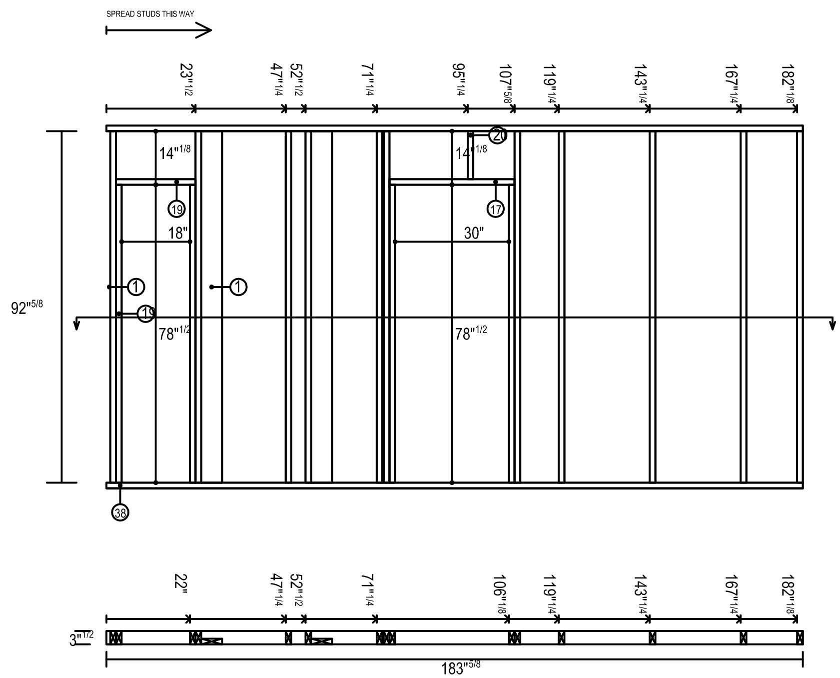
2 i 7



STUDS

TYPE	Q	SIZE	L
1	12	2x4	92"5/8
19	4	2x4	78"1/2
1	2	2x6	92"5/8
20	1	2x4	12"5/8

PLATES

TYPE	Q	SIZE	L
38	2	2x4	183"5/8

SILLS

TYPE	Q	SIZE	L
19	1	2x4	21"
17	1	2x4	33"

NO	DATE	BY

REVISIONS

SECOND FLOOR INTERIOR WALLS

BASE MODEL: Sample File

DRAWING: 2 i 7

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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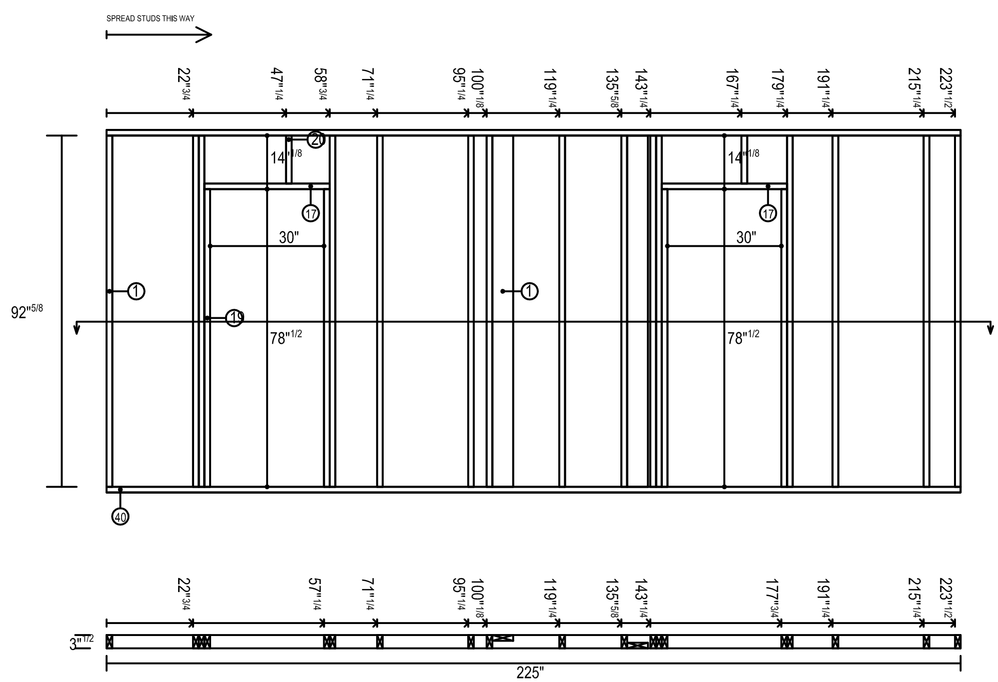
2 i 8



STUDS

TYPE	Q	SIZE	L
1	15	2x4	92"5/8
19	4	2x4	78"1/2
20	2	2x4	12"5/8
1	2	2x6	92"5/8

PLATES

TYPE	Q	SIZE	L
40	2	2x4	225"

SILLS

TYPE	Q	SIZE	L
17	2	2x4	33"

NO	DATE	BY

REVISIONS

SECOND FLOOR INTERIOR WALLS

BASE MODEL **Sample File**

DRAWING **2 i 8**

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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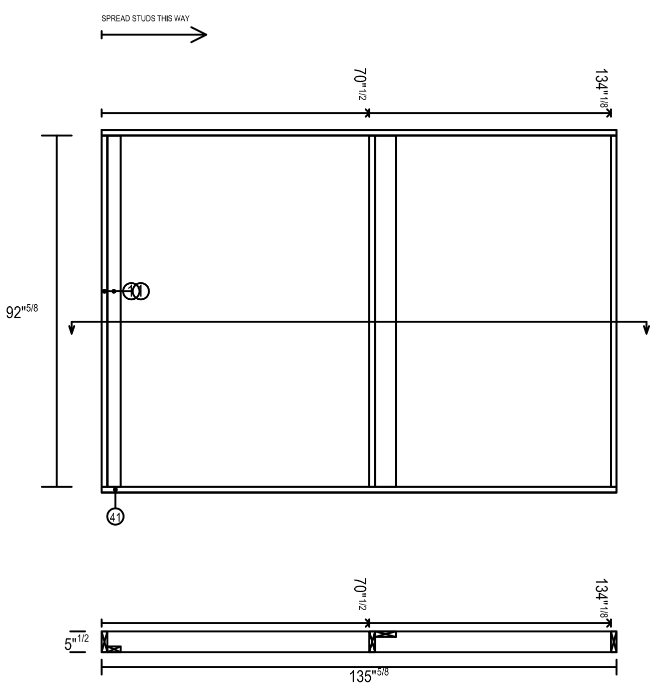
2 i 9



STUDS

TYPE	Q	SIZE	L
1	4	2x6	92"5/8
1	1	2x4	92"5/8

PLATES

TYPE	Q	SIZE	L
41	2	2x6	135"5/8

NO	DATE	BY

REVISIONS

SECOND FLOOR INTERIOR WALLS

BASE MODEL: Sample File

DRAWING: 2 i 9

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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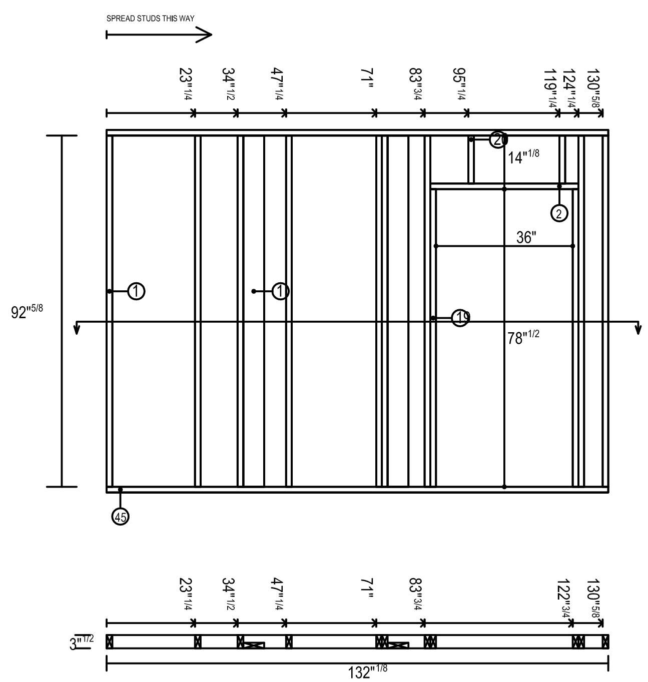
2 i 10



STUDS

TYPE	Q	SIZE	L
1	9	2x4	92"5/8
1	2	2x6	92"5/8
19	2	2x4	78"1/2
20	2	2x4	12"5/8

PLATES

TYPE	Q	SIZE	L
45	2	2x4	132"1/8

SILLS

TYPE	Q	SIZE	L
2	1	2x4	39"

NO	DATE	BY

REVISIONS

SECOND FLOOR INTERIOR WALLS

BASE MODEL: Sample File

DRAWING: 2 i 10

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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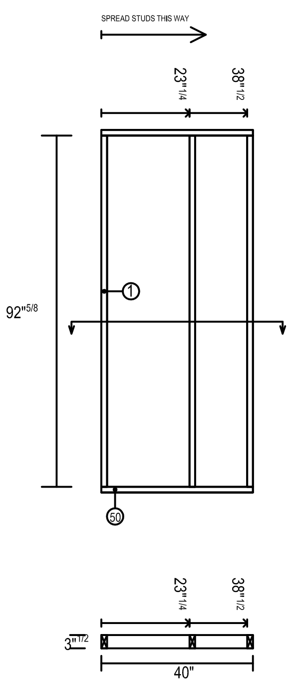
2 i 11



STUDS

TYPE	Q	SIZE	L
1	3	2x4	92"5/8

PLATES

TYPE	Q	SIZE	L
50	2	2x4	40"

NO	DATE	BY

REVISIONS

SECOND FLOOR INTERIOR WALLS

BASE MODEL: Sample File

DRAWING: 2 i 11

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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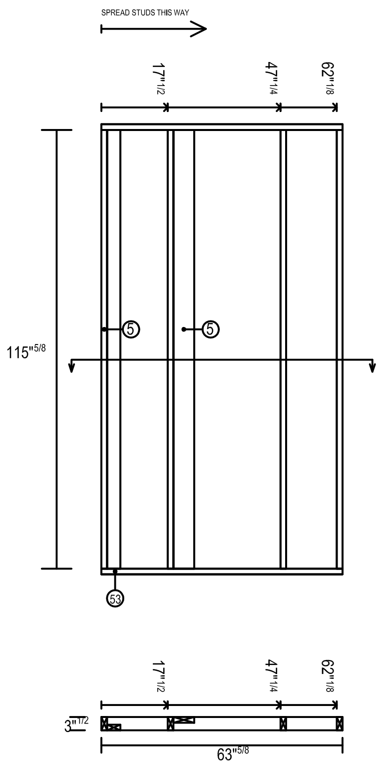
2 i 12



STUDS				PLATES			
TYPE	Q	SIZE	L	TYPE	Q	SIZE	L
5	5	2x4	115"5/8	53	2	2x4	63"5/8
5	1	2x6	115"5/8				

NO	DATE	BY
REVISIONS		

SECOND FLOOR INTERIOR WALLS

BASE MODEL: Sample File

DRAWING: 2 i 12

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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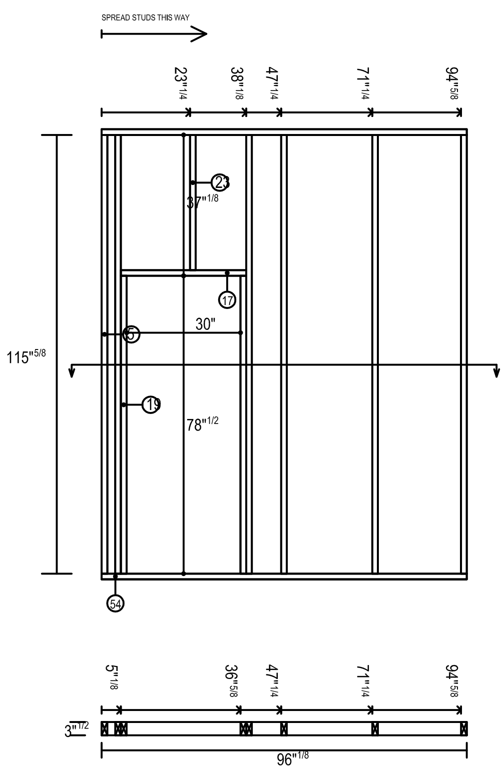
2 i 13



STUDS

TYPE	Q	SIZE	L
5	6	2x4	115"5/8
19	2	2x4	78"1/2
23	1	2x4	35"5/8

PLATES

TYPE	Q	SIZE	L
54	2	2x4	96"1/8

SILLS

TYPE	Q	SIZE	L
17	1	2x4	33"

NO	DATE	BY

REVISIONS

SECOND FLOOR INTERIOR WALLS

BASE MODEL: Sample File

DRAWING: 2 i 13

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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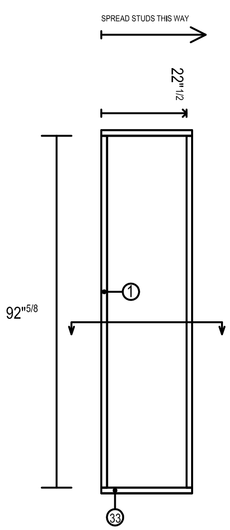
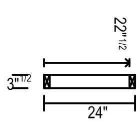
2 i 14





STUDS				PLATES			
TYPE	Q	SIZE	L	TYPE	Q	SIZE	L
1	2	2x4	92"5/8	33	2	2x4	24"

NO	DATE	BY
REVISIONS		

SECOND FLOOR INTERIOR WALLS

BASE MODEL: Sample File

DRAWING: 2 i 14

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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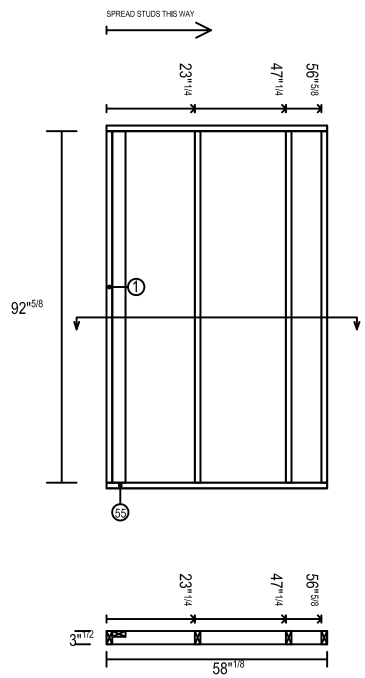
2 i 15



STUDS

TYPE	Q	SIZE	L
1	5	2x4	92"5/8

PLATES

TYPE	Q	SIZE	L
55	2	2x4	58"1/8

NO	DATE	BY

REVISIONS

SECOND FLOOR INTERIOR WALLS

BASE MODEL **Sample File**

DRAWING **2 i 15**

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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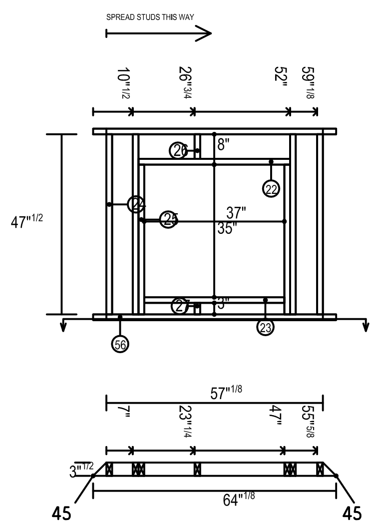
2 i 16



STUDS

TYPE	Q	SIZE	L
24	4	2x4	47"1/2
25	2	2x4	39"1/2
26	1	2x4	6"1/2
27	1	2x4	3"

PLATES

TYPE	Q	SIZE	L
56	2	2x4	64"1/8

SILLS

TYPE	Q	SIZE	L
22	1	2x4	40"
23	1	2x4	37"

NO	DATE	BY

REVISIONS

SECOND FLOOR INTERIOR WALLS

BASE MODEL: Sample File

DRAWING: 2 i 16

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: 3/8in = 1.0ft

Drawn By: Juan M

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TAKE-OFF LIST

STUDS

TYPE	Q	SIZE	L (in)
1	3	2x2	92"5/8
2	3	2x2	88"1/4
1	140	2x4	92"5/8
2	33	2x4	88"1/4
3	2	2x4	81"7/8
5	11	2x4	115"5/8
8	10	2x4	9"1/8
9	6	2x4	72"
19	30	2x4	78"1/2
20	9	2x4	12"5/8
22	3	2x4	8"1/4
23	1	2x4	35"5/8
24	4	2x4	47"1/2
25	2	2x4	39"1/2
26	1	2x4	6"1/2
27	1	2x4	3"
28	3	2x4	88"1/2
29	2	2x4	8"1/2
1	141	2x6	92"5/8
2	9	2x6	88"1/4
3	18	2x6	81"7/8
4	1	2x6	43"5/8
5	45	2x6	115"5/8
6	8	2x6	32"3/8
7	7	2x6	69"5/8
10	2	2x6	84"
11	12	2x6	83"3/4
12	2	2x6	81"
13	5	2x6	20"3/8
14	4	2x6	104"7/8
15	6	2x6	94"1/2
16	3	2x6	33"
17	3	2x6	8"7/8
18	3	2x6	19"5/8
21	6	2x6	74"1/4

HEADERS

TYPE	Q	SIZE	L (in)
1	2	2x10	39"
2	6	2x10	51"
5	2	2x10	55"1/2
6	2	2x10	74"7/8
7	4	2x10	30"
8	4	2x10	63"
9	2	2x10	75"1/2
10	2	2x10	42"
3	1	2x12	15"
4	2	2x12	201"

SILLS

TYPE	Q	SIZE	L (in)
2	5	2x4	39"
12	1	2x4	27"
13	1	2x4	63"
17	5	2x4	33"
18	1	2x4	42"
19	1	2x4	21"
20	1	2x4	35"
21	1	2x4	31"
22	1	2x4	40"
23	1	2x4	37"
1	4	2x6	36"
2	1	2x6	39"
3	3	2x6	51"
4	3	2x6	48"
5	1	2x6	195"
6	1	2x6	37"5/8
7	1	2x6	55"1/2
8	1	2x6	74"7/8
9	1	2x6	71"7/8
10	2	2x6	24"
11	2	2x6	30"
12	2	2x6	27"
13	3	2x6	63"
14	3	2x6	60"
15	1	2x6	75"1/2
16	2	2x6	72"1/2

PLATES

TYPE	Q	SIZE	L (in)
43	2	2x2	33"
48	2	2x2	45"1/2
1	4	2x4	263"5/8
10	2	2x4	220"1/4
21	2	2x4	164"5/8
22	2	2x4	43"1/8
23	2	2x4	24"3/4
24	2	2x4	18"7/8
25	2	2x4	26"1/8
26	2	2x4	116"5/8
28	2	2x4	52"5/8
29	2	2x4	34"
30	2	2x4	18"1/8
31	4	2x4	26"1/2
32	2	2x4	14"1/4
33	4	2x4	24"
34	2	2x4	50"
35	2	2x4	36"1/8
36	2	2x4	17"3/4
37	2	2x4	21"1/2
38	2	2x4	183"5/8
39	2	2x4	45"
40	2	2x4	225"
42	2	2x4	11"7/8
43	2	2x4	33"
45	2	2x4	132"1/8
46	2	2x4	49"
47	2	2x4	21"1/2
49	2	2x4	44"5/8
50	2	2x4	40"
51	2	2x4	39"1/8
52	2	2x4	36"1/4
53	2	2x4	63"5/8
54	2	2x4	96"1/8
55	2	2x4	58"1/8
56	2	2x4	64"1/8
57	4	2x4	63"1/8
58	2	2x4	43"5/8
2	2	2x6	306"
3	2	2x6	173"5/8
4	2	2x6	126"5/8
5	2	2x6	329"3/4
6	2	2x6	162"1/2
7	2	2x6	267"1/4
8	2	2x6	230"1/2
9	2	2x6	120"1/2
11	2	2x6	107"1/8
12	2	2x6	83"5/8
13	2	2x6	146"
14	2	2x6	65"5/8
15	2	2x6	60"1/8
16	2	2x6	89"1/2
17	2	2x6	305"3/4
18	2	2x6	107"3/4

SHEATHING

TYPE	Q	W(in)	H(in)
1	38	96"	48"
2	3	71"5/8	48"
3	9	48"	48"
4	4	23"5/8	48"
5	1	74"1/4	48"
6	5	72"	48"
7	1	69"5/8	48"
8	1	26"1/4	48"
9	1	93"5/8	48"
10	1	83"1/2	48"
11	1	35"1/2	48"
12	1	30"5/8	48"
13	1	48"	43"5/8
14	1	78"5/8	43"5/8
15	1	47"5/8	48"
16	1	66"1/8	48"
17	1	24"3/8	48"
18	1	18"1/8	48"
19	1	48"3/8	48"
20	1	66"1/8	22"3/4
21	1	72"	22"3/4
22	1	24"3/8	22"3/4
23	1	75"1/4	48"
24	1	27"1/4	48"
25	3	96"	22"3/4
26	1	75"1/4	22"3/4
27	1	44"3/8	48"
28	1	92"3/8	48"
29	1	24"1/2	48"
30	1	48"	25"
31	1	72"1/2	25"
32	1	41"	48"
33	1	24"	39"1/8
34	1	89"	39"1/8
35	2	83"5/8	48"
36	1	47"3/4	48"
37	2	24"	48"
38	1	23"3/4	48"
39	2	65"5/8	48"
40	1	65"5/8	22"3/4
41	2	66"	48"
42	1	66"	22"3/4
43	2	89"1/2	48"
44	1	11"3/4	48"
45	1	59"3/4	48"
46	1	11"3/4	22"3/4
47	1	22"1/4	48"
48	1	70"1/4	48"
49	1	47"	48"
50	1	95"	48"

NO | DATE | BY
REVISIONS

TAKE-OFF LIST OF MATERIALS

BASE MODEL: Sample File

DRAWING: MATERIAL LIST

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: N.A.

Drawn By: Juan M

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TAKE-OFF LIST

STUDS

TYPE	Q	SIZE	L (in)

HEADERS

TYPE	Q	SIZE	L (in)

SILLS

TYPE	Q	SIZE	L (in)

PLATES

TYPE	Q	SIZE	L (in)
19	2	2x6	118" 1/4
20	2	2x6	115" 3/8
27	2	2x6	109" 5/8
41	2	2x6	135" 5/8
44	2	2x6	132" 1/2

SHEATHING

TYPE	Q	W(in)	H(in)

NO	DATE	BY

REVISIONS

TAKE-OFF LIST OF MATERIALS

BASE MODEL: Sample File

DRAWING: MATERIAL LIST

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: N.A.

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ELEMENT COMBINATIONS

STUD/CRIPPLE COMPOSITIONS

Q	Size	Stud L(in)	Crip. Q	Crip. L(in)	Crip. L(in)
18	2x6	92"$^{5/8}$	1	81"$^{7/8}$	
4	2x6	115"$^{5/8}$	1	104"$^{7/8}$	94"$^{1/2}$
2	2x6	83"$^{3/4}$	1	81"	
2	2x6	115"$^{5/8}$	1	94"$^{1/2}$	
18	2x4	92"$^{5/8}$	1	78"$^{1/2}$	
2	2x4	92"$^{5/8}$	1	81"$^{7/8}$	78"$^{1/2}$
6	2x4	88"$^{1/4}$	1	78"$^{1/2}$	
2	2x4	115"$^{5/8}$	1	78"$^{1/2}$	
2	2x4	47"$^{1/2}$	1	39"$^{1/2}$	

NO	DATE	BY

REVISIONS

ELEMENT COMBINATIONS

BASE MODEL Sample File

DRAWING ELEMENT COMB.

DATE (dd/mm/yy): 2007

JOB No: 001

Scale: N.A.

Drawn By: Juan M

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