

**Operational, Aesthetic, and Construction Process Performance  
for Innovative Passive and  
Active Solar Building Components  
for  
Residential Buildings**

by Kevin Settlemyre

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for fulfillment of the requirements for the degrees of:  
Master of Science in Building Technology  
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&  
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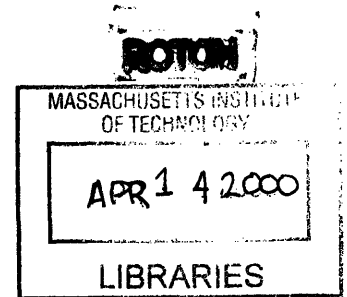
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Submitted to the Department of Architecture and Department of Civil and Environmental Engineering on  
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**Abstract:**

A system-based framework creates the ability to integrate operational, aesthetic, and construction process performance. The framework can be used to evaluate innovations within residential construction. By reducing the constraints for use, the framework is adaptable and flexible to specific projects and to the alternatives developed by the user. Passive and active solar design strategies are brought together in the creation of the Energy Producing Wall (EPW) components. Two component types, EPW1 & EPW2, can be adapted to create five different panel types. These units can be installed on the roof or vertical walls, and provide the innovative subject for evaluation within the framework. Four alternatives within two prototype homes, located in two climates, were analyzed to represent the existing and potential stock of housing and to provide the source of input data into the framework. An adaptable spreadsheet analysis, based on past and current analytical methods, establishes the EPW's potential benefit on the heating, cooling, electricity and total energy consumption loads within the prototype designs. Visualization models combined with physical models assess the aesthetics. The development of a Dynamic Process Model for Light Wood Framing (DPM-LWF) represents the framing construction process for the prototype designs, and provides time and cost impacts of the EPW alternatives. The results from each analytical tool are combined to analyze the impacts of implementation, case results and sensitivities within the cases. A 'case result format' presents the results of the multiple alternatives for direct comparison, and can guide further investigations and information within the document. The EPW components demonstrated a 95% benefit for the electrical load of the "Modern Design" in Phoenix (currently), and the potential to reach over 100% benefit of the heating load in Boston for the "Sears Design".

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## Chapter 1: Introduction

*A large part of the problem we face today in respect of the natural resources of life is attributable to one-sided processes of optimization, in which insufficient attention is paid to potential side effects. Success comes more easily by ignoring disturbing secondary issues than by seeking a balance between the various factors involved.*

*A holistic approach to problems can be achieved only if we succeed in intensifying interdisciplinary thinking in collaboration between the arts, natural and social sciences, engineering and economics, and if environmental design is understood as a complex central discipline.*

### **Solar Building – Euphoria and Skepticism**

*Frank Kaltenbach [1]*

The two quotes above are, in a way, a call to arms for the design and construction community, which includes engineers, architects, contractors, manufacturers and owners, to develop an understanding of the other disciplines' methods and focus, while reshaping the way the individual disciplinary work is performed. The current state of the residential construction industry is one of misperception of innovation, cultural difference, and one-sided optimization of the single family home, resulting in a diminished level of quality. The residential industry provides a prime target for the development of an integrated framework that would allow innovation, and ideas (past, present, and future) to be implemented within the process of design and construction. The overall goal is to raise the level of quality of the built environment, while also increasing the quality of working relationships.

The framework hinted at within the quotes describes an evaluation framework that allows implications regarding the visual appearance (aesthetics), functionality (present and future operations), and the means and methods of construction (construction process) to be visualized studied and understood by the different groups involved. The framework must have the capability to reach the most basic level of assumption, i.e. the task or detail (material), within each category so that the influential factors can be identified and sensitivities understood, while remaining knowledgeable of the impacts at the "bigger picture levels" (component and system). Therefore, it must respond to the dynamics that occur during the design, on-site, or during functional operation, relying on flexible

boundaries to allow the framework to move and be shaped by the user. The interface would be one computationally driven, but with the potential to be enhanced by non-computational means. It would present the aesthetics, construction process and operational results in a format, placing equal importance among all three, allowing the overall picture of implementation criteria to influence the next steps. Also, the interface would provide methods to evaluate the sensitivities of factors deemed crucial by the users, and could be revisited and used throughout the design and construction process.

The potential benefits of such a framework could be a redefinition of the building envelope as a filter versus a barrier. The solar and other environmental characteristics (based upon the location of the residence) could be integrated to improve overall performance and function as a source for the energy that is consumed within the home. Another benefit could be the recognition of sources of innovation currently within the industry, such as builders, and the ability to translate and capture those innovations for reuse. In addition, the ability to foresee the impacts of innovation implementation on a project reduces the amount of risk for the different parties involved, by identifying potential problems and causes of problems at an earlier stage, rather than on-site.

The thesis describes the research involved in the development of the individual tools, combining to form the “system-based framework” for the analysis of innovation within residential construction.

### ***Research Objective***

The purpose of the research is to develop a “system-based framework” capable of evaluating the aesthetic, operational, and construction process implications for innovations within residential construction at the material, component and system levels. The objective centered on the ability to develop tools within each category capable of reaching the level of basic assumptions. Once complete, a method of aggregating the output from the “evaluation toolkit” is required to create a means to assess the innovation from the viewpoint of equal influence from operations, construction process and aesthetics.

The starting point to develop an innovation for the residential construction industry that provided enhanced capabilities, while taking advantage of existing technologies, for the building envelope. Research and past experience on new, developing and extant materials generated potential options for component configurations that would enhance the ability for the building envelope to function as a filter versus a barrier, while utilizing the largest energy source in the world, the sun. An Energy Producing Wall (EPW) component could meet these requirements, through the generation of thermal and electrical energy using solar power. The ability to open the functionality of the building envelope to embrace what the climate has to offer reaches toward the idea of a residence that can create what it needs locally, while reshaping the aesthetic and the processes for construction remaining within the same skill-set currently practiced.

Implementation of the objective was achieved in four steps. First, an operational spreadsheet analysis tool was developed to analyze the operational performance of the EPW within the prototype designs. The material selections for the EPW and their configuration were assessed using this tool and adapted to improve expected performance. Data regarding material selection, component configuration specifics, envelope composition, and factors due to location for each of the prototype designs are variables used to assess the EPW benefit to the total and various types of energy consumption (e.g. heating, cooling, and electricity usage). Second, virtual models and physical models were constructed, altered and reconfigured for the wall assembly and the prototype designs. Third, general research on light wood framing, combined with site observations, interviews, informal discussions, and critique and comment from an “expert review” group provided the framework for the process flow model, which is incorporated into a dynamic simulation model of the light wood frame construction process. The project specifics and design attributes for each prototype design were incorporated into the dynamic process model to assess each design as well as the design with the EPW components. Finally, the “case result format” was developed to serve as the gathering point and the guide to further investigations for the results of the three categories.

*Thesis Organization*

Chapter 2 provides information outlining the continuing growth of the housing industry, the current state of quality, and the impacts both have made within the single family residence. Passive and active solar design strategies are described to provide the foundation for the development of design strategies utilizing both, past and present ideas. In addition, simulation model technology approaches are discussed for construction process, building performance and visualization software, independently and together. Approaches within each category are broken down further, to identify advantages and limitations of each approach, as well as to express the current technological level.

Chapter 3 outlines the theoretical approach for a “system-based framework” to chart and assess the impact of innovations over the development of a project. The importance of the integration between operational, construction process, and aesthetic performance is presented graphically.

Chapter 4 outlines the development of the concepts within Energy Producing Wall (EPW) component for residential building envelopes. Two component configurations (EPW1 & EPW2) were created from investigations of the material selections of thin-film photovoltaics, translucent insulation materials (TIMS), and thermal mass. An in-depth description containing assumptions, parametric breakdown, complementary aspects and system links are provided for each component type. In addition, the module selection (2'x4') is related to a representational design of the EPW frame, and the impacts of these decisions are linked to the larger systems of the home.

Chapter 5 describes the research methodology for the “system-based framework”. The spreadsheet analysis evaluates the operational characteristics of the material selections within the component, and the component within system to calculate the overall energy consumption of the home. Visualization programs and physical models used to evaluate how decisions made at the basic or higher levels of the other two categories, effect the aesthetic performance at different scales are introduced. The description of the computer-based dynamic process model developed for simulating Light Wood Frame (LWF) construction provides the method for to evaluate the construction process. The method of integrating the results of these three categories, the “integrated case format”, is described, in addition to the sensitivity analysis possibilities.

Chapter 6 introduces the results in three sections. First, the results of the implementation investigations of the EPW component are presented. Second, the preliminary results of thirty-two cases in the operational performance analysis combined with the discoveries of the physical and virtual models created and the preliminary results of the DPM-LWF. The results are combined into the “integrated case format”, allowing specific focus to occur on two cases. The third section provides the comparative results of the sensitivities investigated across the “system-based framework.”

Chapter 7 summarizes the research performed during the course of the thesis development and outlines the benefits of the use of the “system-based framework” to evaluate the implementation of innovations, and what is still missing.

### **Summary of Major Results**

A spreadsheet analysis was developed to analyze the impact of specific desing changes, particularly alternatives in the material layers within an individual component, and the component configurations. Virtual and physical models were constructed, manipulated in collaboration with the spreadsheet analysis, re-constructed and rendered to allow visualization of decisions and refine the inputs of the prototype designs into the process model. The computer-based dynamic process model of Light Wood Frame (LWF) construction for residential structures was developed and preliminary results calculated for on the prototype designs with and without the EPW components. The dynamic process model is influenced by the same factors that shape the actions and responses occurring on construction sites. It accounts for the dynamics due the combined effects of shared resources (equipment and labor), spatial and sequential variables, and the variability of tasks required for transforming individual wood members into assemblies (i.e. wall, platform and roof sections). The integration of the three tools was accomplished in the form of a “case result format”, which functions as a learning tool and portal to more in-depth investigations, in addition to a result presentation. The strength of the combined and individual tools are in the ability to not only evaluate the design and implementation of the EPW within the prototype designs, but to assist in the identification of the areas that create the largest potential for future investigations.

The EPW demonstrates the benefit of aesthetic diversity through the five component types of varying opacities within two component configurations on the exterior and the interior. It provides a method of installation within the “skill set” of framing crews currently on residential construction job-sites, to enhance and ease implementation. In addition, the two configurations of the Energy Producing Wall (EPW) components (EPW1 and EPW2) demonstrated that benefits ranging from 50% to 75% of the heating load in Boston, and 40% to 50% of the electrical loads in Phoenix could be realized in use on a “Modern Prototype Design”. The benefits for the “Modern design” and a second design representative of the existing building stock, substantially increased as factors relating to the quantity of panels and the potential for modest technological developments were considered, and results display the potential to satisfy 100% of the load for one, and in some cases two of the categories of the overall energy load for the home (heating+cooling+electricity). The development of the EPW within the system-based framework identified that benefits could be realized in operational, construction process and aesthetic performance.

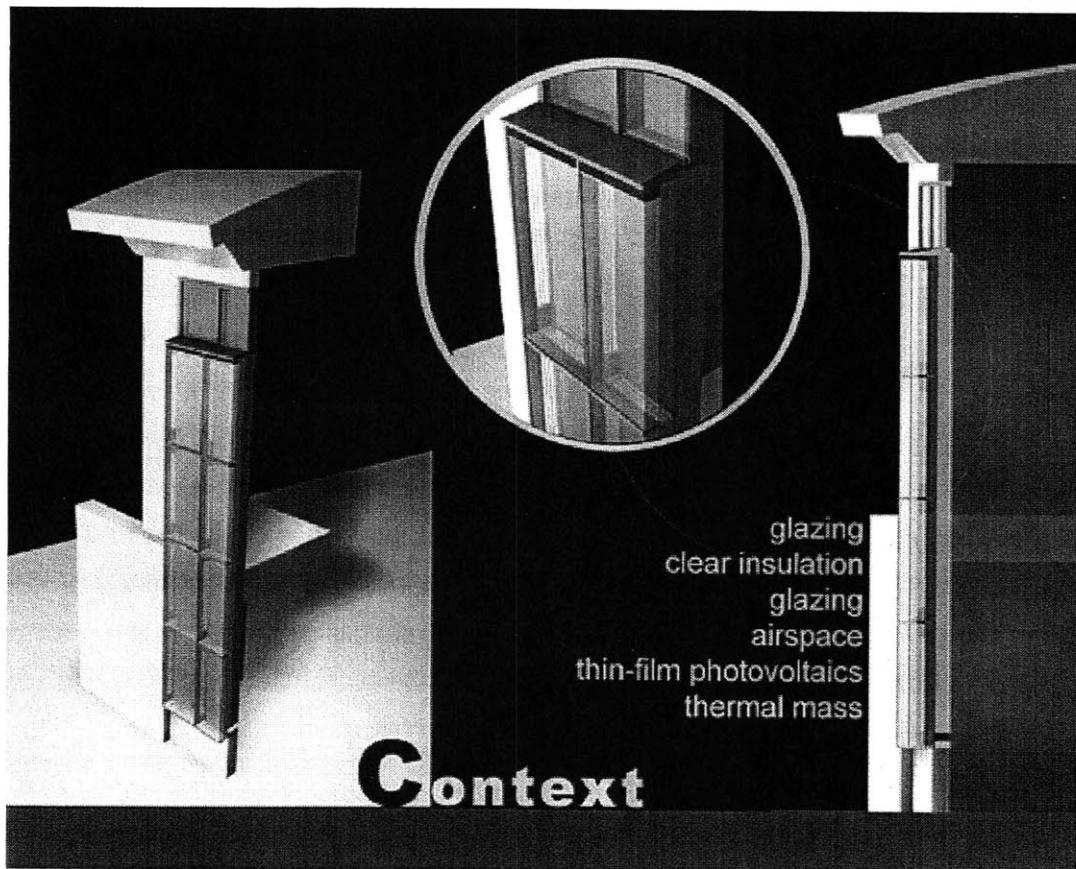


Figure 1.1 - the EPW design

## Chapter 2.0 Background

### 2.1 Housing Statistics

For the current state of residential construction in the suburbs of cities across America the majority of decisions made regarding residential design are occurring in plan, when every spatial experience that we have is three-dimensional. The product of the built transformation from two-dimensions to three results in awkward spaces and facades that only acknowledge the function of the interior plan and not the building overall. In addition, the reuse of manufactured plans ignores even the most basic characteristics of the site, such as orientation and solar exposure, for the possibility to squeeze that one extra home within the cul-de-sac. Overall there is a lack of harmony between the elements in terms of scale, orientation and composition that define the overall performance of the home.

Single Family Housing starts have been increasing steadily over the past five years, reaching highs in overall quantity and rate during the months of 1999. The housing starts in 1999 continued a trend of steady increases that has occurred over the past five years, reaching a peak of nearly 1,850,000 total housing starts (1,400,000 single-family) in February, dropping briefly over the summer, but rebounding by setting record monthly percentage rate increases in July [2]. As housing starts have increased steadily, so has the average square footage per single-family residence (2,190 sq. ft. – 1998). [3] In 1998, the percentage amounts of single-family homes based on square footage were:

	8%	< 1,200 ft <sup>2</sup>
1,201 ft <sup>2</sup> <	61%	> 2,399 ft <sup>2</sup>
2,400 ft <sup>2</sup> <	31%	

#### Average Single Family Home Size Distribution for 1998

[3]

The percentage of larger homes has been consistently replacing the percentage of smaller homes, while the intermediate category has remained fairly constant (61%-69%). Further indication of the increase in the size of single family homes is expressed by other factors such as, 49% are two-stories or more, 50% contain 2-1/2 baths or more, and 33% have four or more bedrooms. [3] With

an increased number of new homes, and an increased size of those homes, material and appliance usage is increasing as well. An example of the materials used in building a 2,085 ft<sup>2</sup> single-family home is [3]:

- 13,127 board-ft of framing lumber
- 6,212 square feet of sheathing
- 13.97 tons of concrete
- 2,325 square feet of exterior siding material
- 3,100 square feet of roofing material
- 3,061 square feet of insulation
- 15 windows
- 1 kitchen sink
- 12 interior doors
- 3 toilets; 2 bathtubs; 1 shower stall
- 3 bathroom sinks
- 2,085 square feet of flooring material
- 1 range; 1 refrigerator; 1 dishwasher; 1 garbage disposer; 1 range hood
- 1 washer; 1 dryer.

### Operation

Numerous external and internal factors have influence upon the operational performance of the home. External factors (site) affecting operations are wind, daylight, water (rain, snow, and precipitation), cold and hot temperatures shaping conduction, convection, and radiation, as well as other extreme events. Internal factors such as appliances and heating and cooling equipment effect and shape the operational capabilities.

In 1997, the average residence in the United States consumed 101 million Btu's of "site energy", which is defined as energy directly consumed by end users. [4] If the overall amount of the "primary energy" (primary energy = site energy + amount of energy for production and delivery of the energy to the residence) is considered, the number per household increases to 172 million Btu, a 76% increase. The amount of "site energy" reflects a 27% overall decrease from 1978, which has been a result of the movement towards better insulated homes, improvements in efficiency of heating equipment, and people's awareness of energy consumption has risen. However, over this time



period substantial increases in consumption have occurred for appliances and lighting. Electricity is the source for the large majority of energy consumed by appliances and lighting with the home. For the context of this document, the overall load of the building is divided into three categories, heating, cooling and electricity loads.

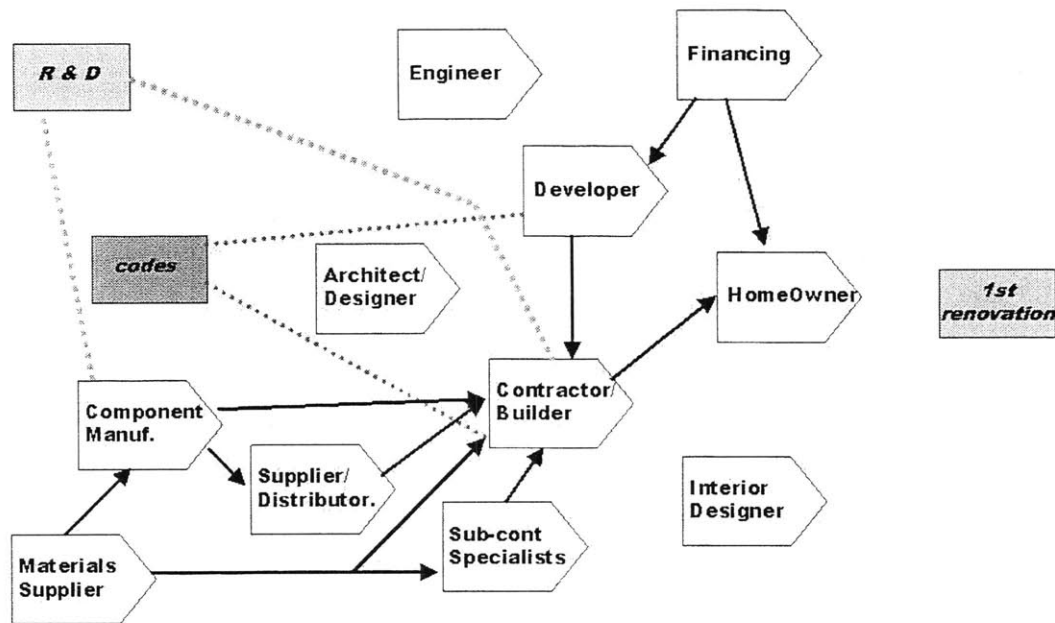
In the northeast region, 121 million Btu's per household are consumed annually. 32% of the homes are built before 1940 and only 18% after 1980. Natural gas is still the predominant main space-heating source for the 76 million BTU per household load. Only 62% of the houses are equipped with air-conditioning.

In the west region, 75 million Btu's per household are consumed annually. 9% of the homes are built before 1940 and 36% after 1980. Electricity accounts for half of the main space-heating source for the 31 million BTU per household load. The amount of homes with air-conditioning increases to 92%. Two-thirds of this amount are provided by central air-conditioning systems. [4]

Based upon the information presented, enormous opportunity exists to improve the aesthetic and operational aspects of current housing in the U.S.

## 2.2 Industry Value Chain and its Roles

By identifying the industry value chain for residential project types, the cultural influences of the parties involved are presented. The development of a building project from start to finish has a number of different parties involved, each with varying cultural implications (Dia. 2.1) The connecting lines identify those involved and those with whom they have relationships. The solid lines express a direct contractual relationship or a working relationship, while the dashed lines represent an indirect relationship, which could be in the form of an information exchange. The groups displayed, but not connected, identify the alternative parties playing a role within other residential project types. Codes, and Research and Development (R&D) provide important factors outside the roles of the distinct groups, which shape and bound the potential decisions made. The prescriptive building, fire, and safety codes (codes) are the dominant influence, while the direct impact of the level R&D that exists plays a minor role. The box on the far right represents an important factor encompassing adaptability of design, the 1<sup>st</sup> renovation. A quote from a lecture by Prof. Eric Dluhosch (MIT) states, "A design should acknowledge, foresee and have the ability to accommo-

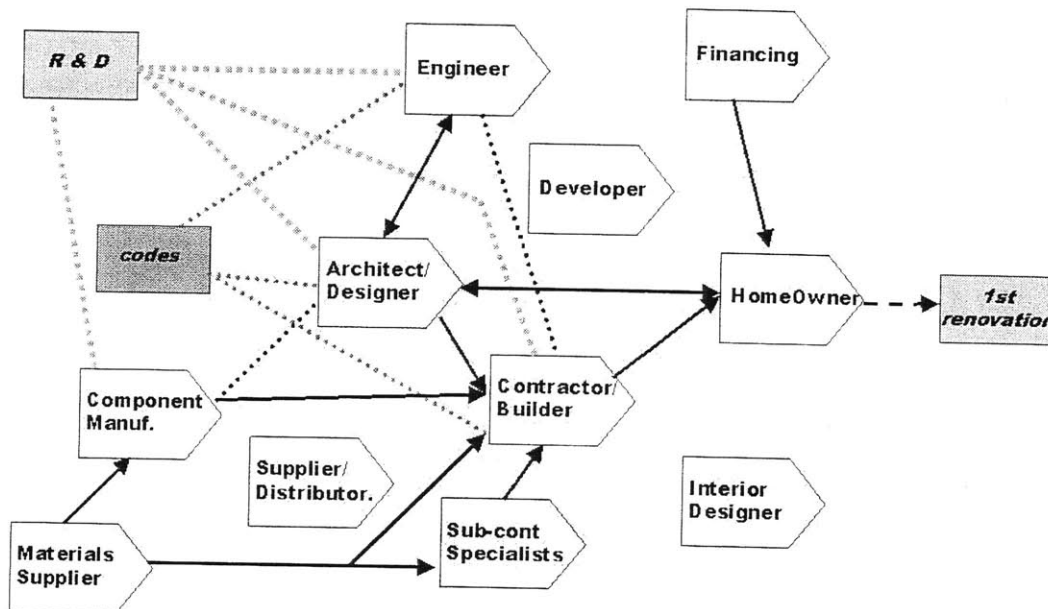


***Diagram 2.1 – Residential Construction Value Chain***

date the 1<sup>st</sup> renovation.” By attempting to foresee and understand the first renovation, a degree of adaptation and flexibility is built into the design, which not only assists in the adaptation itself, but potentially the maintenance as well.

The project type represented in Diagram 2.1 could be a specification home, a home within a suburban development or from a set of manufactured floor plans within a magazine. Developers, owners (client), builders, sub-contractors, manufacturers, and material suppliers are the main parties involved. Note that architects and engineers (designers) are not linked within this value chain.

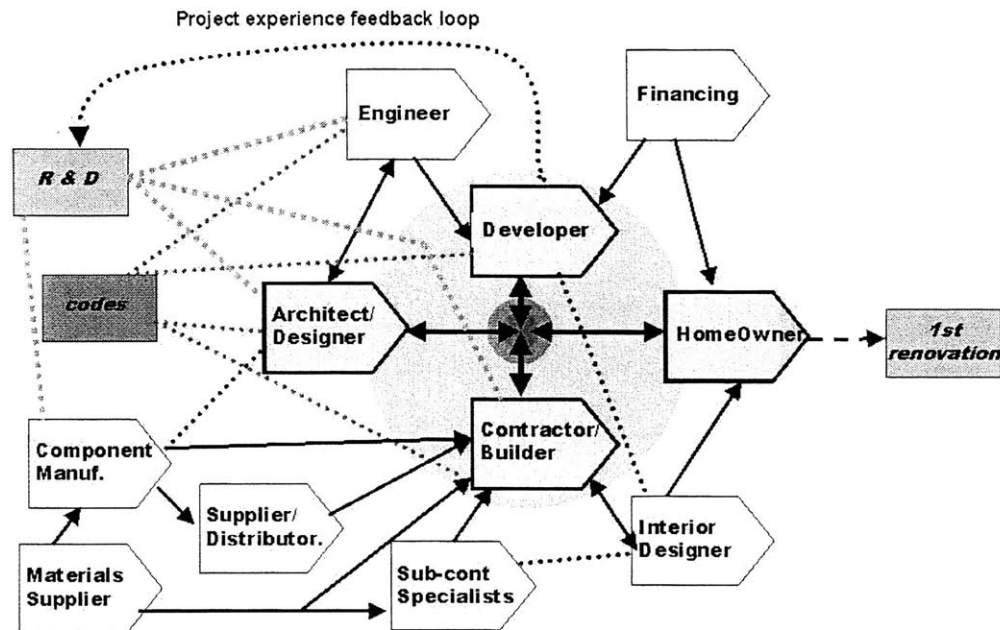
The Massachusetts State Building Code states that any building less than thirty-five thousand cubic feet or enclosed space or any single and two-family home is exempt from the requirements of an engineers or architects professional stamp for construction. [5] Because of this issue the barriers to enter the residential market are low. In past years the publics focus has been placed



***Diagram 2.2 – One-off Design Type Value Chain***

upon the issue of affordable housing, so that more families could own their own homes. Governmental initiatives placed strong emphasis and support on this issue. However, even with all the good intention and careful steps, the issue of quality design began to be replaced by focus upon the financial bottom line. The opportunity arose for groups with financial capital, such as developers, to enter the market to provide services, which the design community was not capable. The designer was slowly delegated to the role of remote consultant on a larger percentage of new construction. Developers have brought positive financial benefits to the process, allowing a larger breadth of homeowners, but at the cost of quality and the perceived standard of quality in the public's eyes.

The value chain of a custom "one-off" design or a residence with extreme site conditions (Dia 2.2) displays the inclusion of the architect and engineers within the process. Characteristic of this value chain is that the owner secures the financing, architect and engineer work directly with owner to shape design while the relationships of the contractor to the sub-contractors, and manufacturers



**Diagram 2.3 – An ideal Value Chain**

and suppliers tend to remain the same. The number of projects constructed each year within this configuration is a very small percentage of the overall number of new residential construction projects each year.

An interpretation of an ideal configuration for the Industry Value Chain is expressed in Diagram 2.3. It brings together the financial benefits offered by the developer, skills of the designers, expertise and knowledge of the contractors & builders, and combines them with a homeowner who has a greater understanding of options, alternatives, and ultimately, quality. The overall goal is to raise the level of aesthetic, operational and process performance for the design and construction (dia 2.3). Key features are the infusion and capture of innovations from the sources of R&D as well as those innovations occurring on-site or within the problem solving of the project team. Research and Development establishes more entry points into the process for the benefits of academic research projects, such as Prof. Sarah Slaughter's "100-year facility life", focusing on the flexibility

and adaptability of structures over their life [6], to develop more direct transfer channels into industry. Due to this resurgence of R&D, the level of awareness of the project team is raised, and the ability to design with the first renovation in mind becomes a possibility. In addition, communication and information flow more readily and easily among the parties.

Technological innovations have begun to provide opportunities for architects and engineers to get back into the residential market, through capabilities allowing the design cycle and construction document preparation time to be reduced, while not sacrificing the level of design. University research projects, such as House\_n: MIT's home of the future, are investigating issues such as how the designer, through these technological innovations, can begin to impact the home of the future. However, the crucial factor that still remains to be addressed is the cultural differences between the different parties involved.

### 2.2.1 Designers

The aesthetic character of the home has been shaped and evolved by designers (engineers, architects, and others), through their interpretation and re-interpretation of the home. The architectural design theory of the home has always been a centerpiece of discussion.

*“Workmanship and design are one thing. Good workmanship has to have a good design because the design is in the nature of the workmanship. You can't separate workmanship from design.”*

***Frank Lloyd Wright, 1955 [7]***

The Usonian concept by Frank Lloyd Wright (late 1920s- 1930s) was the product of five to ten years of development. The movement resulted in five major types of building systems transforming into twenty-six homes completed and thirty-one unbuilt. It emphasized the three innovations of board & batten walls, a planning grid, and underfloor heating, and the importance of mass within the home. The designs were of extremely high quality in spatial experience, materials and appearance. The design acknowledged the language of the builder within the design, but it required a distinct dialect. The tasks and activities of the builder were understood, but the process sequence was not. Frank Lloyd Wright normally called for building the roof first, on temporary supports, to provide a workshop in which to construct the wall sections. However, problems of installation of

the structure and sequence of construction developed due to the ability to maneuver and install walls and other components. [8] Another weakness lay in the inability to integrate the systems into the design concept based on the pre-fabricated wall section. Even with these weaknesses, the homes that were built were built to last. A large number of the twenty-six homes built are still standing and in use. A major reason was the bond between FLW and the “masterbuilders” of the time, who took great care and craftsmanship in all facets of the construction.

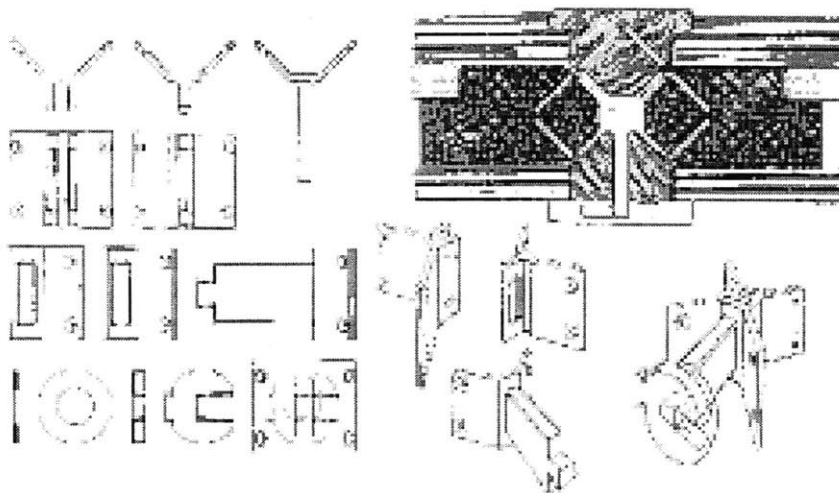


Figure 2.4 Packaged House Wall Detail [15]

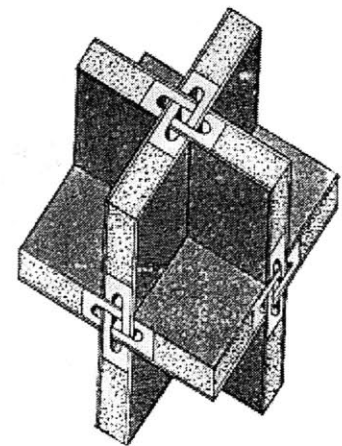


Figure 2.5 Packaged House 3-dimensional assembly[15]

The Packaged House by Konrad Wachsmann with input and support from Walter Gropius, is another example of famous designers developing a building system, which ultimately did not reach its perceived potential. The Packaged House can be viewed in terms of a construction system and a design system. [9] The design system was not focused on economics, but an elegant exploitation of advanced technology. Due to this approach the construction system was developed as a “closed system” with low tolerance levels and highly detailed connectors for the wall panels. These factors, once again were outside the language of the builder, and met with strong resistance. In actuality, only a small number of the 10,000 projected homes were actually built and the project went bankrupt.

Operation Breakthrough (1969) funded by governmental support attempted to generate innovative, practical, economical, and viable industrialized building systems into residential construction. [9] All efforts were placed on the manufacturers as the sole source of innovation. [10] The products were a widely diverse group of approaches and systems that seemingly ignored the builder's language on-site and also had not learned from past mistakes from another governmental funded effort, the 1949 Veteran's Emergency Housing Program. Technology was perceived as the solution, when in actuality its forced implementation was a major source of the problems. [11]

*We create something, then we drop it and do it over rather  
than preserve the older efforts.*

**Marcello Roberto...1955 [1]**

From this period to present, residential building systems continue to be developed in the form of manufactured homes. Few good examples exist (Grow House, Sekisui Homes in Japan, Acorn Houses) of efforts that build upon past knowledge. Society has accepted systems focused upon economic viability, but as mentioned previously, the tradeoff is the compromise of quality, to an extreme.

The operational performance of a building relates to how the building envelope and the heating and cooling equipment (if required) respond to occupant patterns, appliance use and environmental conditions to create a comfortable thermal environment for the occupant/s. Operations of the building are at varying stages over the life of a building regarding maintenance and quantity of energy load required. Factors effecting operations are wind, air movement, daylight, light, water (rain) heat (conduction, convection, radiation), material use, and spatial composition (volume). Methods to reduce heating/cooling loads (energy loads) of the home are explored through the use of natural means (solar, wind, geothermal, etc.), focus upon enhancing efficiency or capabilities of the equipment or a combination of both. The scope of this document addresses how solar and ventilation strategies can be utilized in an effort to reduce the reliance upon HVAC equipment.

At the most basic level, the function of a residence is to provide shelter, from weather conditions, and protection. The residence must support itself and be able to protect the occupants, to a certain degree, from weather events, such as rain, wind and snowstorms. The residence must be selective based upon the climatic location to the effects of water, heat or cooling loss. The requirement

is a home of “tight construction” to the degree that water leakage and infiltration are reduced to acceptable levels.

*“Construction is a means, so important a means, that without it no architecture is possible, just as poetry is not imaginable without language.”*

Willem Dudok...1961 [1]

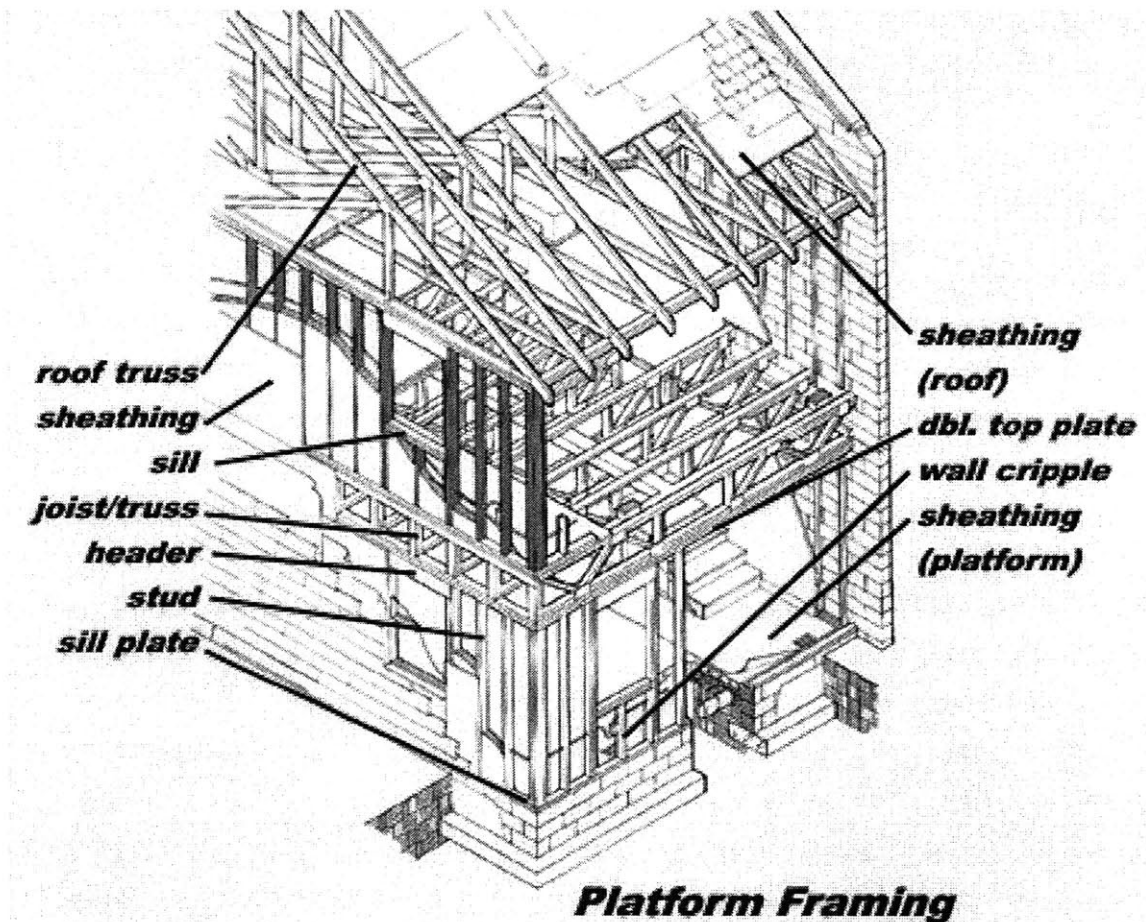


Figure 2.6 Framing Member Terminology

### 2.2.2 Builders

The process of light-wood framing for a residential home is a well-known process, and is often referred to as “stick-built” construction. A small crew of framers can complete the construction of a home. A wide range of terminology is used on the construction site, defining the transformation



and aggregation of each piece of lumber to creating the total structural frame. (Figure 2.6)

The major components within the structural frame of the home are the wall, platform, roof, apertures and stairs. The platform provides a horizontal surface of upon which the walls, furniture, and equipment are placed, allowing occupants the ability to move between spaces. The wall is the vertical surface, which can be divided into the categories of load bearing and non-load bearing. Load bearing walls provide the structural support for the elements above, and, on the exterior, provide the filter between the interior and exterior environments. Non-load bearing walls define spaces while providing concealment for services to and from fixtures. The roof is a horizontal or angled surface that covers the building and sheds water away from the building. Apertures including windows, doors, and skylights, allow an occupant views to the exterior, as well as providing daylight and air to enter the interior. Stairs provide additional means of circulation within the home by allowing vertical movement between platforms to be possible.

“Platform framing” is the generic title given to the standard method of residential framing. Through a repeated process of constructing a platform, building and erecting the structural walls, and building another platform on top, until the roof is reached, the frame is completed. The detail (Figure 2.7) displays the connection between floor and walls. Incorporated within this language are the terms “in-situ” or “stick-built” framing, “site-assembled” and “prefabricated” components. Framing projects often use combinations of all three approaches. In-situ or stick-built framing refers to the piece by piece assembly of components that occurs on-site with each unit placed and connected individually. “Site pre-assembled” describes components, such as complex roof trusses, that are assembled on site

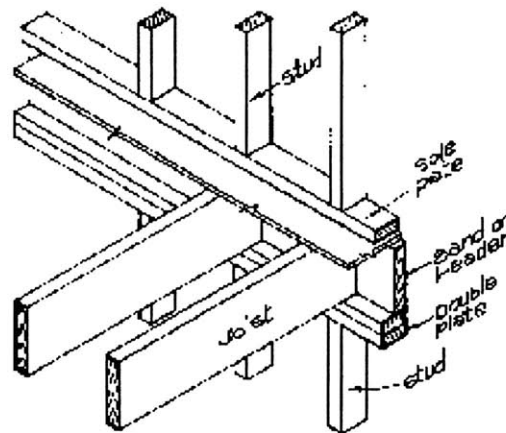
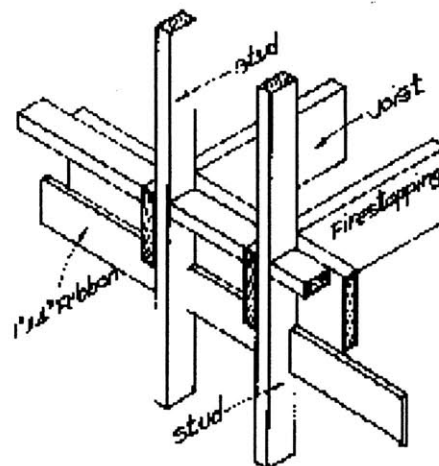


Figure 2.7 Platform Framing Detail [12]



[12]

Figure 2.8 Balloon Framing Detail

and lifted into place as a unit. "Prefabricated" refers to components, such as windows, doors, and wall panels constructed off-site in a manufacturing facility, and shipped to the site for installation.

"Balloon framing" (the past standard) is an alternative method still utilized by framers, but to a lesser degree due to the requirement for fire stops. The difference from platform framing is that the vertical structure components (the studs) span the full height, from the foundation top to top of the highest wall, as a continuous element, without structural divisions at each floor level. In a two-story house, the multi-story exterior walls are constructed (full height) and the additional platforms are then constructed and supported by attaching them to the face of the exterior wall. The detail

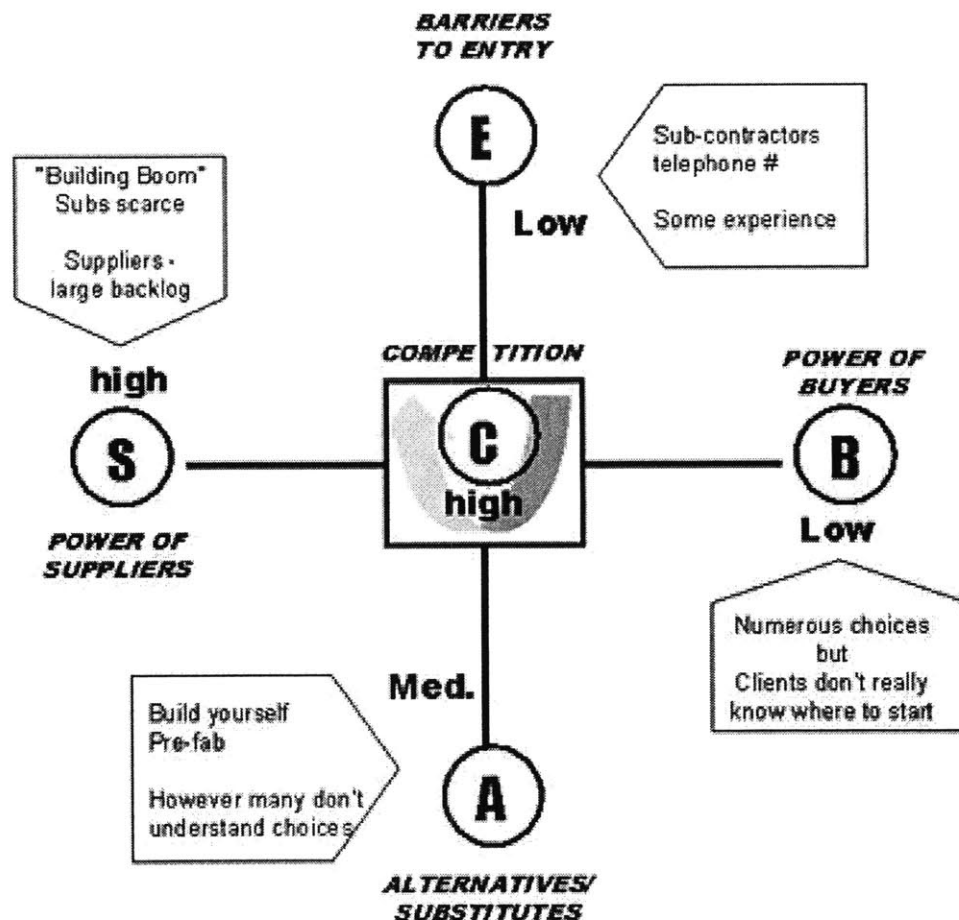


Diagram 2.10 – Five Forces to Competitive Advantage

(Figure 2.8) expresses the differences in the wall to platform connection. Other differences between the two methods lie within the resources necessary, in the form of type of equipment and size of crew.

The five-force method of analysis for competitive advantage [13] (Diagram 2.10) provides a means to discuss the current state of the lightwood framing industry in a contractor's eyes. The method provides a perception of the perceived power position of buyers and suppliers, the barriers to entry, alternatives and substitutes, and ultimately, competition.

The "barriers to entry" for framing contractors are very low for residential construction, due to the low level of expertise to enter and compete, combined with the public's reduced understanding of available alternatives.

The suppliers hold a high power position because of the current building boom around the United States. Material suppliers have substantial backlogs and quality sub-contractors are scarce due to the level of demand.

The amount of "alternatives and substitutes" to light wood framing by contractors are considered to be MEDIUM. For example, an individual could choose to build the project themselves, purchase a pre-fabricated wall system to be installed, utilize steel stud construction, or could purchase a pre-manufactured home.

The power position of buyers is low due to the level of built quality they receive. The cost of the average home continues to increase, but it is arguable if the design and construction integrity match that price.

Competition is HIGH among LWF contractors, even in the current booming market. This high level of competition significantly reduces the possible profit margin and is a factor of the conservative nature of the industry. Contractors fear not being able to secure a project due to another contractor, using standard, low quality means, underbidding them. This predicament has the side effect of reducing the use of "innovative products". Also "innovative products", such as structural insulated panels, can create additional processes and tasks on site during installation that go unrecognized by the manufacturer. [14]

### 2.2.3 Manufacturers and Suppliers

Manufacturers provide the components, such as windows, doors, door frames, trusses, skylights and prefabricated walls, that combine with the materials from suppliers, which were specified by the designer, to shape, through the efforts of the builder, the finished product of the home. They create and develop the capabilities, within the manufactured components that a significant portion of the residential design community views as the range of options. In addition, they impact construction means and methods directly. They hold a strong position and a strong influence, which does not always align with the overall goals of design and construction.

#### *Closed vs. Open Systems*

Building systems are classified into two types, open systems and closed systems. The closed system, such as the Packaged House by Wachsmann [15], utilizes only a specific type of designed components and functions as a stand alone, not compatible with others, creating the system's inability to be adapted after installation or over time. Open systems, such as the "raised floor system" and "2x wood construction", on the other hand, recognize the need to interface with other components and systems and at the level of material, component, sub-system and system. The level and ease of flexibility is determined by the characteristics of the design.

#### *Component-based approach*

A key component of the open system development was the concept of the "industrialized component". The evolution of the industrialized component began with the window unit and progressed to interior and exterior wall panels, doors, bathrooms, storage units, [16] and has continually increased to include all elements utilized within the construction of the home. The strongest resistance has been felt by those components that deal with structural and other issues, which fall under the regulations of the building codes.

The component-based design approach allows for a design and analysis strategy that optimizes each component independently by reducing the context to the component itself and the components directly related, and then minimizes the interfaces in the whole system. The assumption of independence reduces the problem complexity, particularly in the development or analysis of new components, and is therefore the most accepted analysis approach. A quote from R. Bender in 1973 expresses that this approach should be taken farther.

*“The dream of the pioneers of industrialization, to select standard parts from a catalogue, order them and have them easily assembled into a finished building, is now possible. But it seems far from realization. [16]*

## 2.3 Current Technological Developments

### 2.3.1 Perception of Construction Industry...Builders as Innovators

Even though the construction industry is very conservative, and fragmented (expressed by the discussion of the industry value chain and the contractors view of the residential industries environment). The labels placed upon the industry, especially residential, as “backward” or “the industry capitalism forgot”, [ventre] are misperceptions due to a lack of understanding of how and what processes and information go into the completion of a project. The equation for successful implementation of products is the sum of two crucial elements.[17]

$$\text{Successful Implementation} = \text{Generic Technical Knowledge} + \text{Local Practical Knowledge}$$

Generic technical knowledge can also refer to state-of-the-art knowledge or high-tech knowledge, the basis is the technology incorporated into the product to be implemented. Designers and product manufacturers hold the generic technical knowledge, while builders and installers hold the local practical knowledge. However, identifying the knowledge and determining who holds it and who needs it, at the various stages of a project, are crucial to the discussion. Ideally, each group would hold both sets of knowledge, however this would require feedback loops to be in place between these parties. Unfortunately, a large gap exists between those who generate the knowledge and those who use it. [18] The discussion should acknowledge groups existing between the generators and users, integral to technology and information transfer in the construction process. Each constructed facility is made up of varying sets of specific components that must be integrated on-site

structured facility is made up of varying sets of specific components that must be integrated on-site by builders into an effectively functioning unit. [14] [19] As builders are integrators on site [14], designers and architects are integrators at the design stage. Designers must have a balanced understanding of the generic and local to begin to reduce the potential problems on-site for the contractors, because they specify the products used.

One major problem is that the people directly involved in introducing new technology (manufacturers and designers) often don't fully appreciate the creative effort required to achieve effective implementation. [16] This is a main reason why innovation in construction is perceived to be low, and the builder's as sources of innovation versus those in the manufacturing companies and research laboratories have been overlooked. [10] Generic Technical and Local Practical Knowledge are not necessarily of the same type or language. The disparity becomes apparent as one spends time at a construction site. Most innovations in the industry require significant changes in standard practices to accommodate new concepts and materials. [10] Factors become identified, which the design did not, and potentially even could not, accommodate. It is the knowledge-utilized day to day by builders to solve problems on site, which is not easily specifiable to others and has served as a partial misunderstood barrier to innovation. As Ventre[20] states, the problem with high-tech invaders, introducing new products is that they spend little amounts on R&D to understand the builders' processes involved in implementing their product. [20] The world to them is perceived in the eyes of their product and does not accommodate sub-systems that are critical to its installation and performance over time. Manufacturers and product designers can utilize the skill-set of builders to enhance product performance, [slaughter] but they must be open to the conversation.

### 2.3.2 Alternative Design Approaches

Throughout the years, government, manufacturers, architects/designers and builders have created and attempted to implement building systems focused on residential construction, but have rarely established sustained reuse. Each has met with resistance from a number of sources, such as the building community, manufacturing processes, clients or other, ultimately leading to its demise. The point is made to demonstrate the complexity of the issue, but to also demonstrate how each successive effort has not learned from the mistakes of others and has failed to acknowledge the difference between who holds the generic technical knowledge and who holds the local practical knowledge. The re-occurring theme is the lack of understanding of

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Passive solar design is not a new concept; numerous designers and researchers have rigorously explored it. It has reappeared in cycles over time; the principles have yet to take hold as a standard in design. Using sunlight to heat a material of high mass value, such as stone, adobe and concrete, has been utilized over centuries and adapted into various forms. [21] The modes of heat transfer: radiation, conduction and convection have not changed in principle, but have changed in how they are used within a system. The concept appears simple: heat flows from high temperature sources to low temperature sources through radiation, conduction, convection or combinations of the three. However, the relationship and ability to quantify even two of these features in combination is complex and pushes the current analytical techniques.

Historically, mass was used as a thermal buffer in hot climates in the form of very thick walls, absorbing the sun's heat over the course of the day, and radiating it out to the night sky based upon wall thickness and the diurnal temperature difference. The experience of walking into a building constructed of thick stone walls expresses the benefit of mass right away. Even if the temperature is above 100 degrees on the exterior, the interior has a feeling of coolness relating to temperature and feel due to the thermal buffer of the mass and the surfaces one's body is radiating to. Manipulation of this effect can also occur through the use of ventilation.

Designers in the 1930's and 1940's developed strategies where the thermal mass was brought into the interior of a building, and terminology such as "direct gain" and "trombe walls" began to be surface. [21] The basic concept is the same with sunlight striking the surface and heating the mass. The mass absorbs the heat, but rather than functioning as a buffer, the mass radiates the heat to the interior spaces. The control of the system is based upon the extent of solar exposure coupled with the thickness and density of the mass material. Each material has a measurable time lag. This value is the period of time for the heat from the direct sunlight to be absorbed by the material and radiated into the interior space. By understanding the heat flow through the material, based upon exposure, density, heat capacity and conductance, the material and its environmental context can be utilized in a variety of ways to establish relationships between the absorption and radiation of the heat with the occupants patterns and time.

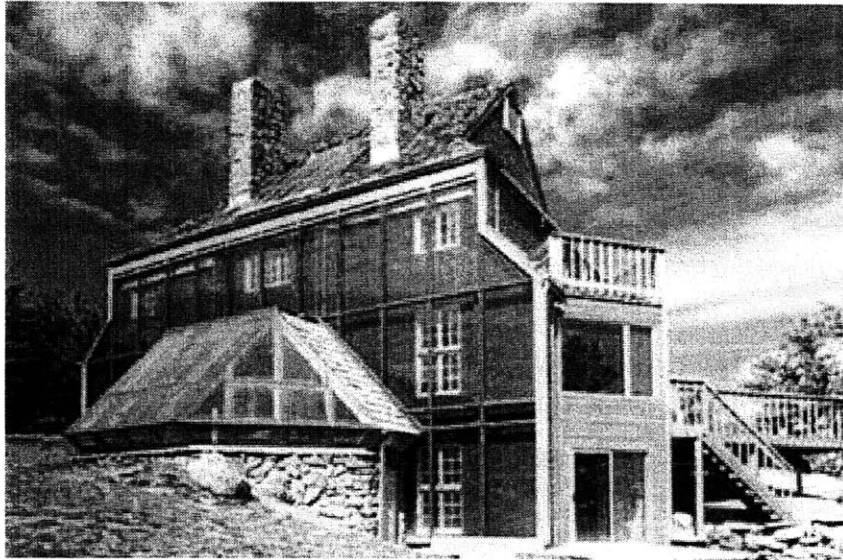


Figure 2.11 – Loffredo Residence with Trombe wall, by Dennis Holloway [23]

### ***Trombe Walls***

Felix Trombe created an adaptation of the direct gain system, the trombe wall, in the 1940's, and it was introduced to the U.S. in the early 1970's in Princeton, NJ in the Kelbaugh House [22]. The trombe wall was constructed initially with double glazing on the exterior, an airspace (approximately 3") and thermal mass (>12" thick). The system provided the ability to expand the control of the direct gain system to not only include absorption of the sunlight and radiation through the material, but also convection by air moving across the thermal mass surface. An example of a residence in Lyons, Colorado is shown in Figure 2.11. The trombe wall pictured accounts for 90% of the heating load for this home. [23]

Two types of trombe walls are common: closed and vented. A closed trombe wall system does not allow the air between the glazing and the thermal mass to move, limiting the function of this air to a static U-value. The vented system through the stack effect stimulates a convective air loop by introducing voids in the mass at the top and bottom, and on the interior and exterior. Through the open/close states of these four openings, three operational states are possible. The coordination of the interior openings can create the loop as shown in Figure 2.12. Another characteristic is the ability to close the top interior supply and exhaust the heat to the exterior. Fresh air supplied from the exterior can also be introduced at the low point of the wall (dependent on exterior temperature), functioning in the same manner as shown. In addition, the whole process can be switched to a

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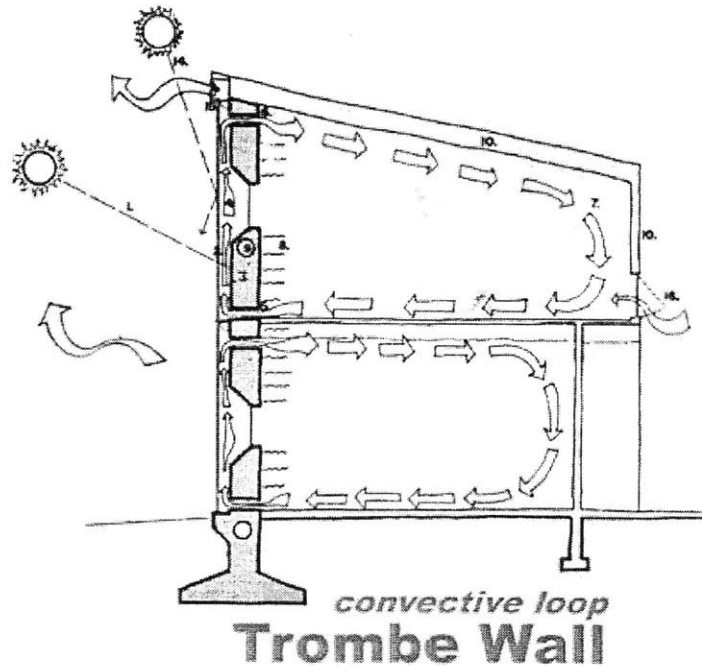


Figure 2.12

“flushing mode” in the evening, when it is beneficial to pull the heat away from the mass and out of the building. The system configuration is for the lower, exterior supply and high exterior exhaust to be open. Then the heat of the mass, through the temperature differential, pulls the exterior air into the air gap, along the mass surface and out of the building, taking the heat with it.

The air gap basically functions as a vertical plenum, with the south side made of glass. Length, width and height of the air plenum, in addition to the temperature difference between the supply and exhaust, shape the velocity of the air within this space. The temperature of the air at the exhaust is also effected by convection of heat from the thermal mass to the air, determined by exposure, time of day, internal temperature, and supply air temperature.

Due to the low R-value of the triple glazing, the trombe wall can lose the heat captured by the thermal mass during the day to the exterior environment due to the temperature difference between interior and exterior. [24] This emittance of heat to the night sky can be significantly

increased on a clear night, in climates experiencing large diurnal temperature swings. Therefore, night insulation of the thermal mass became a requirement. Originally, insulation panels (R-9) were required to be positioned by the user, each evening, totally blocking off this wall from the environment, both thermally and visually. [25] Evolutions of this concept provided various forms of louver and shutter systems, manual and automated, to cover the thermal mass units at night to reduce external radiation of the heat. [22]

Trombe walls operate with a low margin for error, creating substantial disruptions to the overall building performance if the occupants neglect their operational schedule. For example, an excessive amount of heat can be drawn from the mass overnight, due to radiation to the night sky, resulting in a substantially low interior temperature in the morning, even if the night insulation is not put in place, for just one evening. [24] The amount of time the trombe wall needs to re-establish a level of thermal comfort is substantial and reduces the benefits of subsequent solar days. In addition, the variability of the weather, such as periods of cloudy days and rain, can also significantly effect the thermal performance from day to day. The radiation of heat from trombe walls is not controlled by a thermostat, or on/off switch, but is dictated by the natural effects relating to flow and exposure. Because of these factors, most passive solar homes utilize a secondary HVAC unit, even though the trombe wall may have the capabilities to satisfy 100% of the design's heating and cooling needs under optimal conditions. The back-up systems theoretically improve the system's tolerance, providing the user with different options, but partially defeat the purpose of the passive solar design approach.

Trombe walls also have certain design limitations. Trombe walls traditionally were constructed as a large, expansive surface. The thermal mass wall reached from floor to ceiling and spanned a large percentage of the length of building. Since this surface radiates heat to the interior, it must remain clear of obstructions, such as paintings, rugs, interior finishes, etc., and must also serve as the interior finish surface for the external walls. The material of choice has been concrete, because of its combination of heat capacity, high density and thermal diffusivity. If windows are introduced in the proximity of this surface, strong contrast is created between the two elements (i.e. concrete wall and glass window), which normally introduces glare, particularly on a sunny day.

The perceived limits of passive solar approaches, due to construction type and operational characteristics, were heightened by actions of the design and construction community. Even though a trombe wall is composed of common materials (concrete and glass), it has complex functionality. The use of trombe walls was not an exact science when it appeared, and the initial uses were based on trial and error, particularly error. Without a proper integration with the local climate, the designs can not only live up to the potential, but also function as a detriment. Early design failures and failures owners to realize the ramifications of monitoring them on a daily basis, resulted in fewer and fewer project opportunities. Another barrier was in the form of the U.S. construction industry, which did not welcome the introduction of heavy mass into the light wood frame home. The combination of these elements resulted in limited diffusion within the residential community.

#### ***Cycles of Development: Passive Solar Design***

The oil crisis in the late 1970's stimulated a period of extensive exploration of solar design options. When the U.S. federal government sponsored large amounts of research on active and passive solar energy alternatives, numerous groups became interested in investigating these strategies. This period (1975-1985) produced a large number of different systems and adaptations. [26] A new dialogue of building form and types, such as "the cheese wedge" (fig. 2.13) was created to bring as much sunlight as possible to different types of thermal mass configurations based on the determined optimum solar angle. Trombe walls were refined, and sunspaces, water walls, roof ponds and houses buried into the landscape became built reality. It was an interesting time of discovery with regards to the exterior aesthetic. Large external glass surfaces introduced a stark difference in scale from the traditional window elements, while the southern façade became the dominant focus by trying to reach higher

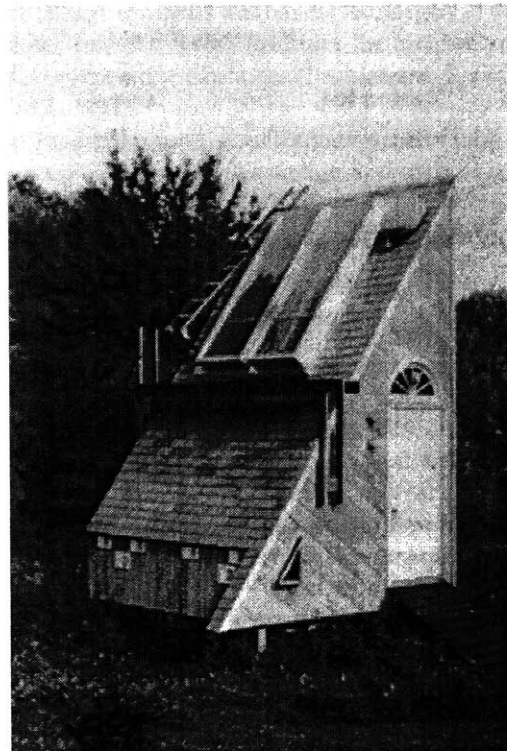


Figure 2.13 – “the solar cheese wedge” [Herzog]

and farther, all in the name of enhanced solar performance. However, once the oil prices dropped and the government funding was reduced in 1981, [27] fewer and fewer homes incorporated these principles.

Solar design developments generated by an active solar system, such as the solar hot water heating systems, could be identified as another cycle. Solar panels are mounted on the roof of the home and used to heat water passing through a network of piping within these panels, which is then pumped into the home. Numerous variations have been developed, but due to the failure modes and maintenance requirements of the system, they have met with limited success. This pattern of development and limited diffusion foreshadows the difficulties for other solar elements, such as PV panels. For example, early PV panels were usually placed on the roof of buildings, due to the advantages of solar exposure and the supposed angular freedom. However, once again the goal was operational performance versus a balance of operation and aesthetic, which often created appendages rather than an integrated approach.

The current cycle involves the development and refinement of photovoltaic materials, components and systems, which have captured the focus of the solar movement for the past fifteen years (1985-present). The movement is similar in nature to the cycle in the late 1970's, with a high level of government sponsored research and the interest of the manufacturing and academic communities. However the interest is held and maintained by the potential and promise of "renewable" energy, because it is from a natural source with low environmental impacts, but more importantly, because it could be adaptable in form and time. PV-generated energy can be stored, accessed and inverted based on need, which is a characteristic not possible within passive solar design. Development has seen the photovoltaic panels change from roof mounted, monocrystalline units of substantial thickness, to thin-film amorphous silicon panels with the potential to mount on any substrate. [28] Also, with current technological advances, the reliance on the optimum solar angle positioning to ensure sufficient power generation has been reduced.

Today, the PV industry is no longer a novelty; it is a \$750 million dollar worldwide industry that continues to grow at a substantial pace. [29] Over 20 companies now produce PV panels in a variety of sizes and shapes. The applications are for installations such as remote power stations for the National Park Service, solar farms for industrial energy production, panels for residential

and commercial projects, building integrated PVs (BiPV) for single family homes, and small power supplies for appliances or other gadgets. [30]

Although material and manufacturing costs are high, often creating a barrier to market entry for PV products in several areas, significant improvements over the last 15 years have led to great advances in manufacturing as well as efficiency and continue to change the focus of the industry. However, the cost of producing the materials and manufacturing the components still makes PV units less economically attractive than the alternatives offered by conventional generated electricity. The strength of PV energy lies in the potential of its development, as a “free renewable source” of energy. This concept is so compelling that governments, as well as a vast number of research groups and large companies, are leveraging their efforts, time and resources to develop it. In addition, consumers currently show support for “solar energy” by paying a premium for this type of energy, even when not cost effective, because it is “renewable”.

The Million Solar Roof initiative, signed by President Clinton in 1997 [31] is a major governmental program to support PV development. The Fiscal Year 2000 budget request proposed by the President increases the funding for PV research to \$93.3 million for the year, which is a 30% increase over the previous year. The Department of Energy (DOE), through the National Research Energy Laboratory (NREL), has the infrastructure to provide the setting for PVs to be used in various types of built projects. However, PV use remains at a limited level. The Photovoltaic Manufacturing Technology Project (PVMaT) is a government/industry research and development partnership that provides the members of the U.S. PV industry the opportunity to continue research and development, with reduced risk, by reducing the amount of capital needed to be invested by the companies. Another recent program awards \$5 million to 18 U.S. universities actively engaged in photovoltaic research. Competition from other countries, such as the partnership Monash University and Sustainable Technologies Australia [32] have also provided a stimulus for governmental interest.

All of the factors mentioned have helped to shape the context providing the opportunity for development of new and innovative design approaches, capable of enabling the building envelope to utilize and build-on the characteristics that the climate provides. On-going material developments and discoveries, combined with the increasing cross-fertilization of ideas across multiple fields, coupled

	focus	Program	Creator	Capabilities
<b>Material</b>	Thermal	Mat-Lab		Dynamic Mass heat transfer of complex systems
	Thermal	HEAT		More simplistic interface for transient mass heat transfer wall configurations
	Thermal	THERM	LBL [33]	Thermal analysis of window at frame based on material and configuration
	Daylight	OPTICS	LBL [33]	Analysis of absorption, transmittance and reflection of material
	Air flow	Phoenics		Analysis of computational fluid dynamics of buildings and spaces
	Daylight	WINDOWS 4.1	LBL [33]	Provides Center of Glass measurement of window configuration and thermal properties
<b>Building System</b>	Building envelope	RESFEN	LBL [33]	Simplified building analysis (5 types), based on location (46 cities) to assess energy performance
	Building envelope	VISDOE2	Eley Assoc. [34]	First floor

Table 2.14 Building Performance Software Descriptions

with advances in analytical techniques to improve appearance, function and actualization, offer opportunities for the exploration of passive and active solar innovations.

### 2.3.3 Analytical Approaches

An explosion of simulation software has occurred and continues to develop at a rapid pace. The areas simulation packages relating to the built community can be classified into the three categories of building performance, visualization, and construction process software. However, even though great strides have been made, a degree of fragmentation has been maintained, which is slowly being overcome.

#### ***Building Performance Software***

Several simulation programs developed by government agencies, universities, and private companies assess different levels of building performance. The programs can be split into the categories of assessment at different levels, specifically by material, system and building level. (Table 2.14) For example, the Lawrence Berkeley Lab (LBL) has developed a series of programs to investigate the design and performance impacts of windows and daylighting within a specific building design, starting from the material level and moving up to the quantity and type of apertures within the building envelope. The material properties can be analyzed initially in OPTICS, with the

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results then transferred into THERM and WINDOWS 4.1 to investigate the edge of glass and center of glass results of the selections. After a group of window types are generated, they can be evaluated within the context of the building envelope by the program RESFEN. The software programs, which include many others beyond those listed, vary by focus, input requirements and interface.

### ***Visualization Software***

Visualization software includes specific tools that allow the creation of a three-dimensional model, representative of the scale, shape, and color, lighting effects and material character of the original object (building or component). These tools can place a higher level of visual information in the hands of the designer that can be related to the client. The visualization software creates the ability to investigate the object as a whole, inside and out, as a substitute to a full-scale prototype. Currently, most architectural firms will utilize one program for the precise model creation (e.g. AutoCAD, MicroStation, etc.), and another for high-resolution rendering and more “fuzzy” model explorations (FormZ, 3dStudio Max, etc.). Current developments are incorporating the capabilities of “objects with intelligence”, which know what and where they are, versus the current use of lines, coupled with the rendering capabilities to understand the visual impacts of material selection and proportion, all in one.

### ***Process Software***

The current state of computer-based simulation models of the construction environment can be characterized by discussing the difference of approaches of queuing models, graphically based models, and dynamic process models. Construction process can be very complex, composed of numerous variables and levels of dependencies, even for small seemingly straightforward project types. For a simulation package to be representative, it must have the ability to develop and track the relationships between these numerous variables relating to the design, resource allocation and usage, processes and tasks that occur during a construction project. Due to the complexity, a balance is sought between how representative a simulation model is of this environment and the level of complexity that is required to be inputted.

### Queuing

The queuing model approaches the balance point of complexity and representation by opting for a more simplified level of input, as compared to the other types. It is suited for processes geared towards the investigations of relationships between large numbers of entities that are being processed at a station or waiting to be processed. The queuing model is focuses on optimizing process time for scenarios, but doesn't allow change within the process itself. Nor does the model contain the capability to change, alter or transform the character of an entity as it passing through a series of tasks during the process any attributes of the entities.

The work by Prof. Daniel W. Halpin of Purdue University, in the form of two computer software packages, CYCLic Operations Network (CYCLONE) and MicroCYCLONE characterize the state of queuing models [35]. By defining the entities and their relationships within a language composed of six types of CYCLONE modeling elements, and mapping them within the process model, the resource sharing among various processes and process interdependence can be identified for the overall process. However, to implement the capabilities allowing the modeling of shared resources across processes to occur involving the introduction of a higher degree of complexity to the model.

### Graphically based models

The virtual representation of spatial characteristics and how the entities can be constructed, in a particular way, is the primary focus of the graphically based models. It is directly related to the developments in the visualization software. The creation of 4D-CAD by Prof. Martin Fischer at Stanford explores the linkages of 3D CAD models with construction scheduling information in the form of Construction Method Modeling Templates (CMMT) to provide a tool capable of assessing the overall construction process of the building. [36] The 4D-CAD models are guided and directed by their relationship to the design. The CMMT, providing the input source of the construction process knowledge, are based upon forms of simplified assumptions that enable the two different types of information to find common ground. Therefore, assumptions are made within the links developed between different construction methods are representative, but unable to completely reflect the type of decision-making that occurs on-site.



### *Dynamic Process Models*

The approach of the dynamic process models differs from the other two through its ability to represent the site dynamics, such as tasks, resources and constraints, within a project. The dynamic process model brings together the project process flow, specifics, and dynamics together as the core for the representational simulation model.

The process flow for a construction type, such as light wood framing, breaks the process down to the most detailed task, for each activity. The combination of all the processes and their associative tasks, in sequence shaped by the construction type, provides the boundaries for the overall framework.

The project specifics are the characteristics relating to design attributes, resources, production rates, site conditions and other factors that are unique to each project. They have the capability to be locally or globally assigned to entities already existing or created within the framework of the process flow.

Construction is not static, and the decisions made regarding processes and activities change on a regular basis, because the “context of the moment” is constantly changing. Every situation found within construction is not ideal, due to what resources are on-hand and available and the relational sequencing of other processes already in motion. Therefore, a process model that has the ability to capture and adapt, to a high level of variability enhances the manner and the number of opportunities a project team has to engage with the tool.

The capabilities inherent within these tools, plus the potential when they are combined provide the opportunity to approach new problems, through innovative methods. For example, a project partially funded by Sandia National Laboratories, provided the opportunity to approach the issue of how damage within residential homes at or during extreme weather events could be identified, assessed, and even dynamically responded to. The research developed application scenarios of Sandia technology to residential construction [37] and demonstrated how a light wood framing dynamic simulation model could be utilized to locate areas within a structure for high-intensity sensing to begin to understand damage impacts. [38] This is just one example of how the technology incorporated into the computational software has opened doors for other influences to be investigated more readily than previously possible.



## Chapter 3.0 Theoretical Approach

**frame-work** 'frAm-"w&rk. *noun.* (1644) - *a basic conceptual structure (as of ideas).* [39]

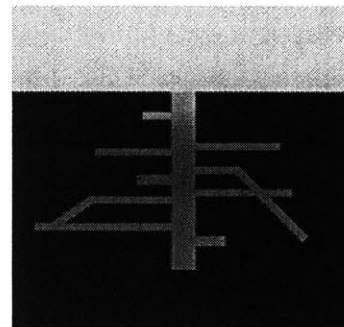
**sys-tem** 'sis-t&m *noun.* (1603) [39]

1 : *a regularly interacting or interdependent group of items forming a unified whole*

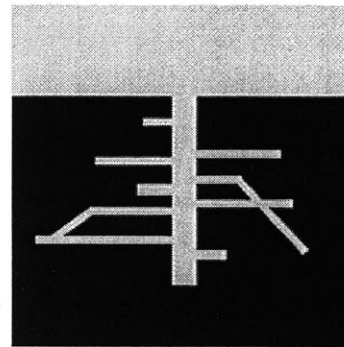
4 : *harmonious arrangement or pattern*

### 3.1 Knowledge Mining

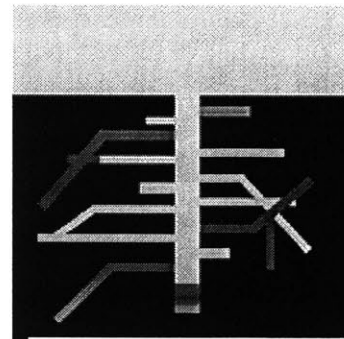
The basis of the theoretical approach is a framework providing the map, the definition of a system providing the goal, and the user formulating the exploration, combining to form the "system-based framework". It is ground in the belief that innovative and integrative designs are based upon the marriage of operational, construction process and aesthetic performance. The creation of flexible boundaries for investigations within each category singular, and combined, reducing the constraints, places the decisions of parameter selection in the hands of the user, versus the established criteria of the tools being used. The system-based framework is to be a gathering point of relevant information providing an adaptive mechanism for evaluating innovative products and technologies within a design at various stages of its development. Aesthetics, Operations and Construction Process performance are to be viewed as equals, by bringing results of all three to a point of comparison and assessment cumulatively, rather than singularly. It provides a comprehensive view from the point of material selection within a component to implementation within the design, thus allowing depth and breadth. By breaking down each category to the most basic level, such as, the number of nails in a sill to wood stud connection, wavelength of absorption of a translucent insulation layer, or



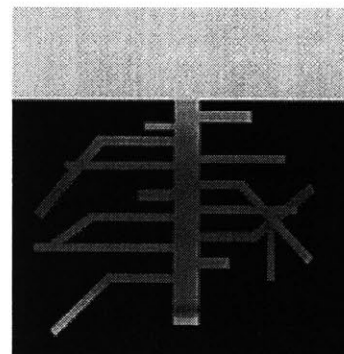
Dia. 3.1 – EPW exploration



Dia. 3.2 – Residual Template



Dia. 3.3 – New Explorations



Dia. 3.4 – The Growing Base

the appearance of the EPW frame from the interior, one can reach to the level of base assumptions. The ability to reach this level coupled with the awareness of the overall picture provides the real strength. The capability to move back and forth between the deeper levels of detail and the higher levels of “shaping the picture” are a key component embedded within the to easily framework.

Adaptability to approaches, information and concepts new and old are within the capabilities of the framework. The capability to add to or adjust over time provides the user the freedom to shape the problem based upon the project parameters, rather than having to conform to a range of assumptions determined by others. The capabilities are to be placed in the hands of the individual (architect, engineer, and builder), and also the project team. By bringing the three categories together, tasks, approaches and processes relating to the people are also brought together. Thus, learning on the part of each individual about the actions of the others within the team brings the conversation to a different plateau. One gains insight into the requirements and the basis of those requirements of the others involved.

If one relates research to the idea of mining, then the series of four diagrams serve as representations of the capabilities of the system-based framework. In each diagram the ‘black’ field represents the unknown information and the differing shades of color represent the three categories of operational, construction process and aesthetic performance. The investigations and explorations of the research on the EPW components are represented by Diagram 3.1. The main shaft and branches stemming in multiple directions indicate the different investigations into the three categories. Some areas of the research went deeper, ran parallel, combined with other branches to form a new path, and passed through other branches to carry the investigation into a combinations of the categories. The knowledge uncovered is collected and brought to the surface to be integrated into the framework and related to the other categories.

When another researcher, practitioner, or project team begins an investigation of implementing an innovative technology within a project, they have a framework (residual template) and precedent to start from. Diagram 3.2 represents the “knowledge mine” previously generated by the EPW investigations. Based upon the user’s capability to define parameters, some of this knowledge may be useful, dependent upon the innovation type, but each investigation is different requiring different

types or more knowledge and investigation to be performed in other areas. Diagram 3.3 expresses how the system-based framework, through reducing the overall constraints, allows the investigations to create new branches, redirect others, and branch off existing to uncover relationships among the three categories that may not have been thought of on the surface. Diagram 3.4 displays what the combined efforts of the two investigations provide to the next participant.

### 3.2 Performance Criteria + Energy Source Options

The Energy Producing Wall (EPW) component functions as the working example of an innovation, evaluated during the development of the system-based framework. An understanding was developed of the type, depth and range of information inputs and the analysis methods required for implementation within a project. A project is composed of design strategies, shaped by site location and quantity and type of loads, which address the performance criteria specific to that project. The system-based framework acknowledges the context of this relationship and provides a “toolkit” for bringing them together, shaping the view of the “big picture”, which is referred to throughout the course of development. The diagram (Dia. 3.9) at the end of this section is the product of each of the sections to be discussed.

Passive	Alternative	“Accepted Standard”
Solar	Photovoltaics	Natural Gas
	Concentrating Solar	Propane
	Power	Oil
	Hydro Power	Power Plant Elect.
	BioMass Power	Nuclear Energy
	Geothermal Power	
	Wind Energy	

***Table 3.5 – Energy Sources***

Energy can be supplied to a residence or other building type in the form of passive, alternative or accepted standard sources (Table 3.5), which are dependent upon the distribution strategy embedded within the overall design. Sunlight striking a thermal mass surface, which stores the energy (in the form of heat) and releases it to the interior spaces, is an example of a passive, renewable, source. The source is ever present, but the quantity is not always known or reliable quantity. The alternative sources of photovoltaics (in solar farms or concentrated configurations), hydro-

power, biomass, geothermal and wind energy all utilize an active component to assist the capture and transformation of the natural features into energy. Natural Gas, propane, oil, nuclear power and generated electricity from power plants compose the “accepted standard source” of energy for residences across the globe. The types are the most readily available for use, but at the expense of consumption of vast amounts of non-renewable natural resources. The selection of an energy source or combination of sources and types, have a strong influence on the overall performance and capabilities of a project.

<b>Solar</b> (thin-film PVs, thermal mass)
<b>Local Internal</b> (fuel cells, lithium batteries, deep-cell batt.)
<b>Grid</b> (PV, Hydro, Wind, Power Plant)
<b>Local External</b> (Biomass, Geothermal, Natural Gas, Oil)

**Table 3.6 – Site & Distributed Source Types**

A large part of the decision for selecting an energy source is shaped by the climate within the location and the site specifics. Each of the circles (bubbles) within diagram 3.6 represents a delivery method of energy to a residence. The energy can be transformed on site by equipment or active components or it can be distributed to the site in its final form for direct use. For example, the sun provides the source on-site, which can be transformed into heat or electricity by photovoltaics, while alternative sources of electricity from power plants and alternative energy sources as are distributed over the grid. Initial questions must be addressed to investigate the feasibility of design strategies. Questions such as:

*How much daylight is available? Is the heating of cooling load dominant? Does the climate allow the building to be opened for ventilation versus reliance upon a variable air volume (VAV) unit or air conditioners? Can thermal mass alone provide the heating load? How much of the overall energy load can photovoltaics provide? Is it best to store the energy created locally or give it back to the grid? What quantities of “standard” sources are required to supplement or back-up passive or alternative approaches?*

Part of the answers to these questions is provided by what sources are available due to location, but the other side relates to what the overall loads for the residence are.

Aspect of Residence	Potential Load Source (looking forward)
Building Envelope	Infiltration, heat gain, sensing/monitoring packages, actuators, switchable glazing
Kitchen	Refrigerator, LCD displays, microwave, range top/oven, dish washers
Home Office	Computer system, printer, external connections
Entertainment	Video projection TV, stereo visual system, video phone
Additional Systems	Computational devices, lighting, air movement, distributed sensors/actuators
Home Infrastructure	External communications, internal communications
Thermal Environment	Air conditioning, heating, enhancement

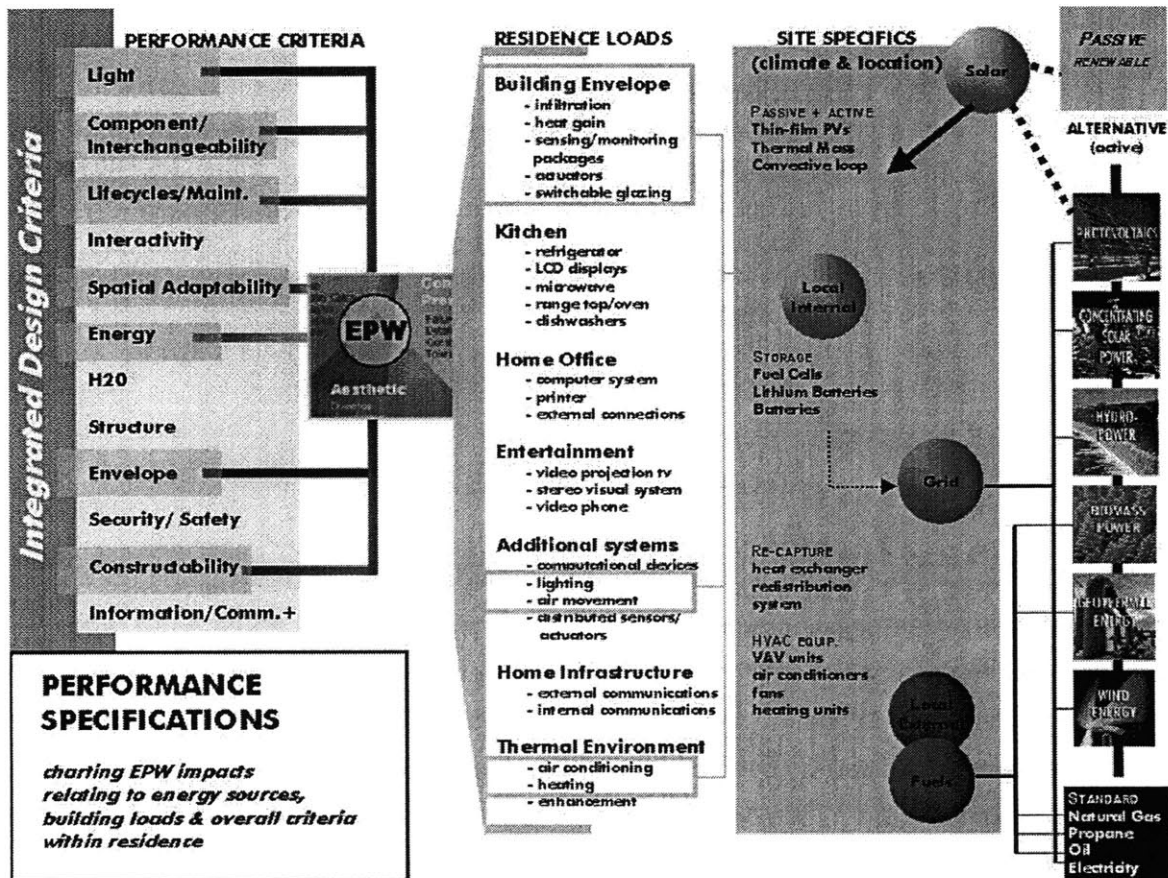
**Table 3.7 – Residence Loads**

Overall energy consumption within a residence is a combination of the heating and cooling loads plus the other appliances and equipment. Appliances and equipment can be short or long-term energy draws of large or small quantities. The overall total energy required to be on hand is the total of this amount, plus the potential for that amount to significantly increase or decrease over time. The building envelope traditionally serves as a point of energy loss for the building, due to the heat loss and the increased effort by the heating/cooling equipment to compensate for this loss. However, there is no reason why the envelope cannot function as a gain or even storage. Diagram 3.7 provides a listing of some of the major factors effecting the balance of energy within the residence due to consumption and loss, which begin to quantify the energy load.

Light  
Component Interchangeability  
Lifecycles/Maintenance  
Spatial Adaptability  
Energy  
Structure  
Envelope  
Security/Safety  
Information/Communication

**Table 3.8 – Performance Criteria**

The performance criteria define the spatial definition of the residence, while the previous discussion outlined the elements that are introduced into this space to provide the desired capabilities of the occupant. The performance criteria list in Diagram 3.8 provides a categorical breakdown



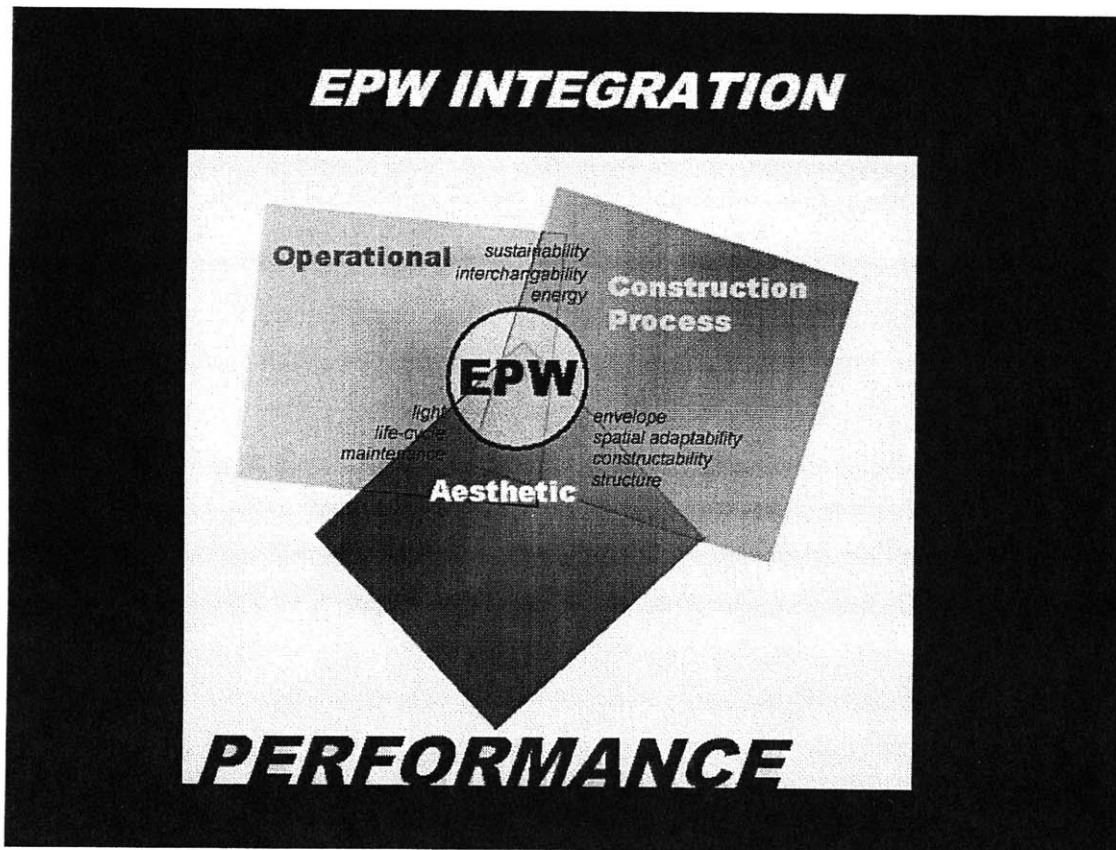
**Diagram 3.9 – Mapping Performance Specifications**

of the factors influencing the design and ultimately the performance of a residence. The assumption is made by the author that the listing is of a level of familiarity to eliminate the need for defining each. The overall combination of these subjects combines to establish the integrated design criteria for the project. The performance criteria subject areas reflect the inputs into the “system based framework”.

The combination of all of these fields creates Diagram 3.9. The highlighted selections within the diagram demonstrate the selections made for the implementation of the EPW (Chpt. 4 EPW description) within one of the prototype designs. The diagram serves as a means to chart the areas of influence regarding the performance criteria and the energy sources. The highlighted performance criteria refer to those topics that are directly influenced by the use of the EPW. For the energy source, a marriage of passive and active strategies using thermal mass and photovoltaics



is used to generate a “local internal” source of energy for the home. The initial concentration is upon the building envelope, the thermal environment and potential support of lighting and air movement facets of the overall energy load. The understanding is that these selections will change through the course of development, as a greater depth of information is gained and relationships with other types of loads prove more beneficial. The dotted line identifies a secondary option of redistributing excess energy created on-site back to the grid. The two sides provide the inputs to the EPW system-based framework.



Dia. 3.10 – EPW Integration of Performance

### 3.3 Integrating Performance

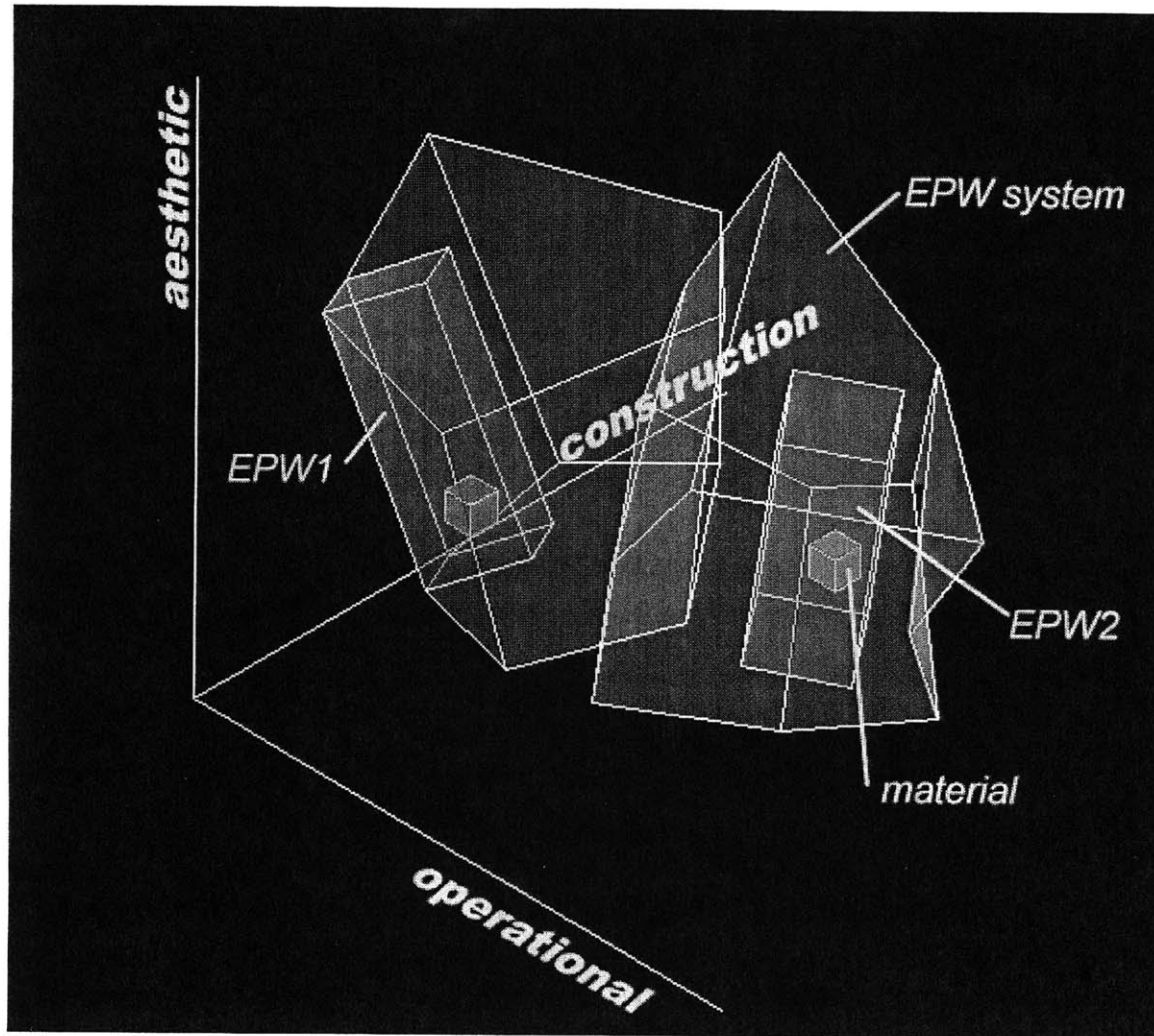
The integration of the EPW into the system-based framework is contingent upon the performance in regards to the categories of operations, construction process, and aesthetics, mentioned previously (dia. 3.10). Each of the three boxes within the field of performance represents a specific category. Note that each of the category boxes overlaps one another to create areas where combinations of categories or all three are relevant. These are the areas where the performance criteria

are mapped representing their inclusion within the overlapping areas. The circle at the center, titled EPW, represent the role of the system-based framework in allowing the investigations to incorporate all three categories at the point of integration.

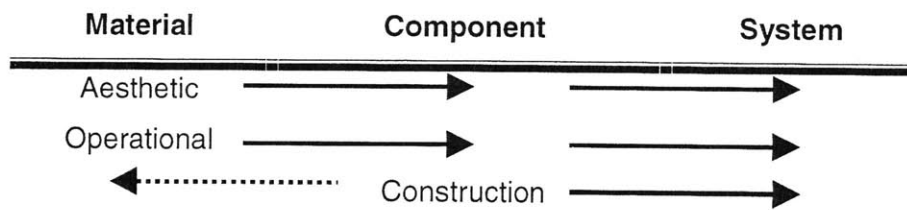
### 3.4 Material, Component, and System

Another facet of the relationship between the three categories centers on the selection of materials, their transformation into components, and the aggregation of components into a system, and how those selections can be characterized and influences charted. Various levels of systems and sub-systems exist and are combined to create other systems. For the context of this document, the term “EPW system” will refer to the reaches of influence of the EPW components types into the aggregation of the various systems within a residence, in particular, the prototype designs (Appendix A & B).

The three-dimensional space defined by the axes of aesthetics, construction process, and operations within diagram 3.11 form the boundaries of the systems of the home. The two smallest boxes within the field represent the area of influence of a single material within each component type. The rectangles signify the extent of impact that each of the material configurations of the two EPW component types has upon this field. The difference in location, size, slope and directionality represent the different characteristics upon each of the axes that are embedded into the two different component types (Chpt. 4 EPW Description). The larger amorphous region expresses how the implementation of the EPW components within and linked to various other systems and sub-systems effect each of these categories to define the “EPW system” for each. The overlap among the two systems indicates that both satisfy some of the same criteria within the overall systems of the home. The shapes within the diagram are not static, but dynamic and adjust in size and shape dependent upon the paths taken over the course of development. Table 3.12 expresses one facet of the potential dynamics due to the approach taken for each of the categories. The approach to evaluation of the levels of material, component and system for aesthetics and operational performance are a building-up process that moves from material to system. The construction process can include specific materials, but can be a composition of pre-fabricated components forming the system.



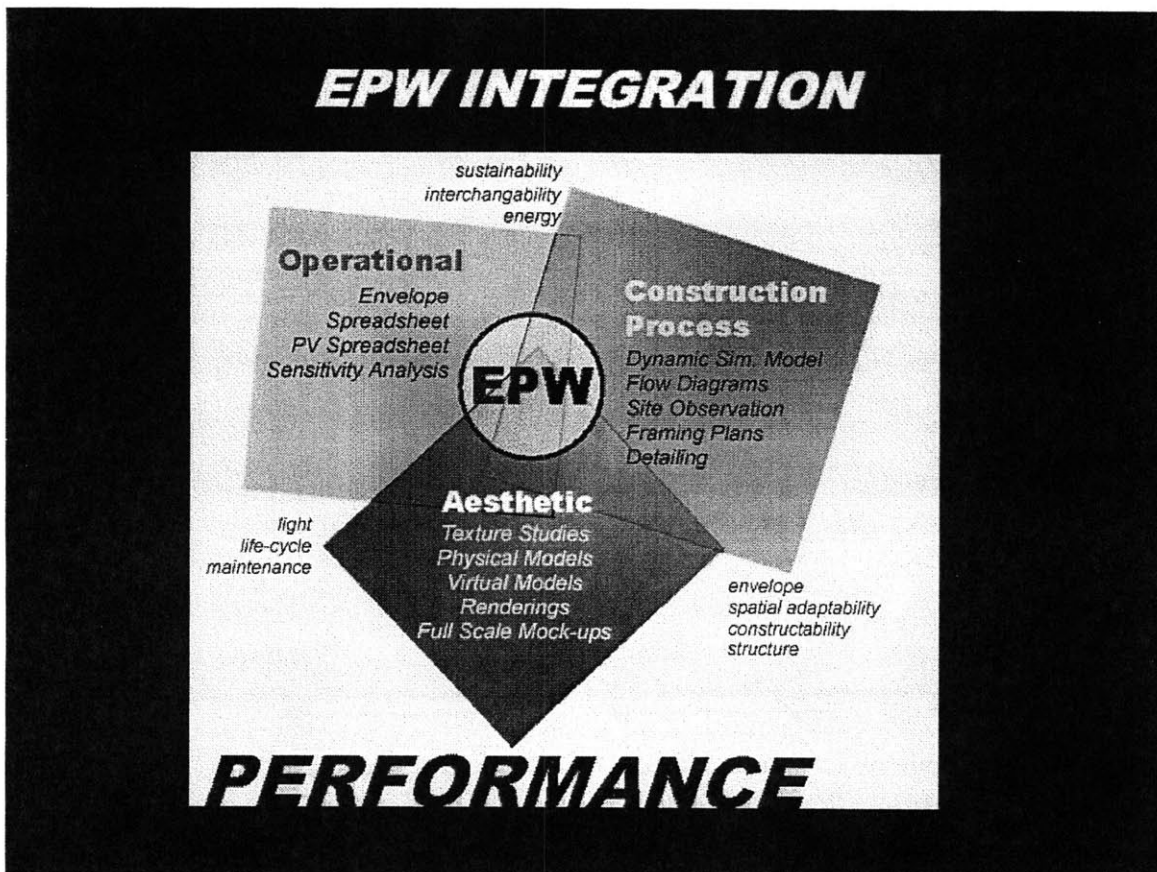
*Dia. 3.11 – Material, component, system*



*Diagram 3.12 Categorical Relationships*

**3.5 Evaluation Tools**

The ability to locate each of the regions of influence, qualitatively and quantitatively, for each innovation within the three-dimensional space, is the task of the system-based framework. The means to accomplishing this task rely upon the formation of an “evaluation toolkit”. Currently, the concept of a unified tool, which has the potential to evaluate all of the information necessary, does not exist. Therefore, a combination of approaches, new and old, methods, complex and simplistic, and tools, created and existing is combined to create the “evaluation toolkit”. Diagram 3.13 identifies the tools utilized to create the evaluation within each of the three categories. Each of the tools will be discussed further within Chapter 5, Methodology.



Dia. 3.13 – EPW Integration and Tools

## Chapter 4.0: EPW description

### 4.1 Material Selections

As a starting point, each layer of the trombe wall (triple glazing, airspace, and thermal mass) assembly was dissected to the parametric layer of the material properties to identify the important parameters of the system. Investigations and explorations were then conducted by researching new and developing technologies to create substitutes, alternatives and/or complements to these extant layers. Material properties were gathered and comparisons generated to begin to develop relationships not only to satisfy the criteria, but also dramatically increase overall performance. Several of the groupings and relational diagrams were explored at the property level as well as brainstorming on component configurations. This process served to not only lay the foundation but also stimulated thoughts towards other potential component configurations as well as insights into other materials that could be used.

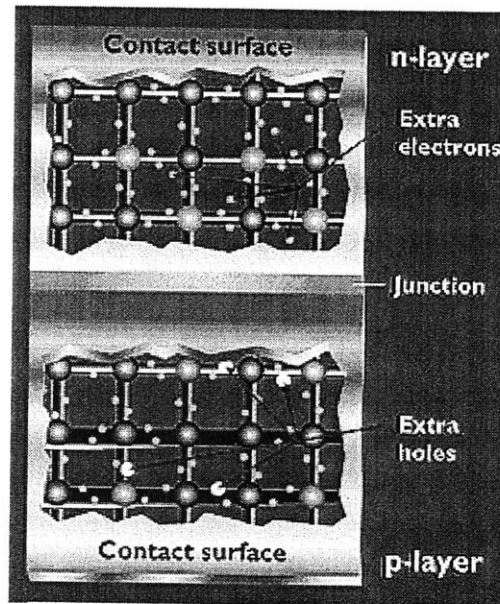
The result was the layer selection of thin-film photovoltaics, translucent insulation, thermal mass and electrical resistance heating. More in depth research was performed on each of these layers to identify the parametric trade-offs that would establish the crucial relationships between the material properties, the component configuration and the system requirements.

#### 4.1.1 Thin-film Photovoltaics (PVs)

The principle of PVs is somewhat simple; a “photovoltaic effect” causes electricity to be generated when direct sunlight hits the component’s surface. However, creating the units, which generate the “photovoltaic effect”, can be a complex process requiring expensive manufacturing processes, materials and components.

*“Broadly speaking, there are no drawbacks to any material, as long as you recognize them. Drawbacks are only with architects and engineers, never with the materials.”*

**Paul Weidlinger...1956**

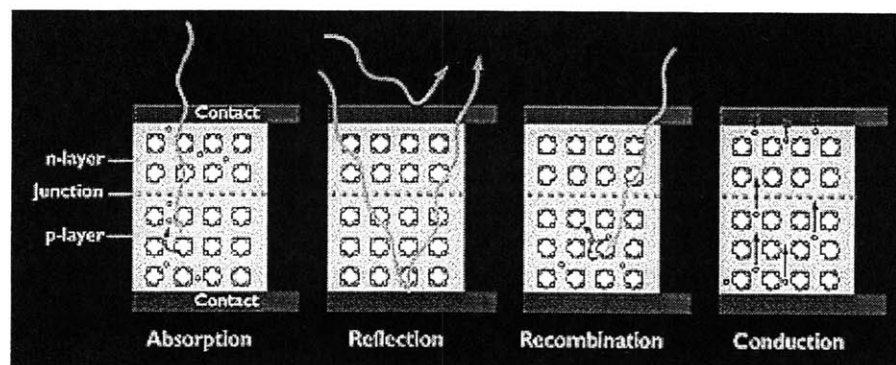


Dia. 4.1 Thin-film PV composition



### Technology & Types

The exposure of photovoltaics to sunlight generates electricity through the Photovoltaic effect. A sandwich of five layers composed of a contact surface, “*n-type*” layer, junction, “*p-type*” layer, and another contact surface form the module (diagram 4.1). The effect is created through a process of doping the thin-film layers to create the necessary polarity. The process of doping involves the introduction of another chemical to obtain a desired effect within the thin film. Introducing phosphorous creates the “*n-type*” semiconductor containing one extra electron, making the layer negatively charged. Introducing boron creates the “*p-type*” semiconductor containing one less electron, also referred to as a “hole” for acceptance of photons. Combining these two semiconductor layers, the extra electrons within the “*n-type*” layer move towards the “*p-type*” and the holes within the “*p-type*” layer move towards the “*n-type*”, creating an electrical field between them. This configuration sets the stage for the photons within daylight to pass through the “*n-layer*” and junction, into the “*p-layer*”, where they are absorbed. The photons strike the extra electrons with enough energy to free them from the cell and, with the help of the electrical field, they reach the contact surface. This carries them into the electrical circuit and creates electricity. The first and fourth images within diagram 4.2 represent the desired result occurring from the two step process of absorption and conduction. The second and third images provide events that can also occur, which can reduce the probability of the desired result. The daylight can pass all the way through the layers, reflect off the bottom contact surface back to the exterior environment, or the “freed electrons” can recombine with other photons before reaching the contact surface even if absorption takes place, thereby negating the effect. [40]



Dia. 4.2 Thin-film PV possible reactions

In the first versions of PV cells, both the “n-layer” and “p-layer” were made of crystalline silicon, which is extremely expensive and time consuming to produce, therefore making them an unattractive economic alternative compared to standard energy sources. Also, an effect called the “Staebler-Wronski effect” occurred, which causes the crystalline silicon cells to reduce their efficiency by 20%-30% over the first few months due to degradation after exposure to sunlight. The silicon cells eventually stabilize to an overall efficiency of approximately 12%[41].

The ability of photovoltaics to be a viable economic alternative over time depends upon three issues; reduced manufacturing cost, increased reliability and increased efficiency. As knowledge was gained relating to the limits of efficiency, research efforts turned to a focused on manufacturing cost to reduce the overall cost of PV systems, while continuing to enhance reliability. [41]

<i>Thin-film PV Material</i>	<b>Composition</b>	<b>Efficiency(%)</b>		<b>Manuf. Cost</b>	<b>Reliability</b>
		<b>Mkt.</b>	<b>Lab.</b>		
Amorphous Silicon (a-Si)	“p” layer “i” layer “n” layer	7-9%	<12%	Low	High
Copper Indium Gallium Diselenide (CuInSe <sub>2</sub> )(CIGS)		<11%	18%	High	High
Cadmium Telluride (CdTe)		6-8%	16%	Med. (unstable)	Low
Film Silicon & Dye-Sensitized (TiO <sub>2</sub> ) cells	“p” layer “n” layer	6%	11%	Low (simplicity)	Med. (outdoor stability)

**Table 4.3 - - Thin-film PV**

Sources: [zweibel]. [ISTA].

Therefore, two major streams of research were developed; the efficiency group, and the manufacturing cost reduction group. The new stream provided a wide range of PV material configurations, which reduced the amount of silicon used per cell, as well as offering options to replace crystalline silicon with other materials or combinations of materials. (Table 4.3)

Prior to the thin-film developments, the silicon wafer PV cell module, which is approximately three inches in depth, was the only type of PV on the market. The new options are not only less capital intensive to manufacture, but also allow thinner and more flexible modules. In addition, a range of

colors, possible substrates and potential materials besides crystalline silicon show strong promise for various applications and efficiency. The table displays the wide range of performance across each thin-film type within the three pertinent areas. Each technology comes with its own set of problems, but also with its own set of opportunities. The three most promising alternatives seemed to be amorphous silicon, cadmium telluride, and copper indium gallium diselenide (CIGS). [41] Currently, amorphous silicon thin-film PVs are the most dominant in the market, due to government support over the past 5 years, but recent breakthroughs are stimulating an industry shift. Two breakthroughs reinforce the benefit of the two research streams. A new efficiency record of 18.8% set by the National Center for Photovoltaics using a CIGS solar cell, [42] and the electrochemical device, entitled the Gratzel Cell, creates a simpler PV device in configuration and manufacture using dye-sensitized TiO<sub>2</sub> cells. [41] The overall market still awaits the fusion of the two.

### ***State of the Art***

Companies offer thin-film PVs in a wide variety of grades, shapes and sizes, dependent upon the type of loads one desires within a system. Large format panels are used in “solar farms”. These are a series of arrays configured to harvest the sun’s energy, (figure 4.4) or concentration collectors to create large amounts of electricity from solar power. The most common PV module sizes in the residential and commercial market are 2’-0” x 2’-0”, 2’-0” x 4’-0” or the PV shingles[43]. The thin-film PVs can use various types of substrates rather than glass, such as metal, aluminum or types of plastics, which allow the PV to become flexible and partially transparent.

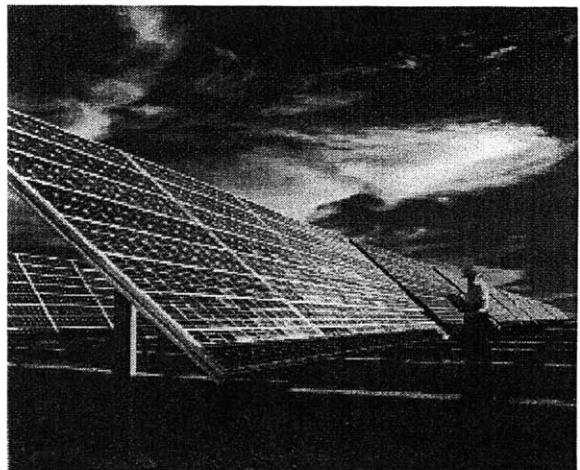


Fig. 4.4 Solar Farm

The current market leaders, Solarex and BP Amoco, have recently merged. [44] Solarex was one of the few companies marketing both the PV cell modules and the thin-film PVs. BP Amoco, which was until recently was BP Solar, has been the leader in the thin-film development. It focused the R&D efforts on the APOLLO thin-film products and high efficiency laser-grooved, buried-grid (LGBG) mono-crystalline cells and modules [58]. The result of the merger will be interesting to track be-



mono-crystalline cells and modules [58]. The result of the merger will be interesting to track because of the resources and funding that are now at hand. In addition, a number of companies in Massachusetts are pursuing niches within the PV market, such as Spire, [45] who has developed a unique cost-saving process for producing and manufacturing silicon panels, and Evergreen Solar, developer of an innovative technique of string-ribbon amorphous silicon creation. [46]

Sustainable Technology Australia (STA) has neared completion of an innovative product entitled Titania Solar Cell® [59]. The product is a thin-film PV that begins to explore the PV as a translucent rather than an opaque object. The technology incorporated within the Titania Solar Cell® serves as

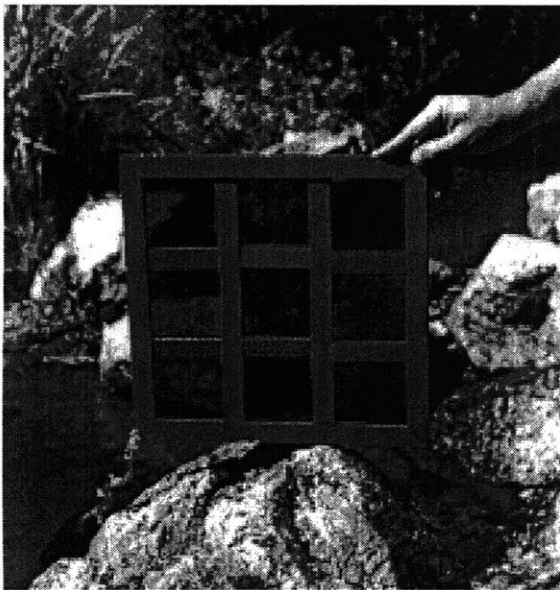


Fig 4.6.1 - Titania Solar Cell (STA)

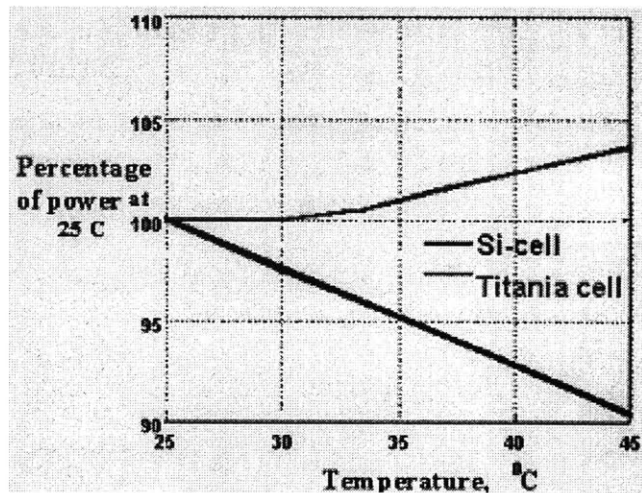


Fig. 4.5 Titania Solar Cell Temperature to Percentage of Power

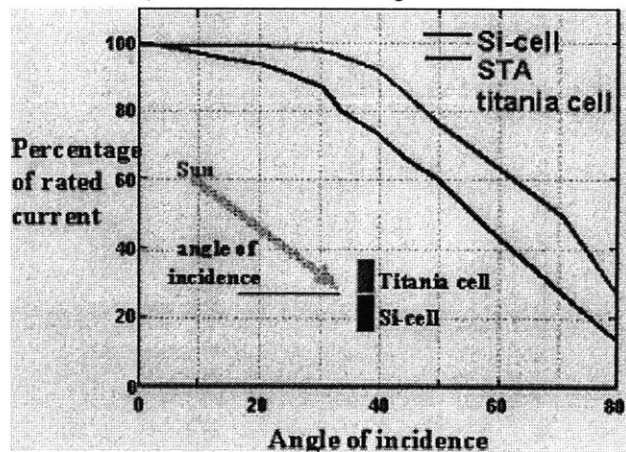


Fig. 4.6 Titania Solar Cell Angle of Incidence to Rated Current

the focal point of the EPW concept. A few characteristics make this product unique and address past problems of the PV development. According to recent test results performed at STA, the Titania Solar Cell maintains and actually appears to increase its performance at higher temperatures. (Fig.4.5) At 45°C, the percentage of power created is 15 % higher than standard amorphous silicon (a-Si) panels. In addition, results also indicate that the panels seem to be less sensitive to the angle of incidence of direct sunlight and can use refracted and reflected light, thus increasing the overall amount of power created and at what times the PV is functioning. (Fig.4.6)

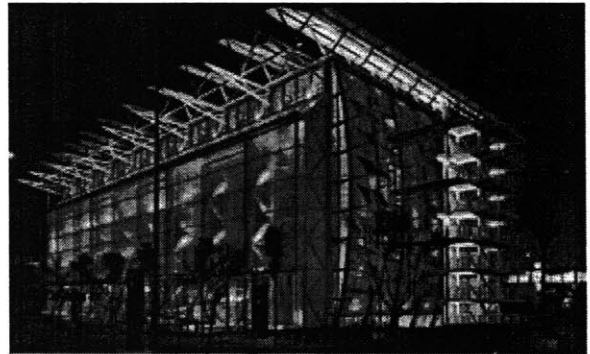


Fig. 4.7 Nichola Grimshaw's British Pavilion. Seville. Spain

Other innovations in batteries, controls, and links associated with the PV system reduce the external pieces or "balance of systems" equipment external from the panel. By incorporating built-in micro-converters, Acension Technology Inc. in Waltham, MA now manufactures a module, SunSine TM300 AC®, which eliminates the need for a converter to transform direct current (DC) electricity into alternate current (AC) electricity (which is the type of energy most used by appliances in the home). The panel is 4'-0" x 6'-0", pre-wired, and is assembled with snap together connections. [47]

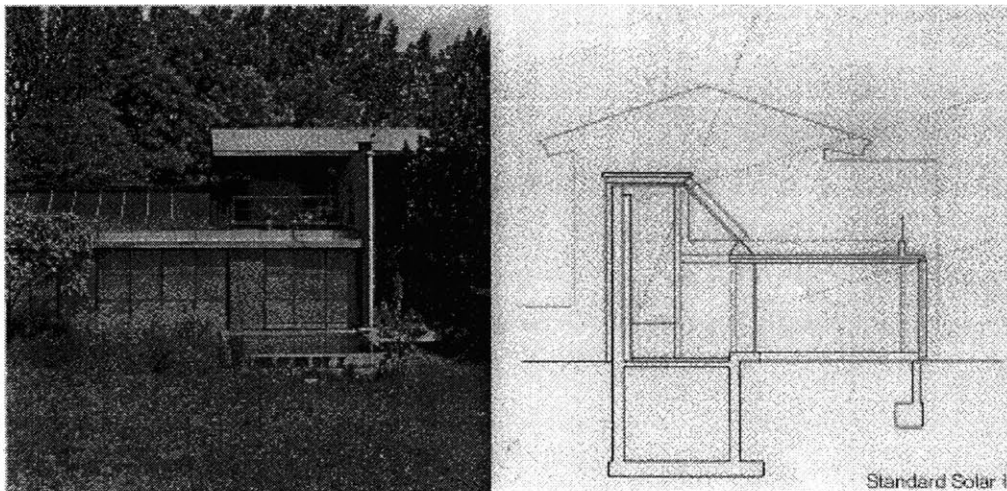


Fig. 4.8 Solar Residence in Tulin, Austria [detail]

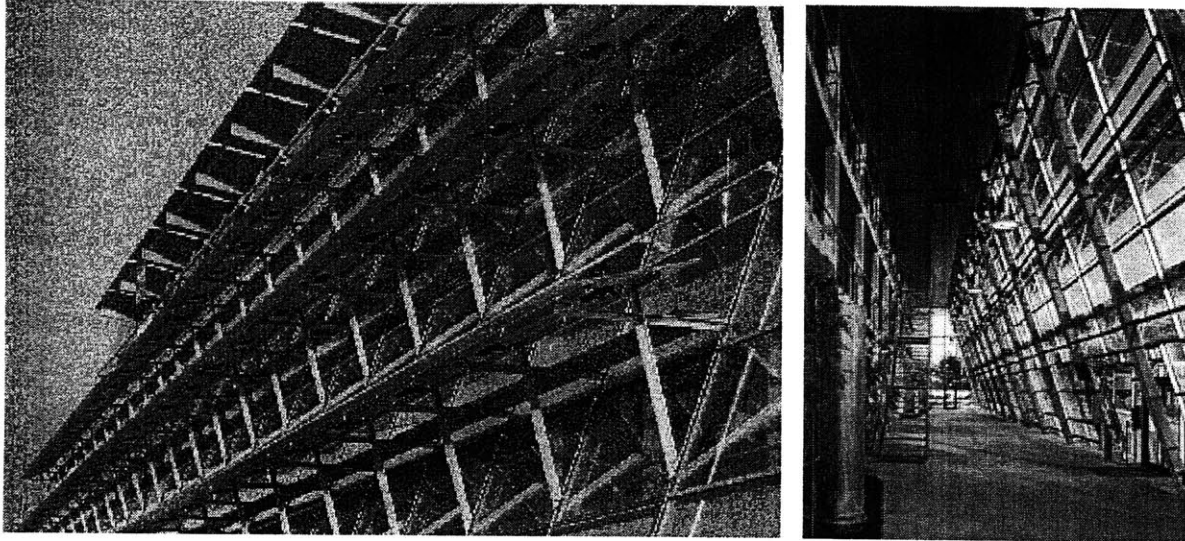


Fig. 4.8.1 Solar Factory Exterior PV sunshades and interior result

### ***Applications***

PV panel applications are becoming more prevalent in the built environment, but the issues of aesthetic applications have yet to be fully addressed. One of the best known projects incorporating PVs is Nicholas Grimshaw's British Pavilion at the World's Fair, Seville, Spain, in 1992. [48] The pavilion demonstrated the potential function and aesthetic value of PV panels incorporated in an overall design in a high profile project. The Solar Factory in Freiburg, Germany (fig. 4.7) utilizes the PV panels as sunshades on the façade, which creates a unique rhythm with a strong visual presence on the exterior and the interior of the building. [49] Another example is the Solar House by Driendl +Steiner, Wien, in Tulin, Austria (fig. 4.8). The house is a prototype for a series of solar houses, designed with system-based modular features to allow adaptation based on climate location. The design is a combination of light steel, wood, thermal mass and solar panels. [49]

The colors and patterns of current thin-film PV's create a very dynamic potential aesthetic that has yet to be tapped. The new generation of translucent PVs allows consideration of back lighting, vision into and through the panels and other features that could begin to energize and mold their appearance. The desire for the future is for projects that not only utilize PVs to reduce the overall consumption of energy in buildings, but to accomplish it an aesthetically pleasing way.

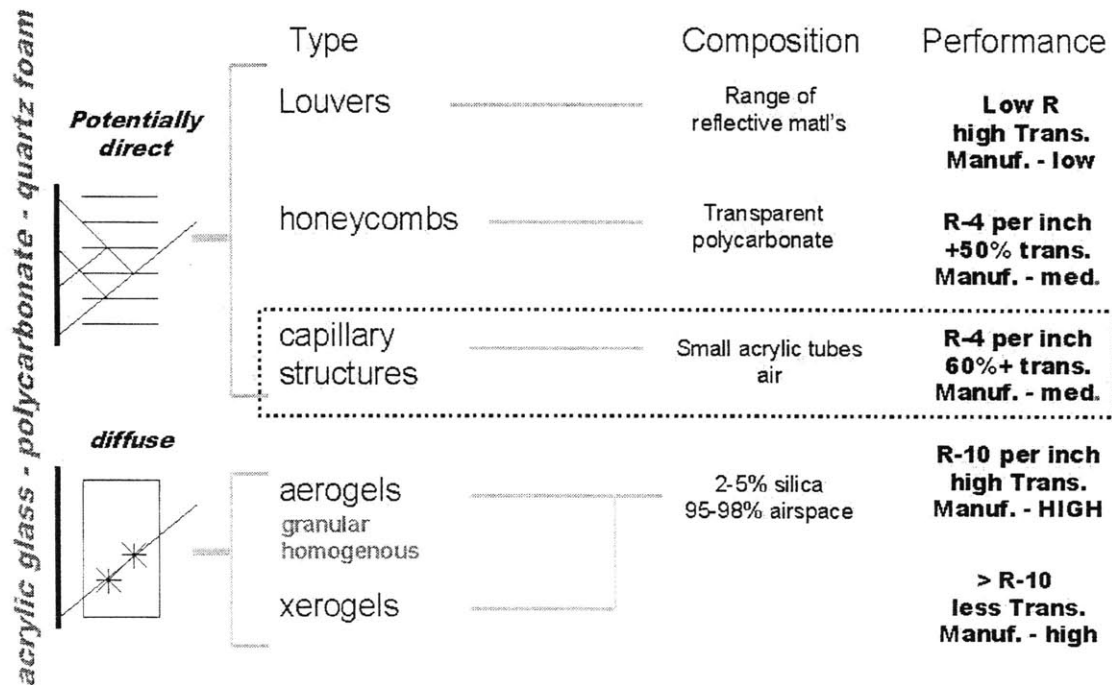


Fig. 4.9 - - Categorizing Translucent Insulation Materials

Sources: [Hausner], [Platzer], [Wigginton]

### 4.1.2 Translucent Insulation Materials (TIMS)

TIMS are not a new line of products, but are now broadening their applications and inclusion in built projects over the past few years. [50] The concept of an insulation that one can see through or transmit light through can be a powerful idea when it comes to potential applications. One can think of many options that can be accomplished when the pink batt insulation within walls can be replaced by an element with light transmissive qualities. The benefit to be explored is the high transmission of incident light and near infrared radiation which allows exploitation of solar energy.

#### Technology and Types

Translucent Insulation Materials can be grouped broadly into the categories of “potentially direct” or “diffuse” (fig.4.9). All of these materials either incorporate glass, acrylic glass, polycarbonate (PC) or quartz foam in their composition or combined composition. [51] “Diffuse” materials can be classified into aerogels and xerogels. These materials reach to the nano-level of material manipu-



lation to create the composition of the material. Aerogels composed of 95-98% air and 2-5% silica are highly porous, microscopic cavity structures capable of being formed into homogeneous or granular compositions. The homogeneous material composition appears solid because at this microscopic level, the particles are smaller than the wavelengths of visible light. R-values of R-10 per inch (1/Btu/h\*ft<sup>2</sup>\*°F) are possible and the material can increase light transmittance into the realm of “potentially direct” as well. But the price paid for the extremely high R-value is an equally high manufacturing cost. Another form is granular aerogel, which increases the reflection of light within the composition due to the amount of surface area of the larger granules. The result is that the amount of light transmitted is

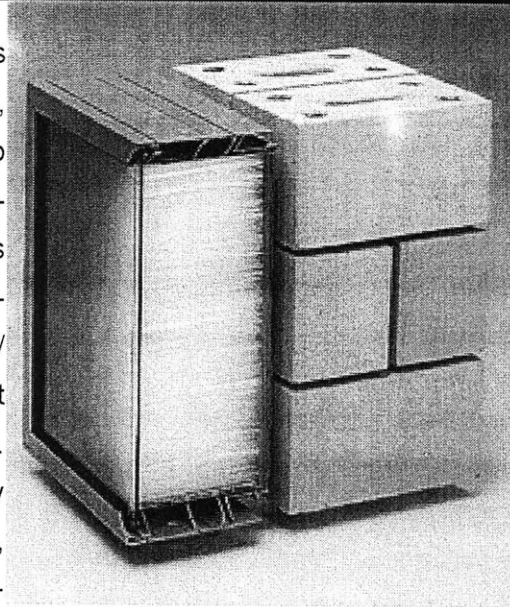


Figure 4.10 Capillary Structure Translucent Insulation material with Thermal Mass. [herzog]

reduced. The second classification is xerogels, which require no special drying process during manufacture, differing from aerogel, increasing the radiative properties and reducing the manufacturing cost dramatically, in comparison to aerogel. However, the trade-off for these characteristics is reduced thermal performance below the R-10 per inch (1/Btu/h\*ft<sup>2</sup>\*°F) values.[51]

The “potentially direct” materials are those with the ability to allow a portion of direct light to pass through the material either by incident angle or controlled reflection. Three types exist; louvers, honeycombs and capillary structures. Louvers can come in various sizes, shapes, incorporate a number of various materials, and either be fixed or operable. The classification in this context describes louvers made of glass or utilizing other reflective materials on the surface to enhance or counter the reflection to the interior. Honeycomb patterns are created from transparent polycarbonate in various sized openings within the pattern. The structure of the material is continuous, providing the basis for the difference in classification from capillary structures. The capillary structures can either be created from small tubes of acrylic, polycarbonate or glass. Values of approximately R-4 per inch (1/Btu/h\*ft<sup>2</sup>\*°F) have been achieved, which are comparable to honeycomb structures. In addition, up to 60% of transmittance of light has been achieved.[52]

Translucent insulation materials provide a selective cover for a wall surface that is transparent to solar radiation, but opaque for thermal radiation.[51] Introducing a plane behind this selective layer, which can capture the heat transmitted through it, enhances the benefits. The solar absorption by the material stimulates solar irradiance within it, resulting in a temperature rise in the material transmitted to the thermal mass. [51] Hausner characterizes the first Translucent Insulation system as a trombe wall. [53] Figure 4.10 displays a potential combination of translucent insulation and thermal mass. [herzog] Opaque and capillary structure systems were developed for systems working at higher temperatures, which could suppress the convection and IR-radiation effectively. [51]

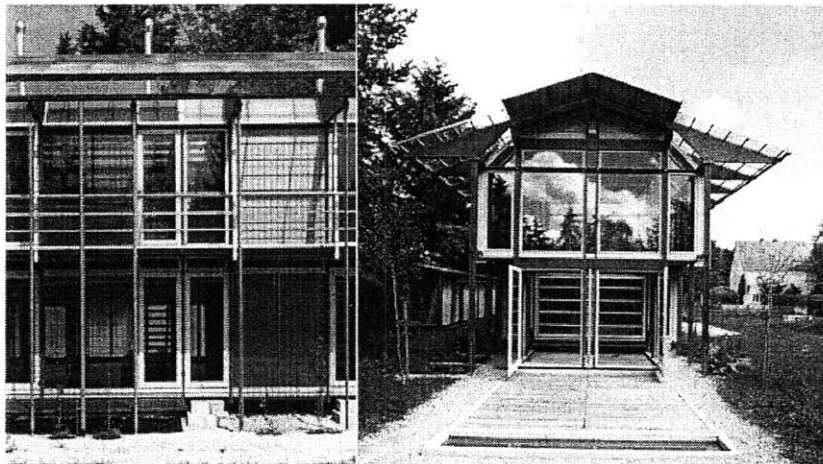


Figure 4.11 & 4.12 Residence in Bavaria. Architect: Thomas Herzog. South and West elevations using “warm wall” panels. [herzog]

### ***State of the Art***

For the purpose of direct sunlight passing through the material, very few products are available. The primary reason is that the industry focus has been on the transmittance of diffuse light. Occupants don't tend to enjoy the heat gain that accompanies the direct light when the design hasn't incorporated it. An example product is from the company Kalwall. They produce a product utilizing polycarbonate exterior layers within an aluminum frame to encase an airspace. The product has a higher R-value than a double glazed window, but only allows the transmittance of diffuse light.

Schott Corporation has a group of interesting products within the category of “potentially direct”, such as Okapane®, Okalux® and Okasolar®. The products allow various methods of manipulation of incoming light. Okapane® is a slab of acrylic capillary tubes, allowing up to 70% light transmittance. Okalux® is a product containing Okapane®, encapsulating it within a highly insulated frame with glazing on each side and a glass fiber tissue on the exterior side. Okasolar® is composed of louvers contained within two layers of glass that can be configured to create a desired reflectance of light based upon the angle chosen. A interesting spin-off product of Okapane®, Kapilux-W®,

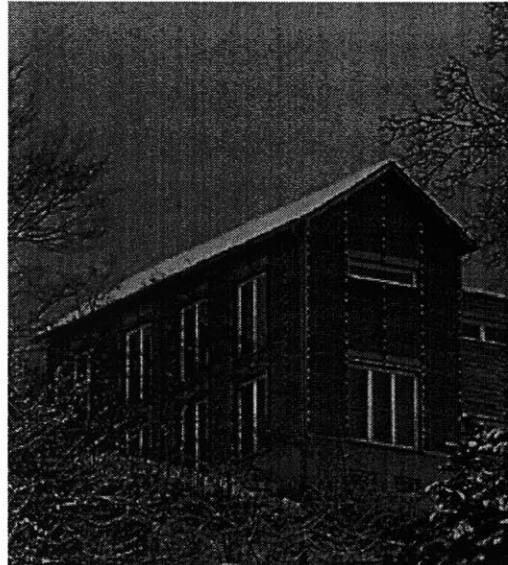


Fig. 4.13 – Residence in Aargu, Switzerland

is also of the acrylic tube, capillary structure family, but the diameter of the capillaries is substantially larger and is designed to allow the transfer of direct light. [52]

### **Applications**

In a two-family house in upper Bavaria, Thomas Herzog utilized a “warm wall” panel in the slender solar conscious home design (Fig. 4.11 & 4.12). The composition of the panel was glass, translucent insulation, and pre-cast concrete painted black. The panel functions by transforming light into heat. The translucent insulation captures the light and transfers the heat to the thermal mass to be radiated to the interior over a time lag. The longitudinal shape of the building allows the radiated heat to effect the overall space as well as allowing sunlight to penetrate the entire width of the building.

Architect Theresia Schreber and Engineer Bad Kreuzen combined efforts to create a panel system utilizing a cardboard honeycombed translucent insulation in a residence in Aargu, Switzerland (Fig. 4.13). A combination of panel types was utilized at various sections within the wall. The overall composition of the panel is glass, ventilated cavity, cardboard honeycomb, gypsum fiberboard, cellulose insulation and gypsum fiberboard as the interior finish. At various locations in the façade, the gypsum fiberboard layers and the cellulose insulation are removed to create other visual effects in addition to the opaque wall and the window systems. [55]

4.1.3 Thermal Mass

Incorporating thermal mass into a building introduces factors into the design that relate directly to the construction process as well as the performance. Thermal mass can function within a project in a variety of ways. It can absorb heat, store heat like a battery, as well as radiate it to the interior. The operational performance of the thermal mass depends on the characteristics of the material, the thickness, the location and the total volume. The operational principle of thermal mass is

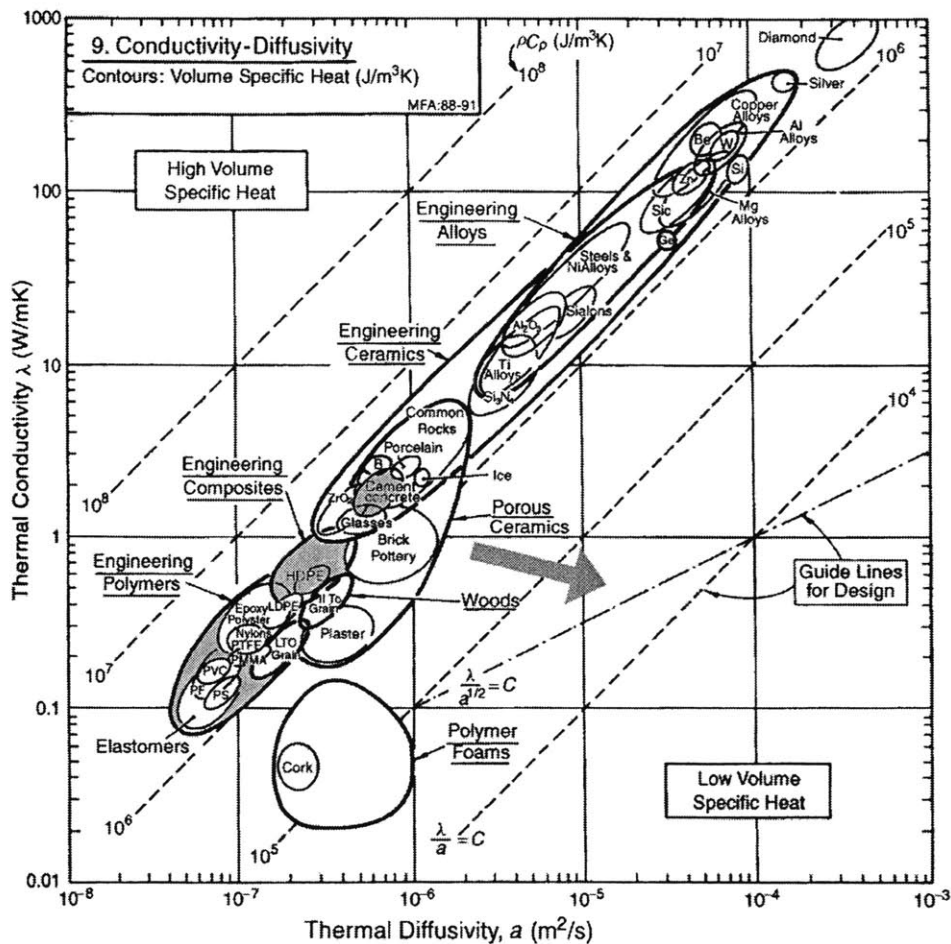


Fig. 4.14 – Ashby Chart comparing thermal conductivity and thermal diffusivity [56]



simple. Heat flows from the point of high temperature to low temperature. The benefits for inclusion of thermal mass within a design is the ability to reduce internal temperature swings of a space (if controlled), which is not fully conditioned mechanically, and to reduce the size requirement for heating/cooling equipment utilized within the home.

Even though water has a higher heat capacity, more than double that of concrete, the material of choice for enhancing performance in trombe wall and direct gain systems has been concrete or brick. Water has the highest specific heat, yet due to the requirement for encapsulation, and potential failure modes, concrete becomes a justifiable selection.

### ***Technology & Types***

The classification of type of thermal mass speaks to the level of technology incorporated in the material. At a basic level only two types of thermal mass exist, “heavy weight” (dense) materials, and “lightweight” (porous) materials. The equations remain the same:

*Density x specific heat = Heat capacity*

*Thermal Diffusivity = Thermal conductivity/Heat capacity*

Density creates the largest range of variance and impact on the performance. The “heavy-weight” materials (concrete, brick, stone) are those that have been traditionally used in the construction industry. They are produced from natural materials, such as sand, limestone, rock and gravel, and typically require a low-level of technological enhancement. The thousands of polymer composites, which represent other alternatives, require a high level of technological input, both in their creation and installation. Figure 4.14 is a chart by Prof. Micheal Ashby [56], which maps the relationship of thermal conductivity (W/mK) and thermal diffusivity (m<sup>2</sup>/s) for numerous families of materials. The arrow on the chart illustrates the location of the ideal material that would satisfy the dual criteria of high performance and reduced weight. Note the absence of any materials in this zone, even with all the innovations in polymer materials over the past decade. Thus, a level of performance must be sacrificed in the material selection to reduce the impact on the requirements of the construction process and containment. However, as the system-based design implies, the reduction of operational performance is accepted as it is, against the impact on the construction process and aesthetics, to achieve the overall objectives.

### State of the Art

Barracell, a foamed concrete, created from sand, cement and air bubbles, is one of the newer developments attempting to provide flexibility to conventional concrete. Others are fly-ash concrete, using the light-weight fly ash from power plants as a cement substitute, and light-weight cellular concrete blocks such as those by Hebel. For example, cellular concrete can be formed into blocks, which can be lifted and placed by one laborer. If an odd-dimension is needed at a corner or other location, the block can be cut to size on site with a handsaw. The benefits are found in the ease of construction and reduction in environmental impact.

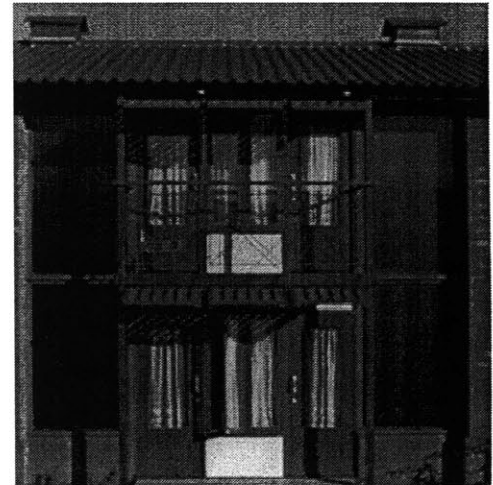


Fig. 4.15 – South Elevation.  
Christopher Taylor Court

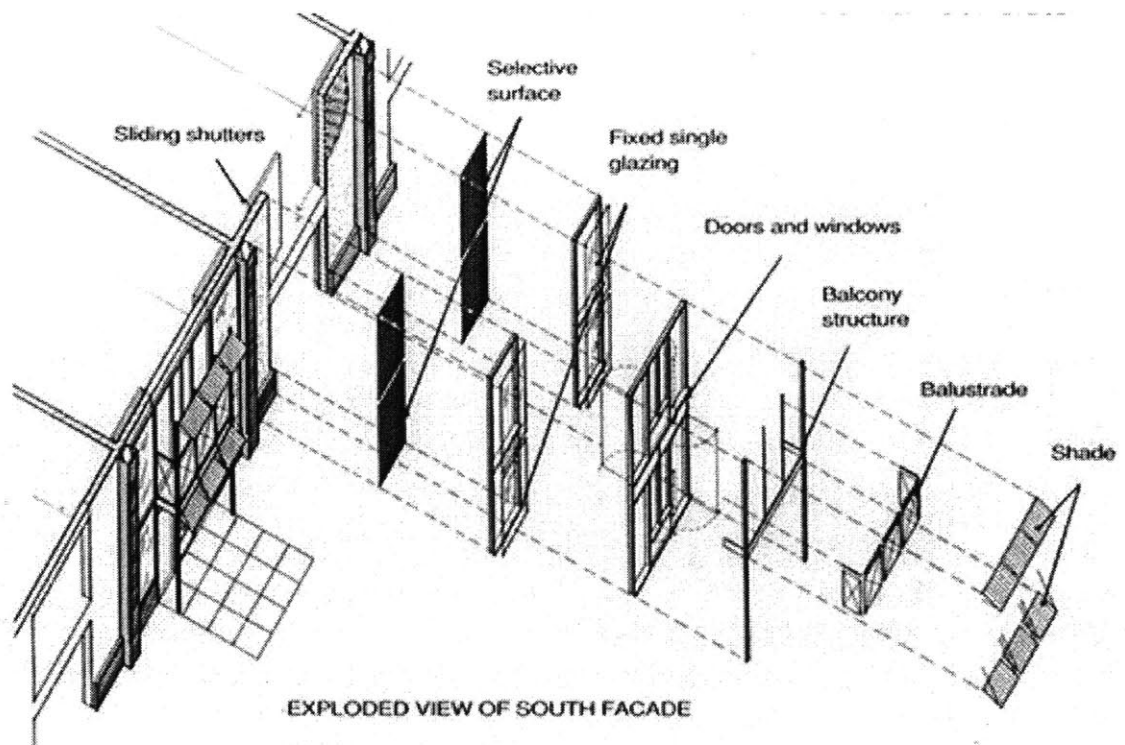


Fig. 4.16 – Christopher Taylor Court. Bournville, UK.

**Applications**

Most interesting contemporary applications are found in Europe. The Christopher Taylor Court in Bournville (UK) (Figure 4.15 & 4.16) breaks from the traditional mold of large expansive trombe walls to go modular. Each of the 42 flats within the two-story complex utilizes a vented, one-story trombe wall. External shades hinged from the balcony block direct sunlight from entering through the windows, while internal shutters are slid over these same windows in the evening to reduce the heat loss, thus enhancing the performance of the heat radiated into the space from the trombe walls. The construction of the trombe wall is simple, with a single glazing, a selective dark surface, and bricks for the thermal mass. [57]

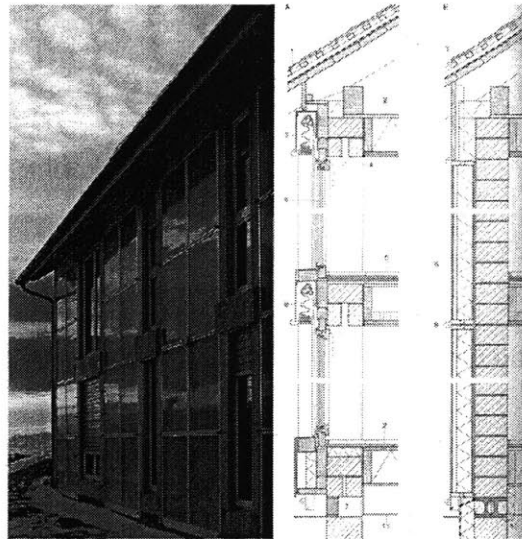


Fig. 4.17 – Residence in Hohe, Switz.

Another application (Fig. 4.17) is a mountain house on the Hundwiler in Hohe, Switzerland constructed completely from pre-fabricated units.[55] The south facing wall panels complementing the windows in a very creative composition is constructed of glass, transparent insulation and dark fiber cement sheets. The panels function in the same manner as the “warm wall” panels by capturing infrared radiation and transmitting the heat to the cement thermal mass sheets. This example and the Herzog “warm wall” panels provide inspiring precedents for the combined use of translucent insulation and thermal mass.

## 4.2 Component Configurations

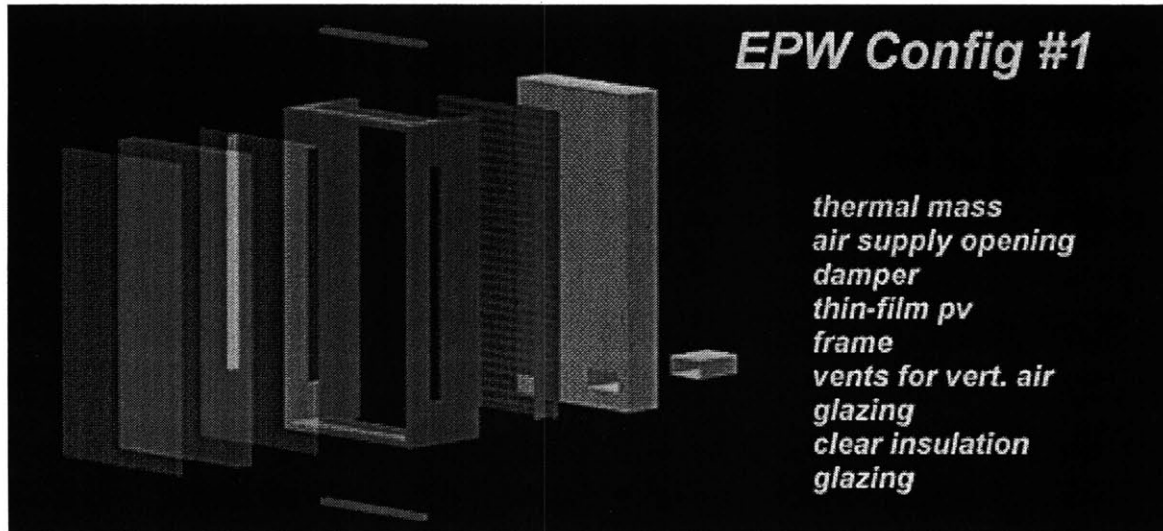


Fig. 4.18 – EPW1

### 4.2.1 EPW configuration #1 (EPW1)

#### **Assumptions:**

- Clear insulation can function similarly to optical fibers to transmit light directly through it without absorption.
- The thermal mass can serve as a heat sink for the thin-film PV.
- The extreme weight of contemporary thermal mass materials can be effectively reduced by developing materials or other approaches.

#### **Description:**

The configuration of EPW1 (Fig. 4.18) relies upon the ability of the system to allow as much light as possible into the assembly, without substantially reducing the qualities of the light which activate the photovoltaic effect. The system also relies on the assembly transmitting the maximum infrared radiation to the thermal mass. Once light and heat are introduced into the EPW1, the component has the ability to generate energy, by way of electricity and heat, to reduce the total load requirements for heating and cooling of the home. One assumption is that the process of the thin-film PV converting light to energy will increase the temperature within the component. The thermal mass will serve as a heat sink for the PV, thus drawing the heat into the mass. The mass will in turn

radiate the heat in the evening hours into the habitable spaces within the home as desired. The effective utilization of the absorbed heat into the thermal mass depends upon limiting the heat losses at night. Clear insulation performs the same capacity as applied night insulation by minimizing the negative heat flow to the night sky. In addition, it is assumed a convective/flushing loop within the panel, and stacks of panels, allows a greater degree of manipulation of the temperature within the panel assembly to prevent extreme conditions.

### ***The Layers***

The ***clear insulation*** layer functions both as a transmitter and as a barrier. It transmits as much daylight into the system as possible, while serving as a thermal barrier to prevent the re-emittance of heat away from the building. The characteristics of light transmittance are based upon the principles of fiber optics; what goes in equals a majority of what goes out. Sandia National Labs has recently created a fiber optic that can transmit 100% of the light from the point of entry to the point of exit. [60] The quality of the light remains unaffected by how many turns, and reflections it is subjected to. Therefore, these properties were incorporated into the clear insulation, so that light can be transmitted at all angles. This innovation implies that the placement of the thin-film PV within the system is possible. The second aspect of this layer is thermal insulation.

The ***air space*** functions as a conveyor and transporter. When the objective is to heat the interior, the openings at the bottom and the top of the inner plane are opened, stimulating the formation of a convective loop. The air supplied low (either internal or external) is heated by the exposure to the sun and the collecting surface, rises and is released into the internal space. The greater the vertical distance the air travels, the greater the velocity of projection into the space and the greater the amount of air brought into the system. This is the main reason why the components are stacked upon each other and incorporated into two-story spaces. One crucial aspect influencing the effect of the loop is where the location of the supply into the interior spaces. If it is too high, then the hot air will remain and stagnate at the high point within the room and not mix with the air at the lower levels. Thus, no benefit would be obtained. The airspace (typically three inches in width) can also transport the heat away from the building on a hot summer day, if the cavity is vented from the outside. Shading elements on the façade reduce the amount of direct sunlight that strikes the surface, but do not completely negate it. Therefore, heat always enters the system. Users do not want the heat to find its way into the building in summer. Thus, external vents, also at the top and

bottom, are opened to stimulate the convective loop, flushing the heat.

The *thin-film PV* is an energy creator and a heat source. Thin-film Photovoltaic panels create energy by exposure to direct sunlight. The PV reaction to short wavelengths generates electricity and a large amount of heat. The heat generation has been a problem in the past, as the efficiency of the panel decreases as its operating temperature increases. Sustainable Technologies Australia (STA) recently announced a product in which the thin-film PV's efficiency can actually increase as the temperature increases within the panel. [59] Thus, the PV could serve as a heat source as well as an energy creator.

The *thermal mass* is a heat sink, storage element and a radiation element. Traditional direct gain approaches expose the thermal mass to the warming effects of direct sunlight. The EPW1 proposal is that the thermal mass is exposed to a strong heat source, which happens to be the thin-film PV instead of direct sunlight. The thermal mass draws the heat away from the thin-film PV, similar in concept to the way heat sinks perform for microchips in computers. The heat absorbed by the mass is then radiated into the interior space after a time lag, which is determined by the thickness of the layer. For example, it takes four hours for the heat to pass through a six-inch concrete wall. One aspect of control is the selection of the thickness of the wall and on the user occupancy patterns of a system. The thermal mass becomes a "battery", allowing the heat to be stored for this four hour period and then radiated into the interior of a home when the users are most likely to benefit from it, such as in the evening.

### ***Component Composition***

The description above is of the complete component, but other benefits can be realized by breaking down the component into various types of components. A building façade is composed of windows, walls and other openings. Today, the components and construction methods for each type of opening are different. In this approach each component configuration has the ability to have layers removed or reconfigured to function either as a wall, window or even both. This is not to say that the component type will replace the traditional wall or window, but instead could be used to increase and accentuate the palate of the building envelope. The diversification of the component types, increasing the ability to enhance the performance aesthetically, operationally and throughout the construction process.

**Type 1A**

Glass  
 Clear insulation  
 Glass  
 Airspace  
 Thin-film PV  
 Thermal Mass

**Wall element****Type 1B**

Glass  
 Clear insulation  
 Glass  
 Airspace  
 Thin-film PV

**Window/skylight****Type 1C**

Glass  
 Clear insulation  
 Glass

**Window/skylight****Complementary aspects:**

The EPW components do not perform as stand-alone elements. Rather, they rely upon a seamless integration within the design at numerous operational levels. The benefits of thermal mass are not realized by a 1:1 ratio of surface area to exposure. A window area of a certain size and a mass element of the same size will not singularly provide a substantial benefit. Research has shown that a rule of thumb thermal mass ratio of 3:1 is a good target for a design. [24] Therefore, other surfaces, vertical and horizontal, would need to be utilized to begin to achieve this kind of ratio.

Photovoltaic systems can require a substantial amount of additional equipment depending upon the selected system parameters. For example, if the user desires to store energy and to sell the surplus back to the utility companies, an inverter, battery, charge controller and converter would then be needed. However, if the user only wants to power certain elements, such as lights or specific appliances potentially no additional equipment would be required. This is important since that the equipment occupies substantial space, must have clearances around it, and has the ability to be accessed for maintenance and control. A trade-off exists between the flexibility of energy usage and the equipment required.

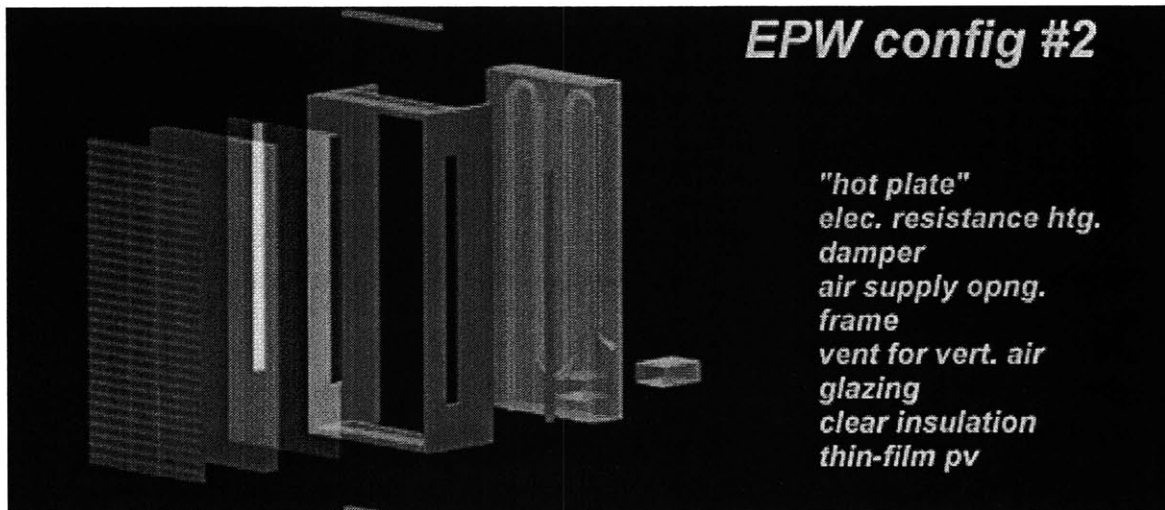


Fig. 4.19 – EPW2

#### 4.2.2 EPW2:

##### **Assumptions:**

- It is more beneficial to create electricity than heat
- The “hot plate” is lighter in weight than EPW1
- The “hot plate” provides a higher degree of control

##### **Description:**

EPW2 brings the concept of heat and energy creation together in a different manner than described in EPW1. The order of the layers has been altered to focus on the creation of energy by the thin-film PV, which then provides the power for other elements within the component. The ability to capture and utilize heat still exists, but is a secondary feature within the design.

##### **the layers**

The *thin-film PV* is an energy creator, transmitter and heat source. Sustainable Technologies Australia (STA) has also announced the development of a translucent or semi-translucent thin-film PV. Therefore, the PV would not only be able to create electricity through exposure to direct sunlight; it would also allow some of that daylight to transmit through this layer. It would provide a “view” into the façade, which has never before been offered



The **clear insulation** layer once again functions as a transmitter and a barrier. Daylight should retain its characteristics from impact to transmission through to the interior. The layer serves as a barrier to the emittance of heat outward.

The **air space** continues to function as a conveyor and transporter.

The **radiant heat system** is composed of a series of tubes embedded in a thin-layer of light weight concrete or adhered to the back side of a conductive material. The concept of heat is broken down into two areas, collection and creation. The collection occurs by gathering the heat that is already within the system due to direct sunlight reaching the mass. The liquid passing through the embedded pipes is heated both indirectly by this secondary heat source and directly through the energy created by the thin-film PV. The heat from these pipes radiates into the inner surface and then into the space at a point in time determined once again by the properties of the material chosen.

**Type 2A**

Thin-film PV  
Clear insulation  
Glass  
Airspace  
Radiant Heat system

**Wall element**

**Type 2B**

Thin-film PV  
Clear insulation  
Glass  
Airspace  
Radiant Chilled system

**Window/skylight**

**Type 2C**

Thin-film PV  
Clear insulation  
Glass

**Window/skylight**

**Component Composition**

The concepts behind the breakdown of the component types remain consistent to those discussed in EPW1.

**Complementary aspects**

The equipment requirements will depend on the extent of the radiant heating system loop in the form of pump power requirements and heating or cooling unit, such as the relation of the system within the floor plane as well as to the vertical wall surface or the ceiling. Other equipment requirements are dependent upon the PV system connections mentioned in EPW1.

### 4.3 Module Selection

The prototype component module size chosen was 1'-9" wide, and 4'-0" tall. The selection was based upon modules common within the United States wood-light frame construction industry. The module is shaped by stud spacing, 16", 18" or 24" on center, and 4'x8' plywood sheets, which are applied to the exterior walls. By selecting a module of 1'-9" wide, the EPW component can fit between 24" on center stud spacing during assembly or after erection of the wall. In addition, a component 1'-9" x 4'-0" is potentially easier to handle and configure on-site with few resources than elements of larger size, providing flexibility to the installation method chosen. The Usonian Houses of the 1940's, designed by Frank Lloyd Wright, provide a precedent for window placement 24" on center stud spacing. [61]

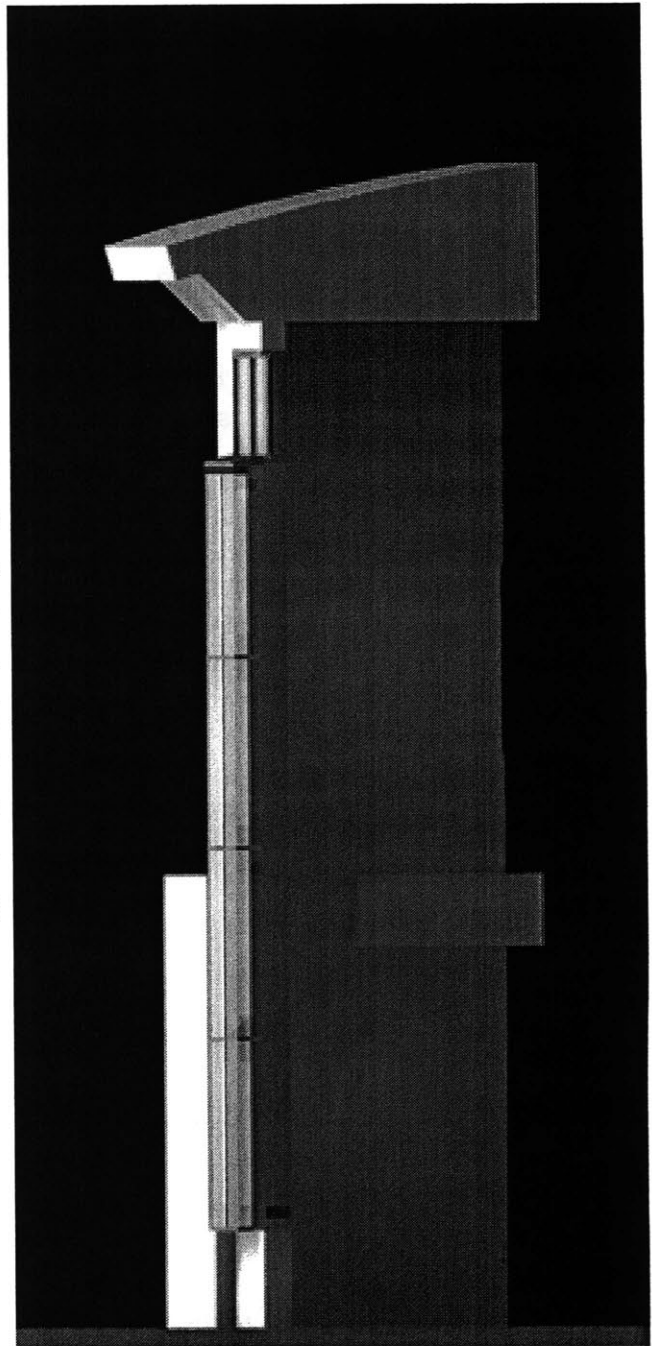
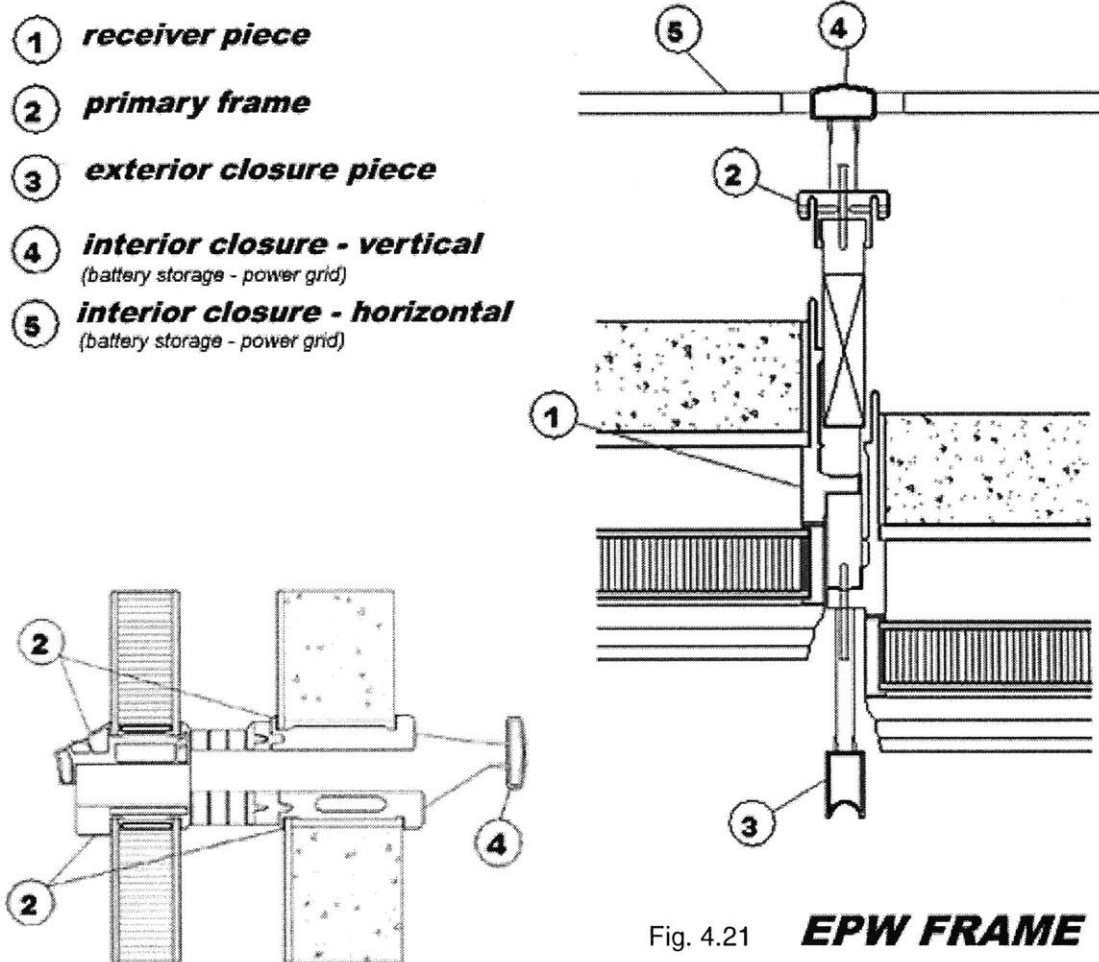


Fig. 4.20 – Section of stacked EPW1.



#### 4.4 EPW Frame

The frame design presented in this thesis is a preliminary design option (Fig. 4.21). It is by no means complete, nor refined. It was developed to provide a representation for the investigation of the complete component, its options for adaptability, connection and layer incorporation.

The EPW component frame is designed to integrate with a 2"x6" wood stud wall with studs spaced at 24" on center. Therefore, the wood studs still serve as the primary structural support and load path for the forces placed upon the wall. The frame is constructed of an extruded polymer composite material. This provides enhanced thermal performance when compared to aluminum, vinyl or wood frames. It also provides the structural support for the overall component. It addresses all

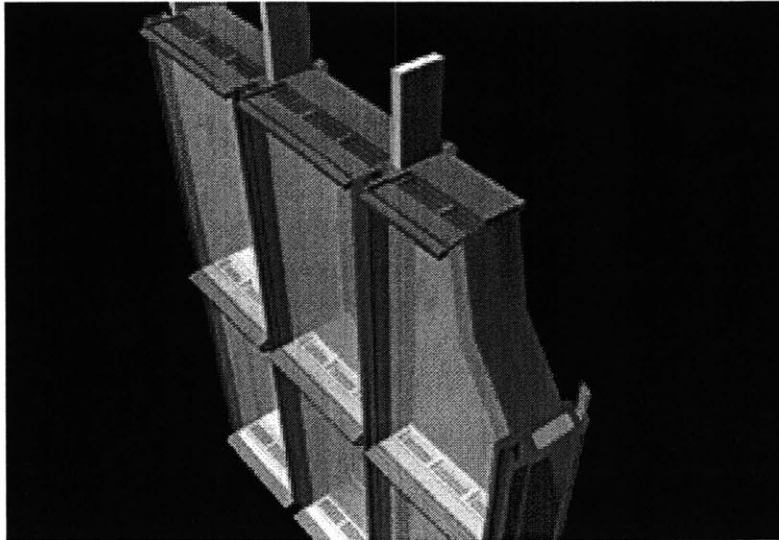


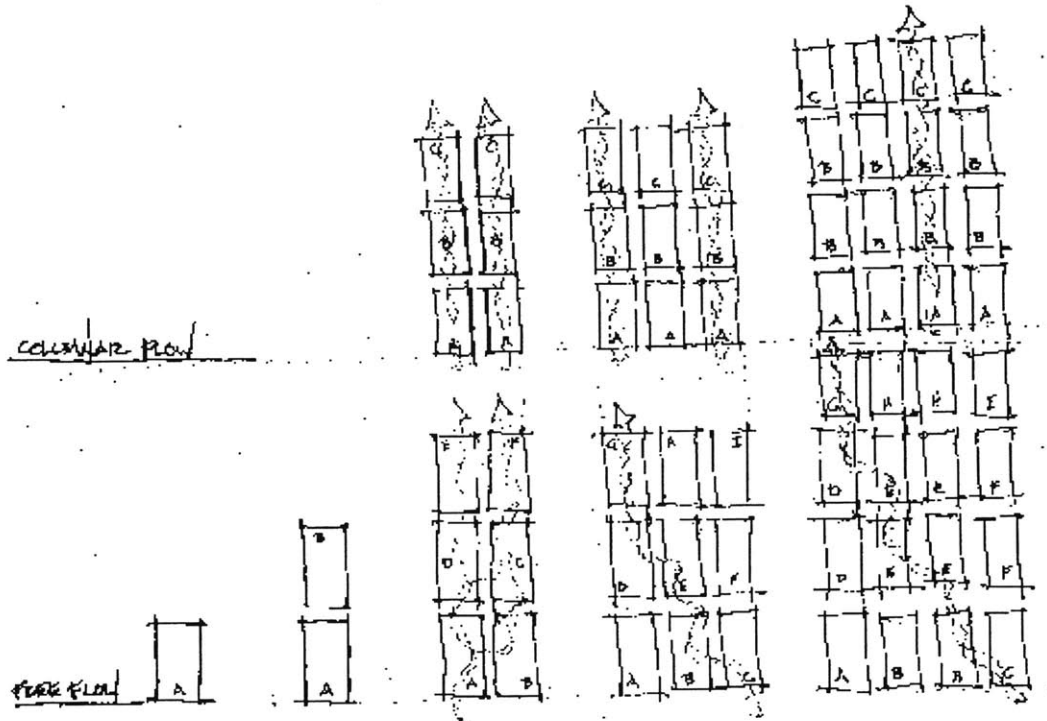
Fig. 4.22 – EPW frame assembly with partial section

the criteria important to the performance of a window frame, such as infiltration, heat transfer, expansion, contraction and water penetration. In addition, elements of the frame have the potential to develop an additional purpose, energy storage.

The frame is a system within itself. It is composed of five pieces, two integral to the integrity of the frame (one of which can be broken down further) and the other three adding to the ease of access, concealment of connections and flexibility of interface. The diagrams (Fig. 4.21) display the frame pieces as well as the proposed erection sequence. The frame (Fig. 4.22) is designed to allow the three different component types (listed under in description) to be manufactured in two frame types for any configuration within a group.

### ***Grouping the components***

Figure 4.23 displays an initial analysis comparing the range of different frame types required to be created for different “groupings” of EPW components due to the air flow within. “Columnar flow” is the air vertical airflow within a single vertical stack of the components. “Free Flow” is the vertical and horizontal airflow between components linked by vents. A change in letter denotes a change in type of frame due to the air exhaust, supply or intermediate vents. Redundancy is not created until the configuration of six is reached, and only for “columnar flow”. Rather than three types of components, six are required for the “free flow”. The differential increases dramatically at the grouping of



Dia. 4.23 – EPW Grouping Frame Types

sixteen, where only four types are needed for “columnar flow” and nine within the “free flow”. The result was the selection of “columnar flow” to reduce quantity of frame types.

By pushing the component slightly forward in the wall plane to the point where the airflow occurs just outside of this plane. The bottom component in the assembly isn’t required to be a different type. The air supply can occur at the bottom of the frame in the same position as it does within the component above. The result is that for in a grouping of three, four, six, ten vertically, only two components types are required.

The main component piece installed on site (labeled 1) has two parts, which are separated by the air space, which are provided and installed on-site as one (homogenous) element, can be broken into two, which are separated by the air space. The separation is for the purpose of maintenance of the thin-film PV layer or other layers develop functional difficulties. It can be accessed from the interior. The nature of the disassembly allows the envelope to retain its thermal integrity, by not being completely opened to the exterior environment. (The interface for separation would be a mechanism triggered from the interior space.)

The receiver piece (labeled 2) connects to the main component piece. It locks the EPW component into place between the two in-situ wood studs. Contemporary construction consists of 2"x6" wood studs.

The exterior finish piece (labeled 3), is attached by a friction-fit snap-in connection after two EPW components are inserted/installed into the stud wall, concealing the screw connection. In addition, the void within the piece functions as a vertical downspout for the weep systems within the components.

Pieces 4 & 5 are attached on the interior through a similar type friction-fit, snap-in piece. When in place, these create a horizontal and vertical distribution path for the energy created by the thin-film pv layer. Housed within these pieces could be the innovation of the lithium battery, developed by Prof. D. Sadoway, MIT. The lithium battery is a thin-film battery, about the depth and feel of a potato chip bag, it can increase its storage capacity by being rolled or folded into a tube. These could provide a substitute for the deep cell batteries used for storage for most PV array systems. A plug-in or surface contact interface could also be included as a power supply to appliances or lighting larger system.

#### **4.5 EPW System and impact on configurations...**

Up to this point the operations of the EPW component has been discussed as an individual component. However, the EPW functions within a configuration of units, which is itself incorporated into a complete house.

##### ***Constructability issues***

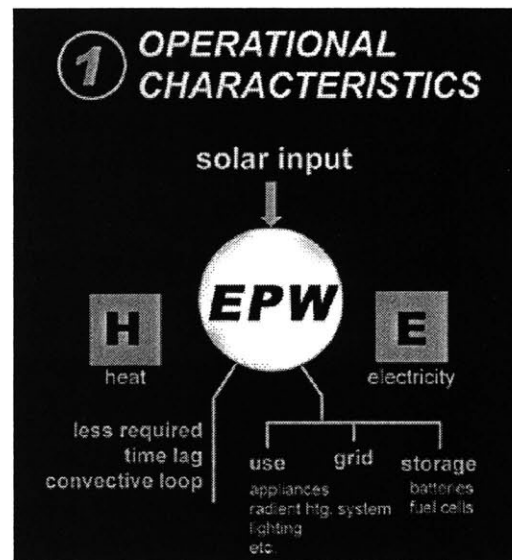
As previously mentioned the EPW module is designed to fit between standard 2x6 wood stud spaced at 24" on center. The components can be grouped together, either horizontally or vertically. The component frame was designed to allow this grouping to occur horizontal on the ground or in-situ, as desired within the process of construction. Therefore, the sequence of construction would remain the same for the wood stud wall and the EPW components compared to standard aperture elements. Components grouped and assembled on the ground could be lifted into place and fixed

to the stud wall. The receiver piece of the frame is placed and connected once the components have been lifted into place.

***“The whole is greater than the sum of the parts.”***

Since air can move from component to component vertically in the air gap, stacking the EPW components atop each other can increase the height of the stack. This increased stack height means a greater temperature differential between bottom and top can be created. This enhances this convective loop and exposes the air to more surface area of the heating element. This results in greater heat transfer thru convection. The air velocity is also increased with an increased stack height. This in turn enhances the supply rate of air to the interior spaces and increases the depth of penetration of the airflow. This increased velocity can provide the same benefits when the system into the spaces “flushing” excess heat, by exhausting it at the high point of the stack to the exterior environment.

The development of the EPW and its components has been not only considered from a linear, built-up process, and a system-down process. The home as an integrated system, has provided performance criteria at the operational, process and aesthetic levels. The energy load of the home, based on climate, appliances and heating/cooling equipment provided the criteria for the number of EPW components that would be required to achieve a significant reduction. The actual methods in the overall load initially and over time. The placement of the EPW components is dictated by a number of factors. Factors, such as maintaining sufficient shear wall area for the integrity of the wall, the appearance of the single component or the group it is within, and the location most beneficial to its operation. The scenario for the web of overlapping criteria mentioned above is just one on an evolving checklist of items that play a role in the scale difference of indi-



Dia. 4.24



vidual component to group and system of components.

### ***Operations***

The effective capture, distribution and utilization of solar energy in the form of electricity and heat is the basis of the EPW component concept. The incident solar radiation is the singular source of energy (Dia. 4.24). The EPW translates the solar input into either heat or electricity, depending on whichever is more appropriate for the climate and system requirements of the building. The benefits of heat are in the reduction of the overall heating load, the time lagged heat transfer through the thermal mass, and into the stimulation of the interior, and in the components convective loop. Electricity can be used directly, supplied back to the grid or storing for later use.

The EPW builds upon the concepts established by the passive solar strategies of the trombe wall and other direct gain systems. Photovoltaic technology provides an active solar element, that can be part of the extant passive solar options. However, the placement of this element, and its relationship to the other elements, is dependent upon the overall performance characteristics of the component overall and to the larger degree, the system of the home. As mentioned previously, trombe wall systems inherently suffered numerous problems relating to user control and maintenance. Therefore, the coupling of the passive and active solar concepts is not enough; other materials capable of complementary properties must be selected to enable the EPW components to maximize the performance.

### ***Aesthetic textures***

Material samples were collected to be explored and brought into a digital format (Fig. 4.25). Their textures, their color, patterns and transparency were grouped based upon the potential EPW configuration layers. These groups were evaluated and assessed for their aesthetic effect. The combination of layers for each EPW type was created to visualize the potential appearance from the inside and out.

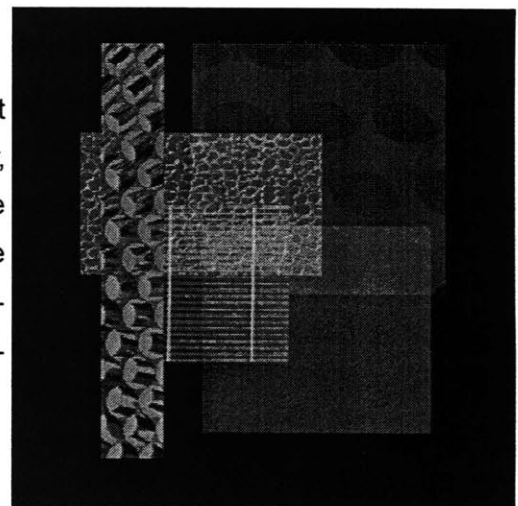


Figure 4.25 – Material Textures



Assumption	Variable	Measure
<b>Thin-film PV generates excessive heat to capture</b>	Thin-film PV material PV substrate	Solar Radiation to efficiency
<b>Translucent Insulation transmits useable light to thin-film PV</b>	Thin-film PV layer placement Thin-film PV layer placement Translucent Insulation material capillary diameter size	Wavelength Manufacturer's data Transmittance if fiber optic material
<b>Thermal mass beneficial as heat capture</b>	Thermal Mass Material Thermal Mass Layer Location	Heat capacity Radiation, conduction, convection
<b>Convective loop effective as natural distribution system</b>	Airspace width Size of supply and exhaust vents Height of stack	Transient measurement of air temperature and flow between two hot plates
<b>Component performance increases if stacked</b>	Number of EPW's stacked Acting on two-story or one story space Vent openings between	Transient measurement of air temperature and flow between two hot plates

**Table 4.26 - - Critical Assumptions**

### **Assumptions**

Two EPW configurations are based upon a set of critical assumptions that relate to the performance of the material, component and system levels. The assumptions, the important variables and the measureables are described in Table 4.26. The validity of the critical assumptions were tested and provided a method of directing the material selection and layer configuration.

The tradeoffs define the relevant performance issues, bringing together choices made at the material, component and system levels. For example, to evaluate the "Role of Heat", of the thin-film PV layer inside the component, one must look at:

- Thin-film pv material performance at various temperatures relating to efficiency
- Heat capacity of thermal Mass
- Heat convection from PV to thermal mass or air
- How height of the internal air stack affects temperature differential (pushing convection)
- Time lag of heat transfer
- User patterns

Given these particular parameters influencing the EPW component design and its effective integration into a house, the research analyzed the aesthetic, operational, and construction process performance of the alternatives through advanced simulation and representational models.

## Chapter 5.0 Methodology

### 5.1 Data Collection

#### 5.1.1 Material Data collection

Before the concepts for an EPW component became established, the ideas behind those concepts had to be shaped. The ideas were created by collecting information on the properties of a wide range of materials that could be utilized to upgrade a trombe wall and enhance its performance. The initial focus was on how “smart materials” responded to light, heat and electricity and how these effects differed from the material properties within float glass and thermal mass materials. Numerous explorations occurred based upon discoveries of capabilities in one material and then building on that idea by investigating other materials in that same family, which would lead to other options. The investigation had no bounds relating to industry, field or type. The common thread was to understand the responses to light and heat of the material and the detriments of those responses. Numerous sources were used including textbooks, manufacturing company information, direct contact with companies, magazines, articles, web-sites, web-databases, people, and any other sources that could be found. The common denominator was to collect the material property data in a manner allowing comparison and contrast among other materials and families of materials.

#### 5.1.2 Climate Data collection

To develop an understanding of the environmental context in which the two prototype designs would be located, climate data was collected, analyzed and incorporated into the “envelope spreadsheet”. Data for various temperature factors, wind, precipitation, humidity, degree-days, percentage of possible sunshine, solar insolation (direct and global irradiance), sun hours available per day, and solar radiation based on latitude were collected in monthly increments. In some cases, daily and hourly data was referred to and utilized, but the decision was made to keep the overall level of refinement at the point of monthly data. The selection of Boston and Phoenix provided two climates differing dramatically in nature. More extreme climates in the United States do exist on both ends of the spectrum, but these two cities provide recognizable boundaries for the investigation.

A residence in Boston, MA (*42° N Latitude, 71° W Longitude, elevation = 15 ft.*) must be capable of dealing with a high degree of change within the weather from season to season, day to day, and hour to hour. A tendency exists for great variance between the same season in different years with large ranges of temperature occurring within that season. A strong influence is exerted by the “prevailing westerlies”, which are the belt of easterly moving winds that encircle the globe in the middle latitudes, which bring in a high level of average winds and strong winter storms. In summer, the winds (*10.9 mph avg.*) become a means to remove excess heat from the building if desired, while the strong winter winds (*15.1 mph avg.*) are detrimental to the residence’s ability to keep the desired heat within the interior, rather than seeping out through infiltration. The design of the residence must have the flexibility to increase ventilation in the summer, allowing crosswinds to move through the space and pull the heat away from the building, and decrease ventilation or be segmented during the winter months to enhance the benefit of the heat available. The temperatures experienced in summer (*82.8°F – July, daily max. avg.*) and winter (*22.8°F – Jan., daily min. avg.*), place Boston in a heating load dominant climate. Only about 5-15 days per year see the summer temperature rise above 90°F on average. The chosen design strategy must have the ability to capture, store, and distribute the benefits that the solar exposure (*3.84 hrs., daily avg.*) provides to the surfaces of the building envelope, while it maintains the flexibility to respond to the variable amount of clear days (*90-120 days per year*) as they are experienced (*53% - Jan., 67% - July*). [62]

Phoenix, AZ (*33° N Latitude, 112° W Longitude, elevation = 1112 ft.*), on the other hand, is renowned for the intensely hot summers, lack of rainfall, clear skies, and little wind, creating a climate with a very high cooling load requirement. The envelope of a residence in Phoenix is faced with a challenge, to either capture the benefits of the sun’s rays and deal with the heat gain or to attempt to shade the exterior from it entirely. The amount of solar exposure (*6.58 hrs., daily avg.*) available (*77% - Jan., 94% - July*) is too much of an energy source to ignore. Therefore, methods must be utilized to create the opportunity for removal or guard the interior spaces from the strong potential for overheating when the exterior temperatures rise (*105.0°F – July, daily max. avg.*) during the summer months. One natural ally is the large diurnal swing (*30 °F avg.*) occurring between daylight and evening hours over the course of the day, which can even reach levels of 50-60°F. A means to “flush” the heat away from the building in the evening due to the cold night sky and cool evening temperature could be developed by working with the wind directionality and quantity (*7.1 mph – July avg.*). Enhancing the “flush” effect relies upon the stack height of the air movement. The taller the stack, the higher the air velocity, resulting in a greater amount of heat pulled away from the

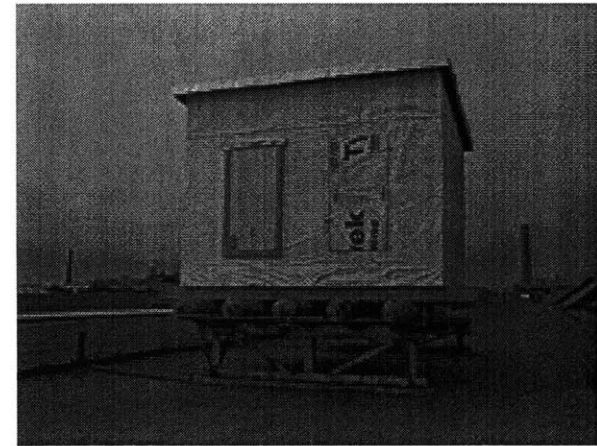
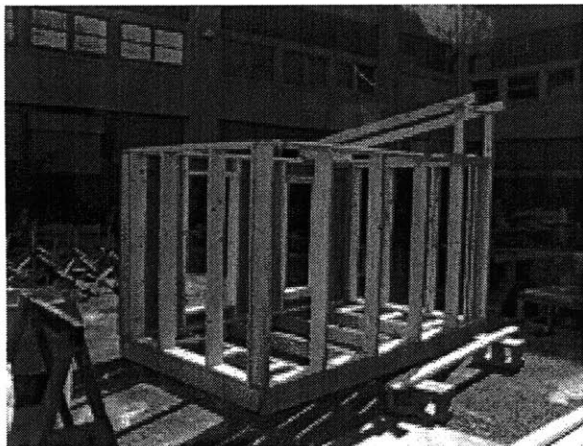
*Masters of Science in Building Technology, Department of Architecture*

building by this air. The impacts on the spatial design signals the importance of linking spaces vertically combined with a slender building footprint, to provide the potential for cross ventilation as well as increased southern exposure. [C-States]

By investigating strategies within these two climates, the ideas for the EPW component types developed. The initial assumption was that the EPW1, incorporating thermal mass, would be most beneficial in colder climates such as Boston, while the EPW2, placing the thin-film pv layer on the southern face and eliminating the thermal mass would be better suited for hot climates, such as Phoenix. The investigation of each component type within both climates pointed to methods to improve their performance due to the requirements needed for that climate.



Fig. 5.1 – Test Chamber on roof of MIT



### 5.1.3 Test Chamber Design

The purpose of constructing a test chamber (Fig. 5.1) in collaboration with Nico Kienzl [63] was to explore the configurations of existing and developing materials in an integrated manner, providing an initial understanding of their combined performance. The goals center on proving or disproving general assumptions on performance while investigating constructability and aesthetic issues in the context of a learning tool. The results of the data collected were rounded to the nearest tenth.

The test chamber design was based upon a survey of past approaches, numerous discussions and input and critique from others with past experience in the area. The final design consists of an outer envelope, with standard 2x6 walls with a shed roof, which contains a space measuring approximately 10'-0" in width, 6'-0"-8'-0" in height and 6'-0" in depth. Within this enclosure, two highly insulated compartments were constructed to isolate a volume 2'-0" in width, 4'-0" in height, and 3'-0" in depth. The only variable for each of these compartments is the southern face, where the prototype component configurations were placed. The outer envelope (R-19) is the initial barrier, which creates the first control zone. Small fans were introduced to circulate the air. The circulation of air coupled with the high amount of insulation around each chamber (R-30) reduced the impact of the solar path and envelope radiation on the sides over the course of the day, of the second control zone. The test chamber design also allowed the flexibility to test components on the north side, as well as the south, with the potential to increase the size of the components or test smaller sizes. *For further specifics refer to appendix H.*

### 5.1.4 Construction Process

#### *Literature review*

The literature review provided a picture of the history of lightwood framing from balloon to platform framing as well as exposure to techniques and methods utilized today and the new developments serving as future trends for the industry. Table 5.2 describes a few of the reference sources for formulating this picture. The other references are listed in the bibliography in Appendix I. For example, textbooks such as Dwelling House Construction by Ed Deitz and Ed Allen's Fundamentals of Building Construction, provided an overall outline for the flow diagram and were a constant source of reference for re-evaluation and refinement.

text	author	focus
Dwelling House Construction	Ed Dietz	Detailing, overall point of reference
Fundamentals of Building Construction	Ed Allen	Overall point of reference
The Very Efficient Carpenter	Larry Haum	Process from Start to Finish
<b>trade journals</b>		
Journal of Light Construction		Task Specific articles, resources
Builder		Task Specific articles, resources
Fine Homebuilding		Technique specifics
Environmental Building News (EBN)		Features relating to wood structures
<b>Organizations</b>		
Sandia National Labs	SNL	Architectural Surety Program
<b>Partnership for Advancement of Technology in Housing</b>	PATH	Level of technology currently in building industry
<b>Cambridge Energy Research Associates</b>	CERA	Applications of research on residential projects
National Association of Home Builders	NAHB	General Information regarding common practices
<b>Western Woods Product Association</b>	WWPA	Characteristics of wood members
<b>Web-sites</b>		
Builder on-line	<a href="http://www.builderonline.com">www.builderonline.com</a>	Current Discussion Topics and articles
Build Core	<a href="http://www.buildcore.com">www.buildcore.com</a>	Featured products

**Fig. 5.2 - - Literature Review Sources**

Trade journals, such as the Journal of Light Construction, Builder, and Fine Homebuilding (refer to diagram at right) were an excellent source for obtaining general information about specific tasks or groups of tasks relating to the resources and tools utilized on-site. The feature articles, such as Stacking Supported Valleys [JLC Sept. '97], depicted current techniques and methods used to assemble a complex roof form, which provided a guide to compare and contrast when the next site visit occurred. The articles also provided detailed descriptions of how different approaches were taken to complete the same task, identifying alternatives, and opening the thought process to other alternatives.

### Site Visits

The diversity of the twenty-one different sites observed provided a large impact on the refinement of the flow diagram (Table 5.3). At each site visit, a set of research tasks were performed:

1. *The supervisor was located, to gain permission for observation and to discuss status, if possible.*
2. *General background data was collected (location, size, state of construction, etc.),*
3. *Equipment on-site, number of crews and crew size were noted.*
4. *Activities relating to single and multiple tasks were observed and documented to verify existing approach or to identify new ones.*
5. *Documentation in the form of digital pictures and notes were obtained.*

The results collected at each site were mapped into the context of the flow diagram serving as an alternative branch for the framework to verify an existing approach or to replace or refine assumptions or to fill in voids. The documentation through the photographs provided an invaluable tool to relay concepts and ideas to others in conversation [Fig. 5.2.1 & 5.2.2].

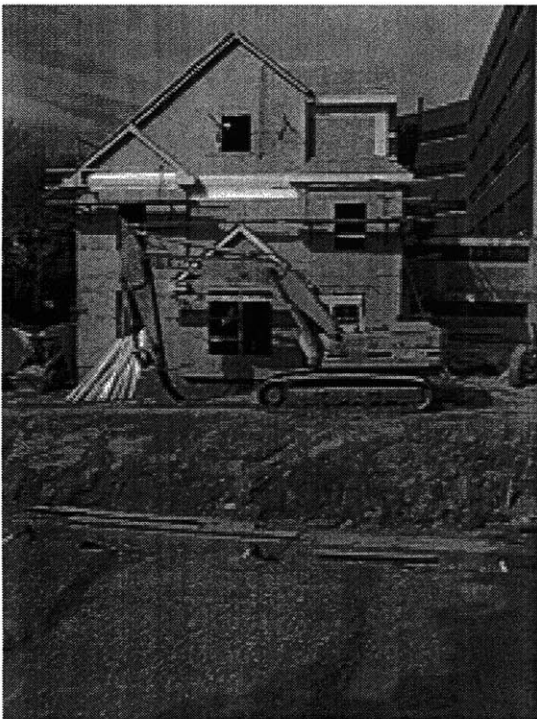


Fig. 5.2.1. Applying Siding to exterior of framing

Fig. 5.2.2. Framing nearing completion on first set of condominiums and beginning on the second set



type	Residential – Single family	Residential – Multi-family/	Apts. & Condos.	Commercial	Manufactured Housing Comp.
New construction	9	2	2	2	2
Addition/ renovation	4				
Total:	21 Projects				

**Fig. 5.3 - - Site Visit**

By visiting the construction sites of single and multiple family homes, three-story commercial building, duplexes, multi-plexes, a boat house, developments, pre-manufactured homes, pre-manufactured home facilities, large renovations on existing structures, and completely customized homes an understanding of the palate possible to builders became apparent. The framework of the flow diagram had to be capable of incorporating the use of “stick built”, prefabricated and site-assembled components, in addition to the numerous combinations of each amongst the others.

### **Interviews**

The literature review provided the guideline, the site visits are the classroom and the contractor/ builder and other experts were the teachers. On-site interviews were conducted informally with contractors on-site. These discussions provided clarity relating to the activity sequences and approach as well as an understanding the site observations. In addition, telephone and personal interviews were conducted with the “experts” listed in the Model Verification section. An informational packet including the current flow diagram as well as a list of design attributes and resources was sent to the “expert group” to provide a starting point for a dialogue. The “expert group members” remarks refined the characterization of the LWF process, as well as validating and building upon the design attributes and resources. Feedback was utilized to further refine the flow diagram, while also assisting in the creation of the framing plans and sequence diagrams for the prototype designs. The “expert group” identified the importance of the framework to handle the potential for customization of the structure within each design, signaling the inclusion of the pre-fabricated and site-assembled components.

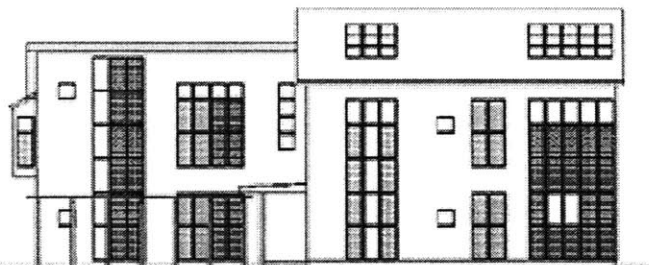
## 5.2 Analysis

The overall analysis is a systematic analytical approach, which can accommodate specific designs, locations, and processes and changes to these project-specific characteristics. In particular, this research uses two prototype house designs in two different geographic locations in the U.S. The methodology outlines the framework of analysis for evaluating the impact of an innovation (e.g. the EPW) within a project at various stages of its development.



Fig. 5.4 – Original Sears Design and South Elevation of Modern Design

Two prototype home designs were designed, one to represent a portion of the existing building stock, and the other to serve as a forward-looking design based upon the integration of the concepts of the EPW within the fabric. The prototype designs provide a range of analysis tying today and a point forward in time



Modern Design

together, creating numerous opportunities and levels for side by side comparisons to be established. For example, a comparison can be drawn between the similarities and differences of approach to the design and the impact of new technologies, such as the EPW, have upon the design. By introducing a standard option (Std) and one utilizing the EPW components (EPW) for each prototype design, comparisons can be made within each prototype design type as well. The two designs, although very different in character and physical form, have similar features incorporated into the design to enhance the ability for these comparisons to be made. The features are listed table (Fig. 5.5). Although the features provide similarities, the definitions of each feature are dependent upon the design. For example, a front porch within the Sears design is defined as a covered entry porch, which one rises up to reach the entry. The definition within the Modern design is a partially covered space that one-steps into to reach the entry.

	Sears design	Modern design
Overall Floor Area	1900 ft. <sup>2</sup>	2200 ft. <sup>2</sup>
Southern exposure	640 ft. <sup>2</sup>	1350 ft. <sup>2</sup> (2:1)
Stories	2	2
Bedrooms	3	3
Stairs	1	1
Incorporation of home office	Second floor	First floor
Decks, porches	Entry porch	Entry Back deck

**Fig. 5.5 - - Prototype Home Similarities**

### 5.2.1 Prototype Design #1 (Sears design)

The basis of Prototype House #1 (referred to as Sears design) is a 1928 Sears Home [64], which could have been purchased out of a catalog for \$1,023. The reason for selecting this home design as a basis for a prototype home is that it has an enduring popularity and quality. In addition, it is an example of a “closed plan” in its square design, where the design incorporates a large amount of interior walls and doors providing separation of the rooms. The 1928 Sears home was re-designed to place it within the current vocabulary of spaces recognized within today’s homes to make it more comparable to Prototype Design #2. The adjustments to the design were:

- Removal of a step-up, step-down transition to the pantry
- transformation of the pantry to a full bathroom on the first floor
- enclosing of the rear porch to increase the size of the kitchen
- re-orienting of the stair to the second floor for cleaner circulation
- transforming one of the upstairs bedrooms to a home office
- removal of the basement
- reconfiguration of the entry porch

The Sears Design basically separates the public and private areas of the home completely by floor. All of the public spaces, the kitchen, living and dining room are on the first floor, while the three bedrooms and home office are in large rooms on the second floor. The building is basically divided into three parts on each floor as well. All of the circulation on both floors occurs within the middle portion of the floors allowing the major rooms to inhabit each of the four corners of the building, giving them two exterior walls of exposure. The roof from the square base is a hip angling in to frame all four directions to a point at the center.

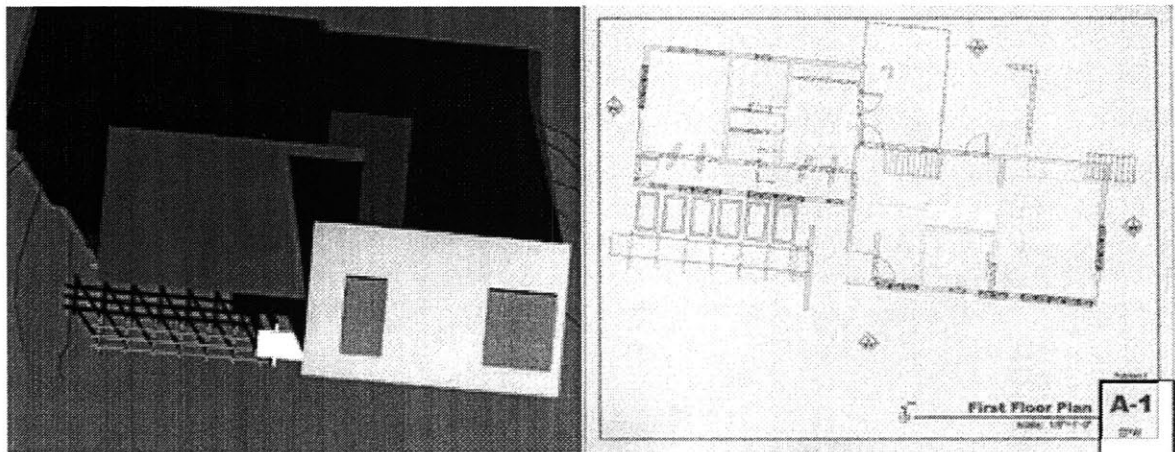


Figure 5.7 – Prototype Design #2 – Overhead view and diagrammatic floor plan

### 5.2.2 Prototype House #2 (Modern Design)

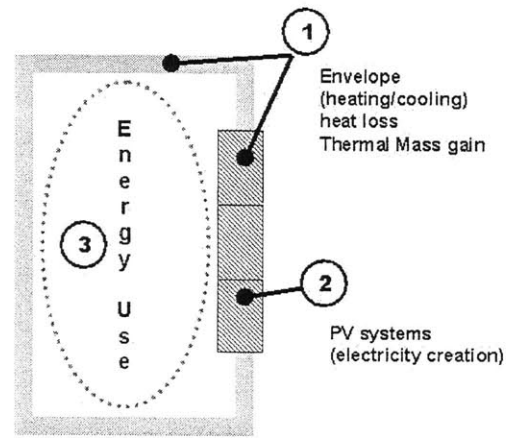
The “Modern” design (Fig. 5.7) is another iteration of personal and collaborative designs based upon solar concepts. The footprint of the building is more linear (actually exactly a 2:1 ratio in southern exposure) and slender in a stepped format to take advantage of solar exposure and ventilation opportunities. The orientation is actually skewed towards magnetic north for Boston, MA to increase the effect. It expresses the concepts of an open and adaptable plan, which could change daily, weekly or yearly, dependent on the occupant’s needs. The public and private spaces are split vertically compared to the horizontal division in the Sears Design. On the eastern side of the building, the lower level contains the service spaces for the building and a large recreation area that could be used for various purposes. The second level is composed of the main living spaces, placing the living, kitchen and dining areas in a larger space that is broken down by spatial features such as connections between the floors and differing ceiling planes versus the use of interior walls. The circulation spine connecting the two areas of the second floor leads on to the private area by crossing a bridge passing over the entry. On this level are two bedrooms and a full bath. The bedrooms are complemented by smaller reading/relaxing spaces that provide differing experiential character. Another characteristic is that the southern bedroom wall of the first bedroom functions as a door as well as a wall creating the ability to open the room to the desired heat generated by the southern exposure. On the lower level is another bedroom, bath and multi-purpose room, which could serve as an additional bedroom, a workshop, or possibly a single-car garage. The roof form is composed of two opposite sloping shed roofs at differing angles. The shed roof on the private sector rises up toward the southern side, while the public side rises to the north.

Floor plans, elevations, wall construction sequence drawings, structural foundation and framing plans, and dynamic simulation input data can be found in Appendix A for the two Sears Designs and in Appendix B for the two Modern Designs.

### 5.2.3 Operational Performance

#### 5.2.3.1 Spreadsheet Analysis

The analysis of the operational performance involves the use of a customized spreadsheet referred to as the “spreadsheet tool”, which has two major categories, the envelope (heat/cooling) and PV systems (electricity) (Fig. 5.8). The results of these categories are evaluated against the overall energy consumption of the residence to derive the benefits. The spreadsheet tool was created to allow manipulation of parameters at various levels relating to the materials within the EPW component, the component type, the number of components used, and the context within which the component is placed.



Dia. 5.8 – Basis of Spreadsheet Analysis

#### **Material and Component level**

The ramifications of the material selections within the EPW components need to be understood, to continue to build upon the concept, and to explore options and alternatives. The material properties were gathered for the EPW configurations, as shown in figure 5.9. Absorption, reflectance, and transmittance values correspondent to wavelengths were gathered for each of the glazing and clear insulation materials, in addition to shading coefficients. Density ( $\rho$ ), specific heat ( $C_p$ ), heat capacity ( $\rho \cdot C_p$ ), time lag, thermal conductivity, and thermal diffusivity values were gathered for each of the mass materials. While the data for the thin-film photovoltaics, focused on efficiency, translucency, wavelength absorption, angle dependency, operational heat range, maximum operating temperatures, degradation, composition and amperage, wattage and voltage for each panel type.

**EPW configuration #1 - material properties**

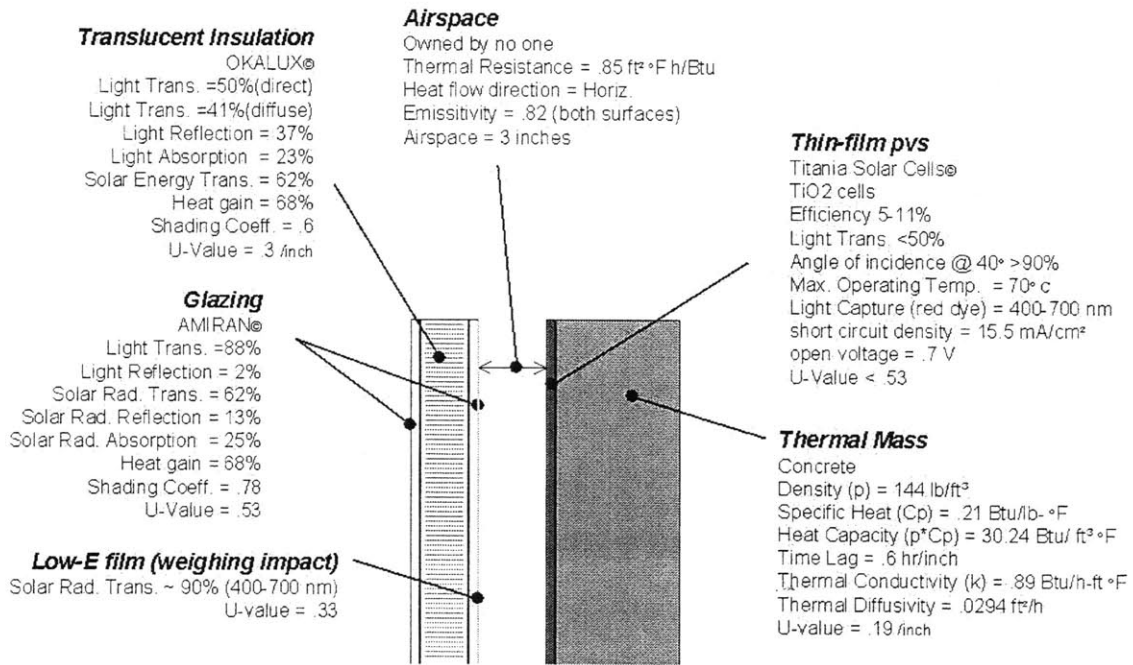


Diagram 5.9

An initial model was developed to analyze the impact of radiation, convection and conduction based on the materials and layer configurations for EPW1. Figure 5.10 is an electrical flow diagram outlining the analysis of the actions within the component. Each point in the diagram represents a surface temperature at or between the two materials. The relative temperature between these points is dependent upon the material in that layer and what other materials or factors to which it is subjected.

Imagine that a box has cut a slice of the EPW 1 component and placed it within Figure 5.10. The first law of thermodynamics states that energy cannot be created or destroyed. One can only change it from one form to another, or it can only be added to the system from the exterior.[65] All the energy inputted into the system, either leaves the system as work or heat. The exterior source is in the form of the solar radiation striking the surface of this slice. The source effects two points within the boundary conditions set. The first is as the solar radiation strikes the assembly, and the



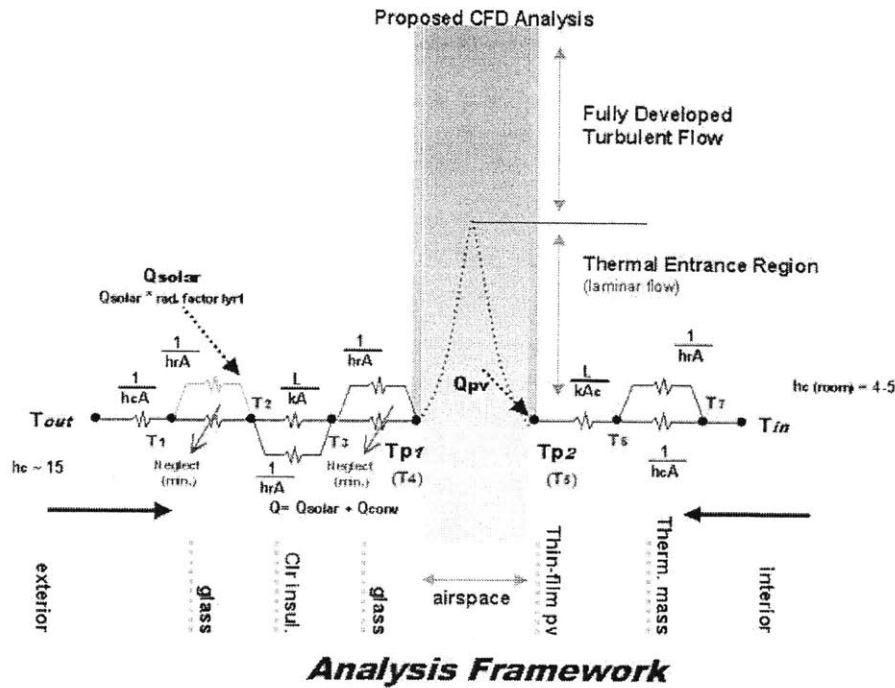


Figure 5.10

second is as the light that is transmitted strikes the thin-film PV, stimulating the “photovoltaic effect”. Energy leaves this system in one of three ways.  $Q_{out}$ , represents the two ways heat leaves the system, and  $Q_{pv}$  is an additive to  $Q_{in}$ , because it represents direct energy captured. For the context of this document, captured equals producing in the title. One factor of  $Q_{out}$  is  $Q_{air}$ , which is the air moving through the airspace. It collects heat from both sides of the airspace as it moves vertically. The second factor is  $Q_{mass}$ , which is the heat generated from the “photovoltaic effect” that is absorbed by the thermal mass. The third way energy leaves is in the form of  $Q_{pv}$ , which is the other component of the “photovoltaic effect”, which generates the electricity that the contact surfaces of the thin-film carry off to distribute to the systems of the home. So, the basic equation is:

$$Q_{out} - Q_{in} + Q_{pv} - Q_{air} = 0$$

Variables	B <sup>1</sup> Balcomb	S&R <sup>2</sup> Stein&Reynolds	M <sup>3</sup> Moore	LMWY <sup>4</sup>
<b>Balance Pt. Temperature</b>	Yes	Yes		
<b>Solar Load Ratio (SLR method)</b>	Yes	Yes	Yes	Yes
Reference System	Yes	Yes	Yes	Yes
Load Collector Ratio (LCR)	Yes	Yes	Yes	Yes
Solar Savings Fraction (SSF)	Yes	Yes	Yes	Yes
Auxiliary Heat Required	Yes	Yes	Yes	Yes
<b>Internal Temp. Swings</b>	Yes	Yes	Yes	Yes
<b>Flow Rate for Night Ventilation</b>	Yes	Yes		

Fig. 5.11- - Envelope Analytical Methods

either side of the air space. By solving for both of these values, working outside to the air gap for T4, and inside towards the airspace for T5, the temperatures on either side of the airflow can be identified. The difficulty of the problem is the dynamics of the airflow, in addition to the dynamics of the thermal mass. The problem quickly turns into a complex transient problem. For the initial investigations, the mass heat transfer effects were simplified to provide a means to assess the impacts of the convective airflow.. The preliminary lessons learned from this initial investigation were inputted into the “spreadsheet tool”. However, the functionality of this analysis were not able to be inputted for the scope of this work due to the parameters that had already been established.

**Envelope Spreadsheet**

The envelope spreadsheet analysis assumes a project is at or near the end of the design development stage, with decisions being made about the number, size and orientation of openings within the building envelope and the materials to be utilized. The “spreadsheet tool” is built upon a combination of passive solar analytical methods from four different sources, Balcomb [26], Stein & Reynolds [24], Moore [25], Leckie, Masters, Whitehouse & Young [66], which have been developed from the early 1970’s to present. The four methods incorporated are; Balance Point Temperature,



**Eq. #1** - -  $BLC (Btu/DD-^{\circ}F) = 24 (h/day) \times UA \text{ non-south } (Btu/h-^{\circ}F)$

**Eq. #2** - -  $LCR (Btu/DD*ft^2) = BLC (Btu/DD-^{\circ}F) / A_{\text{south}} (ft.^2)$

Select Passive Solar System Type  
Input LCR into Sensitivity analysis tables to derive SSF

**Eq. #3** - -  $Q (Btu) = (1-SSF) \times BLC (Btu/DD-^{\circ}F) \times DD (DD)$

Result = Auxiliary Heat Load Required for Home (Btu's)

Allows - the overall heat benefit of the thermal mass and the total heat required to be derived.

### Fig. 5.12 - - Solar Load Ratio (SLR Method)

BLC = building load coefficient  
UA = Total Heat Loss (env. + infil)  
Asouth = Area of Solar Collector  
LCR = Load Collector Ratio  
SSF = Solar Savings Fraction  
Q = Auxiliary Heat Required  
DD = Degree Days

**Eq. #1** - -  $Q_i (Btu/h*ft^2) = UA (Btu/h-^{\circ}F) (T_i (^{\circ}F) - T_b (^{\circ}F))$

**Eq. #2** - -  $T_b (^{\circ}F) = T_i (^{\circ}F) - Q_i (Btu/h*ft^2) / UA (Btu/h-^{\circ}F)$

Result =  $T_b$  (Balance Point Temperature), which establishes the point where heat is required within the home based on the exterior temperature.

Allows adjustment of the Degree Day values to reflect the true context of the design, rather than assuming DD50.

### Fig. 5.13 - - Balance Point Temperature

$Q_i$  = Internal Heat Gains  
UA = Total Heat Loss (env. + infil)  
 $T_i$  = Interior Temperature  
 $T_b$  = Balance Point Temperature

$$\text{Eq. \#1} \quad \Delta T (^{\circ}F) = Q_i (\text{Btu/day}) / \text{BLC} (\text{Btu/DD-}^{\circ}F) + (\text{UA} (\text{Btu/h-}^{\circ}F) \times 24 (\text{h}))$$

Result =  $\Delta T$  (temp. change)

$$\text{Eq. \#2} \quad T_m (^{\circ}F) + \text{Tsw} (^{\circ}F) + \Delta T (^{\circ}F) = T_i (^{\circ}F)$$

Derive Swing factor(sf) from Balcomb tables

$$\text{Eq. \#3} \quad \text{sf} \times \text{Tsw} (^{\circ}F) = \text{Tswf} (^{\circ}F)$$

Result = a final temperature swing value that can represent the high and low temperatures within the space over the course of the day.

Allows an initial look at the factors of the interior thermal environment.

#### Fig. 5.14 -- Internal Temperature Swings

$\Delta T$  = Temperature change  
 $T_m$  = Mean January Temperature  
 $\text{Tsw}$  = Temperature swing [balcomb]  
 $T_i$  = Base Interior Temperature  
 $\text{sf}$  = swing factor  
 $\text{Tswf}$  = Final Temperature swing

$$\text{Eq. \#1} \quad \text{MC} (\text{Btu/h}) = (T_{ph} (^{\circ}F) - T_e (^{\circ}F)) \times \text{A}_{mass} (\text{ft}^2) \times k (\text{Btu/h-}^{\circ}F\text{-ft})$$

Result = by summing the MC values for each hour a total mass cooling amount in Btu's can be calculated

Allows comparison to the total heat gain over a 24 hour period to derive the flow rate of cooling for the thermal mass and the overall percentage reduction possible.

#### Fig. 5.15 -- Night Ventilation of Thermal Mass

MC = Mass Cooling  
 $T_{ph}$  = Mass temperature for the previous hour  
 $T_e$  = Exterior Temperature  
 $\text{A}_{mass}$  = Area of Thermal Mass  
 $k$  = thermal conductivity

**External Sensible** (Btu/h ft<sup>2</sup>)

**Eq. #1 - (Total UxA x (Wallfactor\* x Roofactor\*))/ Total Floor Area**

**Eq. #2 - (Window Area x Shaded Window Factor)/ Total Floor Area**

**Eq.#3 - (Orientation factor x GLF)/ Total Floor Area**

**Ventilation**

**Eq.#4 - (Volume x ACH x ADR x Ventilation factor)/Total Floor Area**

**Internal Sensible**

**Eq. #5 - (people factor + equip. factor + lighting factor)**

**Total Sensible Gains** (Btu/h ft<sup>2</sup>) = External + Ventilation + Internal Sensible

**Design Sensible Cooling (Qsc)**

**Eq. #6 - Qsc (Btu/h) = Total Sensible Gains x Total Floor Area**

**Design Total Cooling Load (Qc)**

**Eq. #7 - Qc (Btu/h) = Latent Load (typically 1.3) x Qsc**

**Design Temp. Difference** (°F)

**Eq. #8 - Summer Outdoor Design Temp. - Summer Thermostat setting**

**Cooling Load Coefficient (CLC)**

**Eq.#9 - CLC(Btu/Ddcool) = (Qc x 24)/ Temperature Difference**

**Annual Energy Cooling Required (Qcool)**

**Eq.#10 - Qcool (Btu/yr) = CLC x Ddcooling**

**Annual Cooling Energy Consumed (Ec)**

**Eq.#11 - Ec (kWh/yr) = .000293 x Qcool/COP**

 **Fig. 5.16 - - Cooling Load Calculation**

\*Refer to [25], [24] for factor definitions

SLR method, Internal Temperature Swings, and Night Ventilation of Thermal Mass. Figure 5.17 outlines the important properties within each and how they relate to the sources. Each of the approaches were studied and broken down to the most basic level to identify where the crucial assumptions were made and how. Each method is outlined below and further information is provided within Appendix D.

Factor	Basis	Source	Result
Vertical Orientation	Monthly Solar Radiation values, contingent on angle of collector	CREST <a href="http://solstice.crest.org/common/crestinfo.shtml">http://solstice.crest.org/common/crestinfo.shtml</a>	1 = Latitude Adjustable factor above and below
Horizontal Orientation	Solar Hours per day vs. tilt angle	Alternative Energy Engineering <a href="http://alt-energy.com/">http://alt-energy.com/</a>	3 options
Balance of System Equipment (BOS)	% losses per equip. piece	Solarex	Variable system configuration
Layers	Material Transmittance properties wavelength dependent	Schott Corporation	Variable reduction

**Fig. 5.17 - - Thin-film PV factors**

The important element was to establish this method of evaluation through the use of reliable data generated by such groups as Center for Renewable and Sustainable Technology (CREST) [67] and the National Research Energy Laboratory (NREL) [68]. A copy of the spreadsheet and associated links are in Appendix D. The categories are listed and defined below:

***PV systems(electricity)***

The impact of the thin-film photovoltaic in creating energy is established and refined through the comparison of the results of three different methods. Each method has one aspect of the energy equation of Wattage = Voltage x Amperage serving as the variable.

***Effectiveness of the PV***

The validity of the analysis of the thin-film PV layer relies on a series of factors. The factors account for location of the PV layer vertically, horizontally and within the depth of the component.

The basis and source are identified within Table 6.4. In addition, data was collected on the Balance of System requirements for the PV systems, relating to the losses introduced by batteries, inverters and charge controllers. Data was also gathered on various PV panel types through consulting catalogs from companies such as Solarex, BP Solar, Siemens and Evergreen Solar.

Answering the questions:

- 1) *Select the PV system type and AC or DC power requirements*
- 2) *What type and size of PV panels and array size?*
- 3) *What is the location and factors of orientation of the system?*

allows the impact of additional equipment (balance-of-system, BOS), the quantity of the panels and the issues of site globally and locally to be put into the model. The results establish the quantity of energy creation possible. These numbers can be related to the Energy Consumption of the Case Study home and combined with the results from the Envelope Template to assess the overall EPW system performance. The breakdown of the emphasis of each method is provided below.

#### **Method 1 (M1)**

*Explores the impact of the overall wattage capable by each panel within the system, identifying a range that considers the products available today and what could be the impact as the "infamous" PV efficiency increases.*

$$Y \times PW_{(w)} \times \text{Solar Hrs./day} \times PV_{tf} \times PV_{sf} \times PV_{lf} = \text{Watts/day}$$

Y = number of panels in system  
 PW = panel wattage  
 PV<sub>tf</sub> = PV tilt factor  
 PV<sub>sf</sub> = PV system equipment factor  
 PV<sub>lf</sub> = PV layer factor (position of thin-film PV)

#### **Method 2 (M2)**

*Amperage takes the primary role in this method, investigating the flow of electricity within the system.*

$$Y \times PA_{(amps)} \times \text{Solar Hrs./day} \times DV_{(V)} \times PV_{tf} \times PV_{sf} \times PV_{lf} = \text{Watts/day}$$

PA = Peak amps of PV panel type selected  
 DV = DC System voltage

**Method 3 (M3)**

The overall energy equation is shaped by the efficiency of the PV panels and in this method that factor serves as the variable. The location of the thin-film PV within the EPW has a major role in the efficiency and from other subsets of data used to determine this factor, the overall energy creation of the panel within the EPW system is determined and compared to the others.

$$Si \text{ (Btu/h-ft}^2\text{)} \times PVlf \times PVEff(\%) \times \text{Solar Hrs./day} \times Y \times PVsf \times = \text{Watts/day}$$

Si = Solar Insolation (Global & Direct), substitute for PVlf  
 PVEff = Thin-film PV efficiency (type selection)

Topic	Characteristic	Percent or Cost
Total energy	Climate zone	No. of Households
Space heating	House type	% of Households
Electric air conditioning	Indicators	
Water heating	Northeast region*	
Appliances	Southeast region*	

Figure 5.18 - House Characteristic Classifications for EIA Energy Survey [4]

\*Within each regional classification, the data was broken down further into three divisions within that region.

The benefit of the three methods is that the problem can be approached from various angles, dependent upon the context. Thin-film PV energy creation for monthly and yearly values can be calculated from these initial values of Watts/day.

**Energy Use within the home:**

The 1997 Residential Energy Consumption Survey, by the Energy Information Administration [EIA] provided the data for the overall electricity usage within the home. The energy data within the report can be broken down into three categories with variables within each. Figure ## outlines the alternatives possible.

The data from the Energy Survey provided the overall electricity loads (Water Heater + Refrigerator + Appliances) in the units of Million Btu's per household, for each region under the classifica-

	<b>MODELS</b>		
	<b>3d Computational</b>	<b>Physical</b>	<b>2d Drawings</b>
<b>Material textures</b>	Full scale		
<b>detailing connection</b>	Full scale	scaled down	scaled down
<b>component frame</b>	Full scale	Full scale	
<b>component configurations</b>	Full scale	Full scale	
<b>spatial studies</b>	Full scale	scaled down	
<b>prototype home designs</b>	Full scale		scaled down

Full scale
  Full scale  
 scaled down
  scaled down

Figure 5.19 Aesthetic Models

tions of low, average and maximum usage for the household. The data for space heating and electric air conditioning provided a point of comparison for heating and cooling load quantities derived within the “spreadsheet tool”. Ultimately, the electricity load from the EIA survey, plus the heating and cooling loads for the prototype design, in its selected climate, totaled the energy consumption (in Watts) within the home.

#### 5.2.4 Aesthetics

The aesthetics develop in the mind, find a way to paper through sketching, and are refined through a balance of physical models and virtual models. The table below displays how drawings, physical models and computational models were used through the development of the EPW components.

Three-dimensional models were created in AutoCAD version 14 and rendered in 3d Studio Max version 2, to bring the two dimensional textures into three dimensions in the context of a 2’x4’ component. The creation of these models allowed ease of manipulation of the component configuration and frame to allow exploration of the various concepts. The next step was to begin grouping the component types to identify the connection between components and the number of different

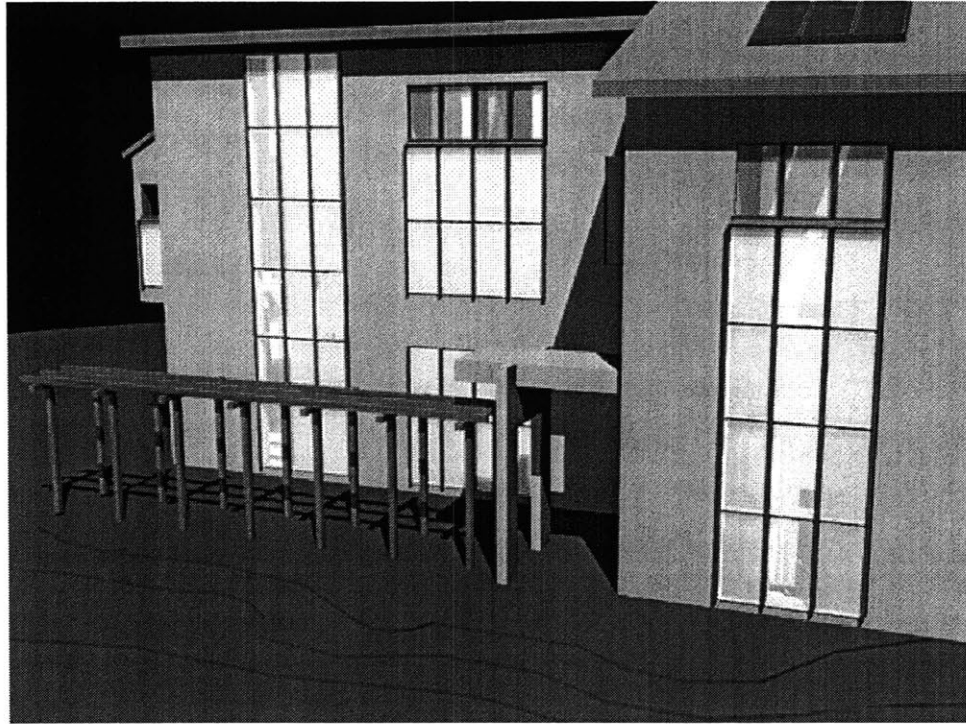


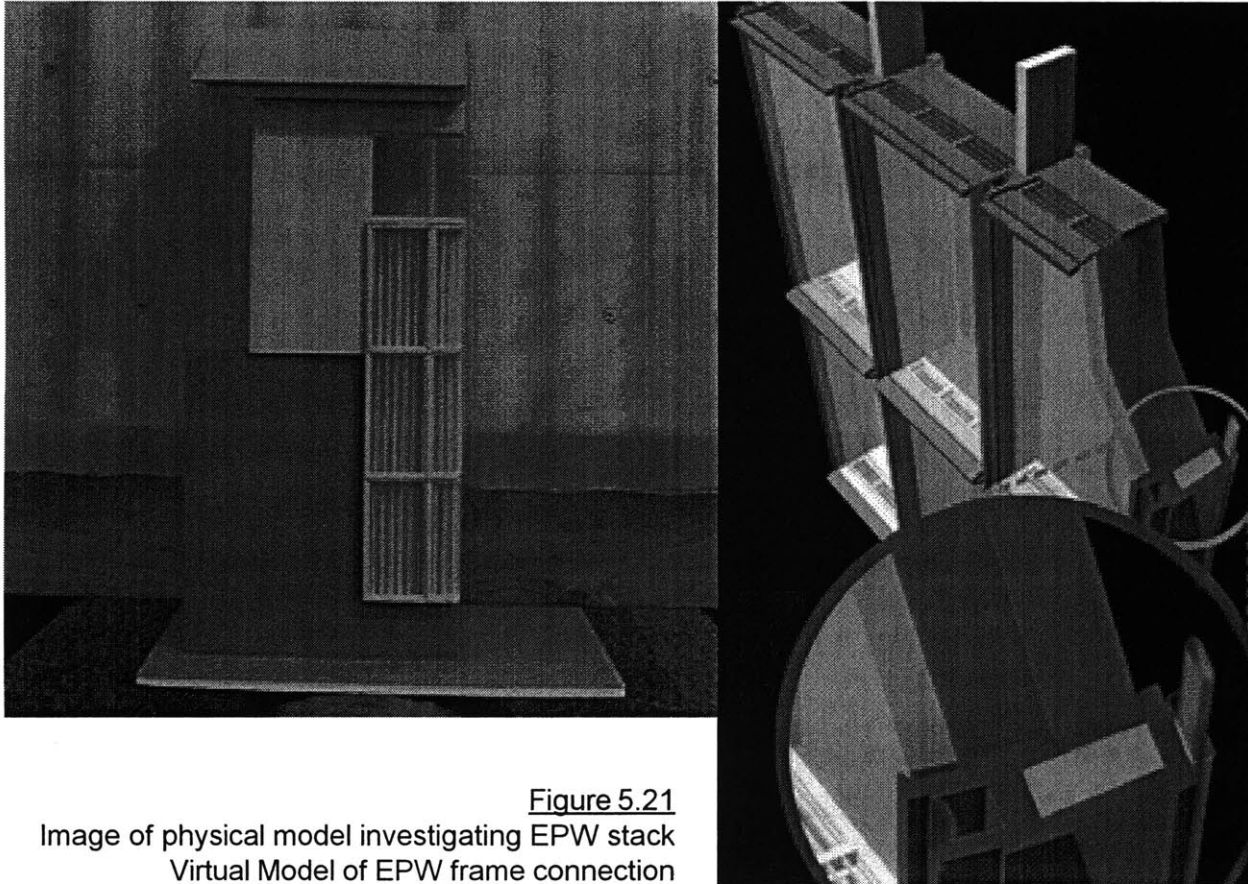
Figure 5.20

interfaces required based upon the composition within the wall. The 3d models were transformed into partial wall sections. In addition, a scaled down physical model was created to express one potential composition of parts. The physical models force the mind to sort through the relationships, connections and potential opportunities in a different manner than during the creation of the 3d visualization models.

Building on the wall section, the scales to follow were the façade and the overall building. A series of three-dimensional AutoCAD models were developed to explore the impact of this jump in scale. The overall context for these models was a past home design done for a competition. The models assisted in formulating concepts relating to operational capabilities and process as well.

The increase of scale not only went from component to system of house in the virtual realm, but from  $\frac{3}{4}'' = 1'-0''$  to 1:1 in the physical realm. Three-dimensional models were created of the two prototype home designs, while a larger physical spatial model was used to investigate the selection of EPW composition to a larger grouping of spaces. Also, a full-size mock-up of the compo-





**Figure 5.21**  
Image of physical model investigating EPW stack  
Virtual Model of EPW frame connection

ment frame was constructed and then refined into a full-size 2'x4' EPW component prototype. The importance to the development was that the model types (physical & virtual) were constructed simultaneously. It forced the acknowledgement of the different scales, and displayed the impact of making designs at the small detail level and how that translated to the impacts in the aesthetic of the overall. Issues began to be addressed, such as, how the EPW groupings could be used within the façade without totally dominating it and destroying the composition. The model types are used as complements rather than replacements.

By establishing this wide range of representations, the EPW component can be evaluated at very different levels, which can easily be viewed at one scale and then placed in a larger context. The variability also allows the adaptability to be expressed, because the graphic representation, which is the key to the aesthetic, also provides the base for conveying information relating to the construction process and operations.

### 5.2.5 Construction Process

The analysis of the construction process of light wood frame construction differs from the other two areas because it is a process of breaking down from the system level, rather than building from material to component to system. The tool developed to provide the ability to track the impact of innovations, such as the EPW, within the construction process is the light wood framing, dynamic process model (LWF-DPM). The data collected through the literature review, site visits and interviews are the foundation of the LWF-DPM.

#### 5.2.5.1 Dynamic Process Model Development

The development of the simulation model began by defining the construction process in a series of process flow diagrams identifying each task with each activity and each activity within each sub-process. Comprehensive enough to represent activities on any project, the **Flow Diagram** serves as the framework for the construction process of light wood framing, representing the “constants” within a project. It is an integrated sequence of tasks that describe the construction process at various levels of detail, ranging from the type of wall to be constructed to the number of nails in the connection of a header. It reaches to the most detailed and basic level of the process, while tying it to the overall building. The basis chosen was dimensional wood construction, because it is the most complex task breakdown of light wood construction types accomplished on site. However, it is not restricted to this type of construction. Other construction types, such as Structural Insulated Panels (SIP), are simplifications to the process because the steps to create these products occur off-site. The differences arise when the labor, equipment and time required to position these larger panels are considered. In other words, when the unique aspects of these panels must be considered. Three elements characterizing the uniqueness of the project are mapped into the **Flow Diagram** and define the **Project Specifics**.

1. The **Design Attributes**, which serve to shape the picture of the project and identify the types and quantities of units to be worked upon.
2. **Resources** in terms of the type and quantity of equipment and labor needed to accomplish the construction tasks are identified.
3. **Production Time Estimates** bring added context to the relationship of the resources and design attributes relating to the time required to perform the construction tasks on units for each resource set.

**Verification of Model**

Validation and refinement of this “rough” model was accomplished by going to the experts, the builders and contractors. On-site observation at over 20 sites, discussions with builders, articles in trade journals and past experience serve as the sources for creating the pool of information from which the **flow diagram** was formed. A packet was sent to an “expert group” composed of builders, architects, engineers and designers from across the United States for review and comment. The packet was also taken on-site for discussions with local builders. Feedback is obtained and the Process Flow Diagram, Resources, Design Attributes and Production Time estimates are revisited and refined.

<b>individual</b>	<b>Position</b>	<b>Location</b>	<b>Company/ association</b>
<b>Ed Allen</b>	Professor Author Architect	Wellesy, MA	MIT, Yale
<b>Randall Luther</b>	Vice President Director of R&D	Austin, Texas	Centex Homes
<b>Patty McDaniel</b>	Designer/Builder	Rehoboth Beach, DE	Boardwalk Builders, Inc.
<b>Devon Hartman</b>	Designer/Builder	Claremont, CA	Hartman Baldwin Design/Build
<b>Jeff Schoelkopff</b>	Designer/Builder	Warren, VT	Edgcomb Design Group

**Fig. 5.22 - - Distribution of Packet**

**Simulation of Prototype Designs**

To begin to solve a problem, the context must be provided in which the problem can be addressed. Two prototype home designs, discussed within the next section, were designed to provide the context in which the dynamic simulation model would be evaluated. For each design, floor plans, framing plans, framing elevations, wall sections, and details are developed to allow the necessary take-offs to be acquired for input into the dynamic simulation model. The design attributes, which include the types and quantities of units, are defined for each of the prototype designs. The selected design innovation, the EPW, is integrated within these house designs for evaluation.

### ***Simulation of the EPW***

The EPW components are an innovation, which can be viewed as a wall element or a window. The method of installation is very similar in character to a standard window, which incorporates a fin system around the perimeter. The window is positioned from the exterior with the fins fitting tight against the plywood sheathing. Shims are used to make the final position adjustments, and the window is then nailed into place. The EPW components incorporate the same tasks, but require the installation of a closure piece to the wall framing prior to erection that serves as a guide and receiver for the installation of the component.

Preliminary simulation analyses performed incorporated the EPW components within both prototype designs to assess their performance within the construction process. The results allow comparisons and contrasts among the multiple Prototype Home design alternatives, as well as among the different methods of construction within a specific prototype design.

### ***Simulation Model***

The platform for the LWF-DPM is a commercially available process simulation program, SIMPROCESS™. The program uses a graphic interface with the ability to draw data inputs from spreadsheets and customized expressions to create a tool representative of the constant and the unique specifics within a project. SIMPROCESS, resource descriptions, design attributes and flow diagrams were used to develop the overall LWF-DPM, which is described within the analysis section.

For the tool to be effective however, one must understand the perceived standard of light wood framing. The following section outlines the basic principles incorporated in light wood framing and the processes utilized for construction to be completed.

### ***General Description of LWF installation***

Figure 5.23 expresses the highest level within the flow diagram for framing the residence. Once the foundations are in place, the platform, serving as the first floor, is constructed. This surface also functions as an assembly area for the exterior and interior walls of the first floor. After assem-

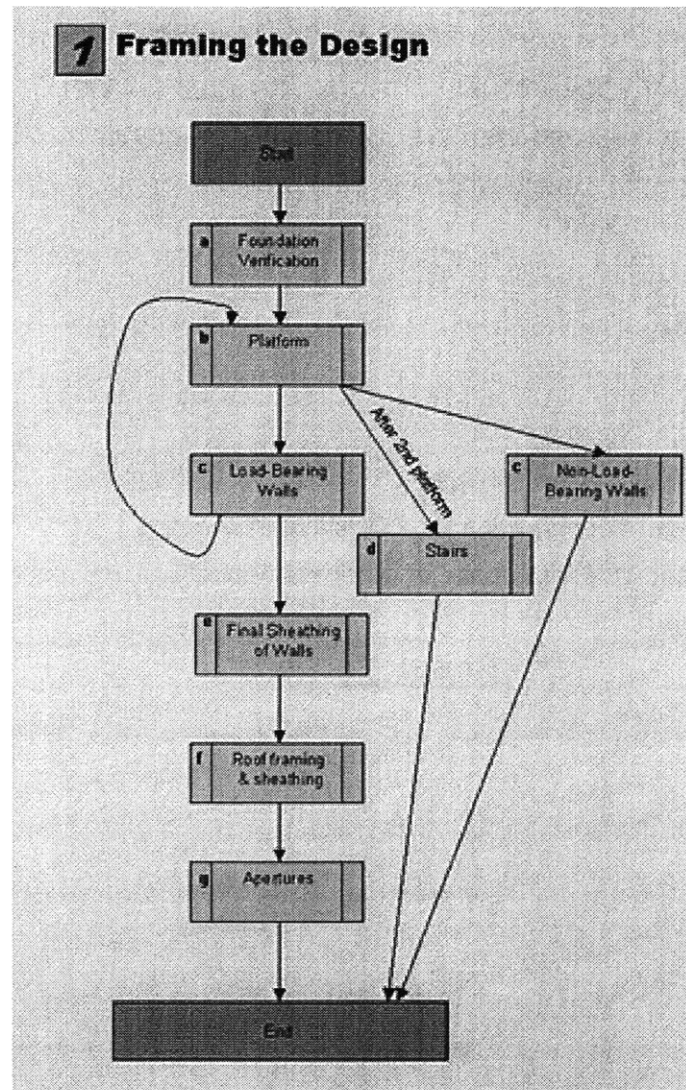


Figure 5.23 First Level of Process Flow Diagram

bly, the load-bearing walls are tilted up into place and temporarily braced if not self-supported. Once the load-bearing walls are erected and connected, the option of constructing the second story platform or the non-load bearing walls is possible. The second platform also functions as an assembly area for the second floor walls. As the figure displays, the process of platform, walls, platform can continue (platform framing). The limit of four floors (based on use and type of construction) for the structure is set by reached the requirements within the local building code. [69] Depending on the treatment of the ceilings within the top floor, another platform can be built to

assist in the construction of the roof. After the construction of the second platform, the stairs can be constructed between the first and second floors. Occurring in parallel can be the final plywood sheathing of the exterior walls and ultimately the framing and sheathing of the roof. The building envelope reaches a point of closure when the apertures (i.e. doors, windows, and vents) are installed.

**Specific Sub-Processes**

Once the construction process of light-wood framing is reduced to the entity level of wall, platform or roof, and beyond, the process becomes very repetitive in nature. The activities are focused upon the transformation of a wood member, its location, and the method used to attach it. Preparation, placement and connection become the activities that are performed at various levels, to single members, wall sections, apertures or other entities.

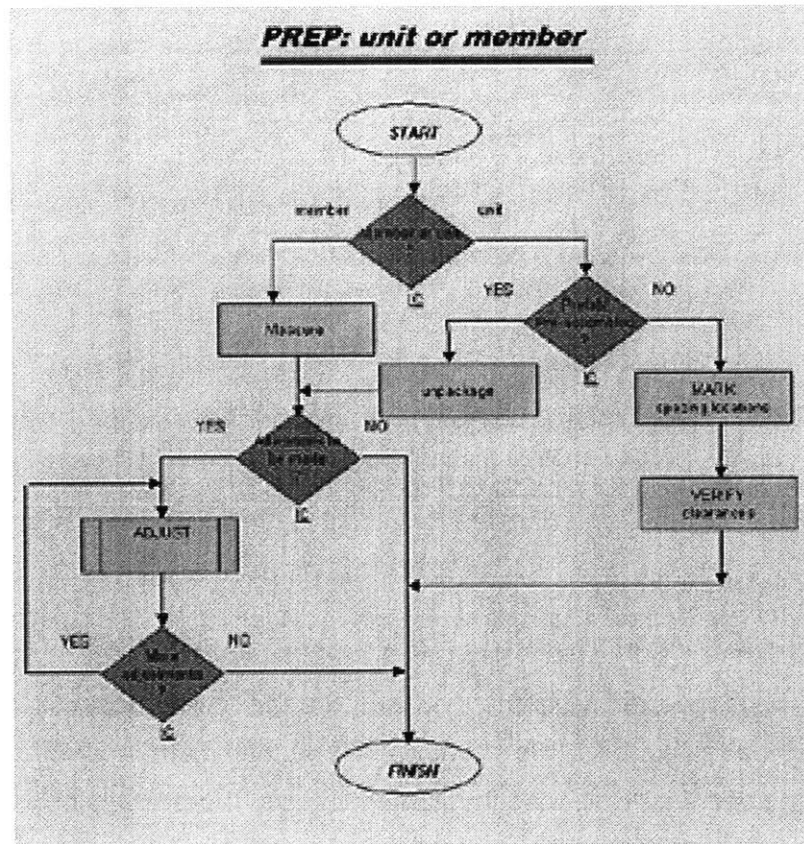


Figure 5.24 Preparation of Unit or Member



### Preparation

The tasks involved in preparing a unit or member are outlined in Figure 5.24. First, the context is defined as to whether the “preparation” is being performed on a unit (wall section) or a member (2x wood). If it is a single member, the carpenter must establish if the member is to be adjusted or not. The carpenter would have previously consulted the framing plans to ascertain the correct length, shape, and adjustments required for the member. She would measure the member, and if not the correct length or shape required, adjust the member accordingly. The method of adjustment could mean cutting the member, drilling a hole/holes, or attaching a connector to it. After the adjustments are completed, the question is reached regarding irregularity of shape. If the shape is required to be curvilinear or incorporated into an assembly of complex pieces shaping the form, the alterations are made at this step. When the preparation is completed, work can begin on another member.

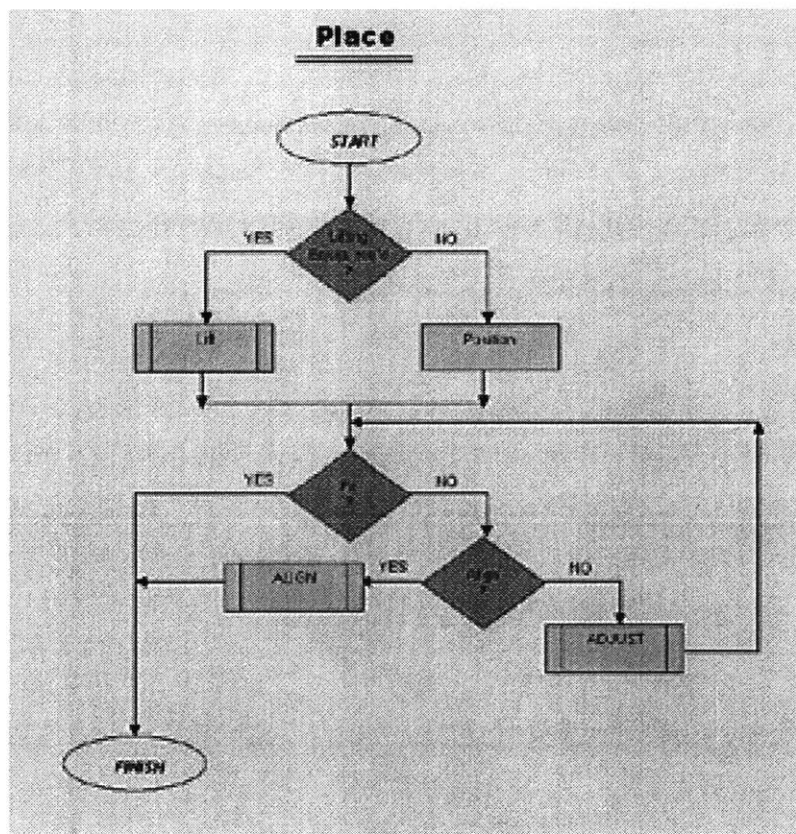


Figure 5.25 Place Member

This is not to say that the process occurs in a linear fashion or one by one. The “preparation” could occur simultaneously on multiple members together or through the use of increased resources performing the tasks in parallel.

**Place**

Continuing to follow the “2x wood” member through the process, Figure 5.25 illustrates how the member is placed. Since it is a single piece, no lifting equipment is required and one carpenter can perform the lifting. Once positioned, the “fit” must be assessed. Assuming the member requires alignment, but not further adjustment, the shimming, trimming or positioning is completed, so that the member is in its final position.

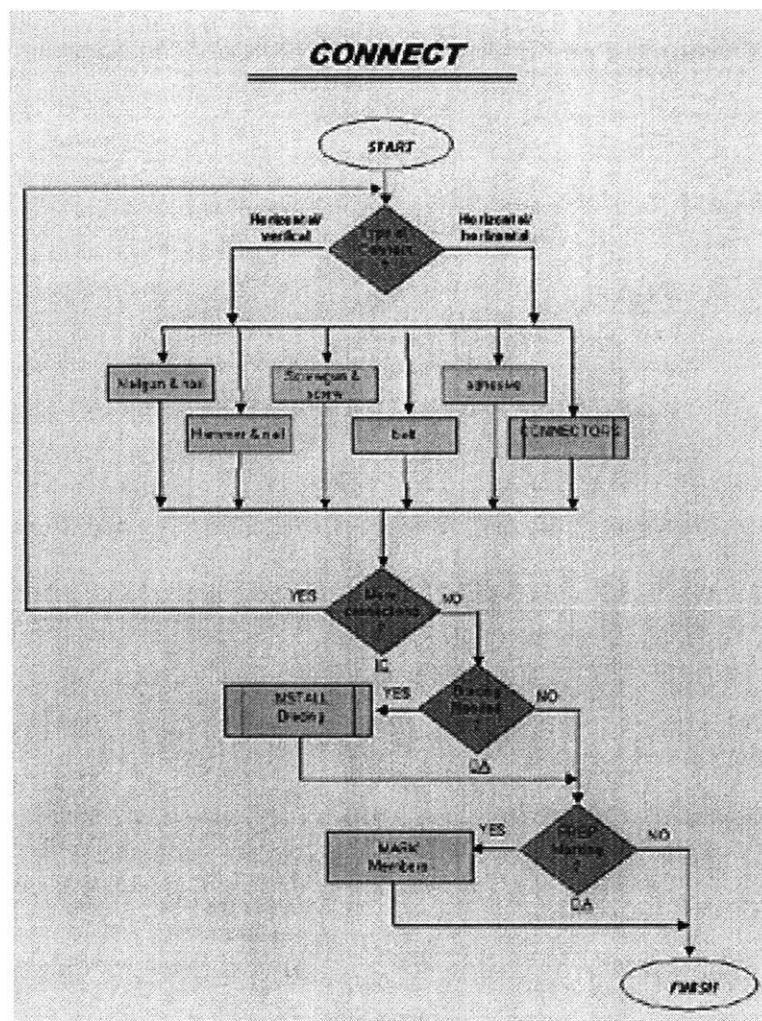


Figure 5.26 Connecting Member



**Connect**

Based on the position of the member (e.g. vertical stud) within the wall section, the connection type is a horizontal to vertical (e.g. to plate)(Fig. 5.26). The general connection method in light wood framing is nailing with a nail gun, as is used in this case. Other types of connections will be used, such as connecting risers to the stringers, or beam to beam connections. Once one end of the vertical studs is connected to the sill plate or top plate, the decision point is reached if further connections are to occur on this member or transition to another member. An example of a transition between members would exist if a carpenter were attaching all the vertical studs to the sill plate first, and then attaching to the top plate. [70] After the connections are complete, bracing is installed if necessary and the members are marked if beneficial for positioning or location of other members.

**Resources**

The carpenter is the primary resource within the LWF process. Unless extensive prefabricated units are used, such as wall panels or roof trusses, a majority of the activities are performed by the carpenter with tools and equipment that they can handle individually or through the help of one other carpenter.

Typical framing crews consist of 4-6 workers of varying skill level. They all might be carpenters, or the crew might be composed of carpenters and laborers. At least one and usually two workers within this group will be of the status of journeymen carpenters, having substantial experience on a wide range of project types. Normal task and activities performed on site require 2-3 carpenters. Only the erection of the large wall sections or placement of large components requires the whole crew to be involved with one activity. Therefore, a crew of 4-6 workers actually functions as two to three individual, coordinated teams for the majority of the project.

The type of project also dictates the role of the "framing crew" to a certain degree. For example, one observed (Green Street Condominium project) had a general contractor supervising the "framing crew". Typically, projects involving a developer or development agency will have a general contractor on site. However, numerous other situations occur where the "framing crew" is the same crew that prepares the foundations, and completes the finishes within the interior of the project.

Tool	Use
<b>Basic Framing Tools</b>	
Chalk line & refill bottle	Marking wall locations, cuts or placement
Tape measure	Measuring
Hammer	Nailing, positioning, moving objects
Screw driver	Installation/removal of screws
Utility knife	Cutting, marking
Duct tape	Temporary holding device or connection
Nail set	Marking
Speed square	Marking, aligning, measuring
Level	Checking alignment
Sledgehammer	Positioning or demolition
5-gallon bucket	Adapted toolbox or container
Extension cords	Power supply
T-square	Marking, aligning
Cat's paw	Nail or connector removal
<b>Customized or Site-Built</b>	
Bolt hole maker	Laying out sill anchor bolt holes
Layout stick	Laying out spacing (i.e. studs, joists)
Story pole	Verification of window, wall, etc. height and location
Plumb stick	Verifying wall alignment and positioning
<b>Power Tools</b>	
Chop saw	Cutting 2x members to size
Circular saw	Gang cutting, member cutting
Pneumatic nail guns	Wall assembly, rafter connection, etc.
Reciprocating saw	Cutting holes in plywood in place
Cordless drill	Drill holes, screw installation/removal

**Fig. 5.27 - - Typical tools used by "framing crews"**

As mentioned previously, the equipment found on site is dependent upon the type of components utilized within the construction process and the approach used by the crew. Carpenters utilize a wide range of tools, some standard, some custom-made that can range from the claw hammer to the hand-held circular saw. The list of tools varies from site to site and is based upon personal preference. Two types of approaches were observed, which fall under the titles of "position adjusters" and "ground adjusters". The "position adjusters" tend to perform the adjustment tasks re-

Tool	Use
<b>Basic Framing Tools</b>	
Bobcat	Moving materials, demolition, site work
Crane	Lifting wall sections, roof trusses, etc.
Forklift	Maneuvering materials or large members
Generator	Power source
Beam lift	Isolated lifting of singular beams
Wall jacks	Temporary support for portion of wall/floor
Larger format table saw	Gang cutting members
Come-a-long	
Vertical lift	Position workers safely at higher points

**Fig. 5.28 - - Larger equipment on-site**

quired on a wood member in close proximity to its final placement, while “ground adjusters” will perform the tasks at one location on-site and carry the members to their final position. Part of the difference is expressed through the type of equipment used (weight, size and power), but also the safety on the job. Figure 5.27 outlines the range of tools, developed through interviews and observation, that could be found on-site. The list is not meant to be comprehensive, but to highlight and demonstrate the diversity.

Larger equipment becomes required as the size of the components increases, prefabricated components such as wall sections are used, or a combination of both. Figure 5.28 outlines the larger pieces of equipment likely to be found on-site.

### **Production Rates**

The variability of production rates can be very high based upon the previous discussions on resource and a component type utilized on site but appears to stabilize at the level of the specific task on the specific component. Tables within the Appendix F express a range of production rate times observed on site for a specific list are tasks. Included within the list is tasks performed by framing crews on “stick-built” projects as well as projects incorporating “pre-fabricated” wall units.

### *Safety Issues*

Safety on a LWF project is partially dependent upon the building form and the technology utilized by the framing crews. If the project is two stories in height, then the use of scaffolding or tie-offs is potentially necessary. In addition, the shape of the roof might also dictate the level of danger within a project. For example, a complex roof form coupled with a carpenter of the “position adjuster” type might find themselves in a higher percentage of potentially dangerous positions, than a carpenter connecting roof trusses from a scaffolding platform.

Technology has introduced a range of new tools onto the typical residential site in the form of nail guns, variations of the traditional circular saw, and types of drills. The technological trend is one of more power and smaller size tools, which can be handled by the individual. The smaller size allows the tools to be carried and used in places that normally weren’t possible, much less thought of. In addition, the power of these tools, such as the nail gun, can lead to accidents on site.

Within Appendix C are the complete processes, sub-processes, tasks and activities in addition to the production rates, resource lists and design attributes pertaining to the LWF process. The information represents the typical site conditions. The model starts at the point of foundation completion and ends at the completion of enclosure of the envelope, signified by the placement of the final aperture. As stated previously, the carpenter or framing crew can be responsible for a number of other activities outside this range, but these activities are not captured within this model. Another assumption within the model is that the framing crews or supervisor has spent substantial time reviewing the framing plans and understands the elements and components involved. The model is presented as a tool to the builder to investigate and identify potential value-added tasks associated with the process of LWF. The potential of the model lies not only within the overall results(time, cost, safety), but in the ability to adapt the model to delays, disruptions and changes in a number of variables relating to the resources utilized.

### 5.2.6 Performance Integration

#### *“Spreadsheet Tool” Result Format*

The “spreadsheet tool” provides results on the individual EPW panel performance, system heat performance, system electricity performance and collective system (heat + electricity) operational performance. The results are compared to the range of values relating to two alternatives: 1) Standard 2x wood Construction 2) Passive Solar Design, utilizing a trombe wall. A percentage of load reduction for the home is established relating to each alternative.

	<b>Prototype “EPW System” benefit</b>	<b>result</b>
<b>Comparison #1</b>	Thermal Mass benefit to Heat Load	% of heat load reduction
<b>Comparison #2</b>	PV creation to Energy Usage	% of energy load reduction
<b>Comparison #3</b>	PV creation to Heat Load	% of heat load reduction (due to PV)
<b>Comparison #4</b>	System benefit (PV + heat) to Heat Load	% of heat load reduction (due to EPW use)
<b>Comparison #5</b>	System benefit (PV + heat) to Cooling Load	% of cooling load reduction (due to EPW use)
<b>Comparison #6</b>	System benefit (PV + heat) to Electricity Load	% of electricity load reduction (due to EPW use)
<b>Comparison #7</b>	System benefit (PV + heat) to Combined (Heat + Elect.) Load	% of combined load reduction (due to EPW use)
<b>Comparison #8</b>	System benefit (PV + heat) to Combined (Heat + Cooling + Elect.) Load	% of overall load reduction (due to EPW use)

**Fig. 5.29 - - Operational Performance Comparisons**

### ***Dynamic Simulation Model Result Format***

The number of total walls, openings, additional members due to the openings, sheathing and total members, which serve as inputs for the LWF simulation model provide a basis of comparison between the construction types utilizing the EPW components and those without the unit. The output of the LWFmodel quantifies the difference of this comparison, while the chart to the left outlines the process flow and the impacts over this duration.

### ***Aesthetic Result Format***

The aesthetic results are in the form of the virtual and physical models, which function as responses, support and an additional way to explore the sensitivity of the desired change.

#### **5.2.6.1 Case Format**

Once the spreadsheet analysis, the dynamic simulation model and the visualization studies are completed, all of the information is brought to a level and in a format that is understandable and allows the direct comparisons of alternatives. A nine-point “case result format” was created to provide this capability. The points are:

1. Location: Climate
2. Prototype Design Type and Quantity of Component Types
3. Rendering describing Aesthetics
4. Overall Residence Energy Consumption
5. Dynamic Simulation Model Results
6. EPW System Creation
7. Passive Solar Layer
8. EPW % Benefits
9. Future Development Impacts

The format summarizes the operational, construction process and aesthetic performance for the specific case relating to the parameters outlined above. The results outline the impact of passive and active solar concepts at the individual panel type up to the percentage benefit of the system as defined by the quantity and orientation of EPW panel types and the other features of the building envelope. This format is used consistently across the cases to allow comparisons from case to

from case to case in addition to those comparisons possible within the case itself. The results demonstrate how decisions within the building envelope, relating to the EPW components, can reduce the energy load initially and over time, change the construction means and methods, as well as duration and safety, and enhance the aesthetics at differing scales. The 'case format' functions as much as a format for learning as much as for presenting results. It provides the portal and guide to more in-depth information included within the thesis document.

Parameter	Options				
Prototype Design	Modern	Sears			
Location	Boston, MA	Phoenix, AZ			
Construction Components	In-situ	Site pre-assembled	prefab		
Resources	Size of crew	No. of crews			
Materials	Matl 1	Matl 2	Matl 3	Matl 4	Matl 5
EPW type	1a, 1b, 1c	2a, 2b			
EPW orientation	Layer config.	Horizontal	Vertical		
PV efficiency	Cycle 1 (5%, 12%)	Cycle 2 (10%, 17%)	Cycle 3 (15%, 22%)	Cycle 4 (20%, 29%)	
Balance of System	System 1	System 2	System 3	System 4	
Electricity Load type	Low	Average	High		

Fig. 5.30 - - Parameter Selections

### 5.2.6.2 Sensitivity Analysis Possibilities

Once the results are compiled, the point where the most interesting conclusions can be derived has been reached. Due to the parametric structure of the framework, specific variables can be isolated, and their effects on the overall values charted to develop a deeper understanding of what is shaping and effecting the overall performance. The alternatives provided in Figure 5.30, outline the parameters that can be manipulated in the process and also the options, within the "spreadsheet analysis" and the dynamic simulation model.

**Basis for Results**

Table 5.31 expresses the type and quantity per building face of EPW components used within each prototype design (EPW Case). The group entitled (EPW Max) represents the maximum number of panels possible for each surface possible, determined by compliance with the guidelines discussed in within the analysis. The table displays the EPW #1 component types. To obtain the amount of the EPW #2 components used in alternative cases, just add the Type 1a & 1b columns together for each case. A point of analysis between the two prototype designs is the relationship of performance to each other and the maximum potential of the design. The Sears design incorporates 56% of the maximum, while the Modern design utilizes 46%. However, the modern design

<b>Sears (EPW Case)</b>				
	Type 1a	Type 1b	Type 1c	Type 1d
	Full	Clr + PV	Clr	Sky Clr+PV
E		11	4	
S	27	5	12	15
W		11	4	
N				
	27	27	20	15
				<b>69</b>
<b>Sears (EPW Max)</b>				
	Type 1a	Type 1b	Type 1c	Type 1d
	Full	Clr + PV	Clr	Sky Clr+PV
25% E		20		
S	40	10	5	33
25% W		20		
N				
	40	50	5	33
				<b>123</b>
<b>Modern (EPW Case)</b>				
	Type 1a	Type 1b	Type 1c	Type 1d
	Full	Clr + PV	Clr	Sky Clr+PV
E	0	9		
S	40	24	12	24
W	0	9		
N				
	40	42	12	24
				<b>106</b>
<b>Modern (EPW Max)</b>				
	Type 1a	Type 1b	Type 1c	Type 1d
	Full	Clr + PV	Clr	Sky Clr+PV
25% E		12		
S	100	24	12	78
25% W		12		
N				
	100	48	12	78
				<b>226</b>

Table 5.31 EPW Design & Maximum Quantities



incorporates a total of 37 EPW components. The percentage difference between the amounts listed and the maximum percentages express an initial layer of the trade-offs embedded within the guidelines in the form of structural requirements and aesthetics.

The percentage of openings in the envelope on each face were generated by totaling the surface areas of each opening type from the component quantities listed in the table and the other openings in the envelope (i.e. windows, doors, glass doors). Dividing the surface area by the overall surface area of that particular building face generating the final percentage.

### Operational analysis

A total of forty-eight cases were evaluated utilizing the EPW spreadsheet. Geographical location, quantity and configuration of EPW components, variable thin-film pv efficiency based upon "layer" location within the component were the variables for the different cases. Table 5.28 outlines the six cycles of eight cases performed and the variable manipulation. The results collected provided output comparison to the heat, electricity and combined loads within the home.

	Case							
	1	2	3	4	5	6	7	8
EPW Config. #1 design	■		■		■		■	
EPW Config. #2 maximum		■		■		■		■
	Cycles*							
	1	2	3	4				
EPW #1 effc.	5%	5%	10%	10%	15%	15%	20%	20%
EPW #2 effc.	12%	12%	17%	17%	22%	22%	27%	27%
Modern Design	■		■		■		■	
Sears Design		■		■		■		■
* each cycle contains case 1-8								

Table 5.32 Case Analysis Breakdown



## Chapter 6.0 Results

### *Context for Results*

No one calculation, chart, image or table expresses the range of factors important to the integration of innovation within the design and construction. The assumption is that by bringing the results into a format where they can be reviewed side by side across the areas of operations, construction process and aesthetics, more insightful and integrative approaches can be used to ease the implementation of innovation. Also, by understanding the viewpoint and interest of the other groups, the information relevant to a project team can be structured and presented in a language recognizable and relevant to all.

The results are presented and in three sections:

- 1) Results of Implementation investigations of the EPW component:
  - a) Construction language
  - b) flexibility and adaptability
  - c) variety and harmony
  - d) operational effectiveness
- 2) Results of the Cases for the proposed integrated framework (case dependent)
- 3) Comparative Results – investigating sensitivities

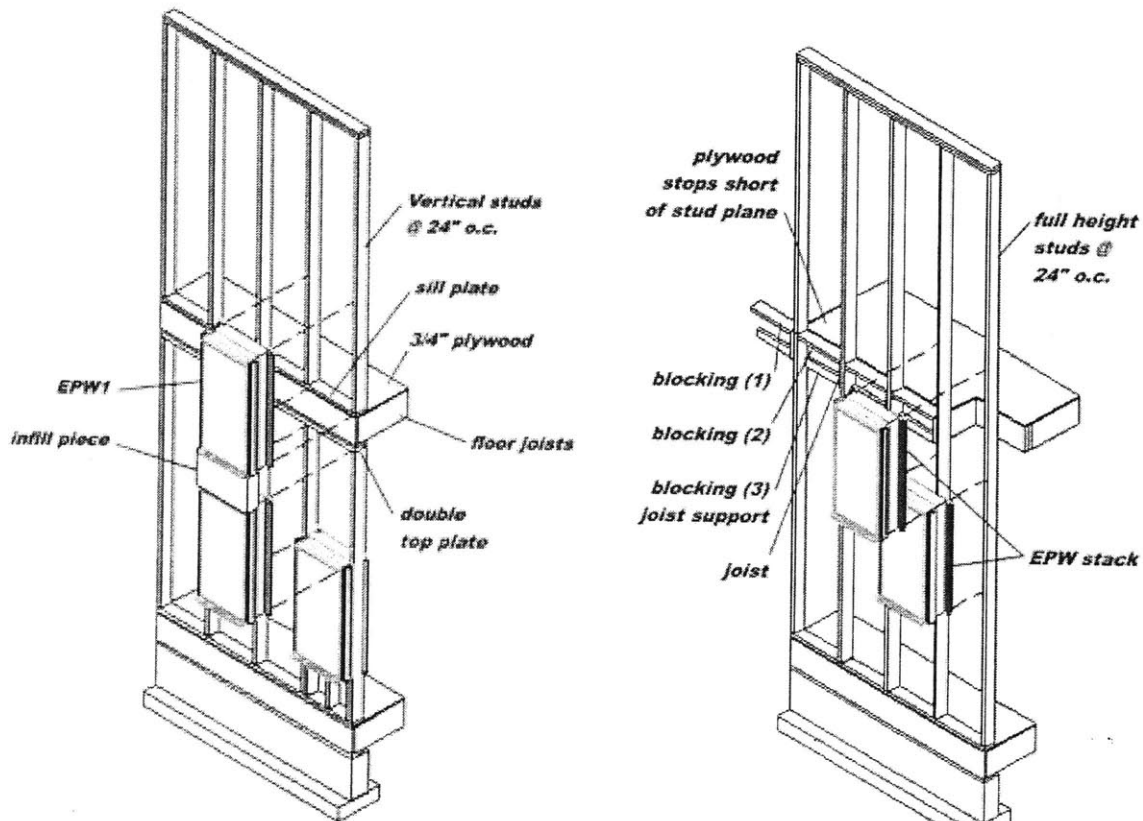
The first section provides the results developed through the various explorations of implementation of the EPW at the material, component and system level. The results are at a global level to demonstrate the capabilities of the EPW and the framework utilized for evaluation. The results in the second section build off of the main points of the first section and provide more in-depth results on a case by case basis. The third section provides a further investigation of the points identified within section 2, but also ties these subjects back to the larger collection of cases. Key criteria, such as selection of thermal mass material, EPW1 vs. EPW2, or the potential for technological improvements are isolated, varied and investigated.

## 6.1 Evaluating the Implementation of the EPW

### *Construction Language*

The development of the simulation model enabled a deeper investigation to occur regarding the installation method of the EPW components. Ease of installation by the builders on site is the crucial element to adoption of use. Interviews and past precedents such as the Konrad Wachsmann design [Herbet], indicate that even if the performance of the other two categories (aesthetics and operation) is improved, if the installation is not within the language of the work performed on site by builders, a strong barrier to use can develop. This concern shaped the design of the frame for ease of installation for new and retro-fit construction. The EPW frame divides into two main pieces (fig 4.21, pieces labeled #1 & #2). Therefore, installation can occur at two stages for new construction; the first, the receiver piece (#1) is installed when the initial stud wall is framed on the ground and the second, the main frame piece (#2), after the wall is erected. The flexibility of the frame allows the unit to be installed in place vertically as well, but requires the vertical stud to be completely exposed for installation on all sides. The EPW component encases the wood stud, therefore requiring the assembly to occur from both the interior and exterior.

Material selection within the component and the placement of components in relation to each other has a strong influence upon how a wall containing the EPW component is constructed. If the EPW components are stacked more than two-high, spanning between floors (to increase the length of the convective loop, therefore increasing the transfer of conditioned air to the interior), then the construction technique must accommodate the floor plane, specifically how the EPW unit engages or by-passes the vertical wall. *Also, the weight distribution of the components must be considered.* The critical detail occurs at this point of transition between floors. This design focus resulted in the development of three approaches to treat the wall plane and the EPW components in differing manners. All three alternatives remain grounded in the dialogue of past and present framing techniques. Building upon the practiced of platform framing, diagram 6.1 displays that the wall treatment remains the same, while an in-fill piece spanning between the two components, maintaining the continuous airflow, is introduced.

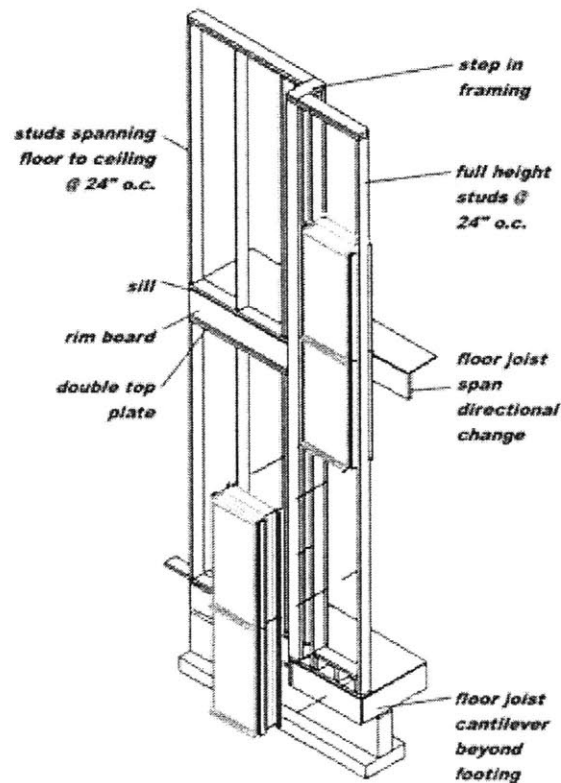


Dia. 6.1 Platform Framing

Dia. 6.2 Balloon Framing

The second alternative reaches back to the traditional method of balloon framing, where the vertical studs span the full height of the wall. The individual joists of the second platform are connected to each individual stud and a series of blocking supports are introduced to allow the transfer of loads at this joint. This approach results in three additional members between studs where EPW components are not used, but allows a gap or small vent cavity to be introduced behind the interior stud plane to promote heat transfer.

The third alternative is a hybrid of the two others. It steps the framing back from the inter-floor spanning components to potentially allow the platform framing of the other walls and platform to pass by the balloon-framed step containing the vertical stack of the EPW components. This approach allows the main load paths to continue in line with the foundation while the floor joists cantilevering beyond the foundation take the load of the EPW step.



Dia. 6.3 Balloon/Platform Step Framing

Each of the three alternatives was explored within both the Sears and the Modern prototype designs. Through the investigations, the second alternative was selected as the most beneficial for the Modern design with the adaptations of the third alternative used in special framing cases, such as the extrusion on the west end of the building (Appendix B). The approach taken to incorporate the ability to position the EPW components within a stacked configuration addressed the issue of joists engaging the plane of the wall. At or near the locations of the desired EPW stacks, the directionality of the framing was altered, so the joists would not be required to engage the balloon framed wall, but instead transferred their load to floor beams. The floor beams would bear upon columns or perimeter platform framed walls, thus allowing gaps to be introduced with greater ease at the EPW stacks. (drawing S-3, appendix B)

The spatial layout of the Sears design, based upon the location of public and private spaces, doesn't lend itself to the introduction of openings at the southern perimeter of second platform, vertically integrating the spaces. In addition, the natural dissection of the floor framing spans, for the second floor platform (refer to Appendix A – S-3), supports the use of platform framing techniques. For example, if five vertical stacks were placed side by side and an area of the second floor platform was removed, then the framing of the floor would take on a completely different character. The ten foot span of the opening in the floor would require at least a tripling of the floor joists (or introduction of a larger beam) on either side of the opening to support the beam carrying the intermediate spans. Also, a column or assembly of at least four vertical studs would be required on either side of the collection of EPW stacks. In addition, if platform framing techniques are used, the spacing of the joists and the vertical studs don't have to be related to each other, freeing the joist spacing to be dictated by other important criteria, based on either weight or location, for the second floor. Based on these considerations, alternatives 1 and 3, still remain options. Either one could be used, but alternative 1 was selected based on the ease of framing and how the decision fits within the intent of the exterior aesthetic.

Inherent within the demonstration is the initial exposure of the range of alternatives that exist for designers and builders for implementing the EPW components within the construction. In addition, each of these alternatives remains in strict adherence to the constraints of the module. Within each of the prototype designs utilizing the EPW components, all of the windows and EPW components fit within the stud spacing to reduce the overall number of large header beams required within the wall plane. The load paths from above remain unaffected and they continue down the stud line, so the header must only accommodate the weight within the stud spacing that is above it. The interlocking of the EPW components also eliminates the need for headers or other pieces between components. The trade-off to these benefits depends upon the EPW type selected for use and the material layer selection. For example, if the EPW1 components (utilizing traditional thermal mass) are selected, the weight of the components themselves will significantly increase, which could have a ripple of effects to the overall structure and neighboring members. Ramifications could include, increasing the height of the foundation wall to the bottom of the EPW stack to allow direct bearing, increasing the overall footing size or increasing the size of the members on either side of the components. However, the extent of this impact should be quantified and weighed against other issues, such as the reduction in operational performance (*minimum of 30%*) that occurs due

to the substitution of light-weight concrete or engineered polymer materials will cause. Also of consideration is the interior aesthetic relating to surface variation, because in reality, the interior surface of the mass isn't required to be flat. This is just one example of how the construction language can direct the exploration.

### ***Flexibility and Adaptability***

The adaptability and flexibility of the EPW components can be defined in numerous ways and provide the opportunity for the components to be introduced into almost any type of design, in any configuration. In addition to the flexibility regarding construction, as demonstrated in the discussion of the three wall-framing alternatives, the components can be located side by side, stacked on top of one another, or spaced apart from each other.

This concept of multiple configurations carries from the scale of groups of components to singular components and on down to the frame of the component. The ability to remove and replace the interior power grid (battery storage), exterior enclosure piece, and take apart the interior portion of the frame to allow service or maintenance to occur on the EPW1 thin-film PV layers, provides an even greater level of flexibility over the life of the building.

When considering the spatial interior, these capabilities of adaptability and flexibility allow the potential for spatial adaptation at the detail and interior design level through the ability to interact with surfaces, cavities or planes within the wall.

### ***Variety***

Varieties of the EPW components within the prototype designs encompass parameters at very different scales. The components can be used on vertical wall surfaces, roof planes, or a combination of both. They can be grouped on their own or combined with other types of openings, such as windows and doors, to shapes that grow from the ground, develop in the middle or step. Each component within the group can be made to appear unique by removing or adding layers, creating the ability for seemingly large surfaces to be broken down by the light that is reflected or transmitted into varying levels of scale. Even at the material level, the capillary size of the translucent insulation material and the thin-film PV color can be altered to enhance the plays on light, which can be viewed from the exterior and dramatically experienced on the interior. Operational variety exists



based upon the relationships that the energy creation and storage can develop with the specific type of energy loads, dictated by climate or by occupant.

### *Harmony*

Harmony is defined as the agreement in action, idea, etc. [39] The ultimate test of the EPW implementation within the prototype designs is how the decisions made at the operational, construction process, and aesthetic levels harmoniously coincide. The theory of the categorical integration developed key principles relating to the harmony of the overall design. Harmony at the operational level is contingent upon the storage and distribution strategies of the EPW. The utilization of a lithium battery (Sadoway) within the component frame eliminates the external space required for battery storage and provides the energy storage in a location that is easily and readily accessible. Combining this local storage with the distribution capabilities of the internal power grid, in the form of the vertical and horizontal closure pieces of the frame, develops the capability to distribute the created energy to other load sources.

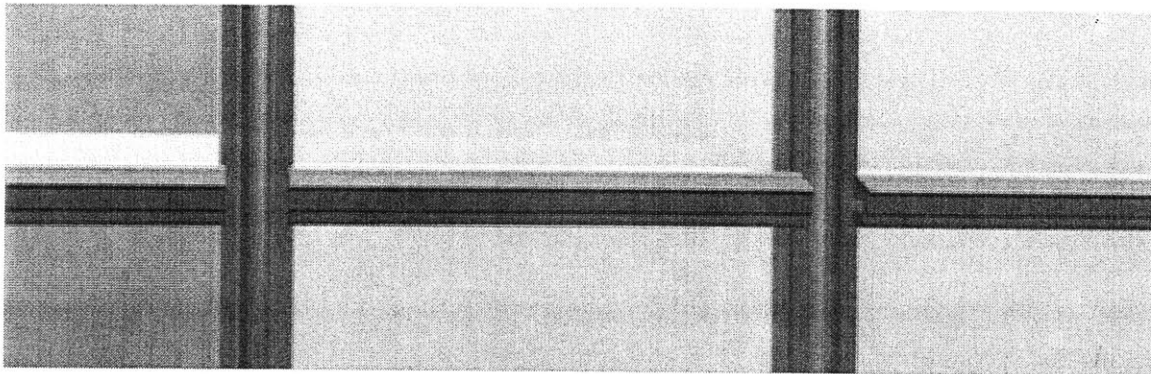


Figure 6.4 – Visual EPW component variety

Construction process harmony develops when the installation of the EPW components within the prototype designs remains within the skill-set of the builders on site. By utilizing the same “fin” method of connection as windows, and the same tools, repetitiveness of tasks involved exists in the installation of the EPW. There is also a relation to the flow of other processes on site occurs increases when the EPW components are engrained more into the overall process, rather than in a few isolated cases.

Aesthetic harmony relies upon proportion, scale and proximity of the EPW components to themselves and to other elements within the design. It involves a marriage of site, climate and building design, through the understanding of long term (weathering and occupant patterns and needs) and short term cycles (daily path of sun and occupant experiences) that relate to the experience of the space and building. The recipe for harmony is different for each context and the variety offered to (competent) designers by the EPW components allows that to be determined for each case by the designer.

The development of harmony within the Sears design proved a difficult task. The traditional lines, form and proportion of the overall design makes it difficult to introduce components of a scale, considered small in this context, within the composition of the facades. Therefore, larger groupings of elements were introduced, to create the appearance of larger punched planes. The daily cycles of shadows cast on the wall by the protrusion will also assist in breaking down the composition. The Modern design allowed a greater ease of scale manipulation, because of the larger southern surface, and the spatial layout. The experiential nature of the interior and exterior spaces can play a larger role in the placement and composition decisions. The ability to vertically integrate the two floors creates strong view corridors and effects of light within the interior spaces.

#### *Effectiveness of operations*

The effectiveness of the operations for each of the component types is different. EPW1 and the thickness of the mass element within, relies on a close relationship of the occupant patterns, regarding use of space and time of day, to its placement to realize the benefits of the heat radiating into the space. Large deep spaces (>25 ft. in depth from the south facade) with large volumes tend to negate the effects of the mass element. However, the ability to stack the components can substantially effect the distribution of air and heat within the room. The height of the stack, the shape of the air gap (depth & width) and the temperature differential of intake and exhaust, shape the velocity and air temperature generated within and carried into the space. The placement of the thin-film PV layer is dependent upon the benefit of the thermal mass being realized. By placing it within the component, it adds to and assists the heat transferred to the mass and introduced into the air within the convective loop in addition to creating electricity.

The “hot plate”(electric resistance heater) layer within EPW2 allows greater flexibility for use based upon occupant patterns, because it can be turned off or on. The power source for it is the thin-film PV layer, which is placed on the exterior surface to receive the most exposure.

The case analysis section provides a greater depth of investigation into these issues of construction language, flexibility and adaptability, harmony and effectiveness, by making and discussing the initial selections of EPW component type and quantities, prototype design type, and climate.

## 6.2 Case Format Result Analysis

Due to the complexity of the comparisons in regards to depth, detail and number of sources relating to the systemic developments, results are presented and discussed for two specific cases. The cases are:

- 1) Sears Design - -Boston, MA (EPW #1) - - Case 1\*
- 2) Modern Design - - Phoenix, AZ (EPW#2) - - Case 6\*

\* Additional information and results on the other scenarios in Appendix C.

The two cases are representative of the results, which were considered key points for this investigation and building blocks for future work.

### 6.2.1 Case 1: EPW1 - Sears Design, Boston, MA

#### 1) Climate

The baseline factors are the 42° latitude and 71° longitude of Boston, which determine that 842 Btu/day ft<sup>2</sup> is the average amount of vertical solar insolation available on the south façade, and the façade is exposed to a maximum of 4.27 sun hrs/day. These given values (Fig. 6.5) provide the

Parameter	Selection
Prototype Design	Sears
Location	Boston, MA
Resources	(1) framing crew of 4
Material (Thermal Mass)	Mat1 (concrete)
EPW type	EPW1 (quantities fig 5.)
Factor: Layer configuration	.65 (between 0 – 1)
PV efficiency	Cycle 1 (5% wall, 12% skylight)
Balance of System Equip	System 1 (battery & inverter)
Electricity Load Type	Low

Figure 6.4.1 Case 1 Parameters

maximum solar resource available (100% exposure) to the hybrid, passive and active EPW#1 component, and the active EPW#2 component. The efficiency loss of the EPW components coupled with the number of clear, partly cloudy, and cloudy days provide initial reductions to this amount.

**2) Prototype Design Configuration**

A total of eighty-nine panels of the four EPW1 types are utilized to reduce the initial and ongoing energy consumption of the 1,840 ft<sup>2</sup>, 19,500 ft<sup>3</sup>, prototype design (Fig. 6.6). However, twenty of these panels are the EPW1c, which does not have the thin-film pv layer within the assembly, which is why the “No. panels” = 69. In addition, twenty-two of the twenty-seven EPW1b panels are located on the east and west faces of the building, and an orientation factor is introduced to account for the reduced capacity of these panels. The maximum amount of EPW components possible, within the non-structural space available, determined by the guidelines mentioned within the methodology, is 123. The

proposed design utilizes 56% of this surface area. The performance could be adjusted by increasing the number of EPW panels located on the roof or the south façade. The R-values for each of the EPW1 types are included to provide context for the upcoming results for the overall envelope performance for heat loss and gain (refer to methodology for description) to allow quick assessment of the impact by changes in material.

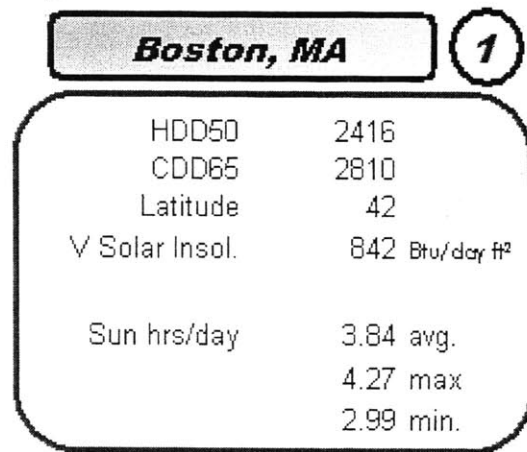


Figure 6.5 Boston Climate

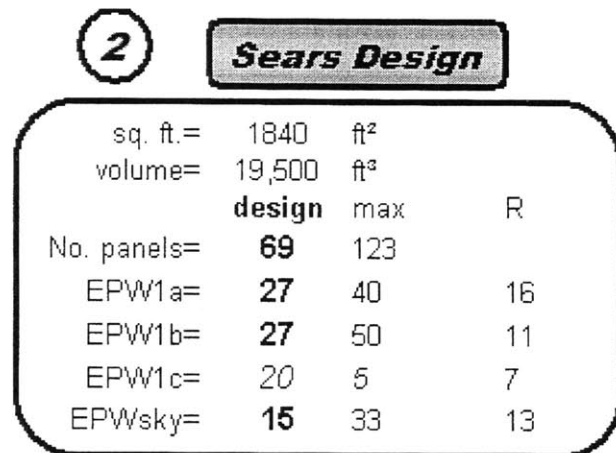


Figure 6.6 Sears Design EPW quantities

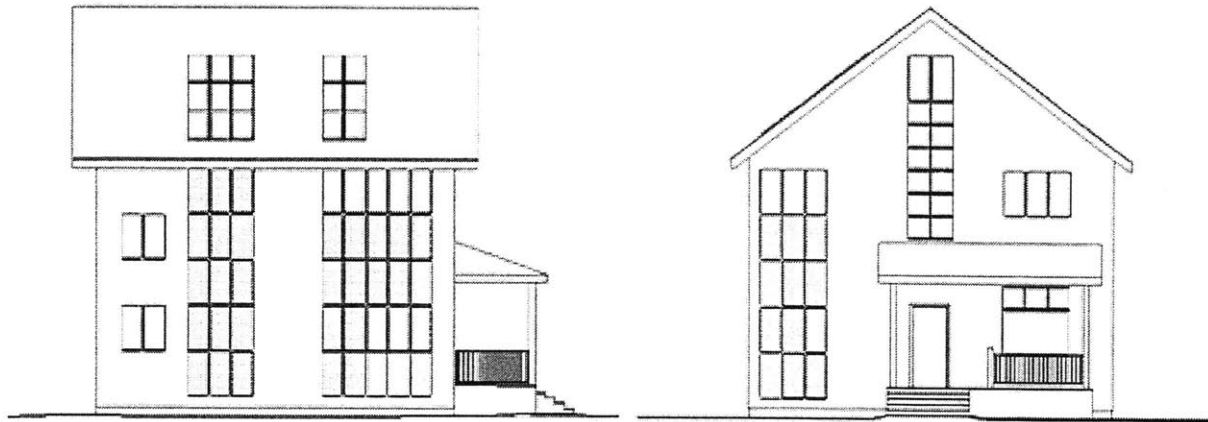


Figure 6.7 Sears Design South & East Elevations

### 3) Aesthetic

The elevations in Figure 6.7 displays one possible configuration for the prototype Sears design. The configuration balances the climatic factors, quantity of required shear wall to maintain structural integrity (since the EPW components are not load bearing) and the aesthetic effect from the exterior and interior.

### 4) Overall Residence Energy Consumption

The overall annual heating (H) and cooling (C) energy consumption for the Sears prototype design combined with the electricity (E) consumption<sup>1</sup> shape the total wattage values listed and displayed within Figure 6.8. Through the ability to reduce the degree designation to 50 vs. the standard 65 (recall Balance Pt. Temp = 49°F), the assumed heating load dominant climate has shifted to a near even balance of heating and cooling and is reduced further by the benefits of the thermal mass.<sup>2</sup>

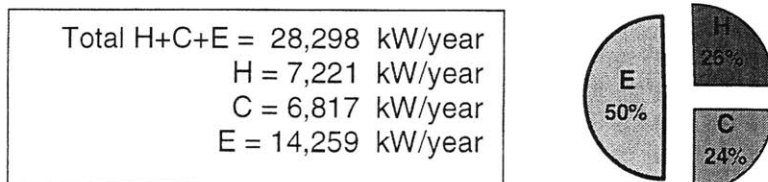


Figure 6.8 Energy requirements for "Sears Design" in Boston, MA.

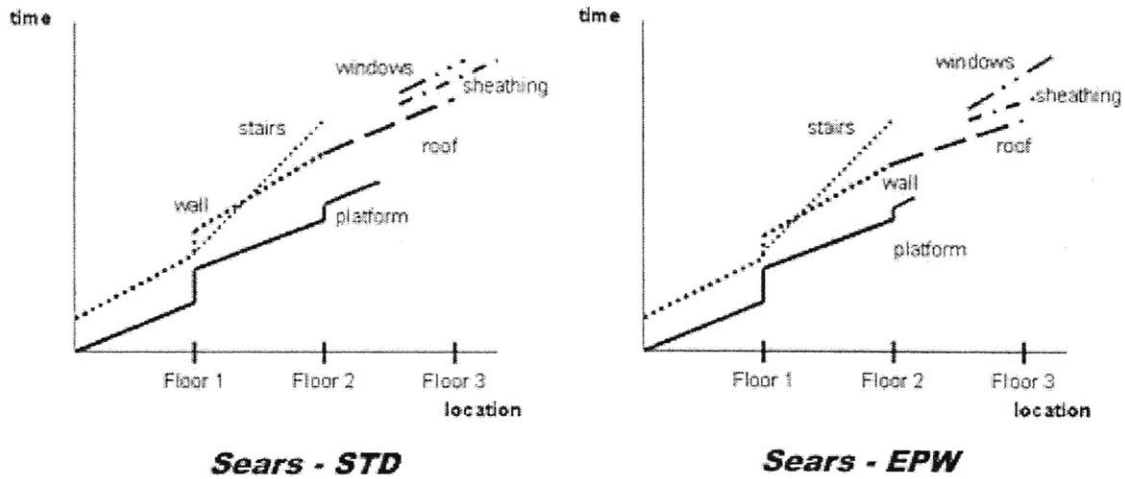


Figure 6.9 Relational Sequencing Diagrams for “Sears-STD” & “Sears-EPW”

Construction type	STD	EPW
No. of total walls	52	49
No. of total members	1,538	1,506
No. of ext. openings	24	106
Additional members of openings	208	209
No. of sheathing	256	242
No. of platform support beams	8	8
No. of platform sections	9	7

Figure 6.10 Member Type Quantity Comparisons

The dominant load is electricity use, accounting for 50% (14,259 kW) of the overall load for the residence. Therefore, emphasis is placed upon the quantity of energy created by the thin-film PV layer, how that energy is stored, and how it can be accessed.

### 5) Construction Process

The number of total walls, total members and additional members due to openings remains nearly the same between the Standard and EPW cases (Fig. 6.10), while the number of exterior openings within EPW construction (106) is substantially larger than the Standard construction (24). A direct result is that the number of plywood sheathing sheets substantially decreases, and if the installation of the EPW components remains in a dialogue similar to the installation of standard windows,

the impact on the construction time could remain consistent and even improve. The preliminary result is that the time for the two construction types will remain in close proximity with the major difference being based upon the equipment needed for placement of the EPW components on the second floor. Correlating this task with other tasks (locating trusses or placement of large members) on site requiring the use of a small crane or other lifting device could reduce the degree of the impact. Another preliminary result is that the safety factors between the two will not differ substantially, due to the fact that placing windows is not a high danger level event, unless it is being done on exterior scaffolding. In addition, the ballooned framing methods used on walls with more than two EPW components stacked atop one other carry a higher risk factor for injury because of the height, weight, susceptibility to wind during erection, and awkwardness of the lift. The benefit of the Sears design using the EPW components should appear in the repetitiveness, ease of installation, and reduced need for horizontal multiple horizontal members of varying scale (headers and sills) within the flow of construction.

The two charts labeled "Sears-STD" and "Sears EPW" (Fig. 6.9) are preliminary results expressing the rate of time to complete, the location, and the relationship of the six main entities within the LWF process (platform, wall, stairs, roof, sheathing and windows). On the "Sears-STD", the process begins with the placement of the first floor platform. At the end or near completion of the platform, the walls begin. At the near completion of the second story platform, the stairs can begin (the starting point refers to preparation of members versus installation). The roof can begin at the point when the exterior bearing walls are in place. The placement of the final sheathing (on the roof and at shear wall overlaps) and windows can begin to be placed once the primary structure of the roof is in place (after initial loading). The steps in the lines, such as for the platform, represent a delay from the start of the second platform, after the completion of the first. The Sears design, with its square footprint, provides a limited staging area, and the main reason for the steps in both the platform and walls. The stairs, with the 90 deg. turn near the bottom (refer to dwgs in Appendix A) have the steepest slope, therefore signalling a substantial amount of time to construct. When viewing the tables side by side, only subtle differences are apparent. Since the EPW1 components really only effect the south face, and parts of the east and west, more than half the home could be constructed in the same manner as the "Standard design". The differences occur at the extent of work needed on the third floor platform (due to more openings for skylights), the sheathing (reduced quantity), and the increased installation time of the EPW components (due to quantity and method).

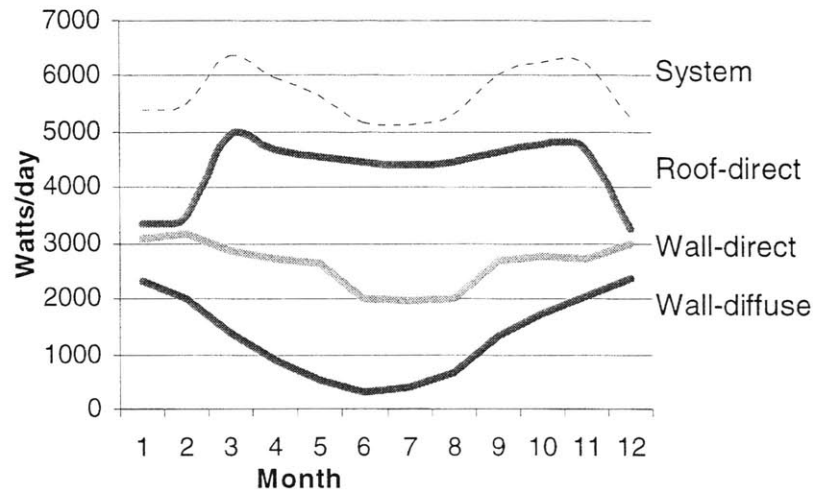


Figure 6.11 EPW System Generation by Thin-film PV layer

### 6) EPW System Creation

The chart titled 'monthly EPW Energy Generation' (Fig. 6.11) displays the amount of watts generated by the quantity of each EPW type listed in section 4 for a typical day within each month for the EPW1 component quantities for the prototype design. EPW1c is not included because the component doesn't incorporate the thin-film PV layer (refer to EPW description). Direct and diffuse sky conditions for the components are displayed to identify the potential of significant reduction in output if prolonged diffuse (cloudy, partly cloudy, rain or snowy) conditions occur. The EPW1 system line (dashed) is composed of the average of the EPW1a & 1b direct and diffuse lines, based upon clear day data [COS], plus the EPW1 roof direct line. The peak system output occurs in the spring (Feb. & March) and fall months (Sept. & Oct.) at about 6,300 Watts/day. This result occurs because a larger percentage of the EPW components within this system are on the vertical surface and the highest solar radiation exposure occurs in the winter months due to the low sun angle.

The effectiveness of the chart could be increased if the monthly appliance usage was also mapped, allowing comparisons to be drawn to it and the overall system creation.

### 7) Passive Solar Layer



Total UxA	425	Btu/h°F
Balance Pt. Temp	49	°F
Building Load Coeff. (BLC)	9159	<b>Btu/DD°F</b>
Load Collector Ratio (LCR)	42	<b>Btu/DD*ft</b>
Solar Savings Fraction (SSF)	19	no units
Solar Benefit	1,968	kW
Heating Benefit over "Std-Construction"	27%	

**7** **Case 1**

Figure 6.12 Case 1 SLR Method Results

The results to this point reflect the role of the active solar layer of the EPW1. To capture the impacts of the passive layer, first return to the climate givens. The global position (longitude and latitude), an elevation of 15 ft, and a balance point temperature of 49°F (result of case 1 section), determine the values of the heating and cooling degree days to be HDD50=2416 and CDD50=2810. However, the argument is made that the CDD, could be decreased to CDD65= 695 DD°F, due to the other buffer elements (ventilation and thermal mass) within the design. The result of the envelope thermal performance, based on the quantity and orientation of the EPW1 types, combined with the other apertures (double-glazed windows and wood doors), roof and floor composition is an initial heat load reduction of 1,968 kW, which converts to a 27% benefit annually. This amount is a saving as compared to a residence of the same size and specifics, not utilizing passive solar strategies. The key factors of this result are embedded within the BLC, LCR, and SSF values (Chpt. 5 Methodology). The Building Load Coefficient (BLC) is a measure of the overall building losses (UxA value), except for the south side. The Load Collector Ratio (LCR) is simply the BLC/Area of the Solar Collector (example below).

$$\begin{array}{rcl}
 \text{BLC /} & \text{Asolar} & \text{.} \\
 9159 & 216 & = \\
 \text{Btu/DD}^\circ\text{F} & \text{1/ft}^2 & \text{LCR} \\
 & & \text{42} \\
 & & \text{Btu/DD}^\circ\text{F} \cdot \text{ft}^2
 \end{array}$$

From the LCR the Solar Savings Fraction (a non-unit number ranging from 0 to 100) can be derived by inputting the LCR amount into a table with the LCR on one axis and the Solar collector type (direct gain, trombe wall, etc.) on the other. (Balcomb created these tables in the 1970's through an extensive sensitivity analysis study, and the decision was made that work was not needed to be repeated. Therefore, the capabilities of the results were inputted into the "spreadsheet tool".) The benefit of this method is that one can track the effects of changes in the solar collector quantity (thermal mass element of the EPW), the materials of the solar collector, and the overall envelope composition.

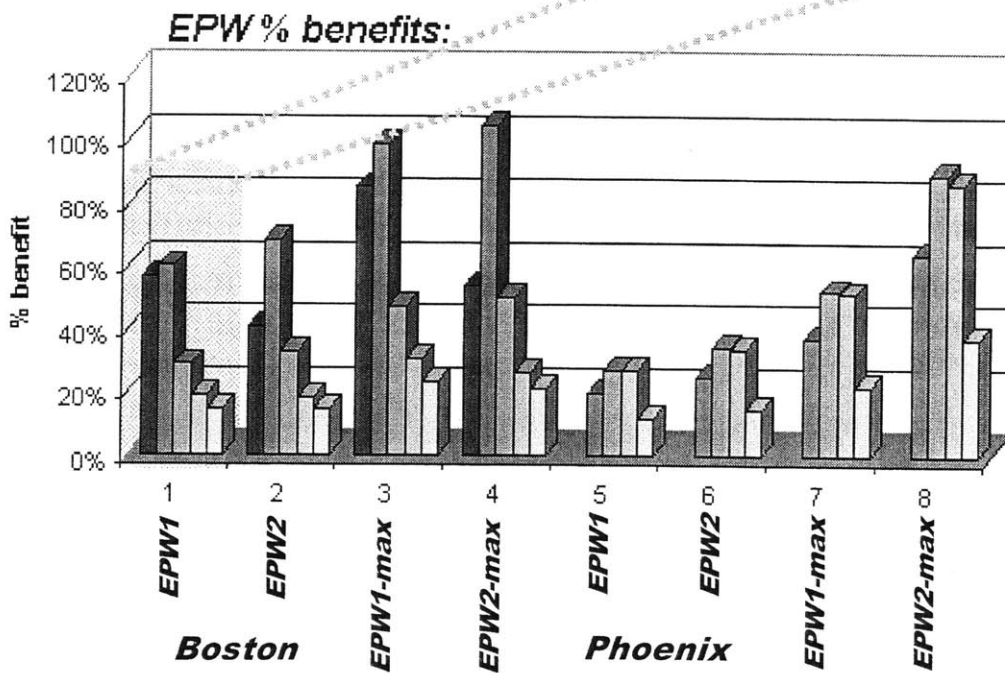
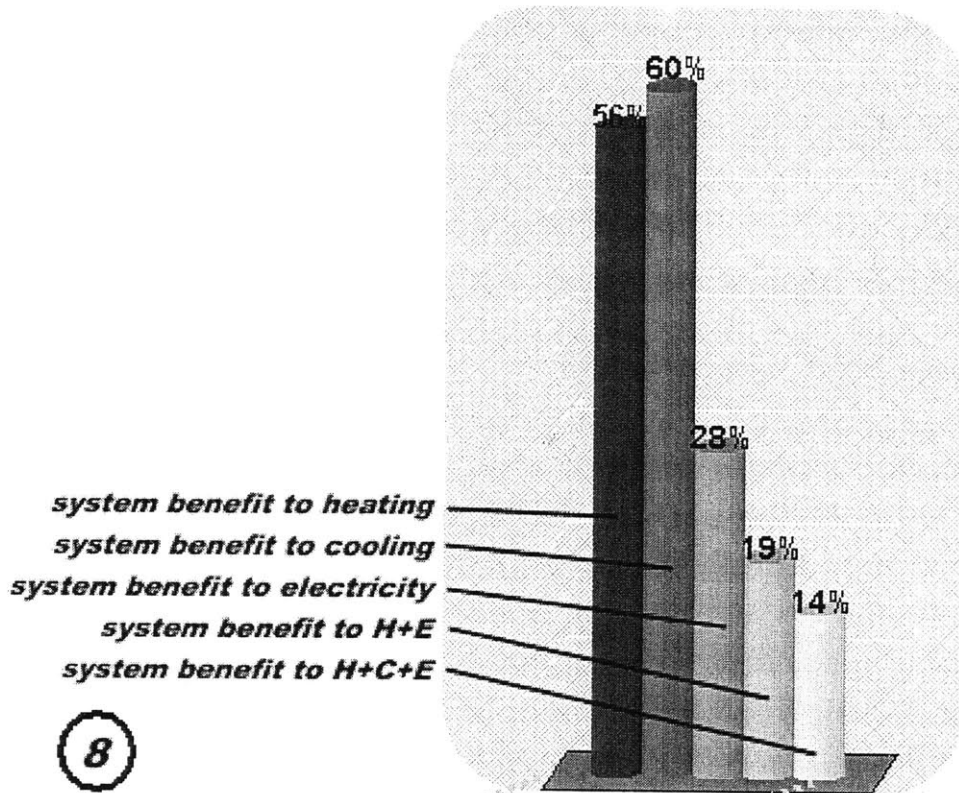
### **8) EPW % Benefits**

The two charts to the right (Fig. 6.13) display the EPW % Benefits for each of five categories. The categories are the heating load, cooling load, electricity load, heating + electricity (H+E), and the total residence load (H+C+E). The chart above is a "blow up" version of the one labeled "1" in the lower chart. The lower chart identifies the impact of the same criteria for the EPW1 Sears Design in Boston for seven other cases of different EPW types, design quantities, and location (listed below). By explicitly calling out the percentage benefit of each separately, possibilities for matching the energy created to the load type most suitable can be identified for further investigation. In addition, the ability to visualize the results of case 1 within the context of the results of the other cases can stimulate further ideas and provide more information to trade-off decisions, such as using EPW1 or EPW2 components within the design, increasing the percentage benefit if the number of EPW panels is increased towards the maximum, and implications for the what design of a residence in Phoenix.

For case 1, the EPW1 system has the largest impact upon the cooling load (60%) and the heating load (56%), while the impact upon the total load is 14%. Since the overall impact is fairly low, a singular focus, on the heating/cooling load, might prove more beneficial. Plus, the home is either heating or cooling (for a majority of the time), so both of the percentage benefits could be captured. Flexibility across the consumption load types requires electricity to flow through multiple pieces of equipment, each reducing the useable quantity and affecting the type and size of battery for storage. Therefore, one to one relationships between source and load result in more useable electricity, increasing the benefit. However, the impacts of the thermal mass and thin-film PV layers will need to be investigated further. Of interest is the effect of the thermal mass heat storage in the

Figure 6.13 EPW % Benefits for Sears Design

**Cycle 1**



winter and how that storage, coupled with the convective loop, can reduce the heating load initially. Then the quantity and method of storage and distribution of the thin-film PV to the heating or cooling equipment would be required to also be tracked as well.

The benefits increase to the point of 85% for the heating load and 98% for the cooling load, as the number of EPW panels used within the design reaches the maximum. Note that the impact of EPW2 on the heating load at the EPW2 maximum amount is sufficiently lower (54%). This signifies the role of the thermal mass layer in providing benefit to the heating load.

### 9) *Future Development Impacts*

The results presented express the current state of the technology for the thin-film PV layer (**cycle 1, 5% wall, 12% skylight**). The two charts (Fig. 6.14 & Fig. 6.15), assess the potential benefits of this specific EPW system, for this prototype design, in each of four cycles where the efficiency percentage increases for each component type by 5% (listed in Table 5.28) on the overall electricity load for the residence. The EPW1 system “design quantities” for the Sears design is represented by the four columns on the left, while the EPW1 system “maximum quantities” are the four columns on the right. The chart above is the percentage benefit in comparison to the electricity load, while the chart below is the percentage benefit to the total load (H+C+E).

Currently (cycle 1), the EPW1 system is providing a 28% benefit to the electricity load and a 14% benefit to the total load. At cycle 2 (10% wall, 17% skylight) the benefit to the electricity for the design load increases by 8%, while the benefit to the total load increases by 4%. Since, the benefits for the design system are low, alternative configurations, between the design load and the maximum load could be explored. The maximum benefit at cycle 4 (20%, 27%) is 97% for the electricity load increasing at a rate of just under 20% per cycle step, while the total load benefit reaches a high of 47%, at approximately a 10% step.

The conclusions to be drawn are that for the EPW1 system, technological improvements alone will not significantly increase the benefits at the current energy consumption rates. Other alternatives would need to be explored, such as increasing the thermal mass surface area on other surfaces (walls or floors) or exploring methods to reduce the overall load, initially and over time.

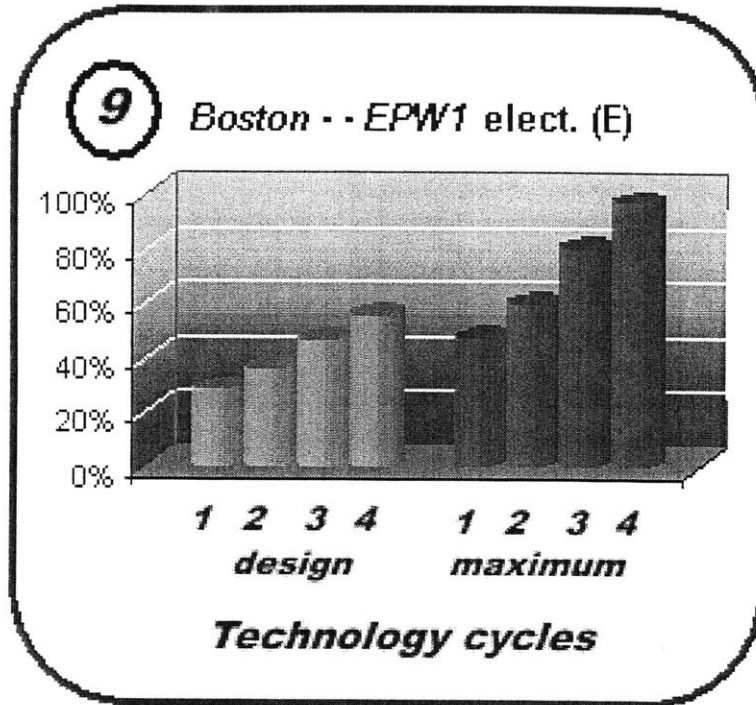


Figure 6.14 Percentage Improvements in PV performance for Electricity Loads

*Boston - - EPW1 Total Load (H+C+E)*

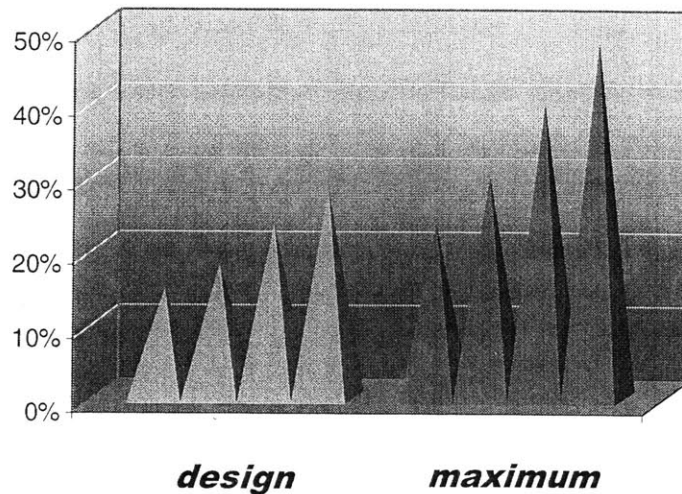


Figure 6.15 Percentage Improvements in PV performance for Total Loads



Parameter	Selection
Prototype Design	Modern
Location	Phoenix, AZ
Resources	(2) framing crews of 4
Material (Thermal Mass)	none
EPW type	EPW2
Factor: Layer configuration	.9 (between 0 – 1)
PV efficiency	Cycle 1 (12% wall, 12% skylight)
Balance of System Equip	System 1 (battery & inverter)
Electricity Load Type	Low

Figure 6.16 Case 6 Selections

<b>Phoenix, AZ</b>		<b>1</b>
HDD50/65(DD-F°)	90	1382
CDD50/65 (DD-F°)	7830	3647
Latitude	33	
∇ Solar Insol.	1310	Btu/day ft <sup>2</sup>
Sun hrs/day	6.58 avg.	
	7.13 max	
	5.78 min.	

Figure 6.17 Climate Highlights

### 6.2.2 Case6: EPW2 - Modern Design, Phoenix, AZ

#### 1) Climate (Fig. 6.17)

The solar exposure of the 33° N Latitude, 112° W Longitude, of Phoenix, yields 1310 Btu/day ft<sup>2</sup> of vertical solar insolation, and a period of time ranging from 5.78 hours as a minimum, and 7.13 hours of sun as a maximum. These conditions present the most ideal setting for the energy generation by the EPW2 components. However, the ideal conditions are balanced by the high number of cooling degree days (CDD65 = 3647), which relates to the average daily temperature, and translates into a large cooling load for the residence.

		<b>Modern Design</b>	
sq. ft.=	2250	ft <sup>2</sup>	
volume=	20,940	ft <sup>3</sup>	
	<b>design</b>	max	R
No. panels=	<b>100</b>	238	
EPW2=	<b>76</b>	136	13
EPW2b=	18	24	
EPWsky=	<b>24</b>	78	13

Figure 6.18 Modern Design Specifics

2) *Modern Design*

The Modern design utilizes nearly double the amount of EPW panels (100 - excluding EPW2b due to orientation) as the Sears Design (69), but is still just under fifty percent of the maximum amount of potential EPW surface area available (Fig. 6.18). As the diagram displays, both of the EPW2a and EPW2sky have substantial room for the number of panels to increase before approaching the maximum. The R-values are expressed to compare with the overall envelope performance in section 7. The square footage of the re-design has increased to 2,250 ft. <sup>2</sup>, with a volume of 20,940 ft. <sup>3</sup>.

3) *Aesthetic*

The south and west elevations are shown for the Modern design (Fig. 6.19). The different shading for the panels represents a difference in type. The darker shades of panels are those EPW2 components with the “hot plate” electric resistant heat panels, the clear panels of the same size are the EPW2b panels with only the thin-film pv and clear insulation, and the other clear openings shown are the windows. The initial cycle through the elevation expresses the variety of composition possible, even within the three window shapes shown. However, further refinement of the



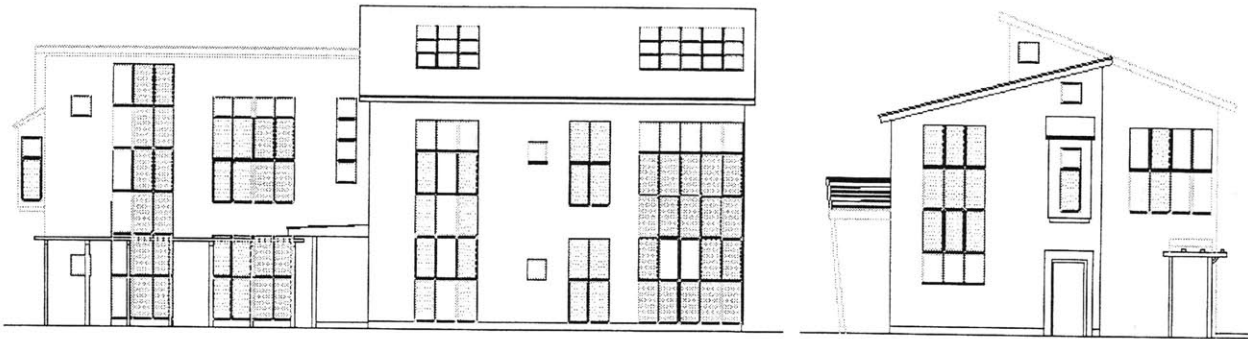


Figure 6.19 Modern Design - South and West Elevations

elevations would serve to bring more harmony to the overall composition. The east elevation is more successful in composition, currently, than the south elevation. However, the interesting aspect is how the differing opacities would express color on the exterior, and the impact on the spatial experience on the interior. As one enters into the front door (refer to plans in Appendix B), they are presented, on their right, with a two-story wall of varying shades of light, some glowing in a tint of blue, others allowing direct sunlight to shape patterns on the neighboring wall, and others opaque.

#### 4 energy consumption

total =	38,128	kW/yr
H	464	kW/yr
C	23,203	kW/yr
E	14,460	kW/yr

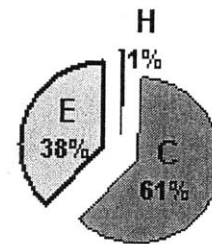
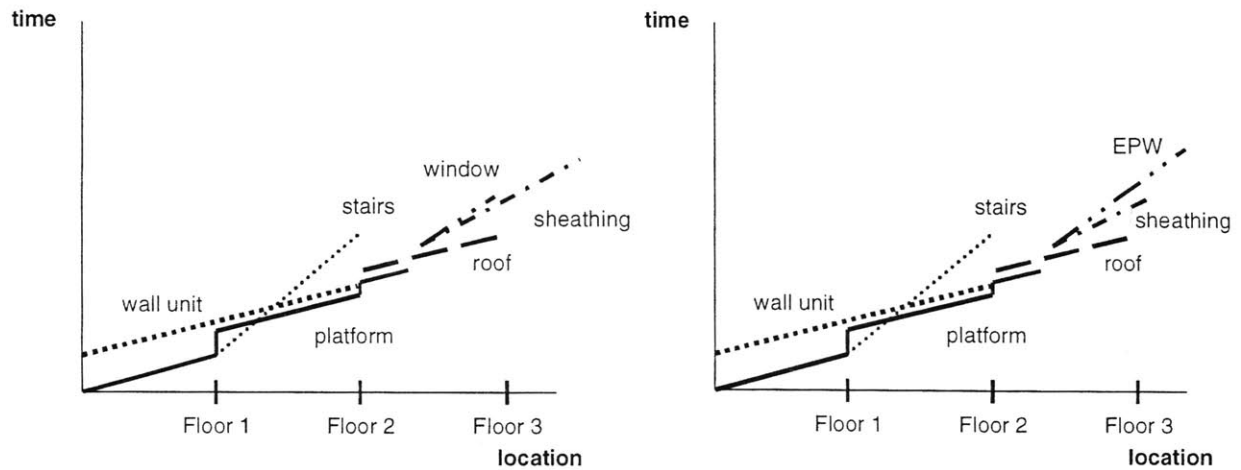


Figure 6.20 Energy Consumption of Modern Design in Phoenix

#### 4) Energy Consumption

The total energy consumption (Fig. 6.20) for the residence is 38,128 kW/year, which is a very high number. The heating load is basically non-existent, while the cooling load of 23,203 kW/year provides 61% of the load. The electricity load provides the remaining 14,460 kW/year of the load. Further investigations will be required to understand and reduce the overall cooling load. These values provide the base from which the percentage benefits are derived from.



**Modern Design - STD**

**Modern Design - EPW**

Figure 6.21 Sequential Process diagrams for Modern-Std & Modern-EPW

Modern Design Construction type	STD	EPW
No. of total walls	60	59
No. of total members	1,970	1,193
No. of ext. openings	57	106
Additional members of openings	203	206
No. of sheathing	332	330
No. of platform support beams	17	17
No. of platform sections	15	16

Table 6.22 Modern Design Quantity Take-offs

5) Construction Process

The quantities listed in Table 6.22, representing quantity totals functioning as inputs to the dynamic process model for the standard and EPW design cases, demonstrate that even though the approaches to framing are different (refer to framing plans in appendix B), the quantities remain fairly similar. The main difference occurs in the number of total members, specifically that the member spacing for the standard is sixteen inches on center and the member spacing for the EPW is twenty-four inches on center. In addition the quantity of openings is nearly double for the EPW design, due to the component use.

The relational sequence diagrams (Fig. 6.21) display a nearly straight, sloping line representing the walls. This feature combined with the slight reduction in the height of the step of the platform are directly related to the building form chosen for the Modern Design. The footprint of the building (Appendix B), naturally separates into two separate staging platforms, which could be utilized by two crews in unison. For example, both crews could begin work on the platform in both areas, and then on the walls on the public (east platform) area. Once those walls are complete, the first crew can begin work on the second floor platform, while the second crew begins constructing the walls in the private (west platform) area. This staggered approach could be utilized all the way through the process into the placement of the EPW components. Where the first crew that had finished placing the roof trusses and purlins could begin work on the installation of the EPW components, while the second crew completed and connected the roof of the two sections and installed the final roof sheathing. The example highlights the other two differing features between the diagrams, relating to the differing time and quantities of sheathing and windows or EPW units.

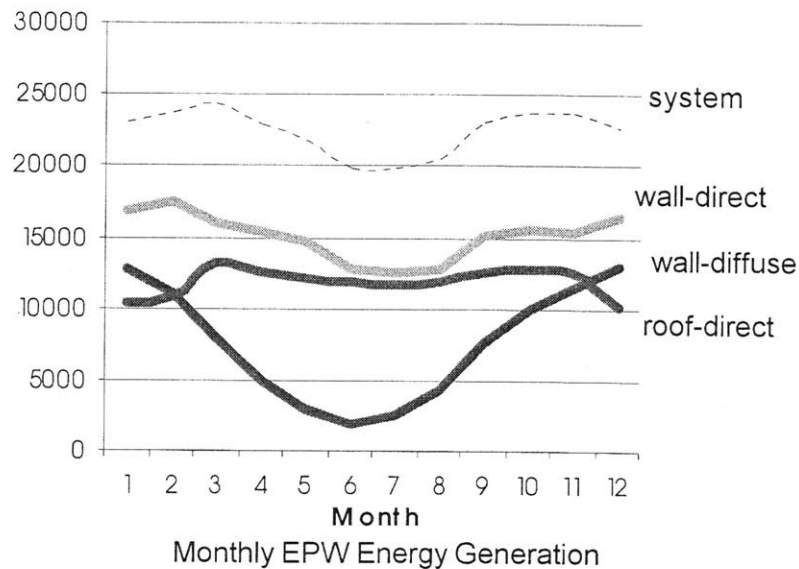


Fig. 6.23

#### 6) EPW System Creation

The Monthly EPW Energy Generation chart (Fig. 6.23) displays that at peak EPW2 system generation, around February and March, the system can generate nearly 25,000 Watts/per day. Other characteristics display the drop in the wall units creation over the summer months. However, this is somewhat deceiving, because the Phoenix climate is known for its high percentage of clear

days, so the diffuse line has little impact upon the overall system capacity. The output could be increased significantly by increasing the number of skylights. Thus, pushing the “roof-direct” curve further upward and also levelling out the sytem curve.

<b>7</b>	<b>Case 1</b>		
Total UxA	592	Btu/h°F	
Balance Pt. Temp	36	°F	
BLC	9472	Btu/DD°F	
LCR	na		
SSF	<b>na</b>		
Solar Benefit	na		

Fig. 6.24 - Passive Solar Layer Influence

7) Passive Solar Layer

The results of this area are shown (Fig. 6.25) to highlight the characteristics of the envelope, plus to show that the EPW2 system does not perform in the same manner as the EPW1. The lack of thermal mass within the components eliminates the relevance of the LCR, SSF and Solar Benefit quantities. However, the usefulness of the numbers presented are in a side by side comparison with the same case design within the Sears Design. This comparison introduces the significant difference between the Total UxA values, which describe the overall U-value of all Area surfaces exposed the exterior environment, for the two design types. Factors such as this are presented within the comparative results section.

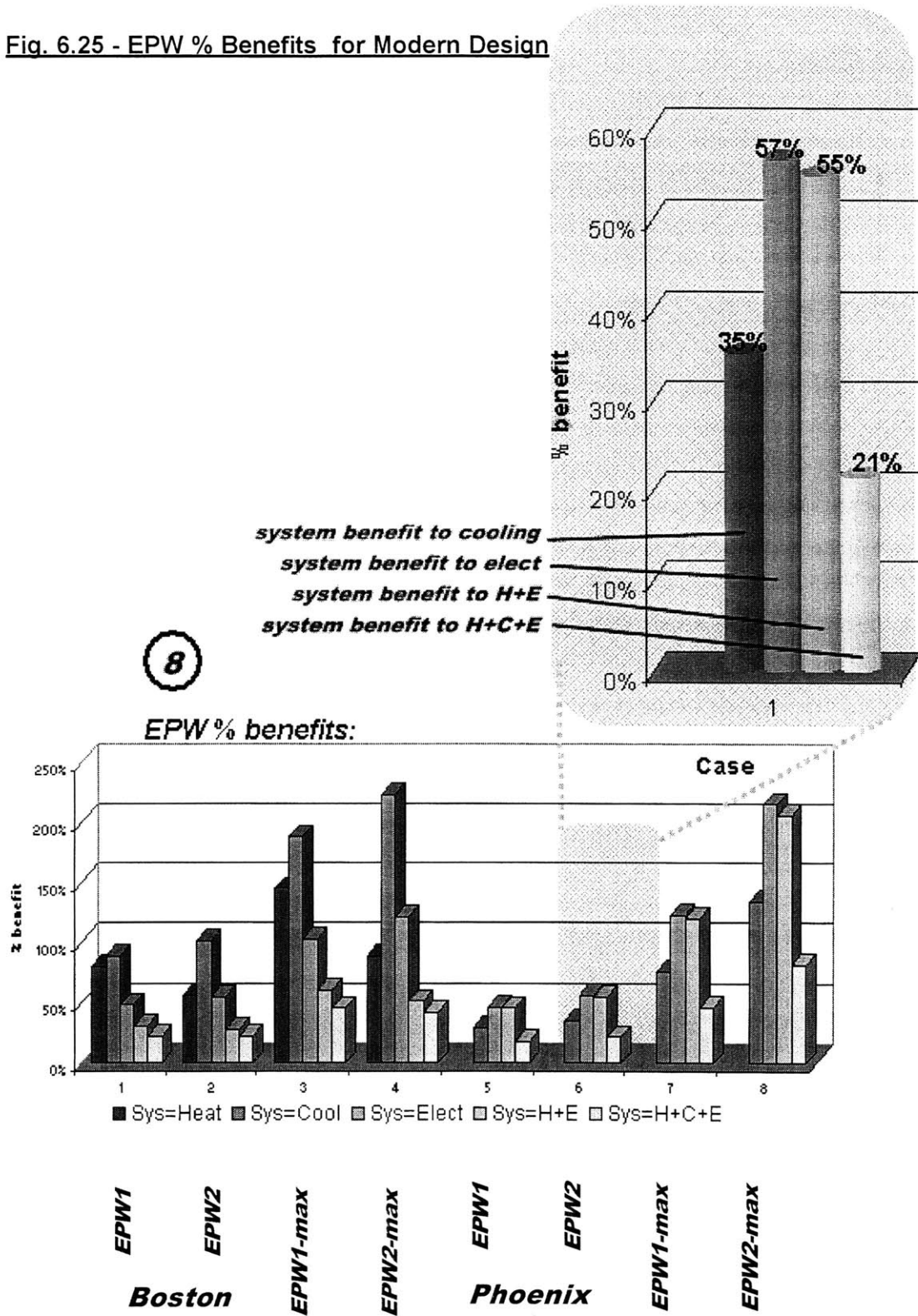
### 8) EPW % Benefits

The results specific to case 6 (Fig. 6.25), displayed in the larger, highlighted chart, express a different approach than was proposed on the first case. The larger benefits created by the system are on the electrical load (57%), versus the cooling loading (36%), and the total load (21%). The system benefit to H+E is misleading, because of the fact that there is little heating load.

This result is in part to the significant cooling load required, even when considering the CDD65 vs. CDD50 degree day values. The building form and spatial layout of the Modern Design was designed considering the issues of cross and stack ventilation, however the capabilities to quantify those amounts are currently outside the scope of this document. Another aspect of this issue is the convective flow within the EPW2 component and the ability to quantify the “flushing effect” possible within the stacked assembly to the exterior at night. The framework was established to complete the computational fluid dynamic (CFD) assessment, but these calculations are beyond the scope of this research. However, that stated, the system seems better suited or enhanced by a direct relationship to the electricity load (appliances), to capture a greater benefit. The EPW2 system could be matched with appliances, such as the refrigerator or others that are more constant in use. The recommendation is based on the assumption that a greater benefit is experienced across the systems of the home, if certain load types or elements of that load can be made autonomous. The load type or element of that load becomes autonomous when the EPW2 system can account for 100% of that load, plus the amount of tolerance needed if the thin-film PV is not functioning at capacity for periods of time due to weather conditions.

Reviewing the results of the other cases displays the strong potential for the EPW2 component, if the recycling of the design was to occur and increase the quantity of panels to a number closer to the maximum. The EPW2 maximum for Phoenix, displays that 216% of the electrical load could be created. The excess 116% could be used to supply other loads within the residence or given back to the grid. The quantity generated is still not at the point of satisfying the total load (81%). The Boston side (cases 1-4) also express that the cooling or heating loads could be provided completely (cases 3&4).

Fig. 6.25 - EPW % Benefits for Modern Design



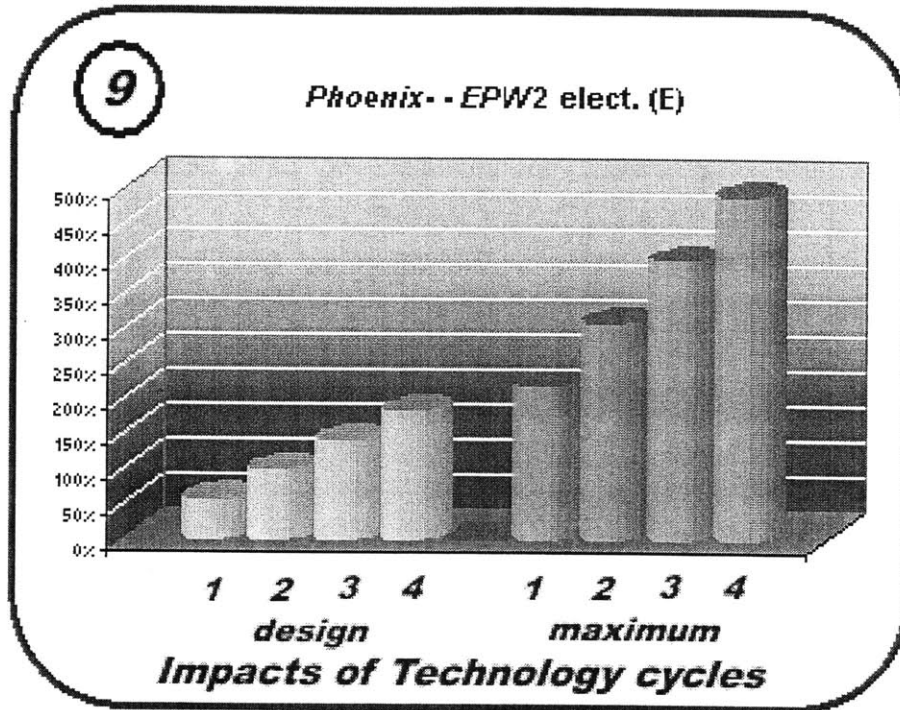


Fig. 6.26 Percentage Improvements in PV performance for Electrical Loads

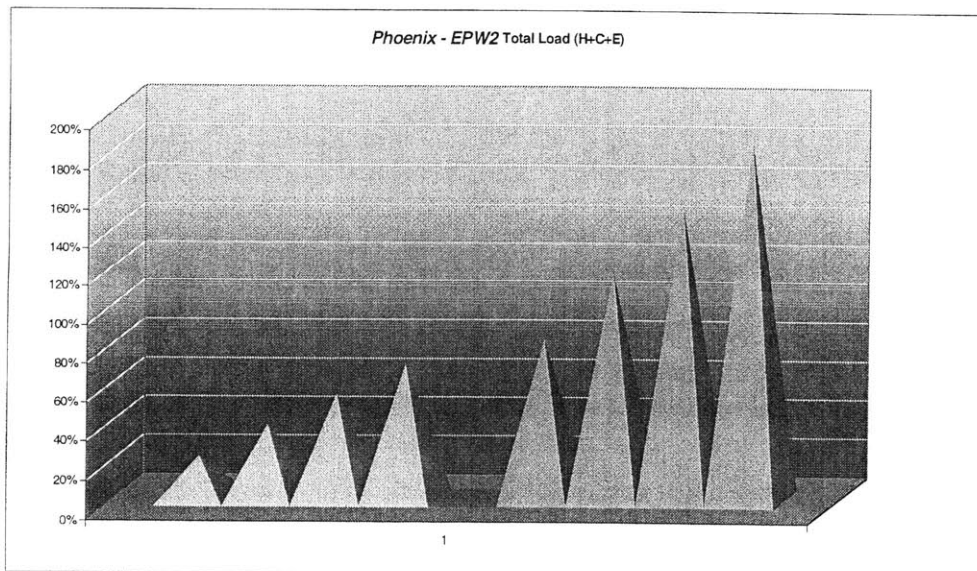


Fig. 6.27 Percentage Improvements in PV performance for Electrical Loads

### 9) *Technology Impacts*

Building upon the points from section 8, as one looks forward when thin-film PV efficiencies begin to increase, the concept of a home powering itself, become possible (Fig. 6.26 & 6.27). At cycle 2 (10% wall, 17% skylight) the EPW2 design covers 98% of the electrical load. At the maximum amount for this cycle, 306% is covered. The point where 100% of the total load is compensated for is between the cycle 2, design amount (37%) and the maximum (115%). or the cycle 3 (15%, 22%) design (53%) and maximum (149%) amount. The difference being the number of EPW panels within each cycle that would be required to achieve that level. The cycle 4 (20% wall, 27% skylight) maximum value of 183%, directs thought towards the potential of sharing or distributing among a community versus just a single residence.



### 6.3 Comparative Results

The sixteen cases within the tables presented in Section 8, EPW % Benefits, for the analysis of each of the two cases, provide the ability to further analyze the relationships of four main categories. The Prototype Design type (Sears, Modern), climate (Boston, Phoenix), EPW component type (EPW1, EPW2) and the quantity of each of the EPW component types (range between design and maximum) are the specific categories. For the category of component type and quantity, it is important to remember that the quantities for the “design” and “maximum” for the EPW1 & EPW2 component type are composed of the three EPW1 types (EPW1a, 1b, &1c), the two EPW2 types (EPW2a, 2b) and the EPW skylights. The quantities presented are representative of the actual diversity within the design, rather than the optimal number of components and the EPW type that would provide the optimal performance.

Points of reference are:

- Prototype Design Drawings for the “Sears” & “Modern” prototype designs are in Appendix A & B:
- Quantities for the “design” & “maximum” loads for each prototype design are located in the last two figures of Chapter 5.0 Methodology.
- EPW1 & EPW2 configurations in Chapter 4.0 EPW description
- Total energy consumption values for the prototype designs are located in Part II, Section 4 – Energy Consumption within this chapter.

*Context for results:*

Two things are to be considered when reviewing this information. First, the sixteen cases fall under the umbrella of Cycle 1, equating to the thin-film PV efficiencies of 5% for EPW1 wall components, and 12% for EPW1sky, EPW2 wall and EPW2 sky. Second, even though EPW panels are shown on the elevations on the east and west sides of the building, their potential benefits are not included. As more information is known, and a more relevant/valid factor can be inputted into the “spreadsheet tool”, these panels are only impacting the evaluation of the envelope due to their thermal capacity (R-value). Only the EPW panels on the south side of the designs are considered for the overall generation of the EPW systems.

*Impact of Climate*

The climate and its relationship to the specific prototype design shapes the overall visual character and the relationships expressed among the eight Boston cases (left side, case 1-4 on each chart) and the eight Phoenix cases (right side, case 5-8 on each chart). The climate of Phoenix results in a large cooling load (61% of total load), that has the overriding effect of reducing the percentage benefit for each category within the cases. It reduces the energy consumption equation to two variables (cooling + electricity) versus the three (heating + cooling + electricity) for Boston. For this reason, only four categories are represented, versus the five for the Boston climate. The energy loads in Boston shift the dominant load to the electrical load, while the heating and cooling nearly split the remaining fifty-percent in two equal parts, due to the envelope design. A comparison between the two climates demonstrates that the Sears and Modern designs in Boston require only 81% (+/- 3%) of the energy that is required for the same designs in Phoenix.

*Overall Trends*

The graphs for the eight cases, relating to the Sears Design, display that the largest benefits can be made on the heating and cooling loads in Boston, and on the electricity loads in Phoenix. The categorical impacts remain similar in the eight cases for the Modern Design, however they are more substantial and consistently higher for every case when compared to the Sears Designs. The range is from an 8% improvement in the benefit to the overall load for the ModernEPW2 in Boston, to over a 120% improvement in the benefit to the electricity load for the ModernEPW2-max in Phoenix. These results should not be surprising, since the Modern design was created with the EPW and the solar exposure it requires for performance in mind. However, the underlying point is that the design decisions regarding the building form, orientation and quantities of EPW components did make a significant difference in the results obtained. The slenderness of the building form for the modern design creates a larger percentage of south-facing surface area raises the "maximum" of 95 EPW wall components and 33 EPW skylights for the "Sears" to 136 EPW wall panels and 78 EPW skylights for the "Modern". The trade-off of this building form is a greater surface area of the envelope is exposed to the environment, increasing the opportunity for heat loss, or gain. However, the results demonstrate the benefit of the use of the EPW components significantly outweighs those envelope losses, and in addition the "Modern" design has the adaptability to introduce buffers, such as storage space or service equipment, to reduce the effects.

*Sears Design*

In Boston the largest impact of the benefits is on the cooling load for both the design quantities of each EPW type (listed as EPW1 & EPW2 on chart) at around 60%, while the maximum quantities allow the benefit to reach over 100% for the EPW2. The initial target load, the heating load, shows over 50% benefit for EPW1, while around 35% for EPW2. The differential increases at the maximum values to over 80% benefit for EPW1, and 50% for EPW2. This differential is due to the ability of the thermal mass to capture the heat within the system and use it for a positive effect, through its natural radiation to the interior. The overall energy load is at the lowest point for the EPW2 design load at 14%, while the EPW1-max has the potential to obtain a 20% benefit. The case in this group expressing the largest potential is the EPW1-max (case 3), where both the benefits to the heating and cooling are above 80%, with the cooling over 90%.

For Phoenix the overall shape of the case grouping is significantly different, and the progression from case to case increases the benefits to each category. This tendency is created because the EPW2 component outperforms the EPW1 component, and is the reason the largest benefits are displayed for the electrical loads. The EPW2 system goes with the strength of the climate, the solar exposure, by placing the thin-film PV layer in the front of the assembly. The results indicate this point due to the lowest benefits for the electrical loads occurring in the EPW1 (22%) and EPW1-max (45%) cases versus the EPW2 (30%) and the EPW2-max (83%) cases. The EPW2-max benefit is nearly double the amount for the EPW1-max, and shows that over 50% improvement in the electrical load benefit could be realized by increasing the amount of EPW2 panels on the Sears house above the design load. The effects on the dominant cooling load are lower, but due to the size of the load, substantial. For the EPW2 design case, a 20% benefit exists with the potential to increase the benefit to 60%. The impact of these two areas on the overall energy load indicates a range of benefit from 15% to 35%. The focus demonstrates the selection of EPW2 over EPW1. However, that balance could alter if the potential of the convective loop combined with the effects of the thermal mass could be brought into the equation. For example, this combination could prove effective in Phoenix if viewed as a "heat flushing" mechanism versus a heat capture. Preliminary calculations of the "flush effect" indicate that a larger percentage of mass surface area, either in the form of EPW panels or other surfaces, are required to be effective. The conclusion for this group is that before any loads can be completely accounted for one or a combination of three factors needs to happen. The efficiency of the thin-film PV layer must increase, complementary design strategies must be integrated, or the energy loads must be reduced.

*Modern Design*

For the Boston cases the target heating load has increased to over 75% for EPW1, with the potential to reach 140%, and also increased for EPW2 to 50% with the potential of 75% improvement. The level of benefit for the cooling load of the EPW1 and EPW2 has increased to 90%, (30% more than the Boston cases) with the maximum for the EPW2-max case reaching over 200%. The benefits to the overall loads are at their lowest for the EPW2 20%, and their highest for the EPW1-max (case 3), at 45%. The benefits at the “design quantities” are 8-10% higher than the EPW1 & EPW2 for the Sears design, while the “maximum quantities” are more than double. As with the Sears Design, the EPW1 panels provide the greatest impact, and express the substantial savings that can occur within the proposed Modern design on the heating (75%) and cooling loads (80%), and that these benefits can be significantly increased as the number of panels within the design increases.

The Phoenix cases for the Modern design provide the most beneficial setting for the benefits of the EPW2 use to be realized. Although the stepped increases don't appear as significant when displayed next to the Boston cases, it doesn't mean they are not there. The proposed modern design for EPW1 provides a 50% benefit to the electrical load, with the potential to increase to over 200% for the maximum. The range of the EPW1 is at 40% for the design and 110% for the maximum. The impacts on the cooling load stay lower for the EPW1 (20%) reaching to 60% for EPW1-max, but increase for the EPW2 to 25% for the design, and 120% for the maximum. The overall load reaches a highpoint for the EPW2-max at 70% and just over 20% for the EPW2. This result demonstrates what was known. The EPW components at current technological levels and as a stand-alone system could not provide 100% of the energy required for either of the prototype designs. However, the results of the EPW1-max (case 7) demonstrate that if the EPW component quantity was increased above the proposed design quantity by a reasonable amount the electricity load for the residence could be completely satisfied.

*EPW1 to EPW2*

Through the discussion of the cases the matching of the climate to the operational characteristics of the EPW1 & EPW2 are better demonstrated. The cold climate of Boston has a significant use for the heat generated within the system. Therefore EPW1 captures that heat in the form of the thermal mass layer and provides it to the interior spaces. The impact of the thermal mass layer within the component is demonstrated by the percentage benefit to the heating load within the cases in Boston for both the “Sears” and “Modern” designs. For the “Sears” design, a difference of nearly 20% in heat load reduction exists between the case using the EPW1 and the one using EPW2. The same comparison made for the Modern design is a difference of around 25%.

Although the EPW2 increases the benefit for the cooling load in case 2 of each, it does not accomplish this naturally. The system benefits show that the EPW2 selection over the EPW1 increases the benefit slightly, but the overall benefit is basically the same. The conclusion drawn is that the EPW2 system creates more energy overall, in the form of electricity, versus the heat + electricity of the EPW1, but the thermal performance of the component itself (due to the difference in R-value) within the envelope negates this increase in the overall load. This heat load reduction becomes less of an issue in the hot climate of Phoenix reaches a point where even the integration of ventilation strategies within the design can't reach the comfort level necessary for the space. Therefore, the emphasis is placed upon the electricity required to power the cooling units for the space.

This difference in electrical load impacts is expressed within the cases (5&6) of the Sears Design in Phoenix. The 8-10% of the additional energy created by the difference in efficiencies for the thin-film PV layer in each configuration (EPW1 = 5%, EPW2 = 12%) translates into between a three and four percent difference in benefit to the overall load. By placing the thin-film PV layer at the exterior face and the removal of the thermal mass layer and replacing it with either a “hot plate” or “cooling plate”, the component has the ability to create the most energy within its capabilities. It also provides a source of heating or cooling that can be turned on or off by the occupant.

The discussion of the comparative results demonstrates that the EPW1 use in Boston, and the EPW2 use in Phoenix, can have substantial impacts on categorical load reductions for the prototype designs. Also, the ability to compare the relationships among the climate, prototype design type, and quantity and type of EPW components provides additional insights about the operational performance of the proposed configuration, and what can be adjusted in other investigations to improve the performance. The strength of the “spreadsheet tool” is that if one variable is changed, sixteen new cases, with new results, and potentially different relationships are generated for comparison.

## Chapter 7.0 Conclusions

### 7.1 Summary

The purpose of this research was to develop a “system-based framework” capable of evaluating and integrating the operational, construction process, and aesthetic performance of innovations within residential construction.

The innovation of the EPW Energy Producing Wall component was created. Two 2’x4’ component types (EPW1 & EPW2) capable of forming five configurations, due to layer manipulation, were developed based upon the strong potential for benefits from the union of passive and active solar concepts.

An “evaluation toolkit” utilized throughout the investigations was composed of the “spreadsheet tool”, dynamic process model for light wood framing (DPM-LWF), and use of visualization programs, such as AutoCAD, 3d Studio Max version 2 and Lightscape.

The operational performance evaluation tool, the “spreadsheet tool”, incorporates analytical approaches to evaluate the benefit to heating, cooling, electricity and total load reduction attributable to active and passive solar layers in the EPW components, as they function within the building envelope. The customized Excel spreadsheet creates the ability to bring five passive solar methods (quantifying heating and cooling needs for the specific residence), and three active solar methods (quantifying the thin-film pv energy generation based upon size, type and orientation) together. The interface allows manipulation and isolation of numerous variables to investigate the quantified benefits to the total and categorical breakdowns of energy consumption in the home.

The dynamic process model represents the non-linear flow of activities in a project on a construction site, to enable the examination of alternative courses of action and decisions. Data were collected from multiple sources, including construction site visits, and interviews with industry professionals. The model was created to be representative of construction site reality and has the flexibility and adaptability to be modified for differing types and designs of LWF structures.

The evaluation of aesthetic performance did not rely on one specific tool, but many, some computational in nature, others not. Initially, material textures in the form of graphics and physical samples were gathered to gain an understanding of the visual characteristics of various layered configurations. Physical and virtual models (AutoCAD, 3D Studio Max v.2) were created and rendered to assist in the refinement of the configurations of the EPW components, the creation of the EPW frame, the detailing of the EPW groups, and the role and placement of the EPW within the wall section.

Two prototype designs were created to provide the context and variation for the investigations within the “evaluation toolkit”. Each design had two versions, a version with the EPW components, and one without. The “Sears Design”, based off a 1928 Sears & Roebuck catalog home, was readapted to present day standards and selected to be representative of the existing building stock. The “Modern Design” provides one interpretation of what the integration of this passive and active solar union, in the form of the EPW components, could be. Data for each of the “evaluation toolkit” tools, relating to building form and spatial character, building performance, and construction process were extracted from the four versions as inputs.

Finally, the implementation of the EPW components within the prototype designs was conducted. The results from the thirty-two operational cases, the preliminary simulation runs, and the aesthetic investigations were brought together within a nine section “case result format”. Comparisons were made possible between the EPW’s active and passives solar layers individual and collective impacts on reducing the energy to be supplied to the home, the standard construction and EPW construction versions for each prototype, the visual appearance inside and out of the prototype designs and numerous others.



## 7.2 Conclusions

A “system-based framework” to evaluate and integrate the operational, construction process, and aesthetic performance of innovations within residential construction differs from other frameworks previously proposed. First, it has a comprehensive view of the relationships between operational, construction process, and aesthetic performance, and second its flexible boundaries and reduction of constraints, allowing the user to shape the path of exploration. The “spreadsheet tool” allows a parametric investigation of the materials, components, and systems of a residence for assessment of energy creation, loss, consumption, and ultimately balance. It can adjust and even isolate selections, while maintaining the ability to see the impact at the overall level in addition to the local level. Some examples are; material use within the EPW; layer configuration within the EPW; number and size of openings in the building envelope; and building form. The process model for light wood frame (DPM-LWF) construction like the “spreadsheet tool”, has the capability to take the investigation to the level of the most basic task/assumption. However, it differs through its ability to also capture the dynamics that occur for each project, based upon the resource sharing, construction processes chosen and the design attributes involved. In addition to these two tools was the importance of the virtual and physical models to capture the visual impacts occurring due to the results from the other two.

The design and evaluation of the implementation of the EPW components provides an example of the potential and the depth of integrated thought that could be utilized by the design community to begin to increase the spread of innovation and raise the level of quality. Emphasis was placed upon identifying the benefits within the three categories. The research demonstrates that the EPW can provide substantial benefits, quantitative and qualitative, even in climates such as Boston and certainly in climates like Phoenix. In addition, the forecast of those benefits over time based on technological development patterns within the thin-film PV layer displayed the strong potential for significant increases. An efficiency (Cycle 4 – 22% for wall panels, 27% for skylights), which is not too far out of the realm of technical possibility, could provide nearly 100% of the total energy loads of the Modern Design in Phoenix and 48% of total loads in Boston.

The performance of the EPW at the component level is dependent upon the configuration of the material layers of the translucent insulation, thin-film photovoltaic, and thermal mass. The re-

search demonstrated that the manipulation of the layers within the component can make a significant difference. The enhanced performance is not only due to the individual materials, but to the relationships, and benefits of combining the characteristics of the layers to create something greater, in integration, than exists in isolation. The ability to direct light to light to the thin-film PV layer (translucent insulation + fiber optic concept + thin-film PV), capture and utilize heat (thermal mass as a heat sink for the thin-film PV), and allow light transmittance into the interior (translucent insulation, translucent thin-film PV's, and varying opacity configurations) provide the way that the EPW combines the "layered relationships".

The "case result format" is just one of potentially numerous ways to configure the results from the three categories, but it demonstrates the significance of providing this information together. The insight and perspective gained by bringing the data together, forcing acknowledgement of all sides, is an incredible learning tool in the short term and the long term. It points to the issues on specific projects or cases that are crucial to the course of work for the other parties involved, while also providing insight into how problems or situations could be avoided or enhanced on other projects. The ability to identify the crucial factors influencing performance and then have the ability to further investigate the sensitivities of those factors can point to relationships and discoveries that can't be imagined or drawn on the surface.

The exciting potential of the dynamic process model is its coupling and integration with other models that have previously developed through on-going research at MIT. The construction process models completed include; structural steel erection; exterior enclosure erection; Cast In Place concrete construction, plumbing installation, HVAC systems installation, electrical services installation, interior finishing. Current research is investigating the creation of a single dynamic process meta-model, capable of simulating the impacts of changes within one building system and have it ripple through the others. If the meta-simulation model could be combined with a more refined "spreadsheet tool" capable of a similar type of dynamics (e.g. computational fluid dynamics and capture of intricacies of radiation, conduction, and convection) and have those visible in real-time, the long sought goal of simulation would be achieved.


The research initially sought to explore the feasibility of an integrated component composed of passive and active solar concepts, and placed in the building envelope in various climates, and its

potential to significantly reduce the energy needs of the home. However, over the course of the investigations and development of the EPW component type, the focus shifted of the analysis themselves, particularly the creation of a “system-based framework” to evaluate the implementation of innovations within a project, at various stages, with respect to the combination of operations, construction process, and aesthetics. The course of the research, at times, was a form of trial and error. Attempts were made to develop capabilities within the framework to address a certain focus within the prototype designs, while also attempting to incorporate it into the framework in a manner that would serve as universal, versus project specific. However, this significantly increased the complexity of not only the tool, but its relationship to the others. The capabilities of the system-based framework allow investigations at the material, component, and system level, by allowing the user to play with the sensitivities of various parameters. Since, the operational, construction process, and aesthetic performance assessments occur at various stages in the design process, it is a method for different groups within the “project team” to engage and communicate with each other throughout the evaluation process for different types of innovations. It also allows the flexibility to investigate the current state and forward in time and development to explore the potential, by reducing the constraints. The development of the “system-based framework” for evaluation of implementation is not complete, but the evidence brought forth by this research establish that the initial pieces are in place.

### 7.3 Future Research

Further research can improve the performance of each of the tools used in this research, as well as further combining and integrating the analyses. Although a method of determining the role of conduction, convection, and radiation within the panel was introduced, the “static” nature of the input into the “spreadsheet analysis” could be upgraded to include a dynamic analysis. This development requires a marriage of the concepts of thermal mass heat transfer with computational fluid dynamics, which is no small feat. For example, within the EPW configuration, the heat storage capacity of the thermal mass combined with the convective airflow loop provided two dynamic variables that are difficult to represent simultaneously.

The research presented investigates the link between building performance software, construction process modelling, and visualization software. However, the steps to enhance the compability of this relationship, can be made through exploring the links between aesthetics and construction



process, as well as between operational building performance and construction process. The potential link between aesthetics and construction process is crucial due to the impacts that can be made in the information that is on-hand and can be explored by the project team, but also as a communication mechanism between these culturally different groups. The ability to have the construction process information on-hand at earlier stages of the process can be beneficial to the difficult task of estimating an overall project, much less one involving very customized and unique features. It can also serve as a means for demonstrating where potential problems through implementing the design could occur, and provide a medium for both designers and builders to work through and evaluate each others approaches to the design. The link could function as a translator, by providing the visual imagery that designers are accustomed to dealing with, and the process information that serves as the builders language.

Further research can also improve the link between the operational performance and construction process. The way a building is actually built and the methods used to achieve that can play a more crucial role than how the building is designed. Overlaps exist between the type and depth of information that must be known about the detailed design for input into the dynamic process model and into the “spreadsheet tool”. Research could begin to highlight how these overlaps could be broadened to create a stronger relationship between the two, and raise awareness among both groups how their approaches really affect or complement the other.

Further development of the EPW depends upon the ability to understand how the thin-film PV performs if it is within the component. Earlier stages of this research explored the concept of physically testing a full-scale prototype within the test chamber that was constructed and placed on the MIT campus. However, numerous barriers, including the ability to obtain samples of the developing materials, such as the translucent thin-film PV, caused the focus of the investigations to shift. Physical testing on a full-scale prototype of the EPW would allow a level of understanding to be developed about the relationships of the materials, that a software program, no matter how sophisticated, cannot produce. In addition, further exploration of the potential link between fiber optics and translucent insulation could produce insight into how light can be brought to the interior of a component assembly, regardless of the angle that is incident on the surface. The continuing developments within the growing thin-film PV industry will also prove beneficial, because as the efficiency improves, and the manufacturing cost reduces, the operational benefits, in addition to the construction process and aesthetic benefits will continue to improve.

*Masters of Science in Building Technology, Department of Architecture*

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# Appendix A

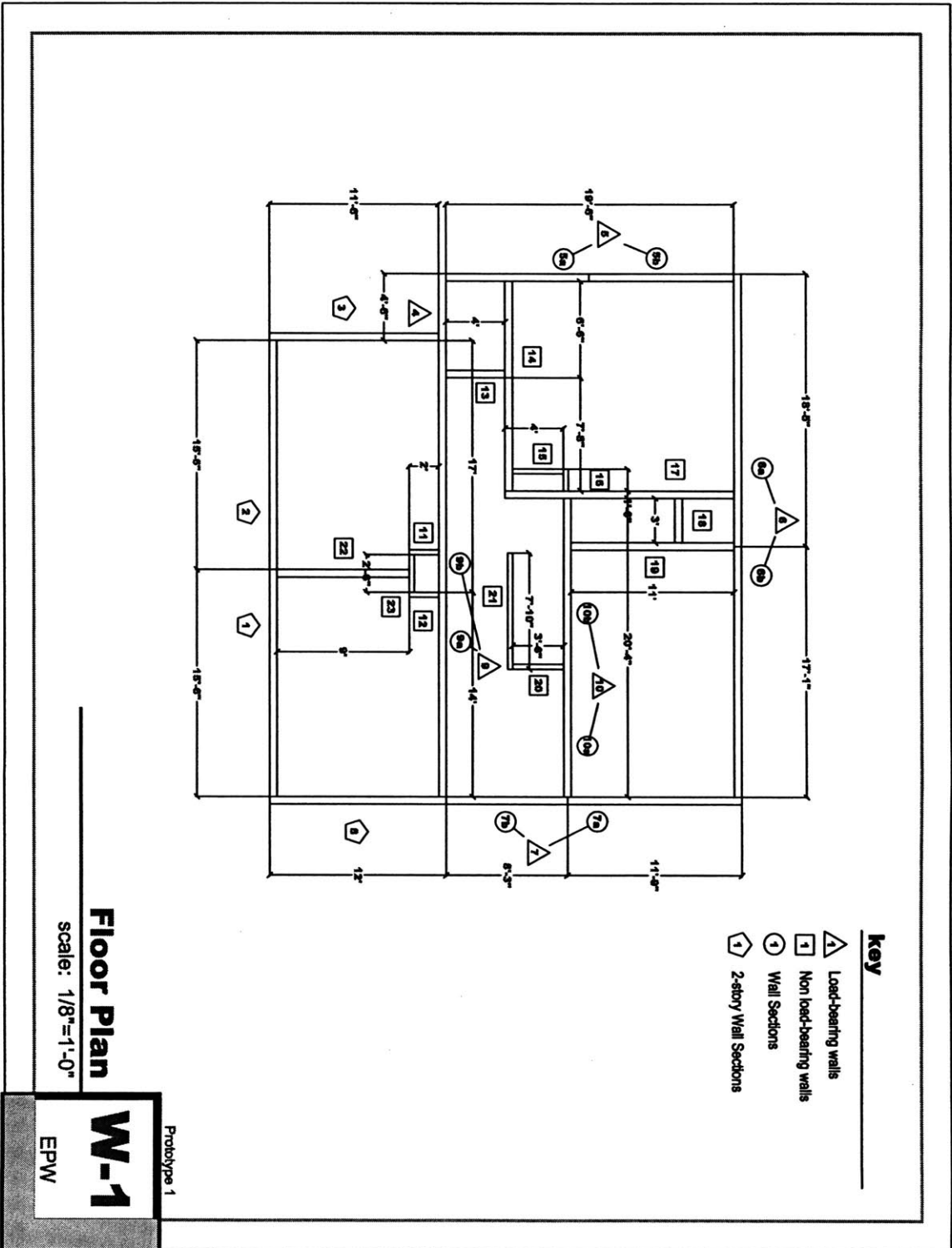
## *Prototype Design #1 “Sears Design”*

### 1. Sears Home incorporating EPW

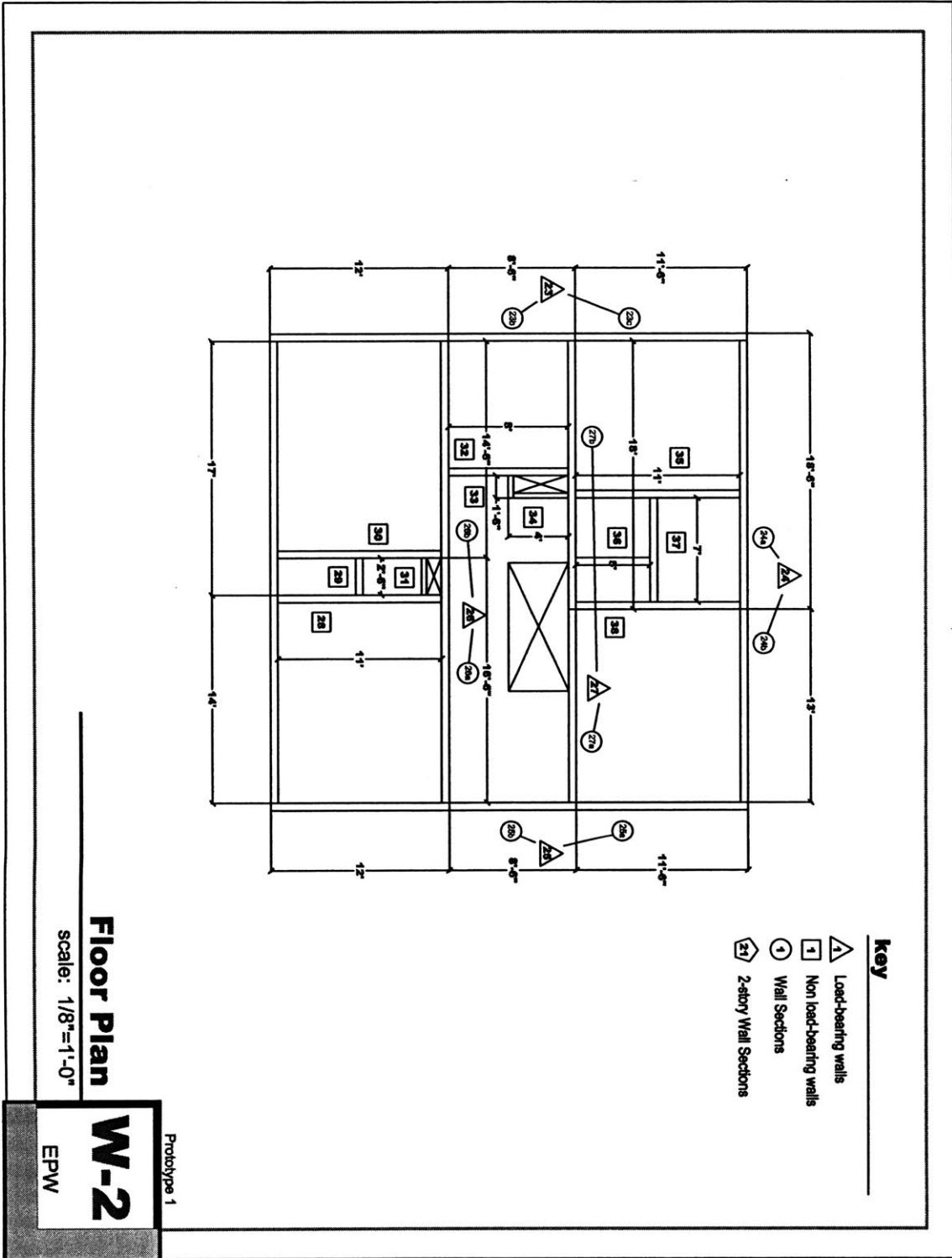
Construction sequence plans (W-1, W-2)  
Floor plans (A-1 to A-3)  
Framing plans (S-1 to S-5)  
Elevations (E-1 to E-4)

### 2. Sears Home - - standard construction

Construction sequence plans (W-1, W-2)  
Floor plans (A-1 to A-3)  
Framing plans (S-1 to S-5)  
Elevations (E-1 to E-4)

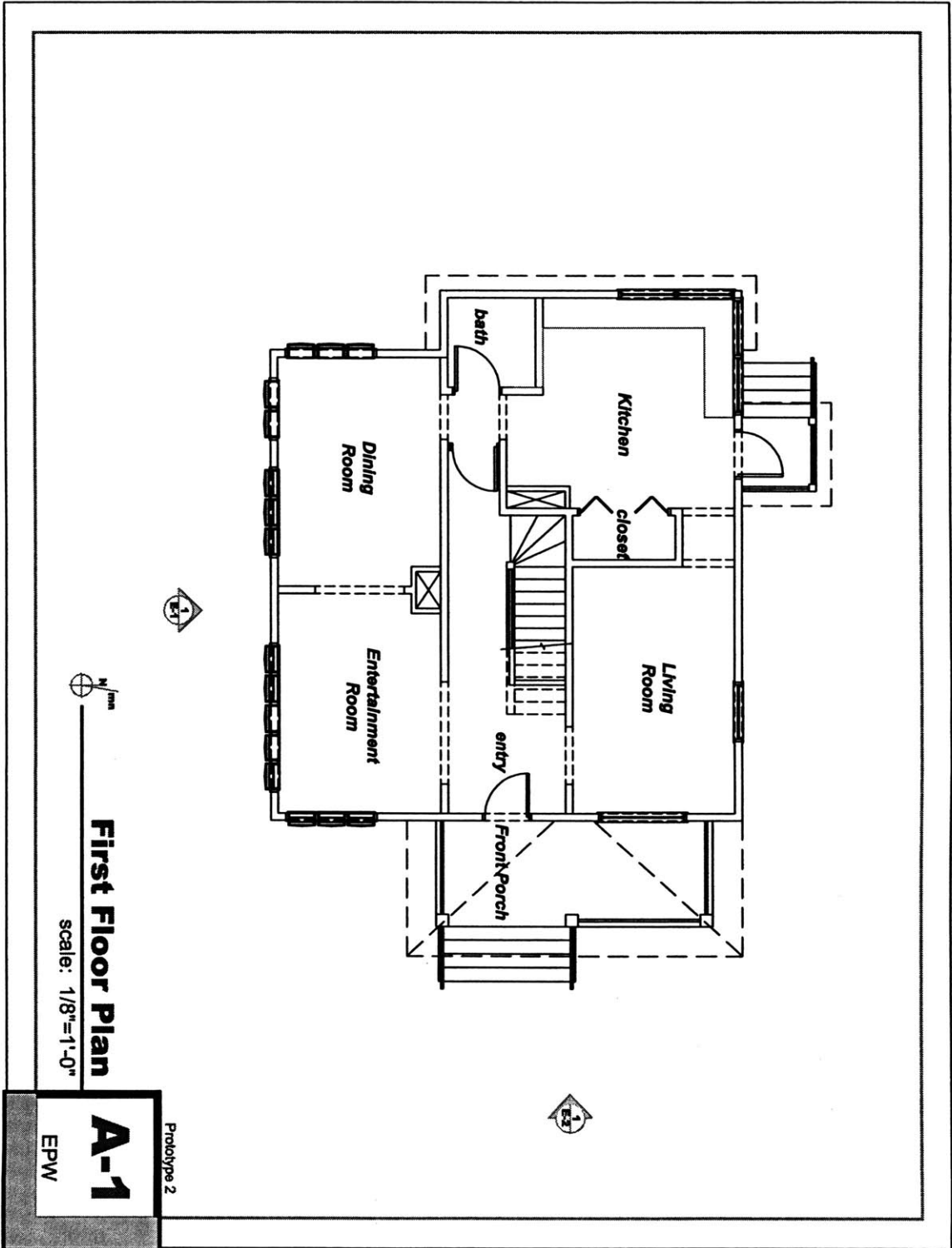


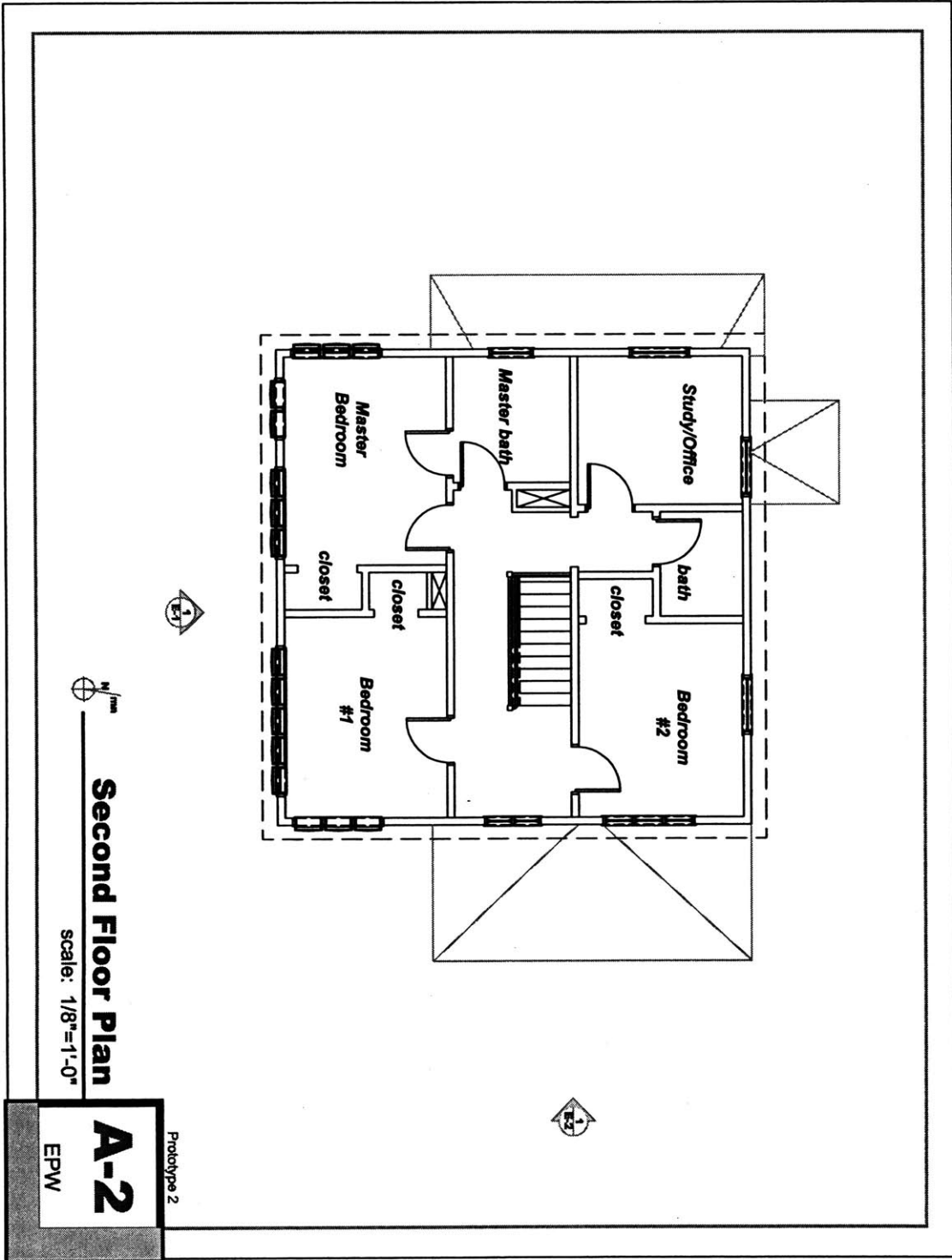


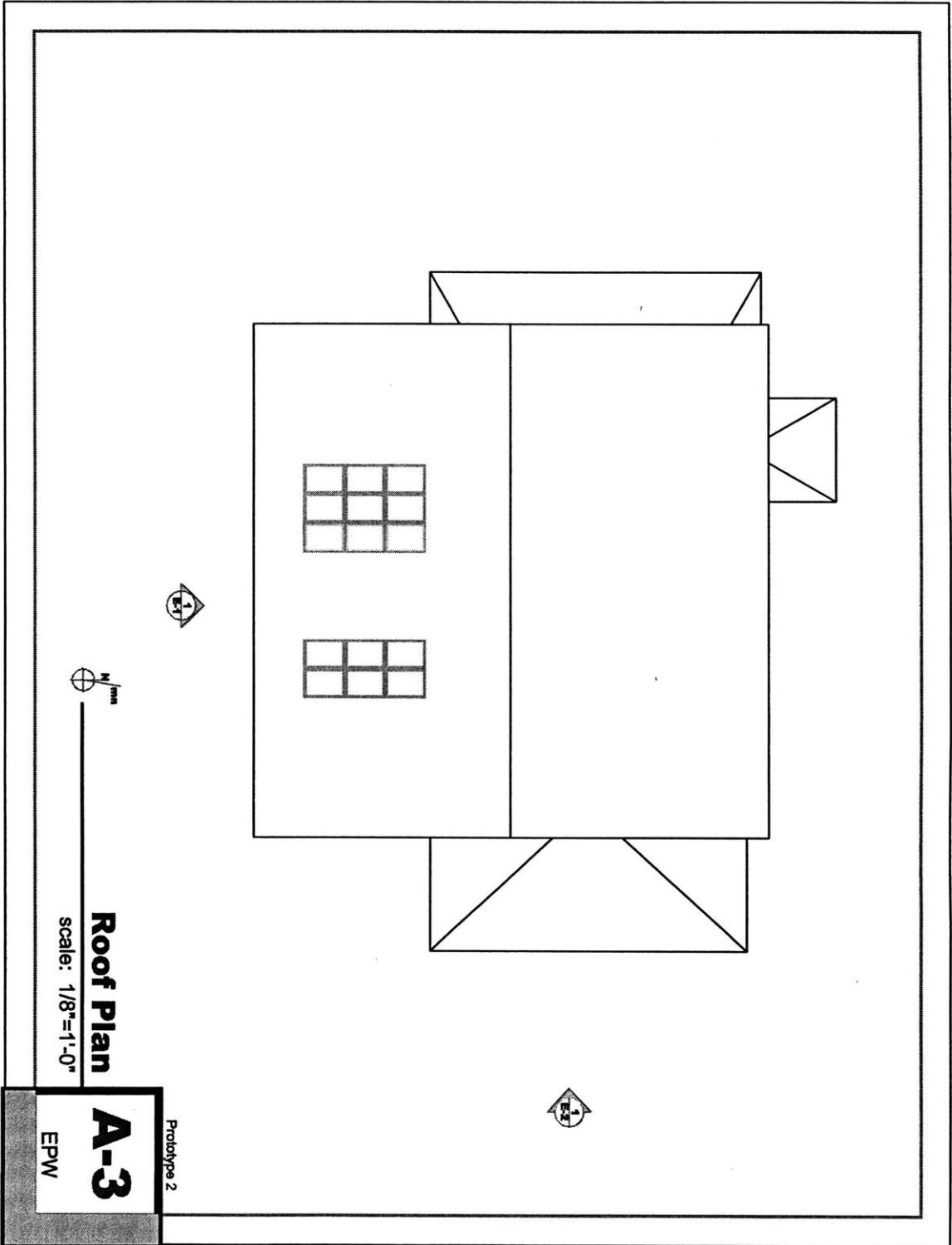


**Floor Plan**  
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**W-2**  
 EPW  
 Prototype 1

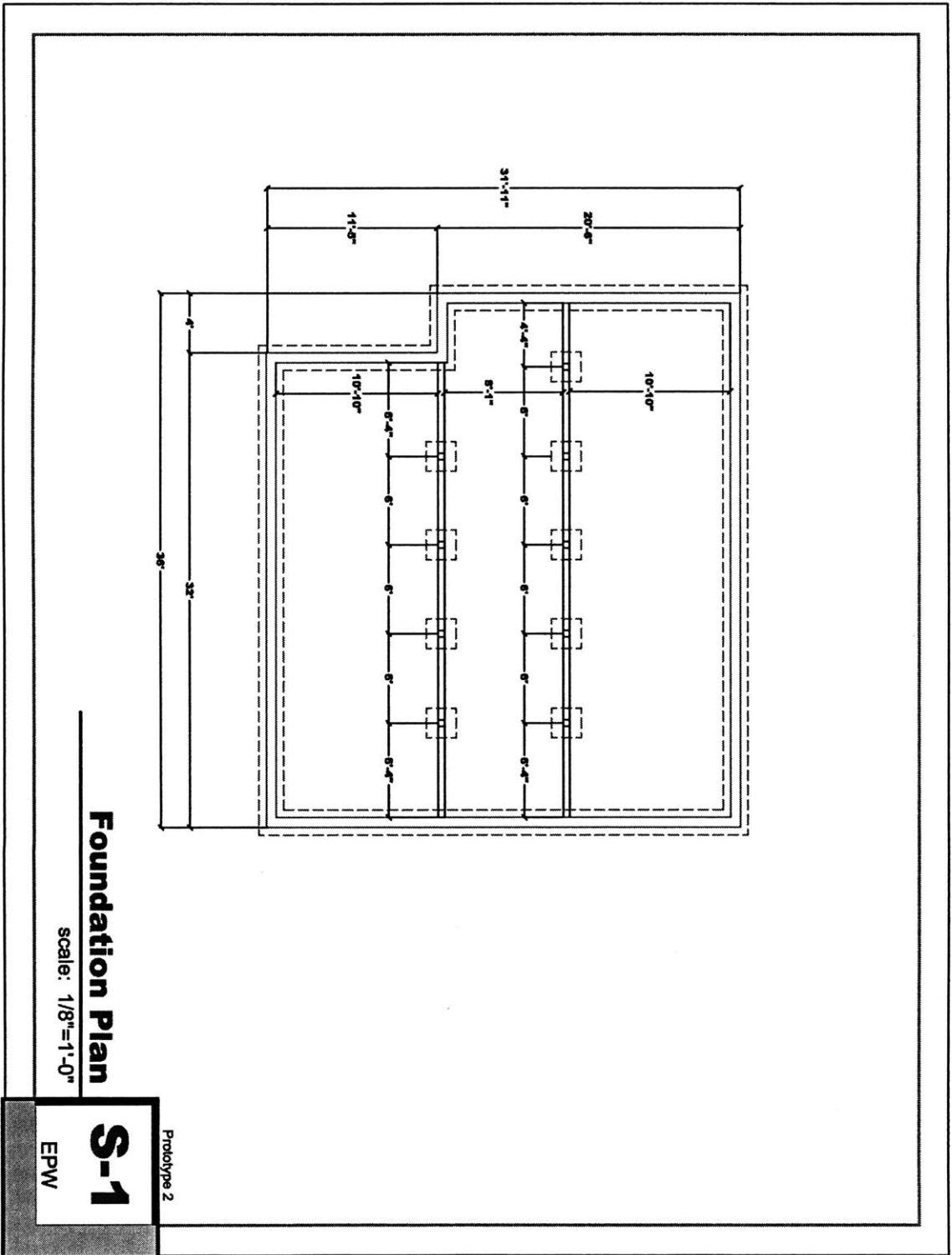






**Roof Plan**  
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Prototype 2  
**A-3**  
EPW



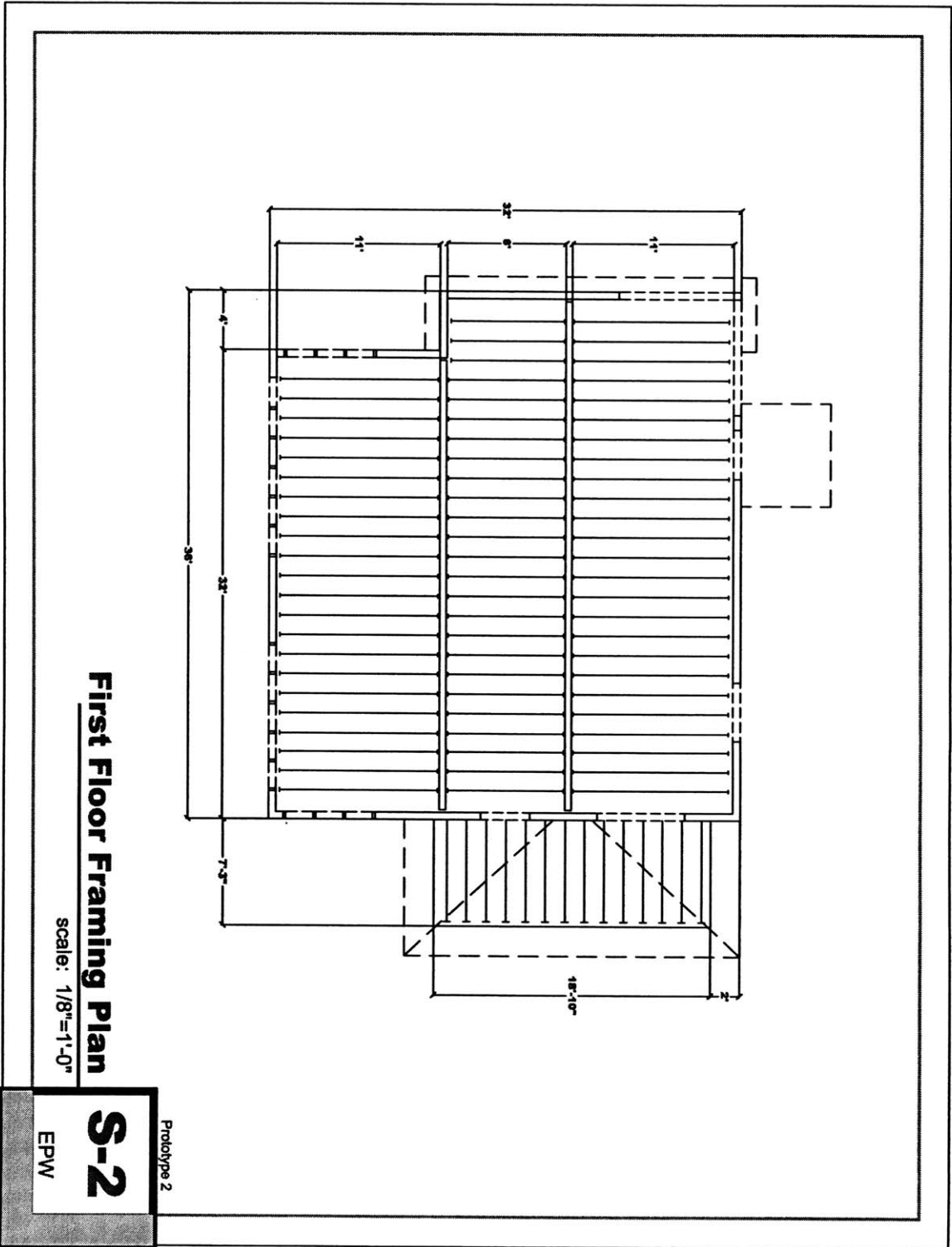
**Foundation Plan**

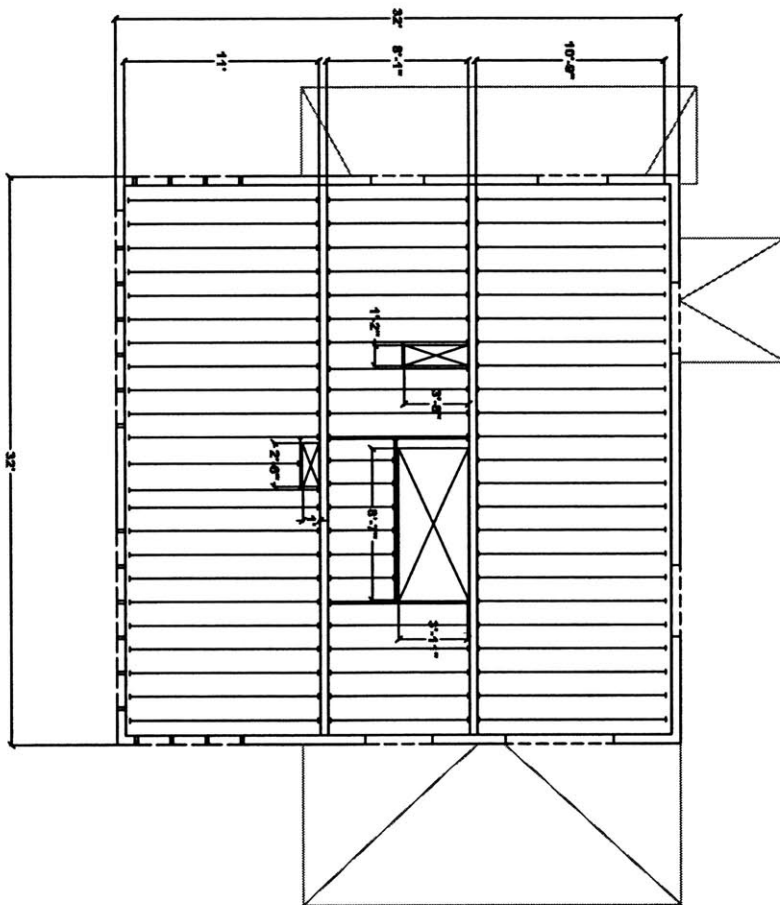
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Prototype 2

**S-1**

EPW

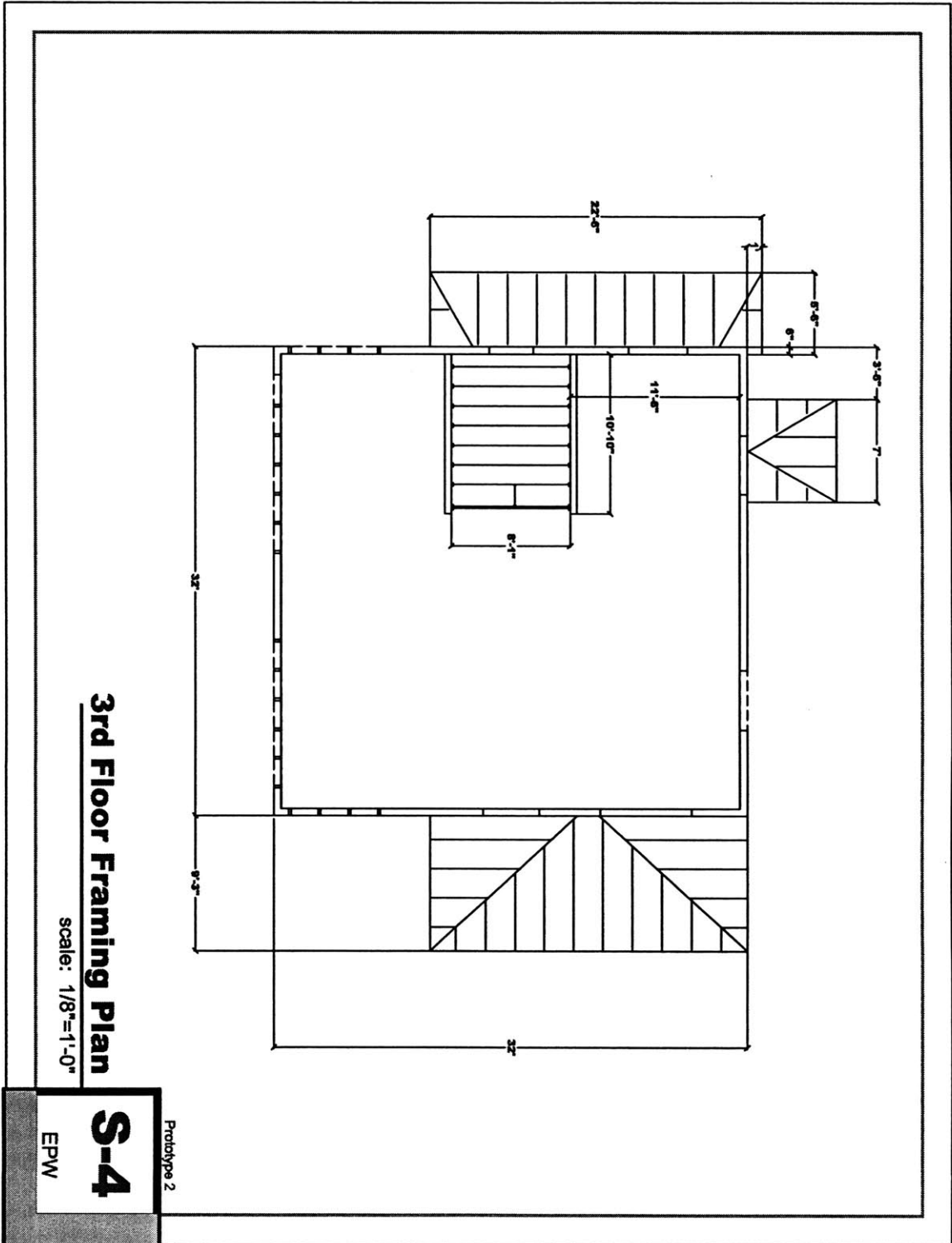




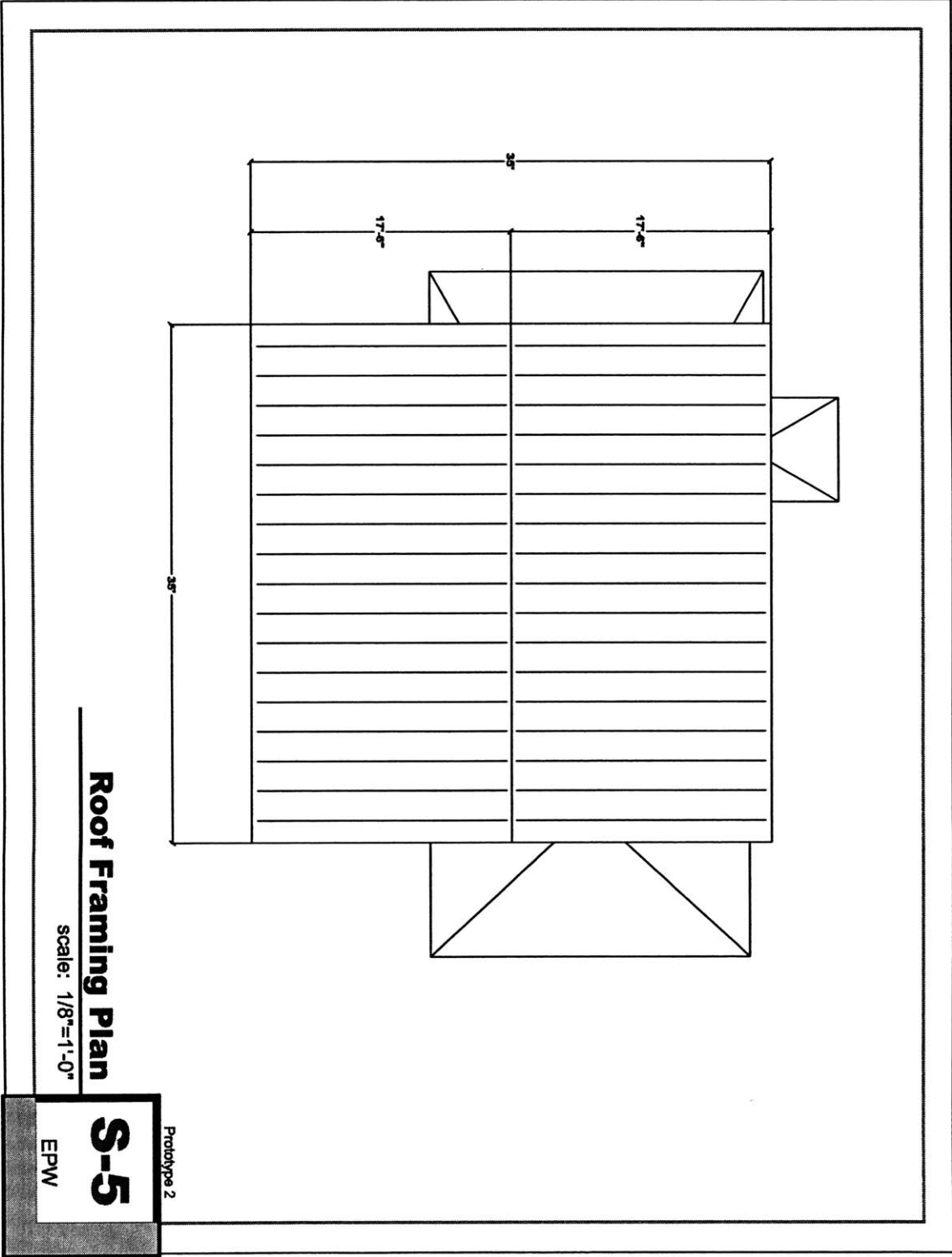
**Second Floor Framing Plan**

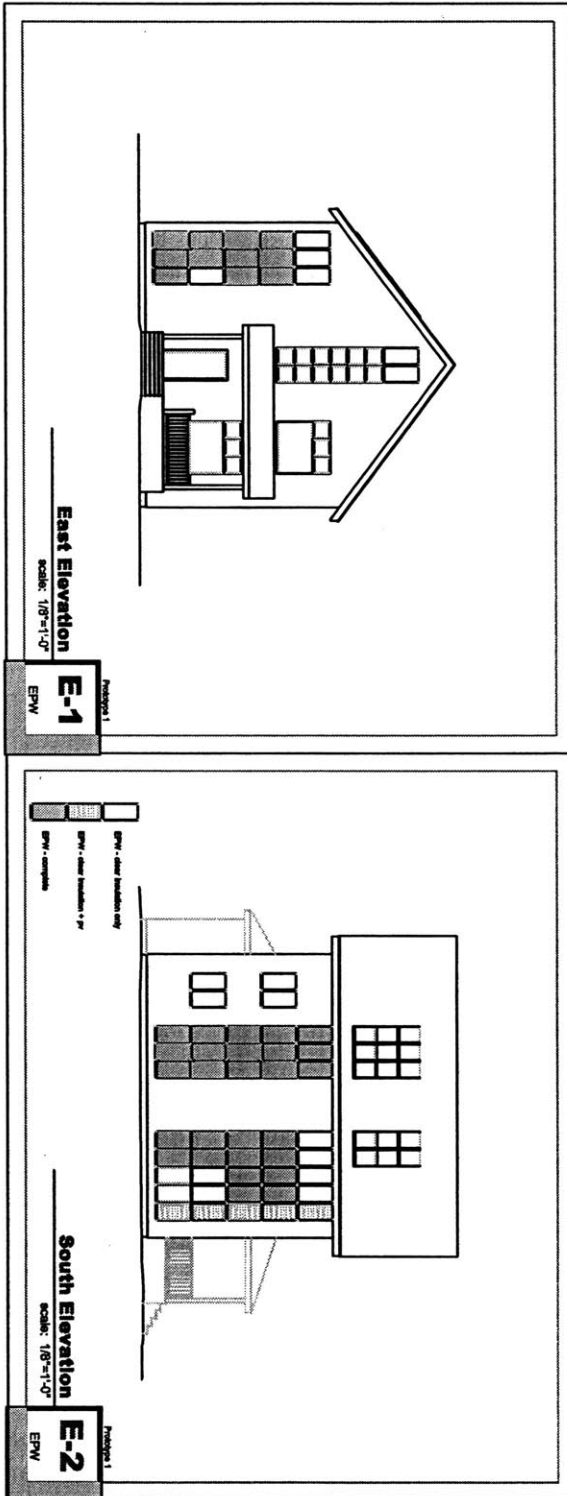
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Prototype 2  
**S-3**  
 EPW

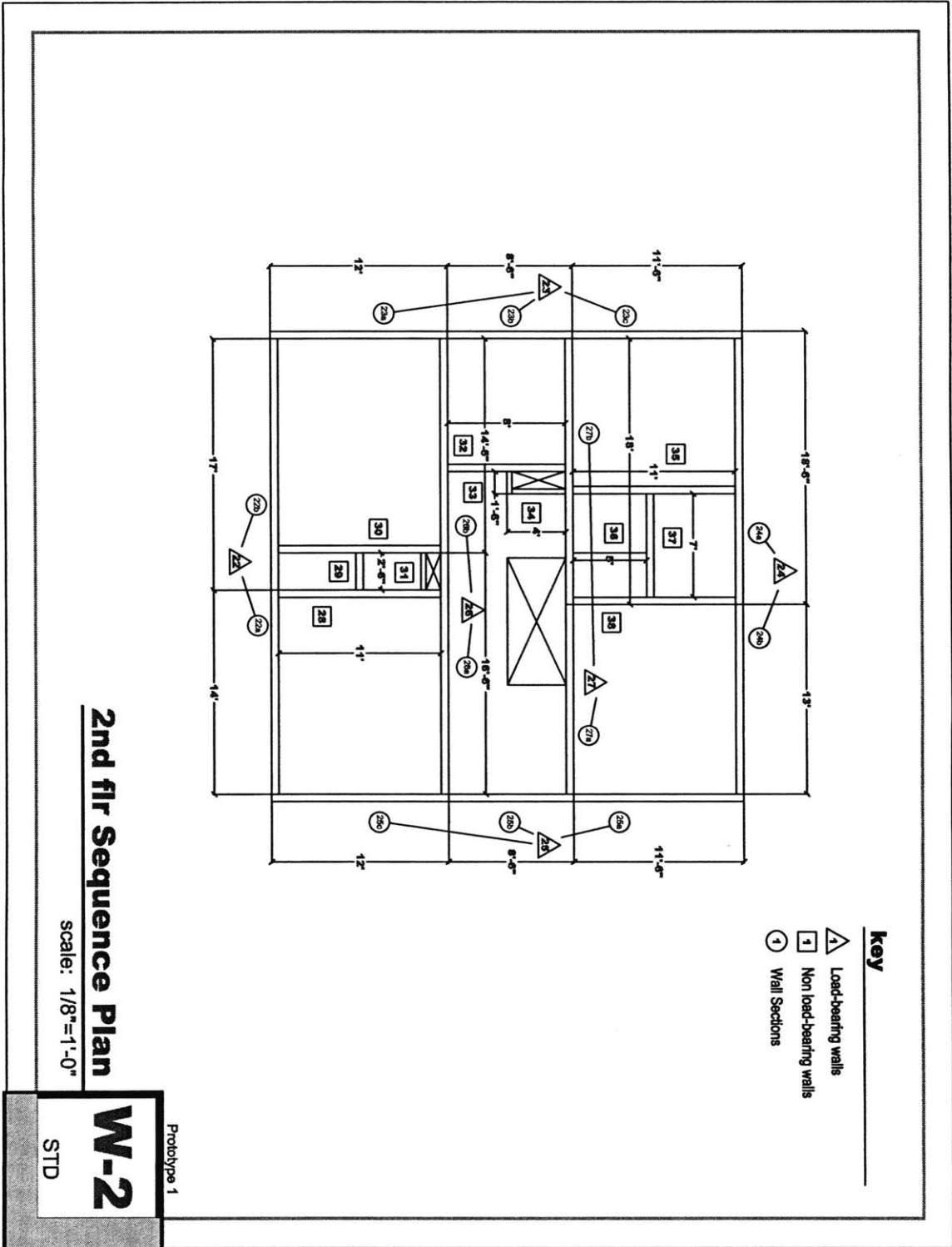


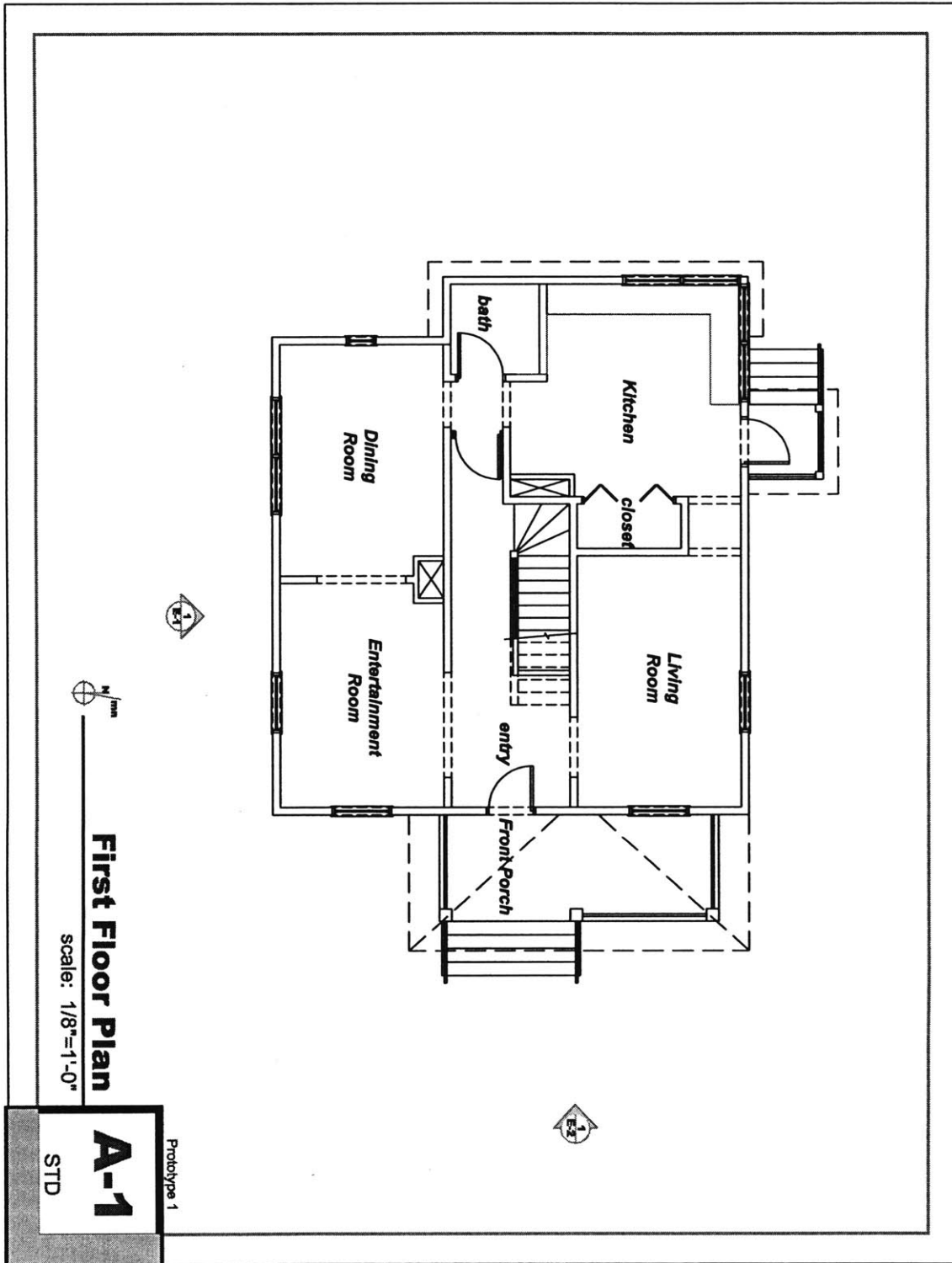


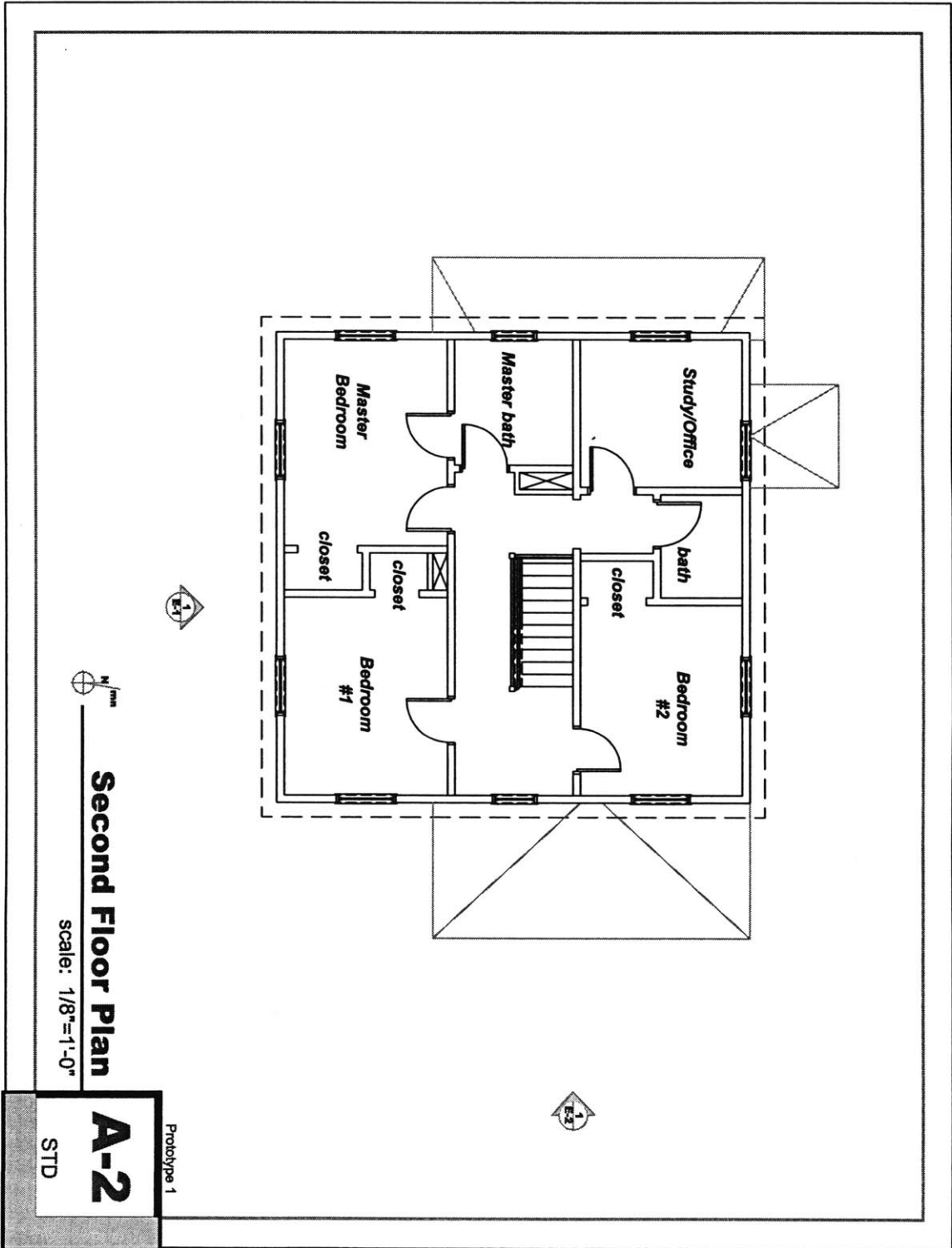


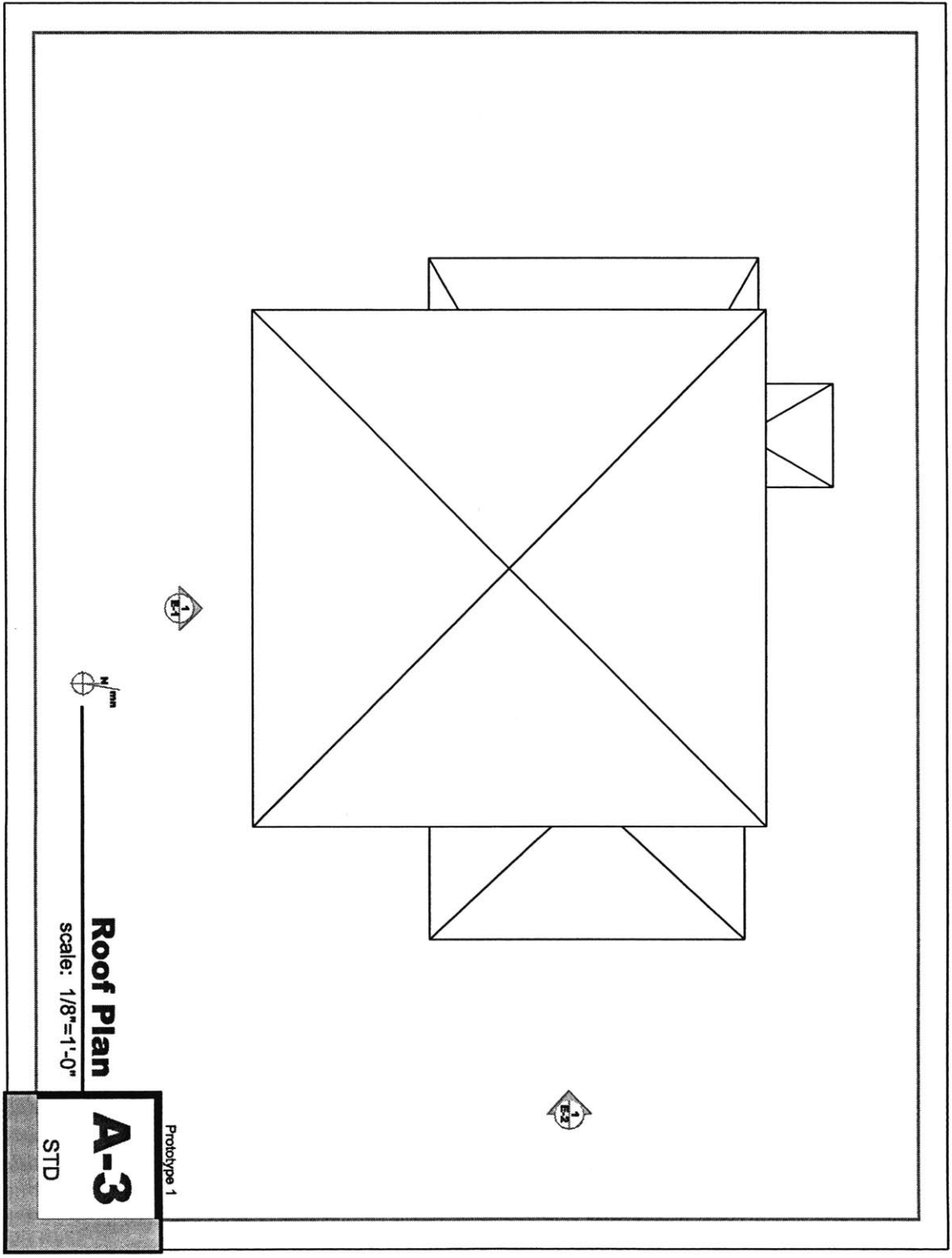


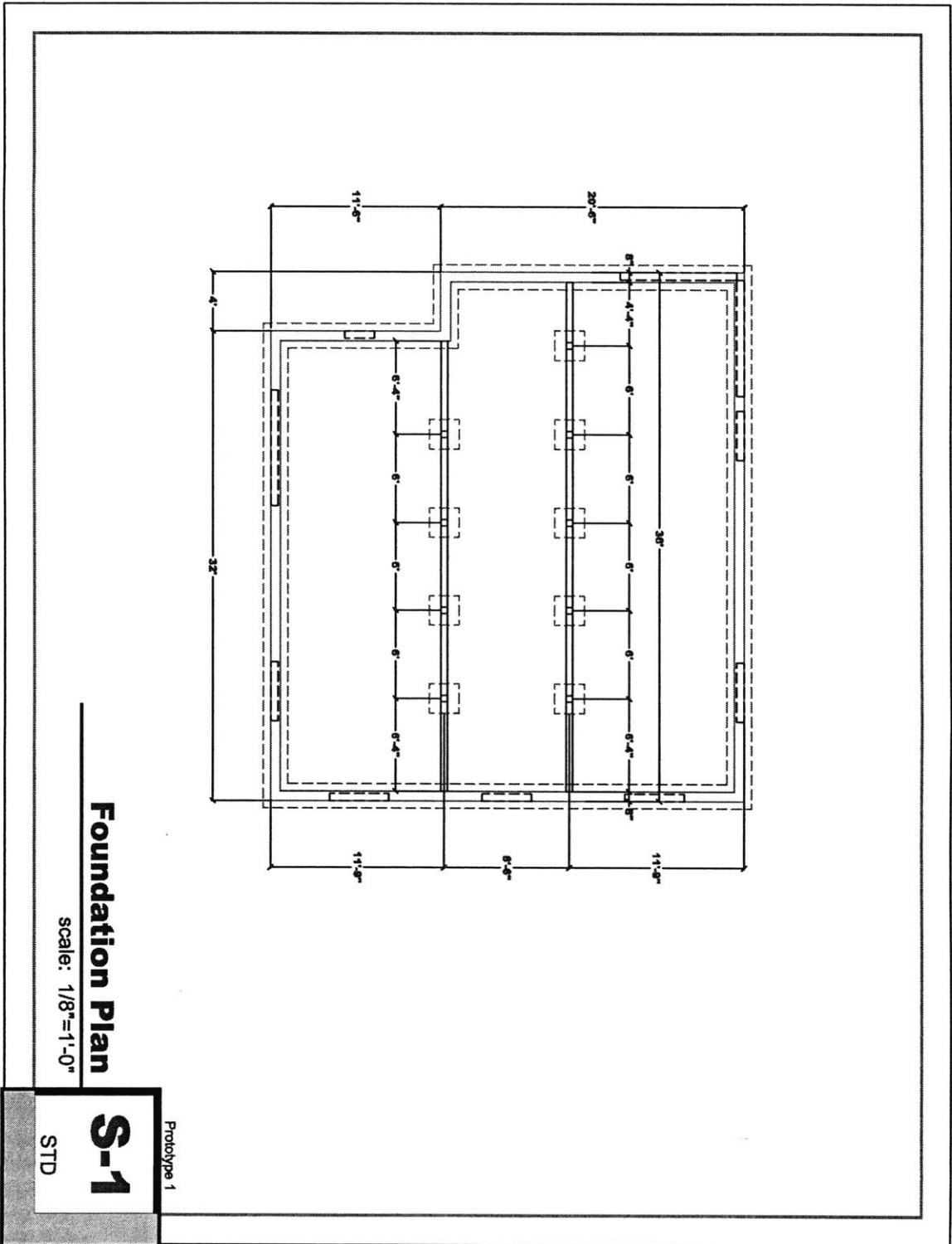








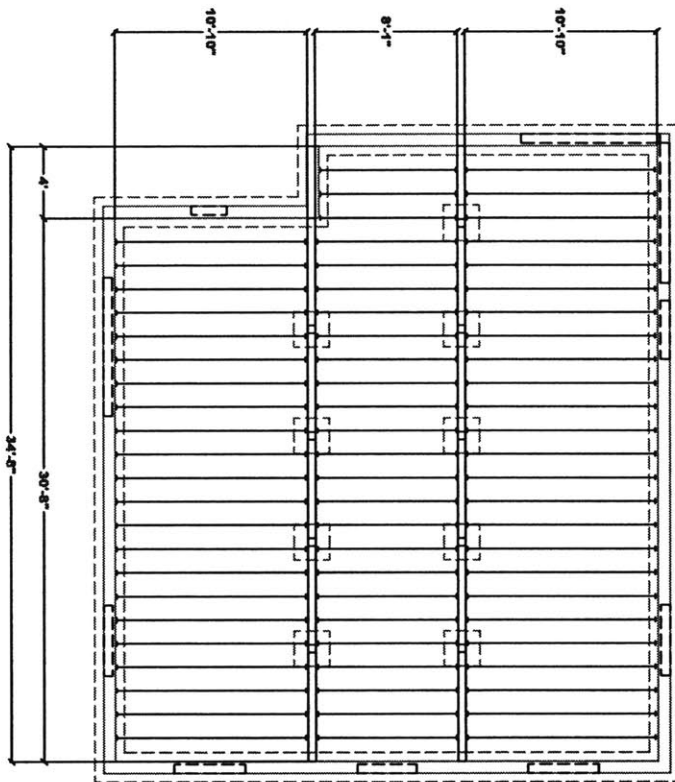




**Foundation Plan**  
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Prototype 1  
**S-1**  
 STD





**First Floor Framing Plan**

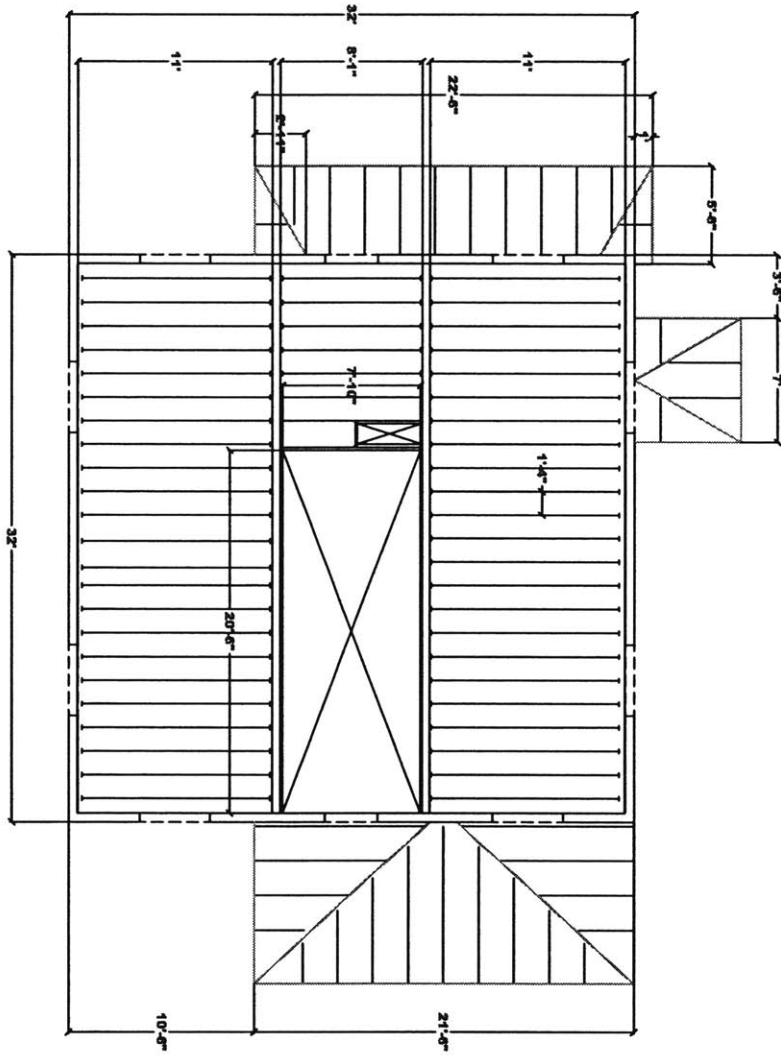
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STD

**S-2**

Prototype 1



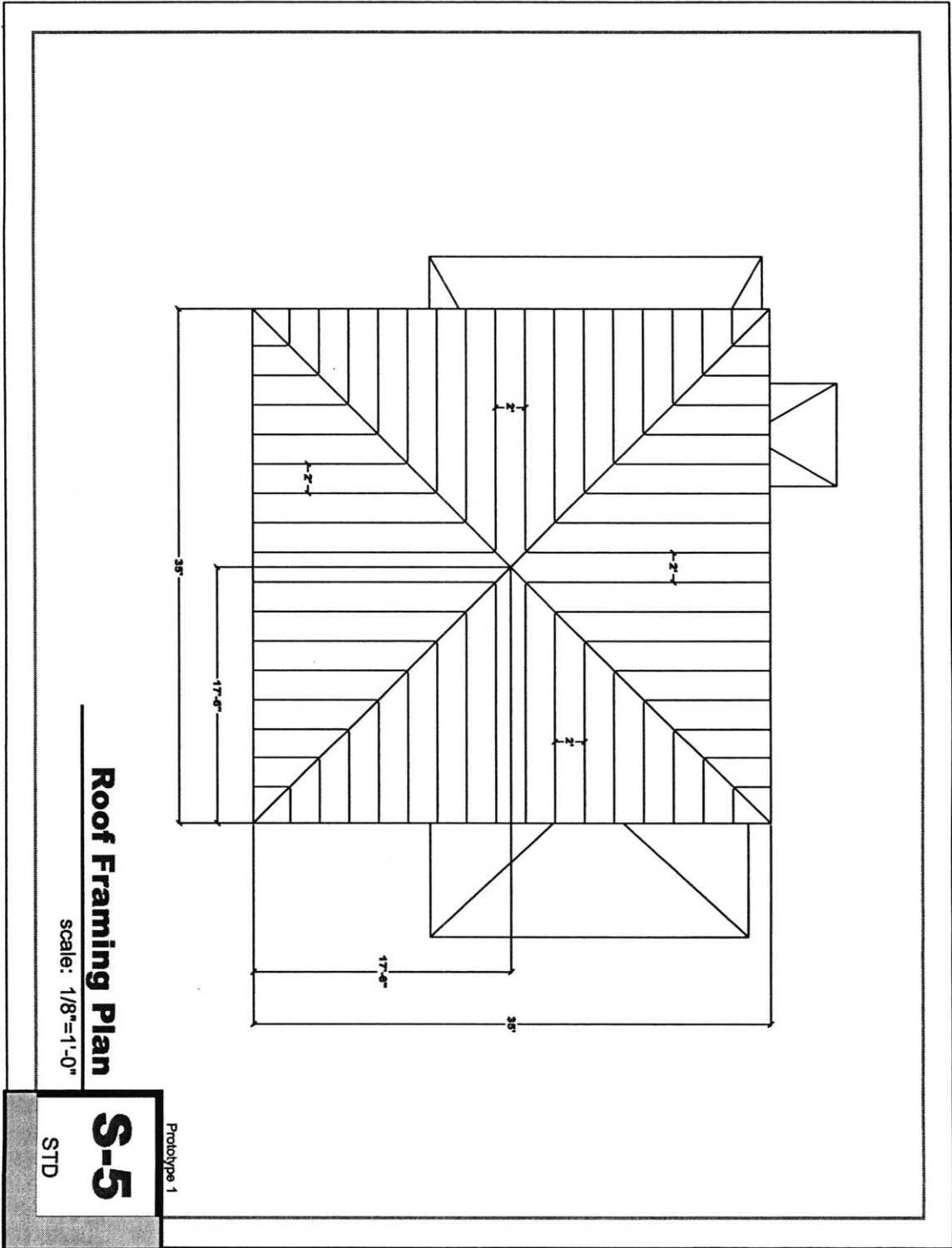


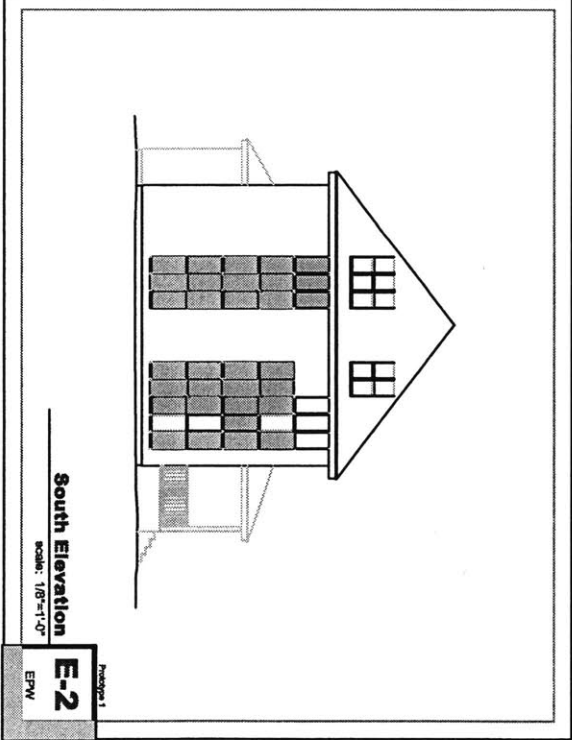
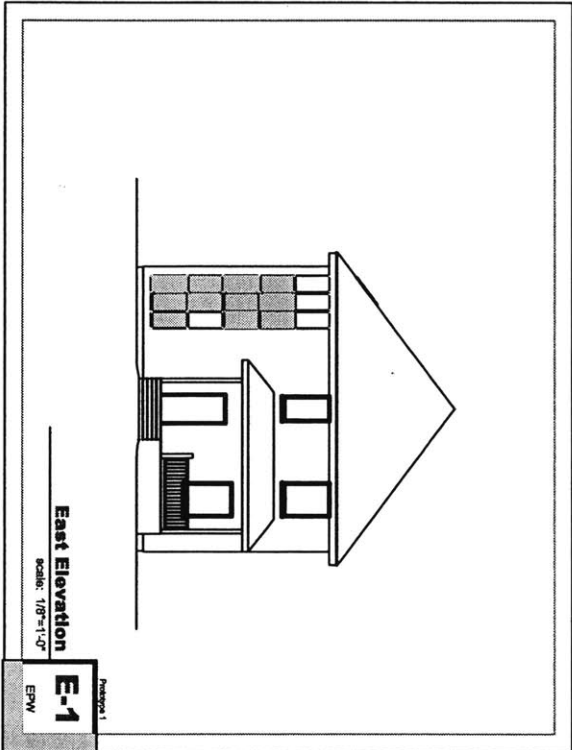
**Floor 3 Framing**

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**S-4**  
STD

Prototype 1









# Appendix B

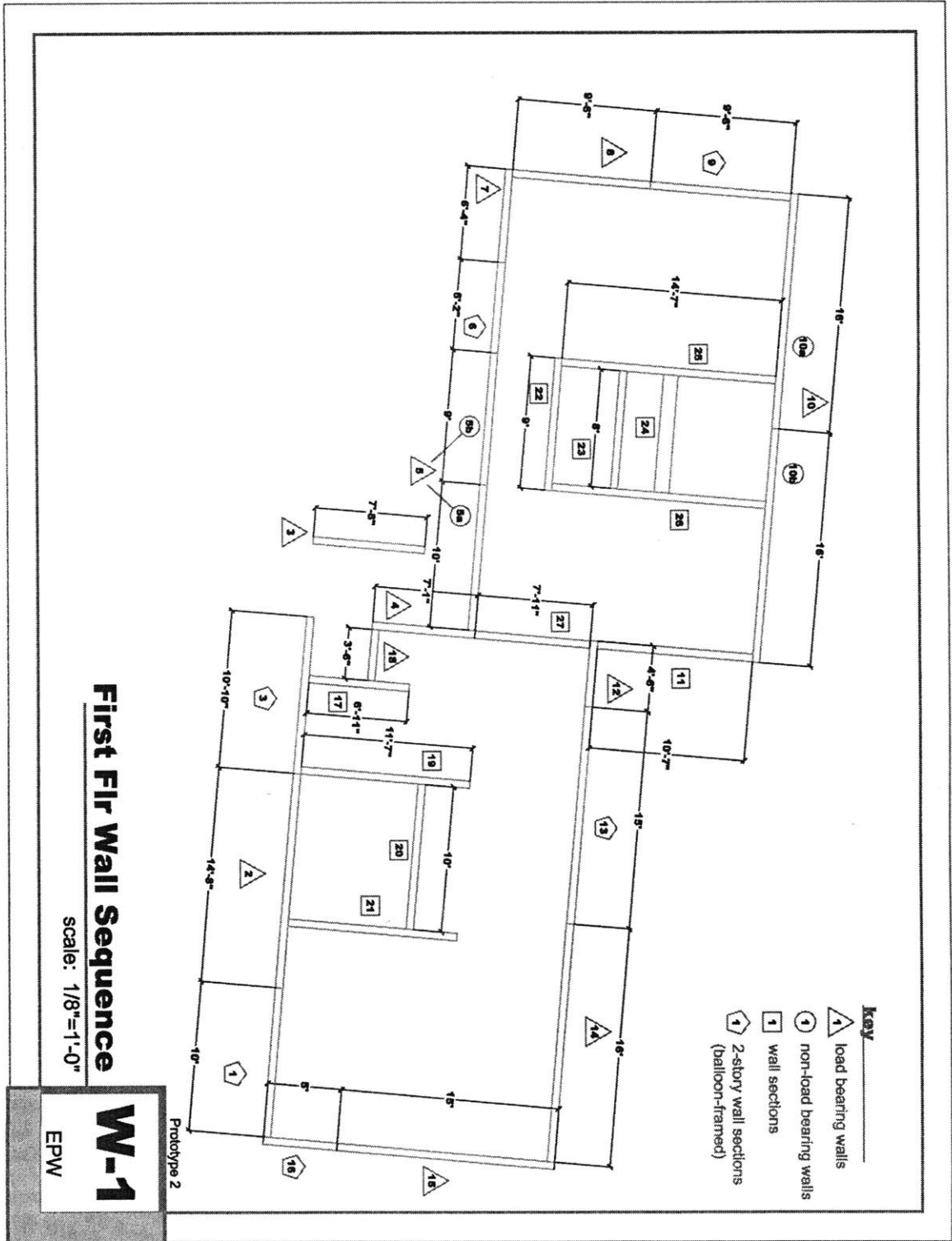
## *Prototype Design #2* *“Modern Design”*

### 1. Modern Design incorporating EPW

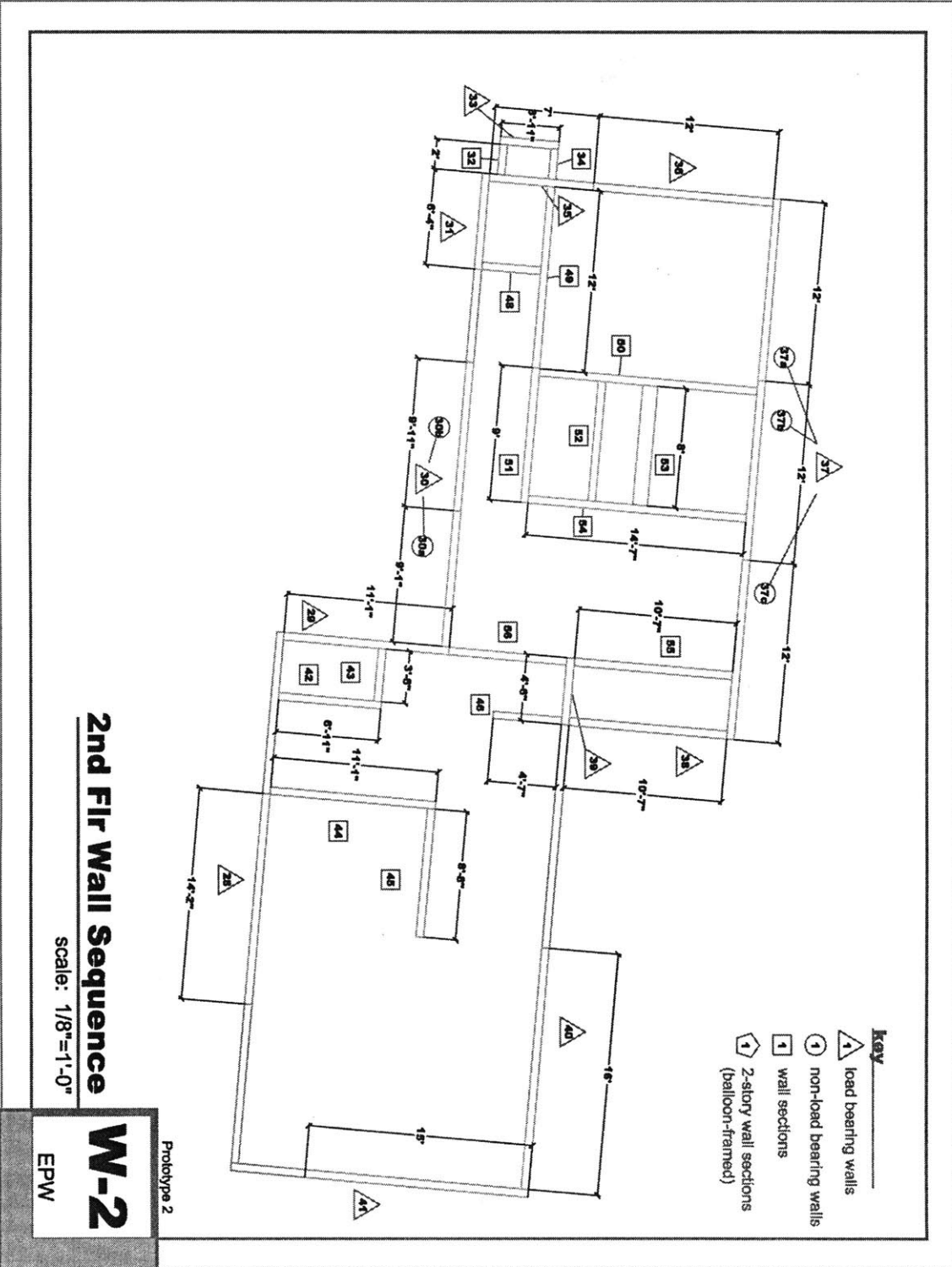
Construction sequence plans (W-1, W-2)  
Floor plans (A-1 to A-3)  
Framing plans (S-1 to S-5)  
Elevations (E-1 to E-4)

### 2. Modern Design - - standard construction

Construction sequence plans (W-1, W-2)  
Floor plans (A-1 to A-3)  
Framing plans (S-1 to S-5)  
Elevations (E-1 to E-4)





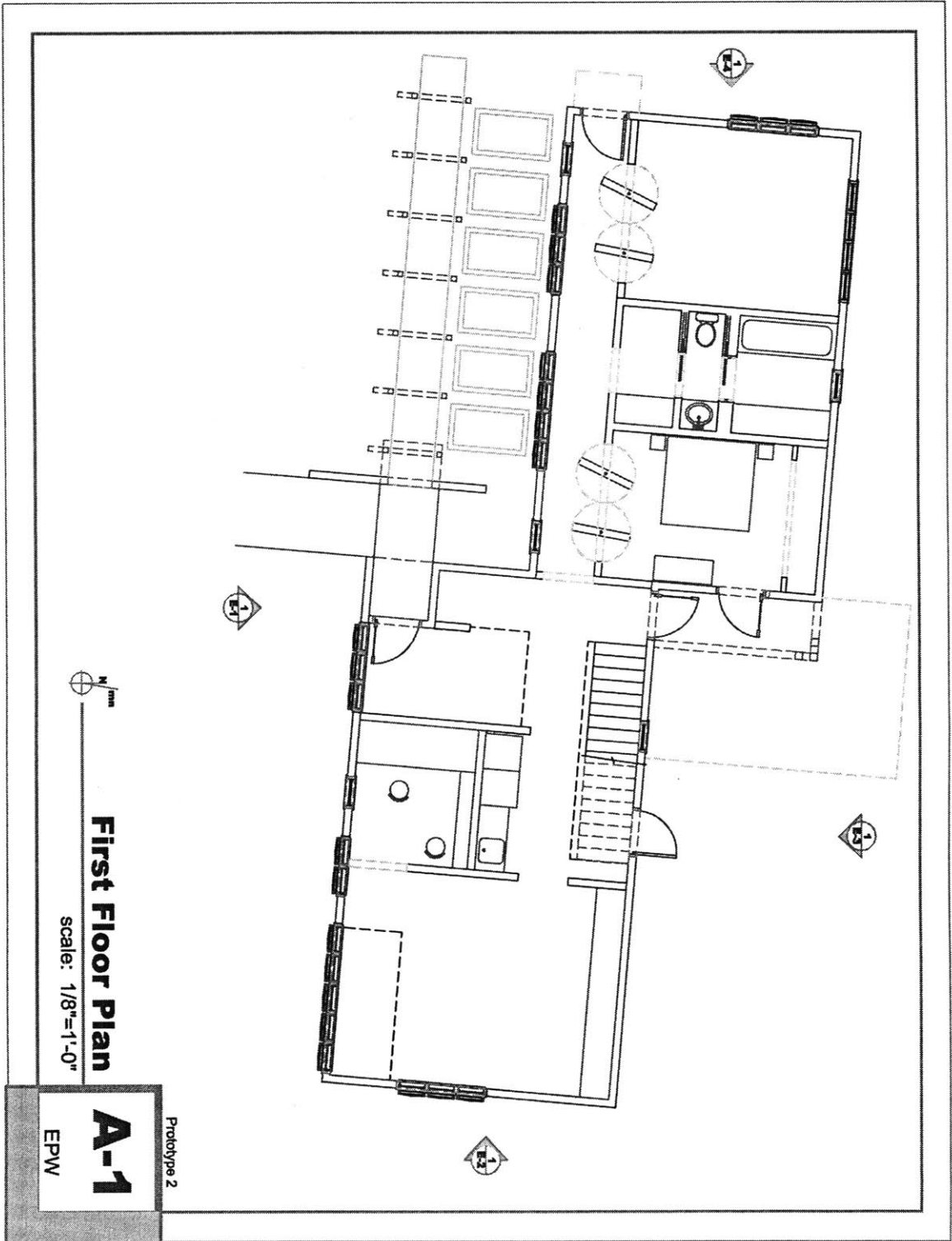


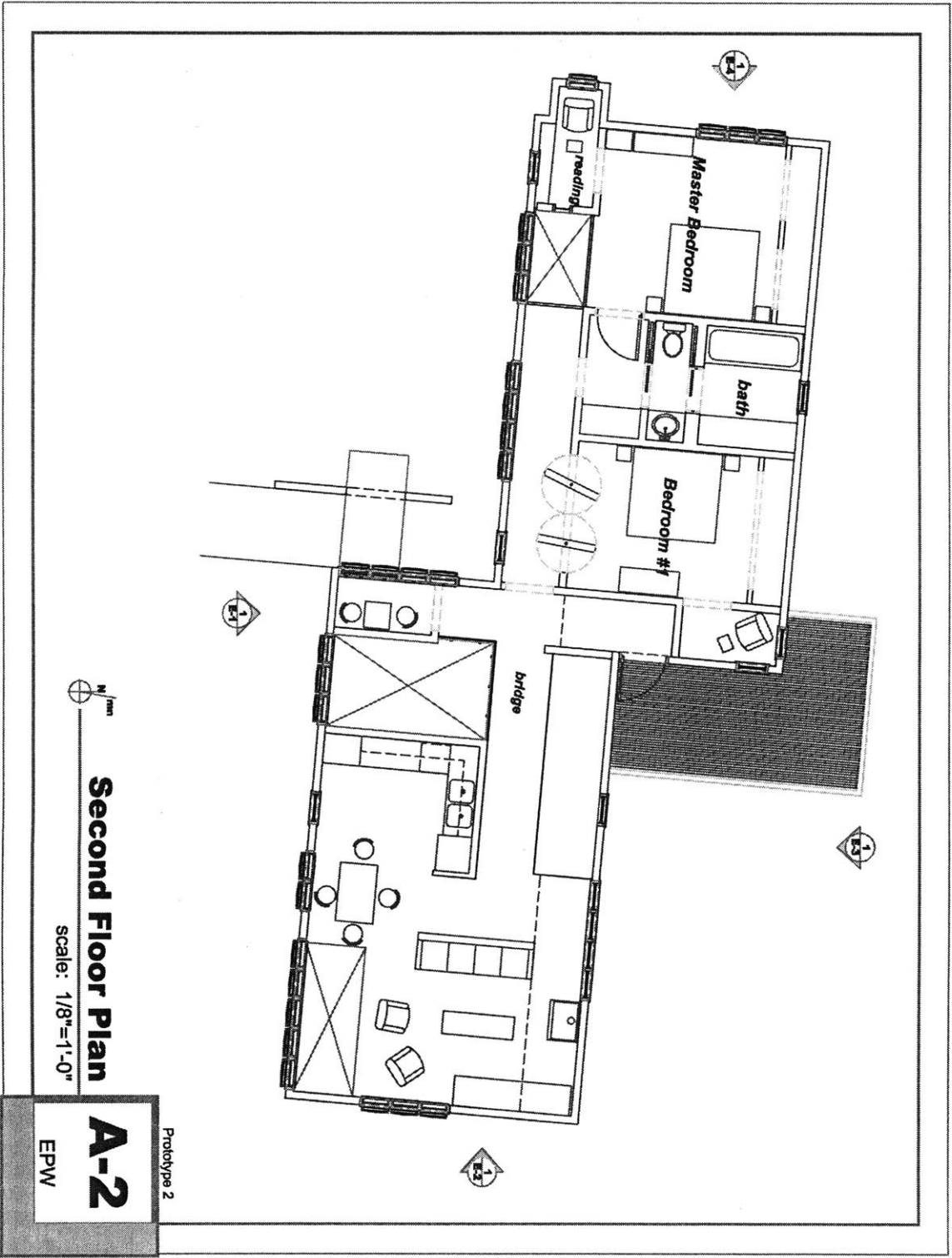
**2nd FIR Wall Sequence**

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**W-2**  
EPW

Prototype 2

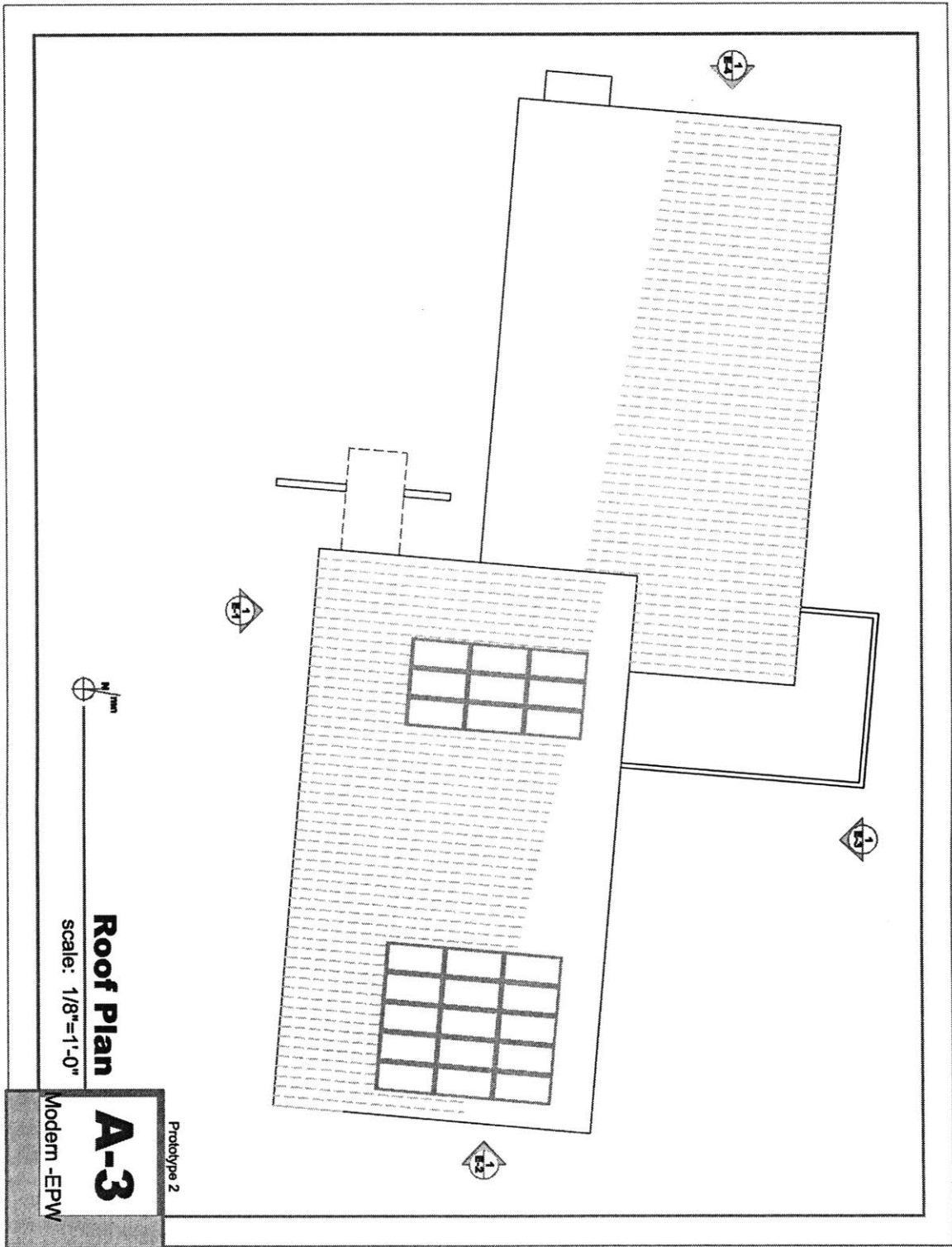





  
**Second Floor Plan**  
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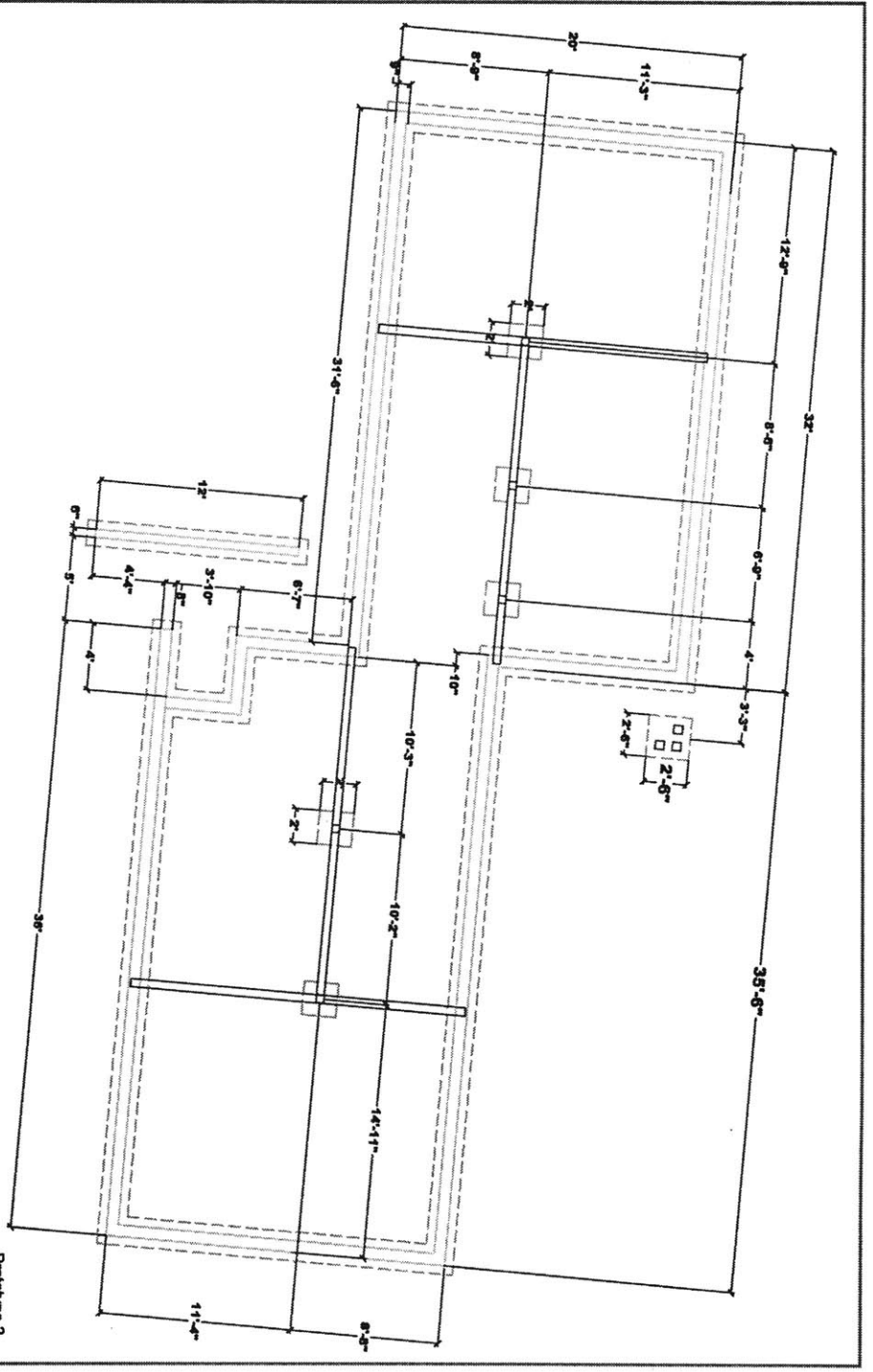
**A-2**  
 EPW

Prototype 2



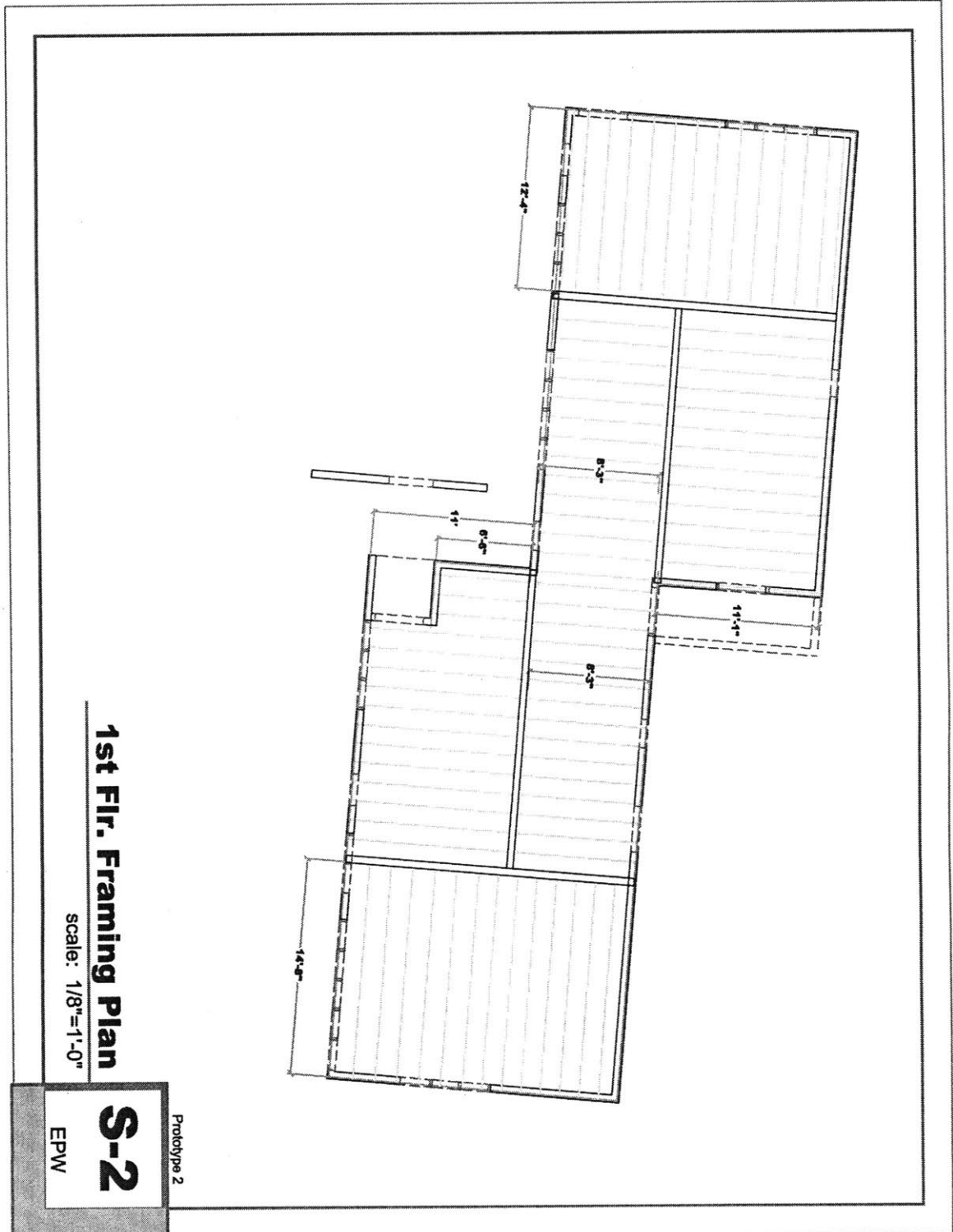
**Roof Plan**  
 scale: 1/8"=1'-0"

**A-3**  
 Modern -EPV  
 Prototype 2



**Foundation Plan**  
 scale: 1/8"=1'-0"

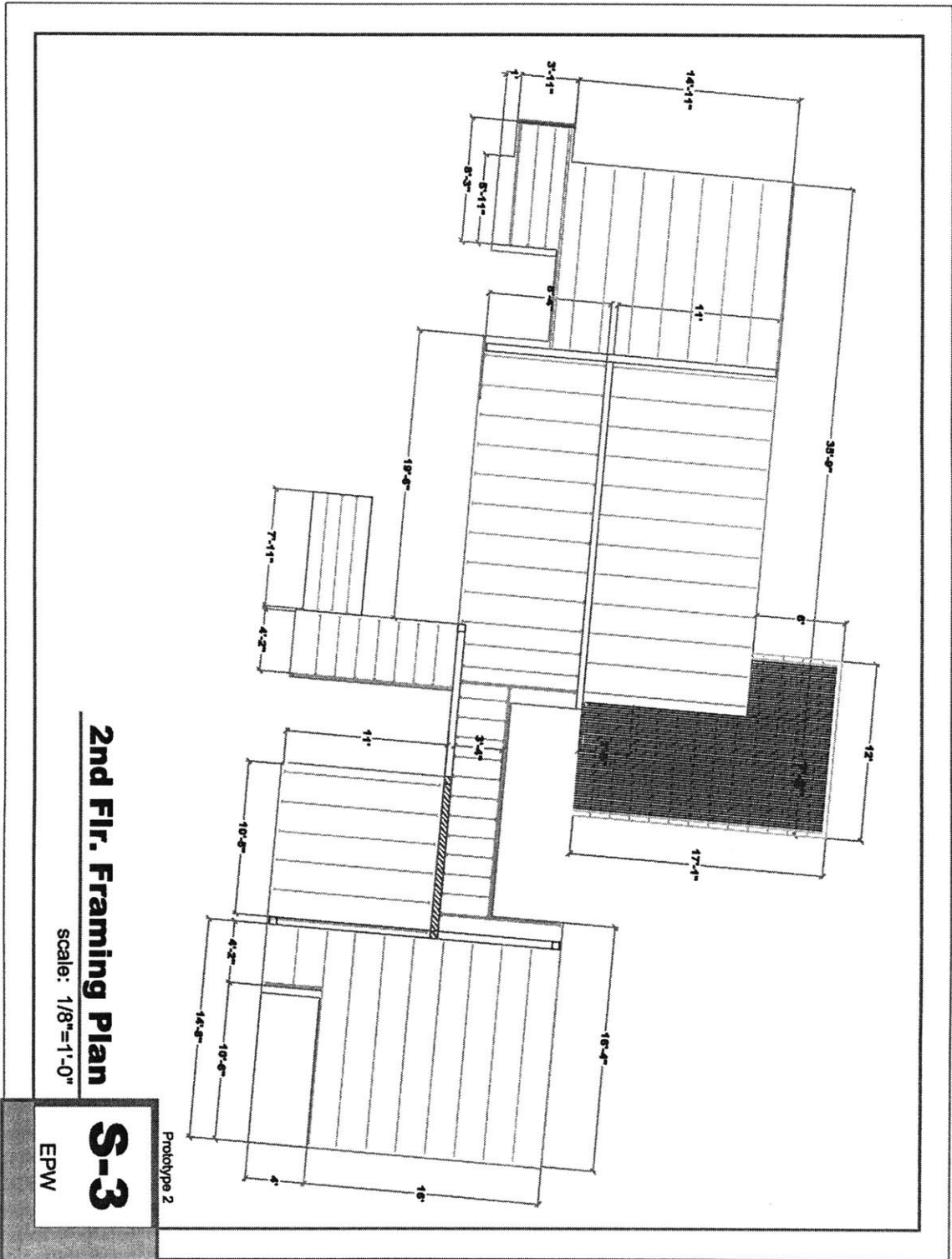
**S-1**  
 EPW  
 Prototype 2

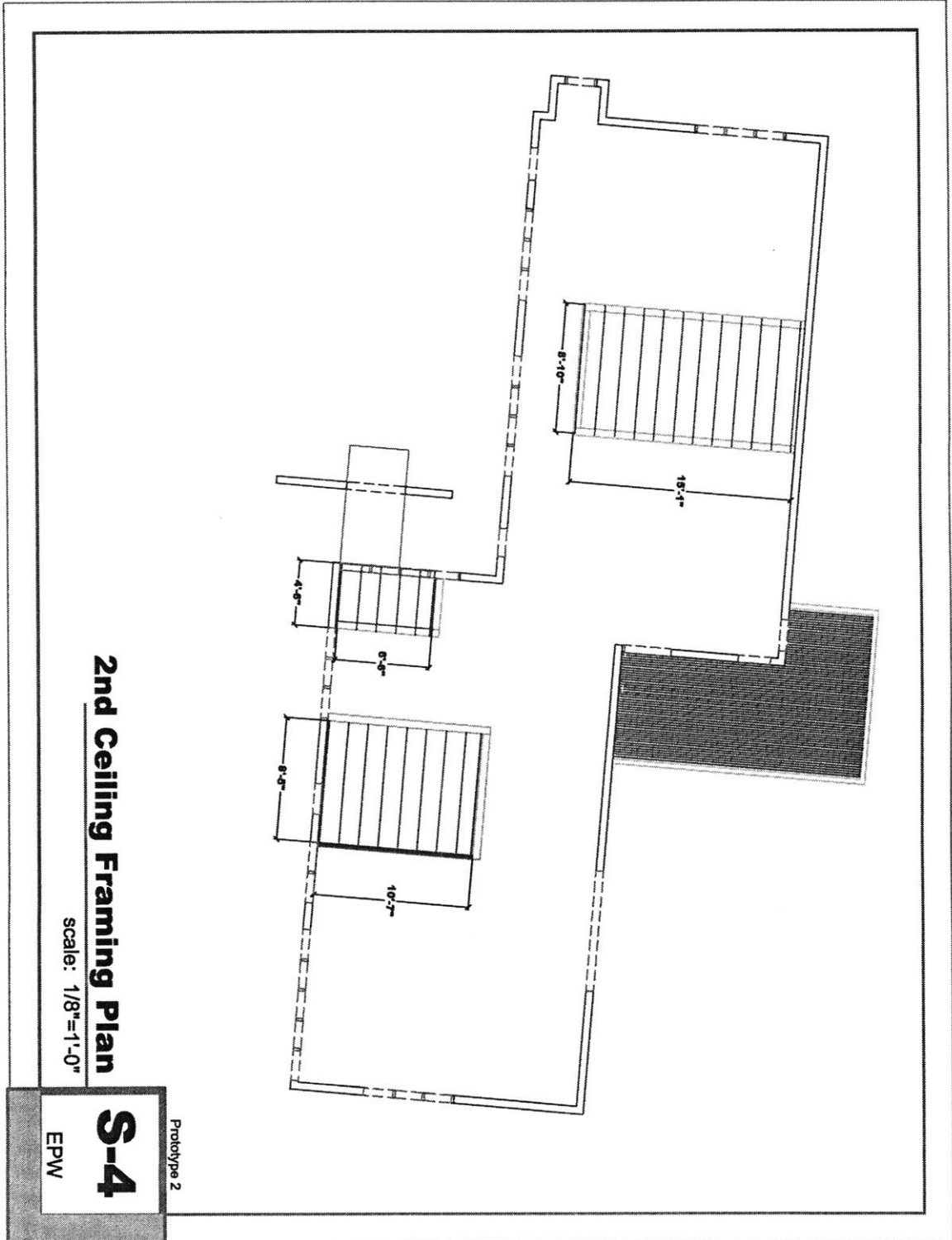


**1st Flr. Framing Plan**

scale: 1/8"=1'-0"

Prototype 2  
**S-2**  
 EPW



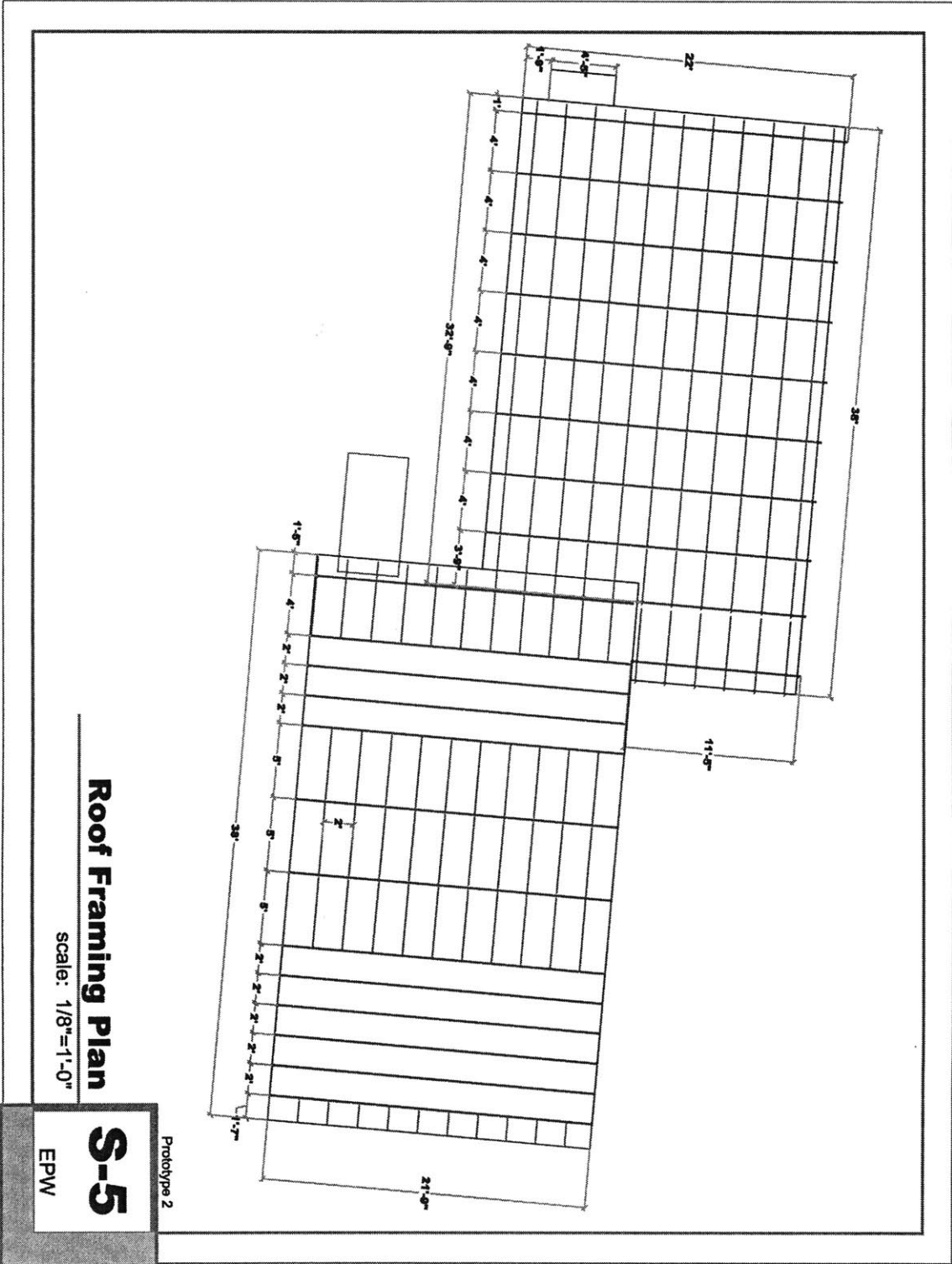


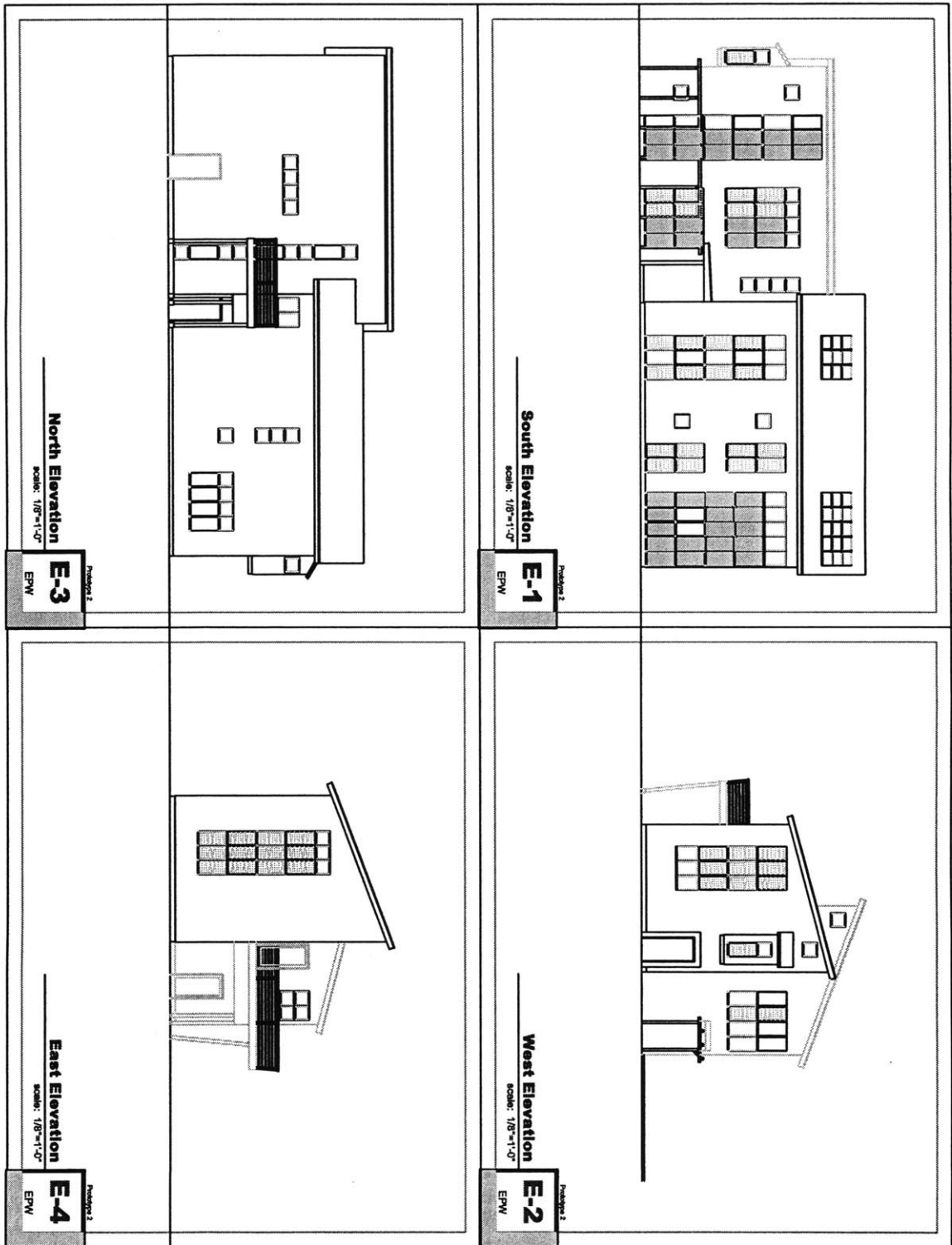
**2nd Ceiling Framing Plan**

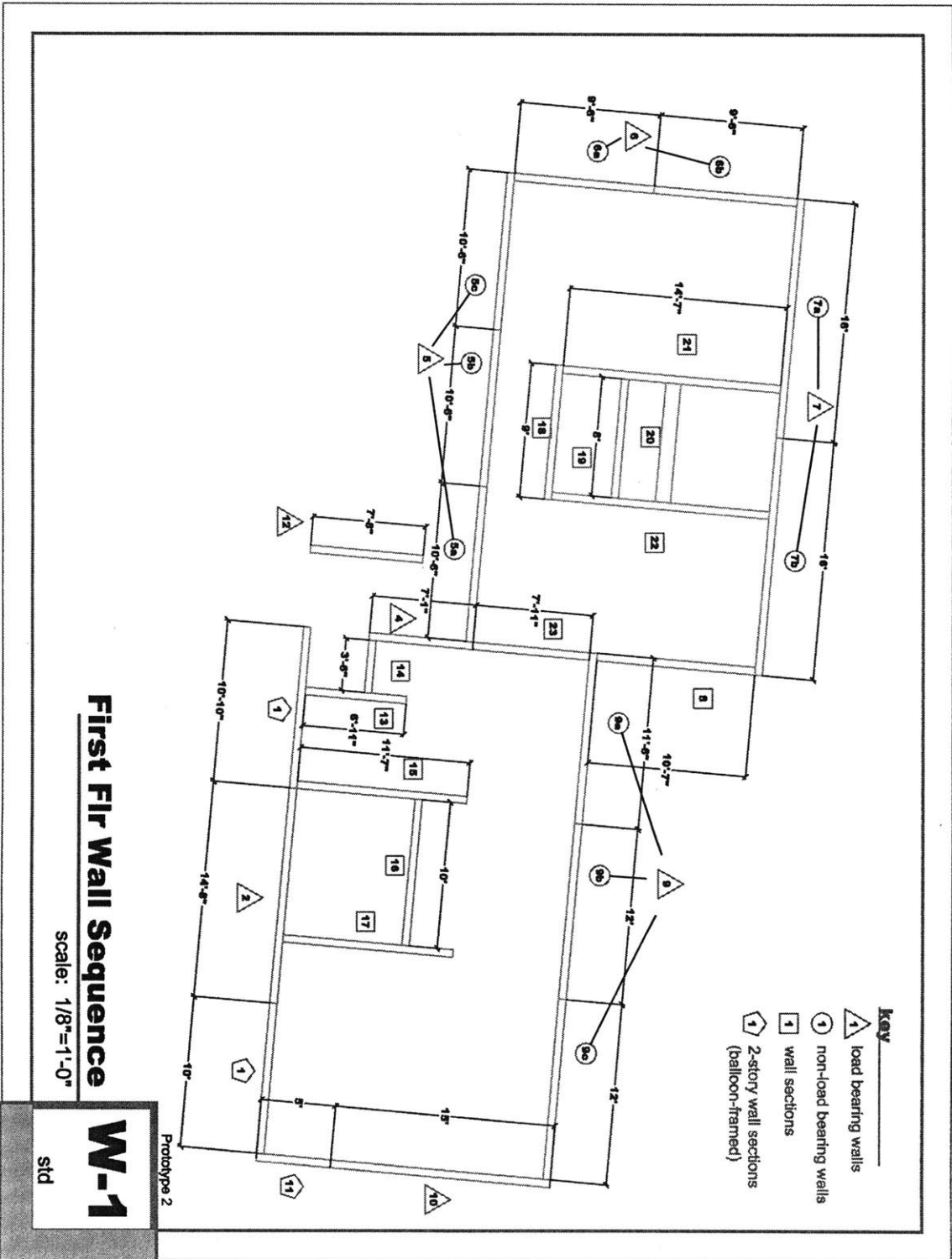
scale: 1/8"=1'-0"

Prototype 2  
**S-4**  
 EPW









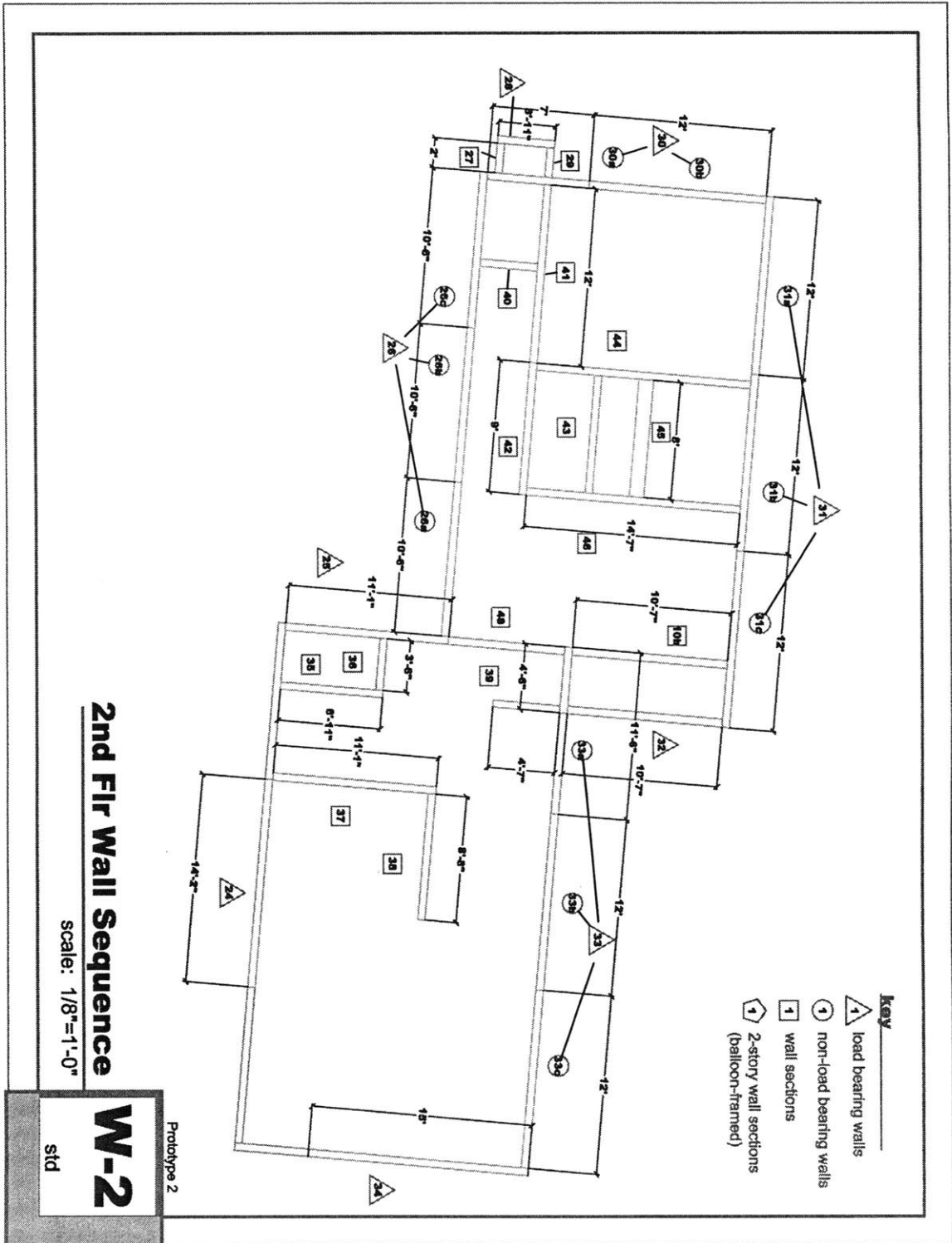
**First Flr Wall Sequence**

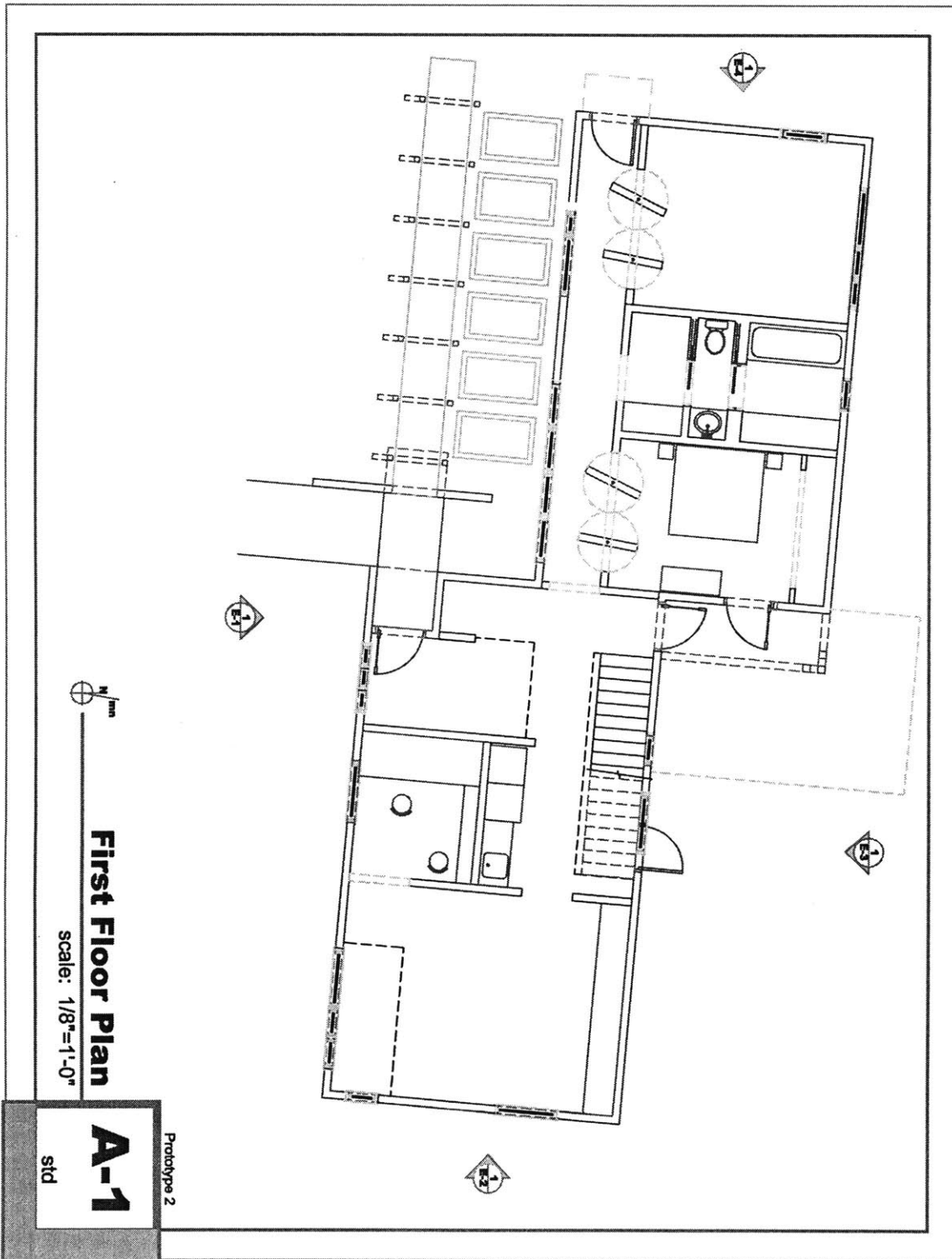
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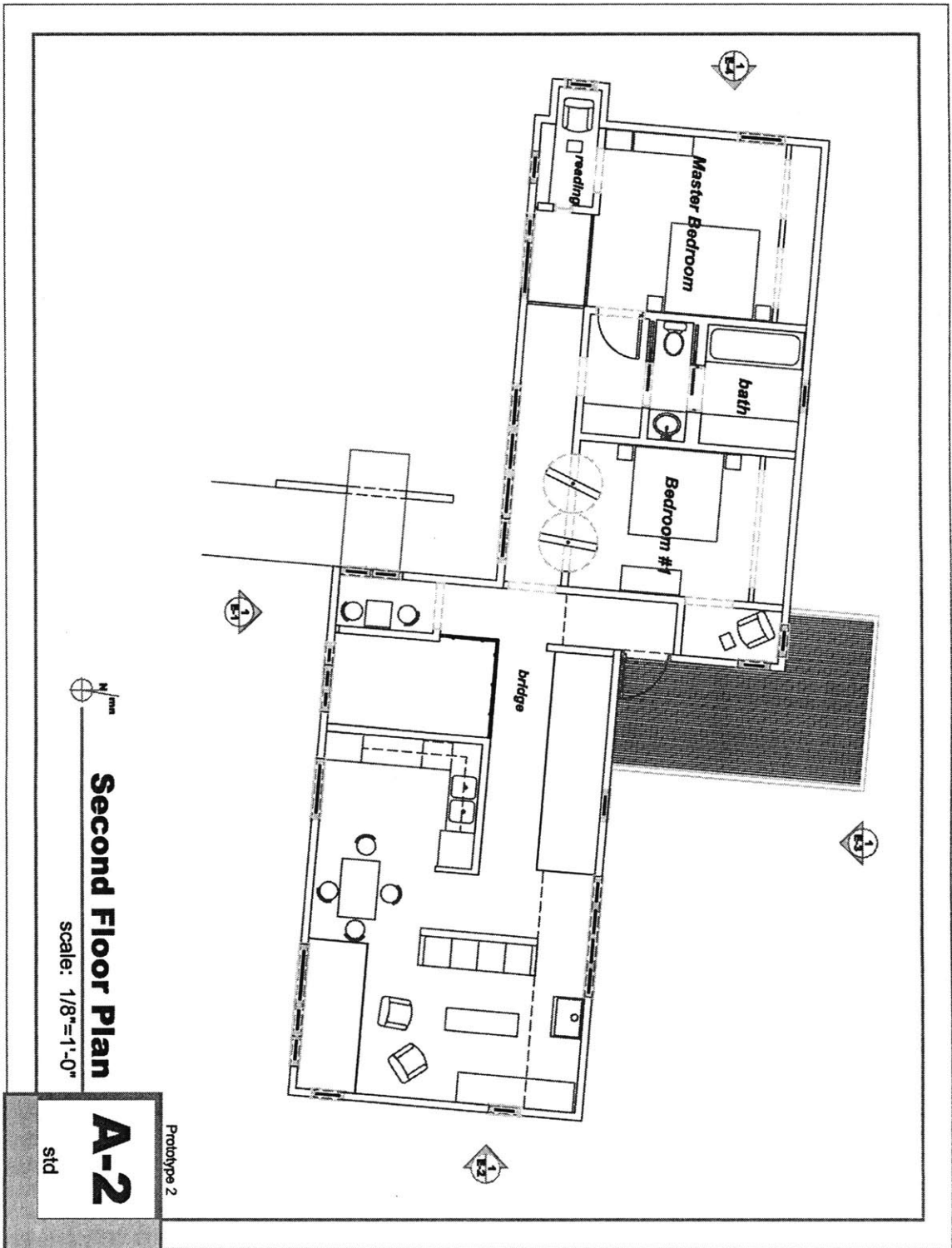
Prototype 2

**W-1**

std







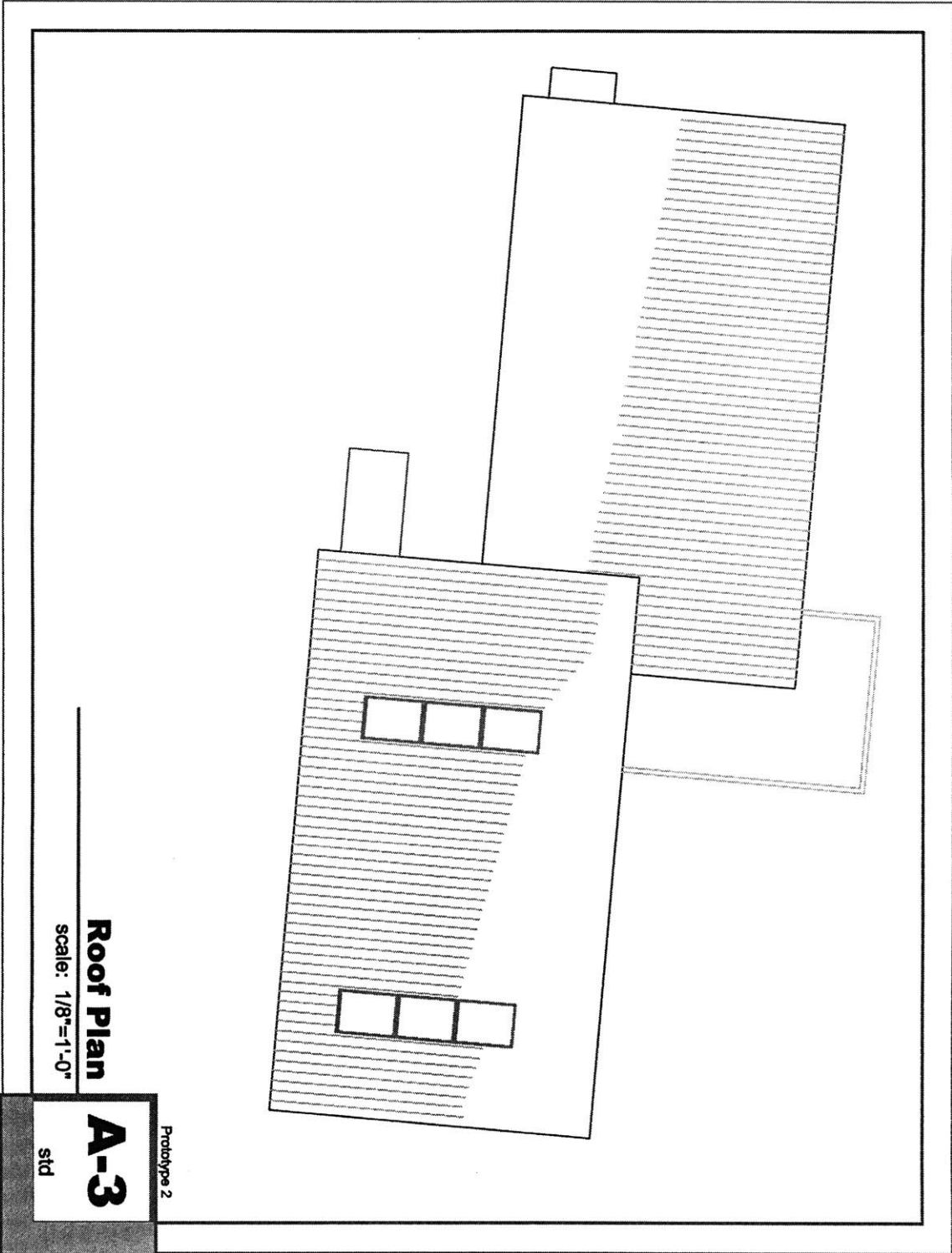
**Second Floor Plan**

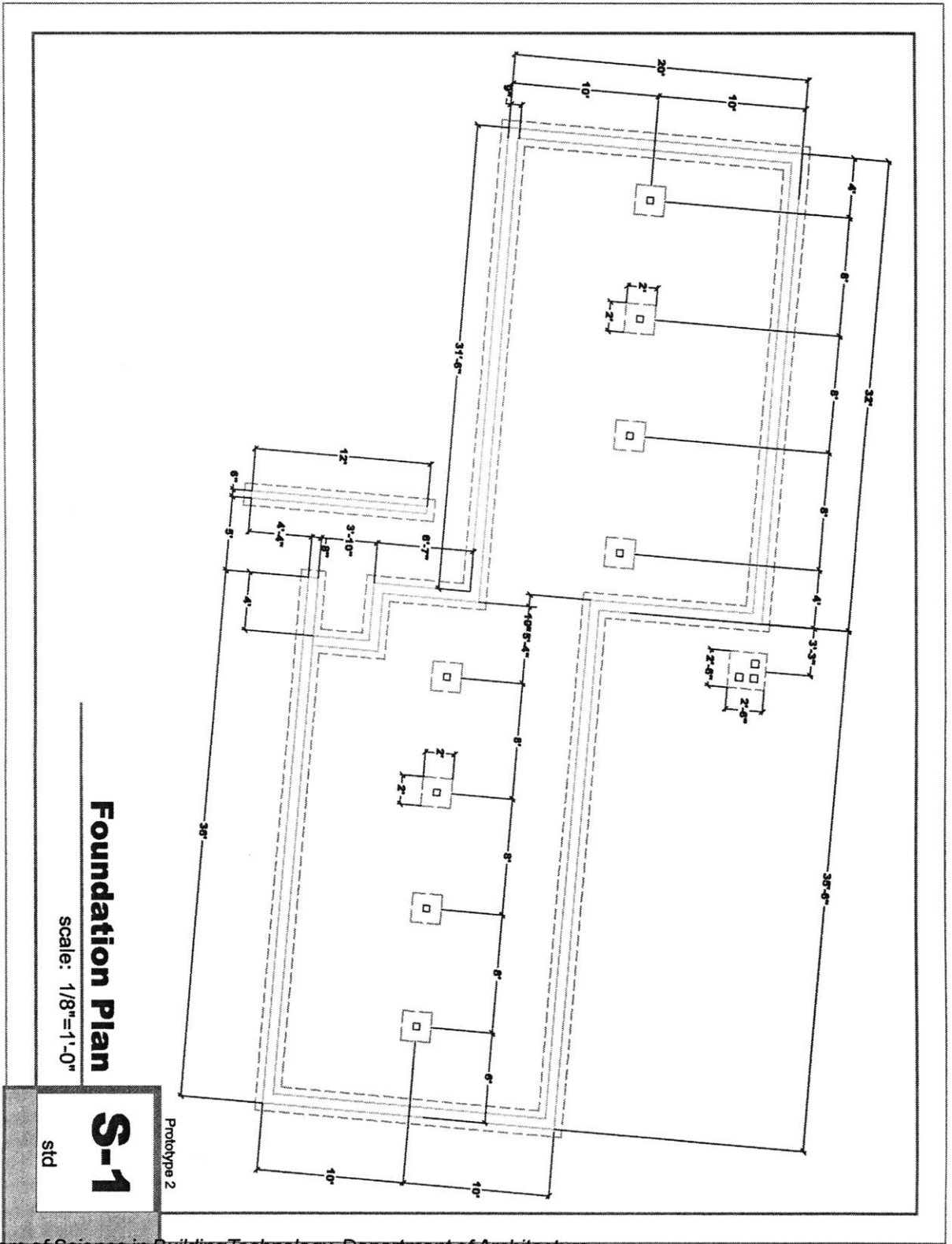
scale: 1/8"=1'-0"

**A-2**

std

Prototype 2



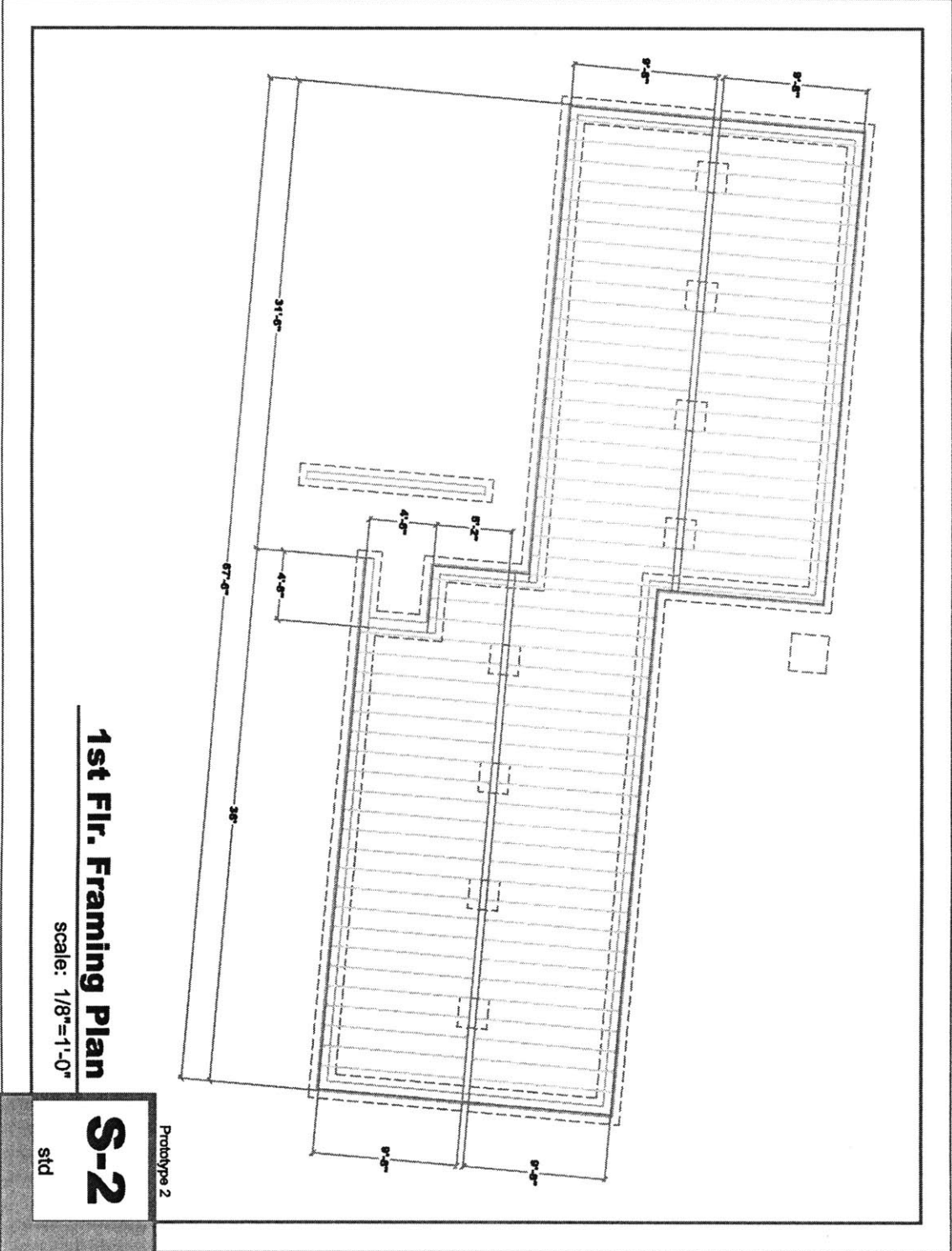


**Foundation Plan**  
 scale: 1/8"=1'-0"

**S-1**  
 std

Prototype 2





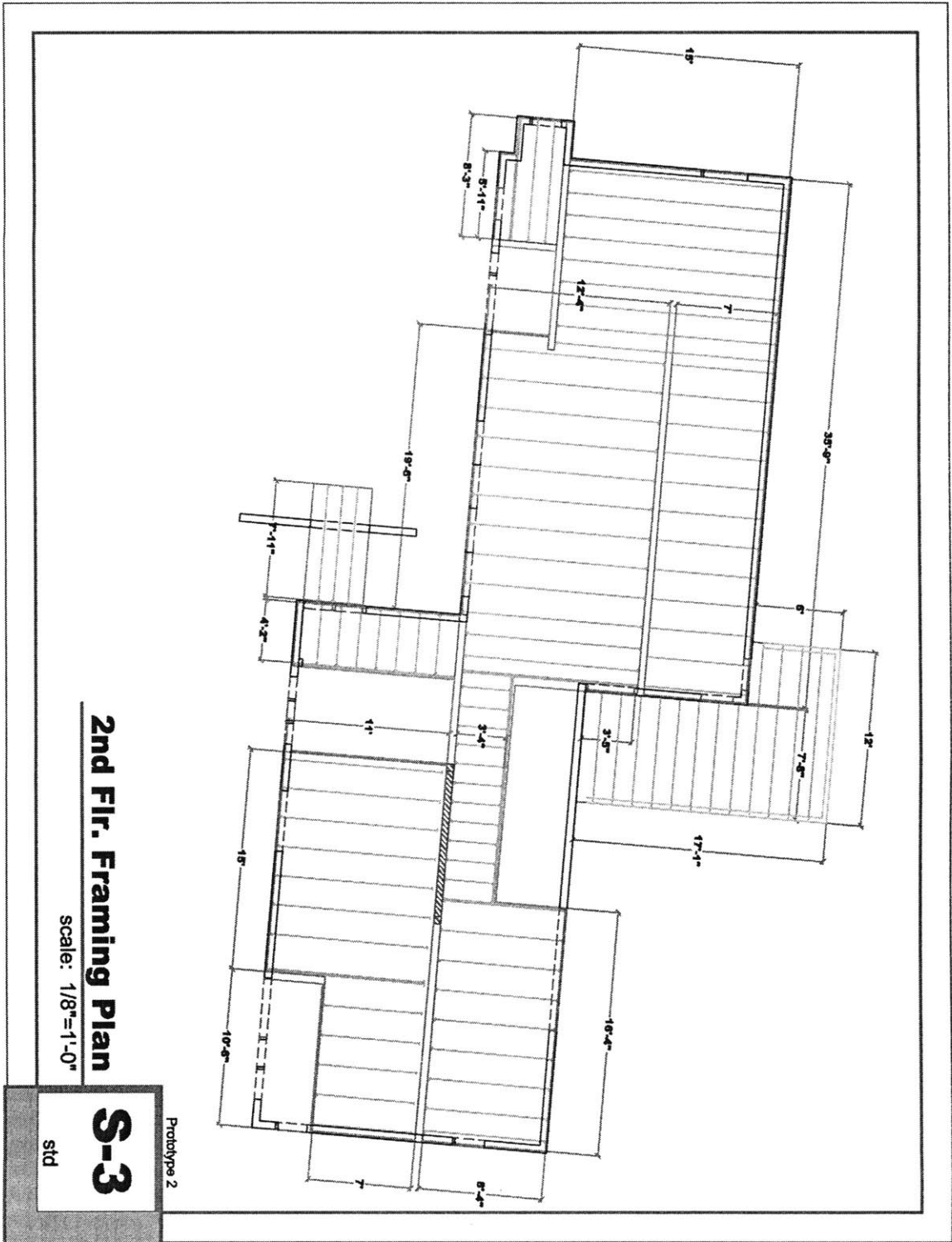
**1st Fir. Framing Plan**

scale: 1/8"=1'-0"

**S-2**

std

Prototype 2



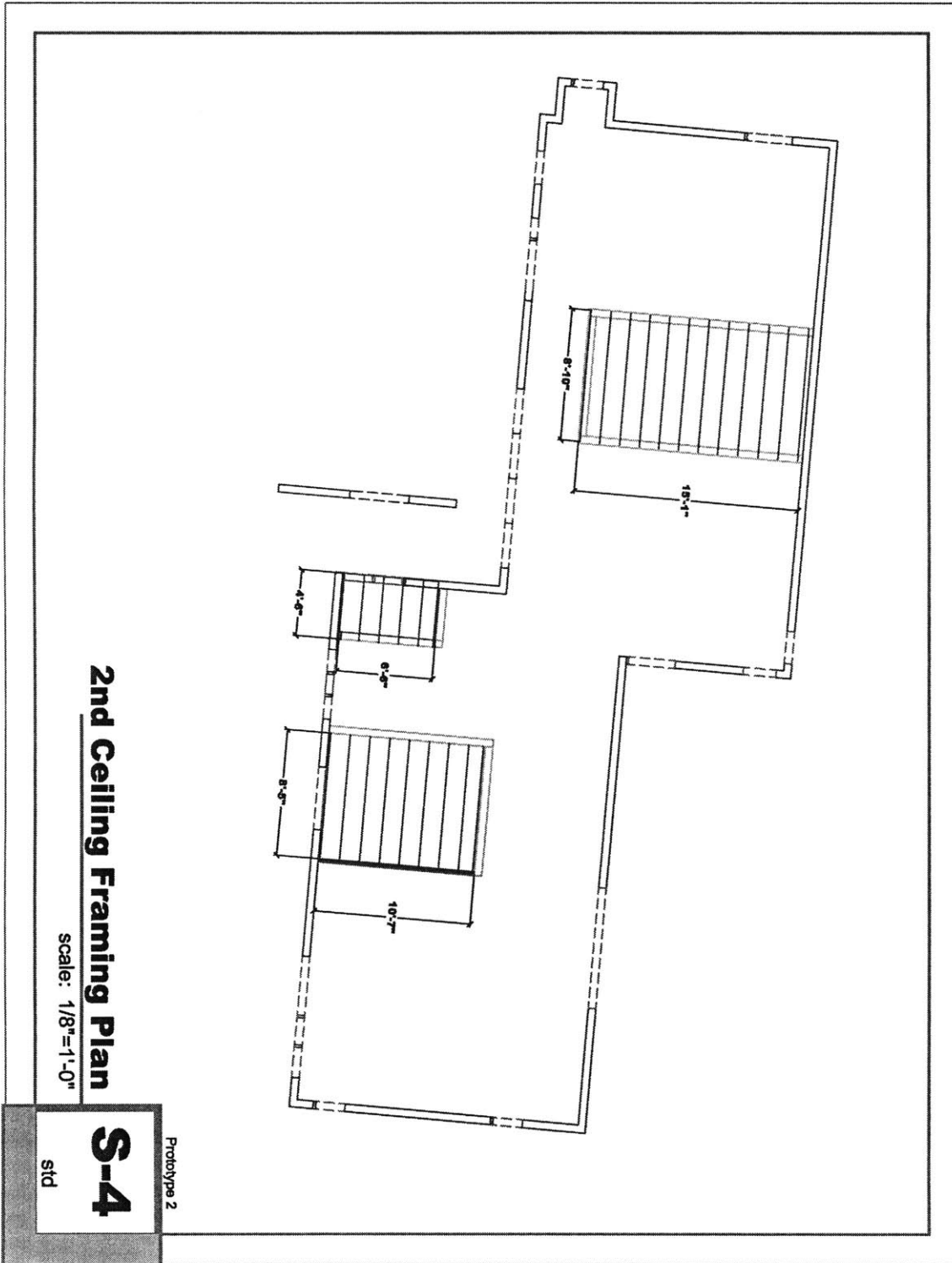
**2nd Flr. Framing Plan**

scale: 1/8"=1'-0"

**S-3**

std

Prototype 2

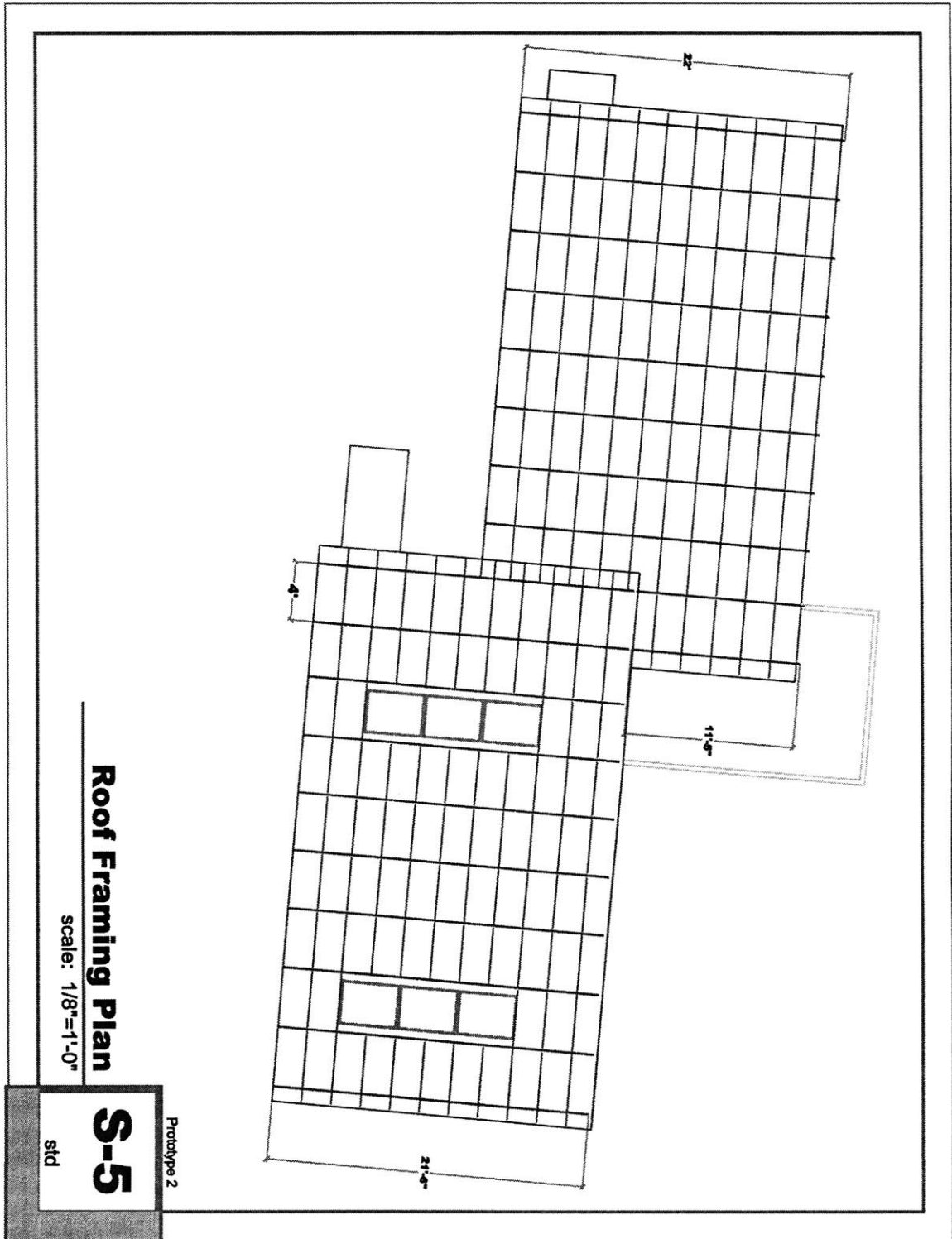


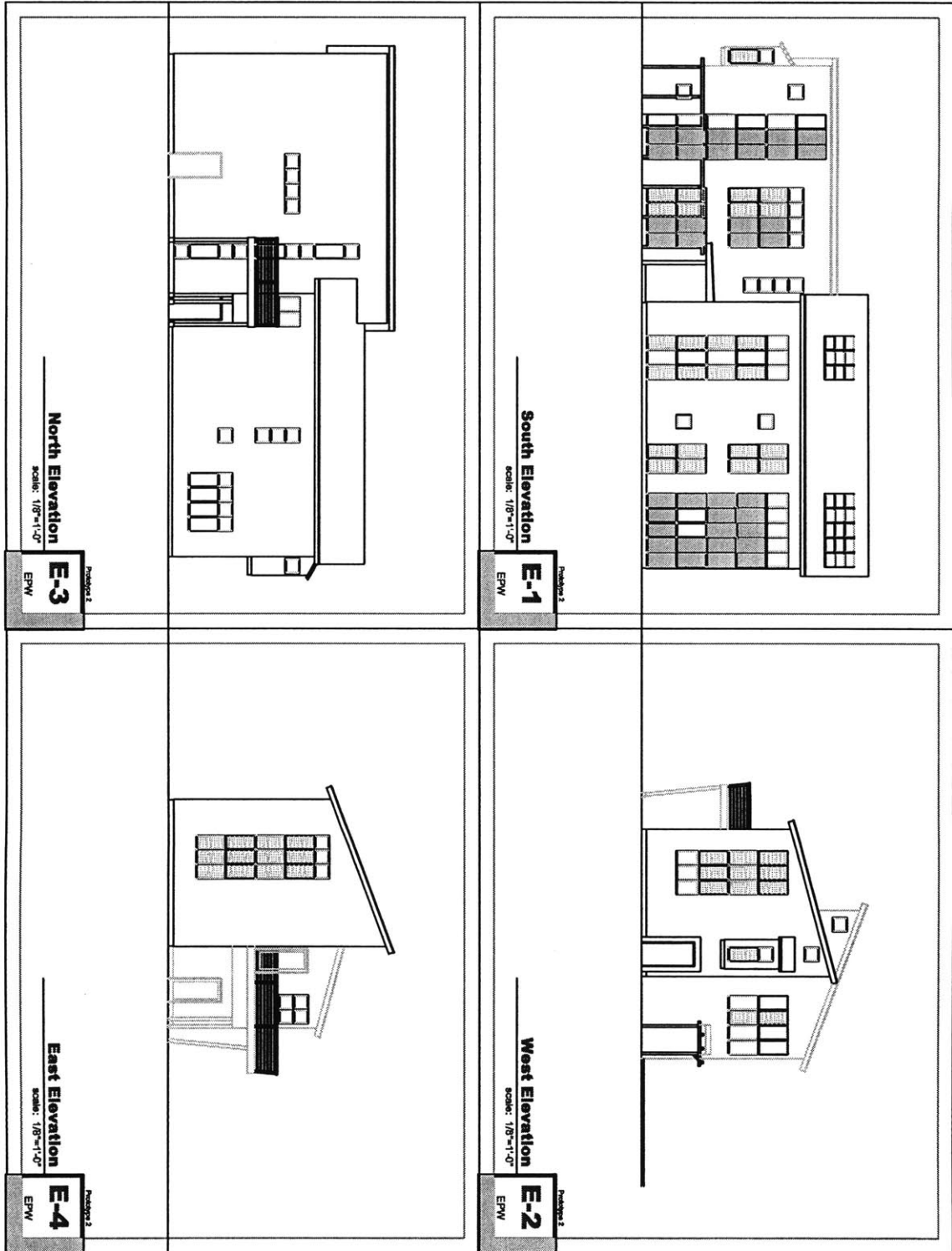
**2nd Ceiling Framing Plan**

scale: 1/8"=1'-0"

**S-4**  
std

Prototype 2





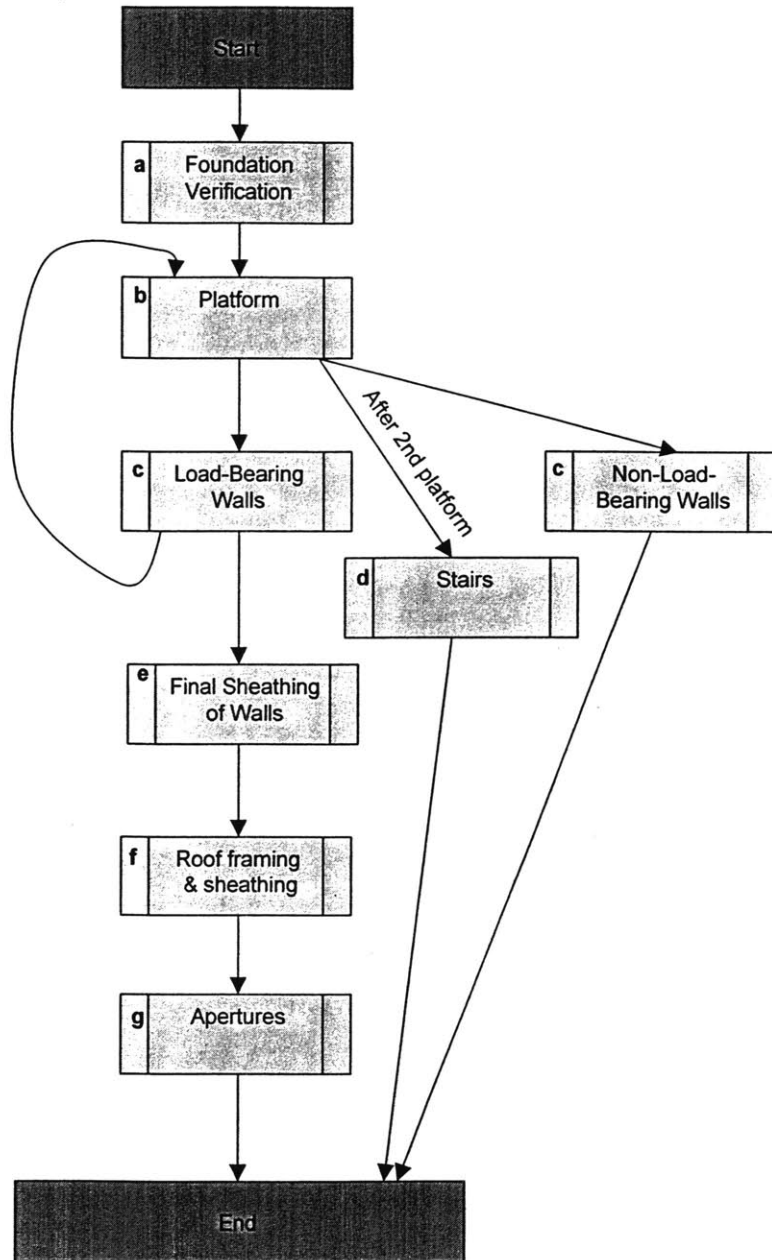




## Appendix C

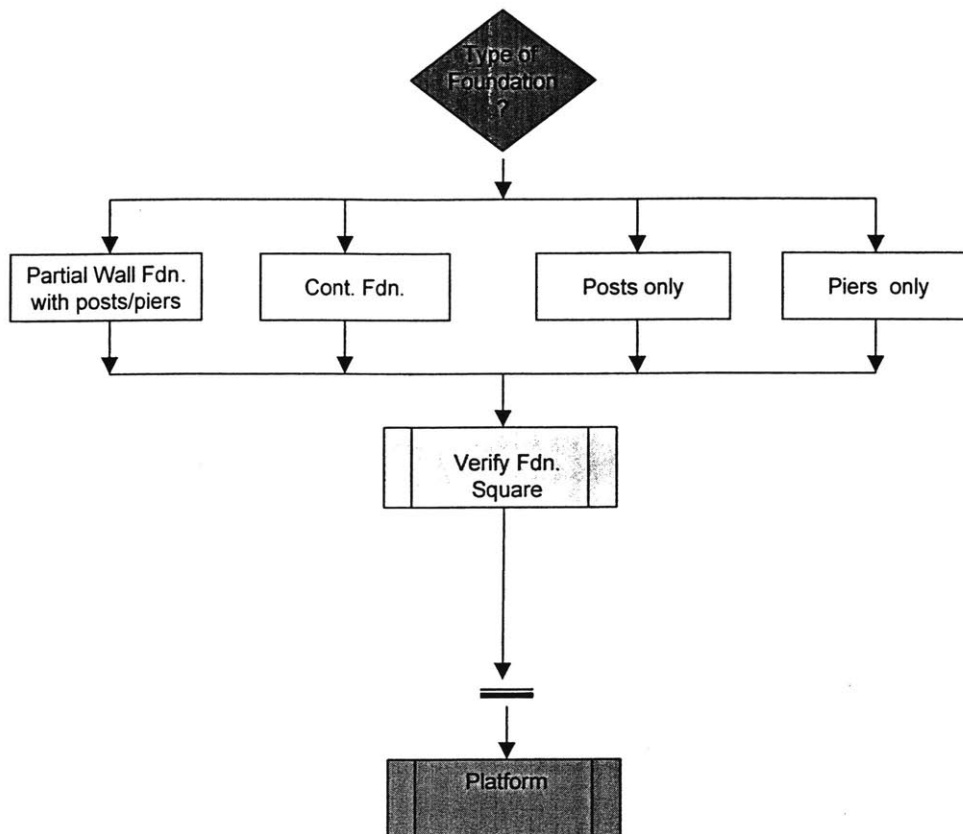
### Construction Process Flow Diagram

# 1 Framing the Design

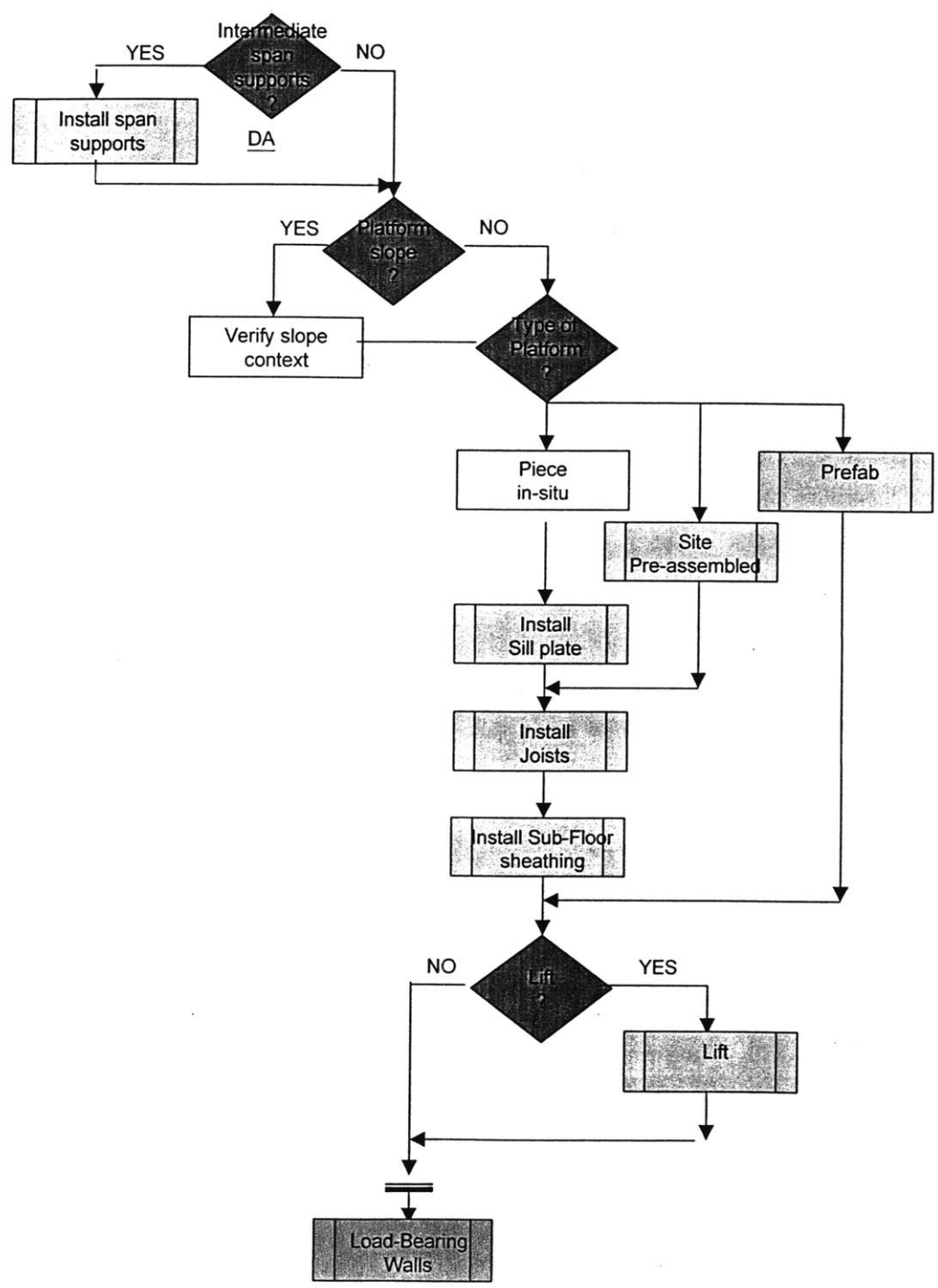




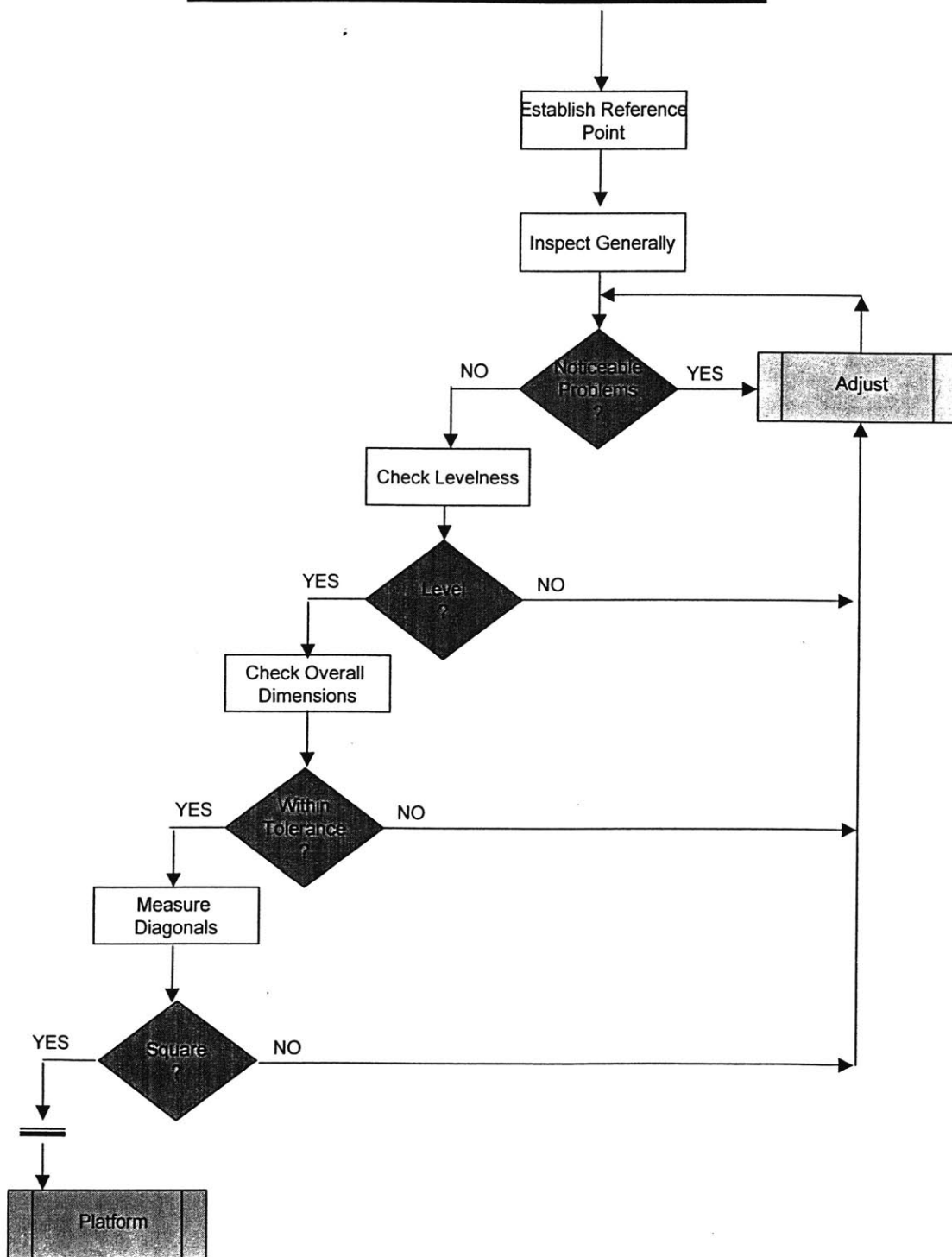
## 2 a: Foundation Preparation



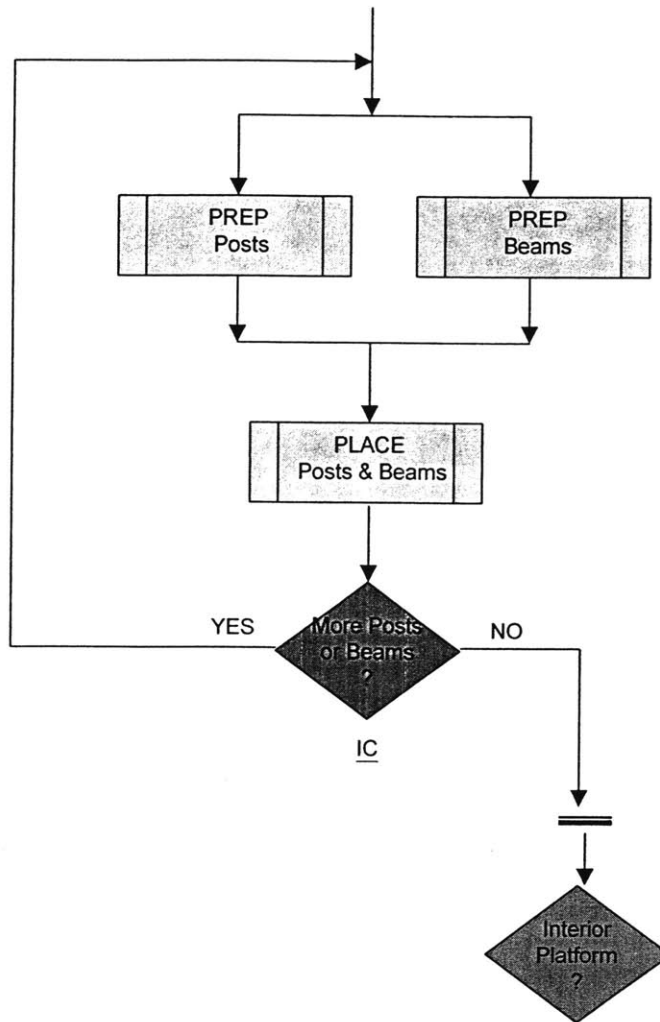
## 2 b: Platform



### 3 a: Verify Foundation Square

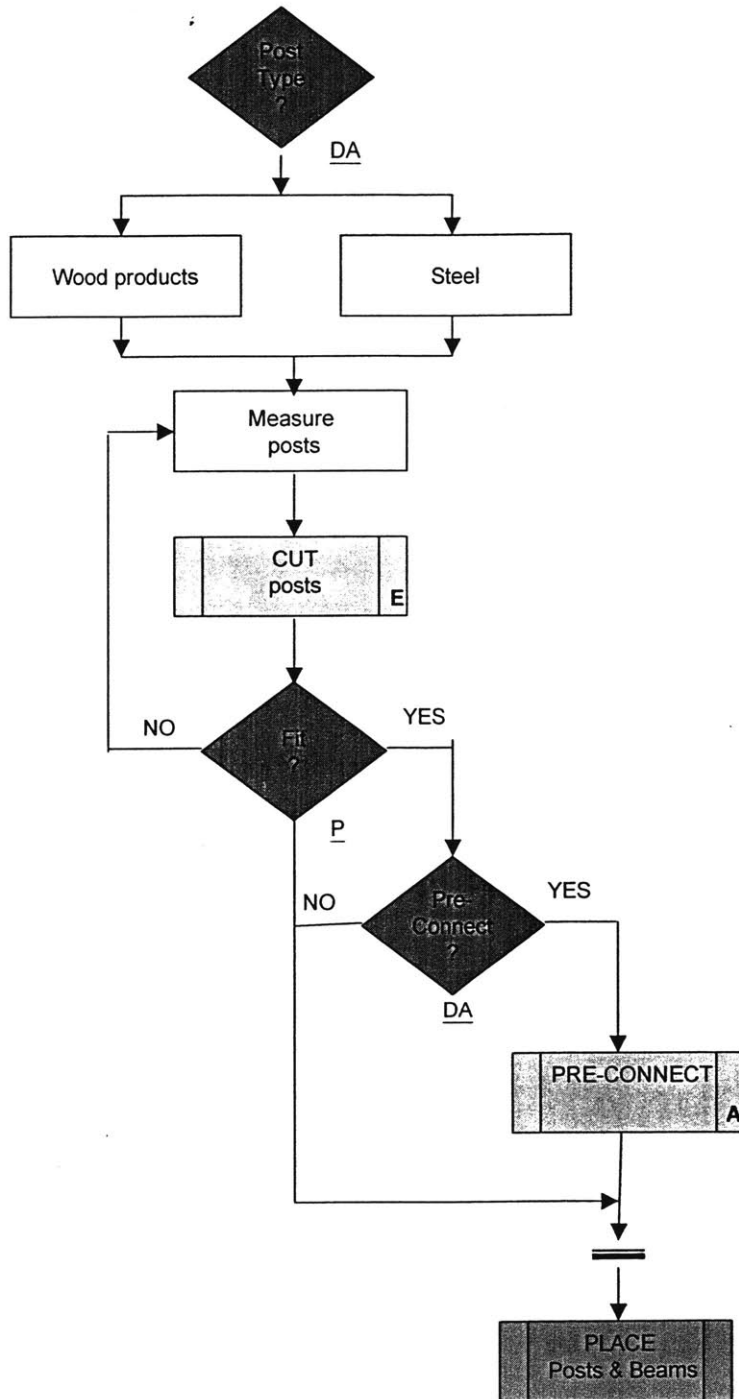


### 3 b: Install Span Supports



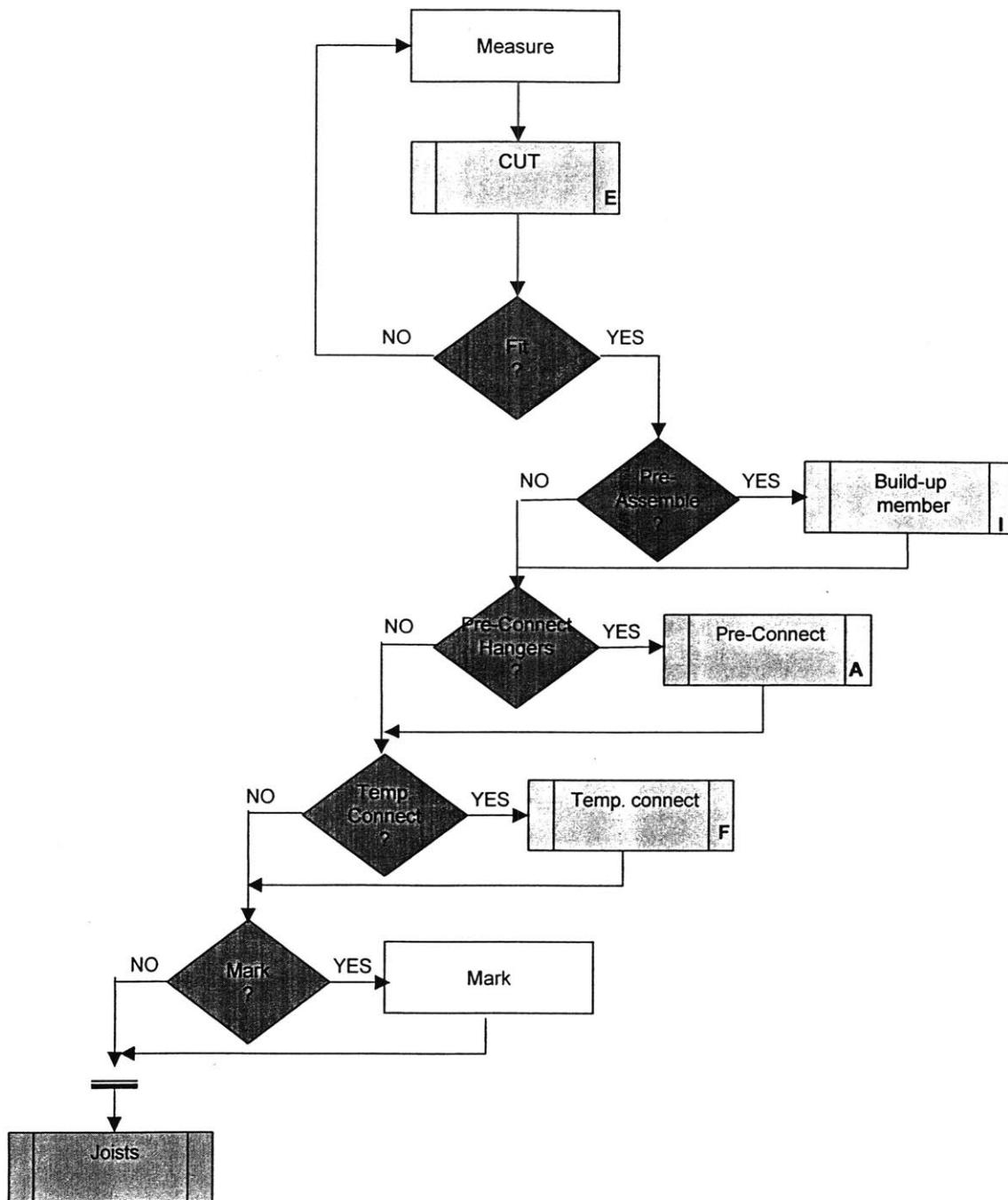
4

## b: Prep Posts

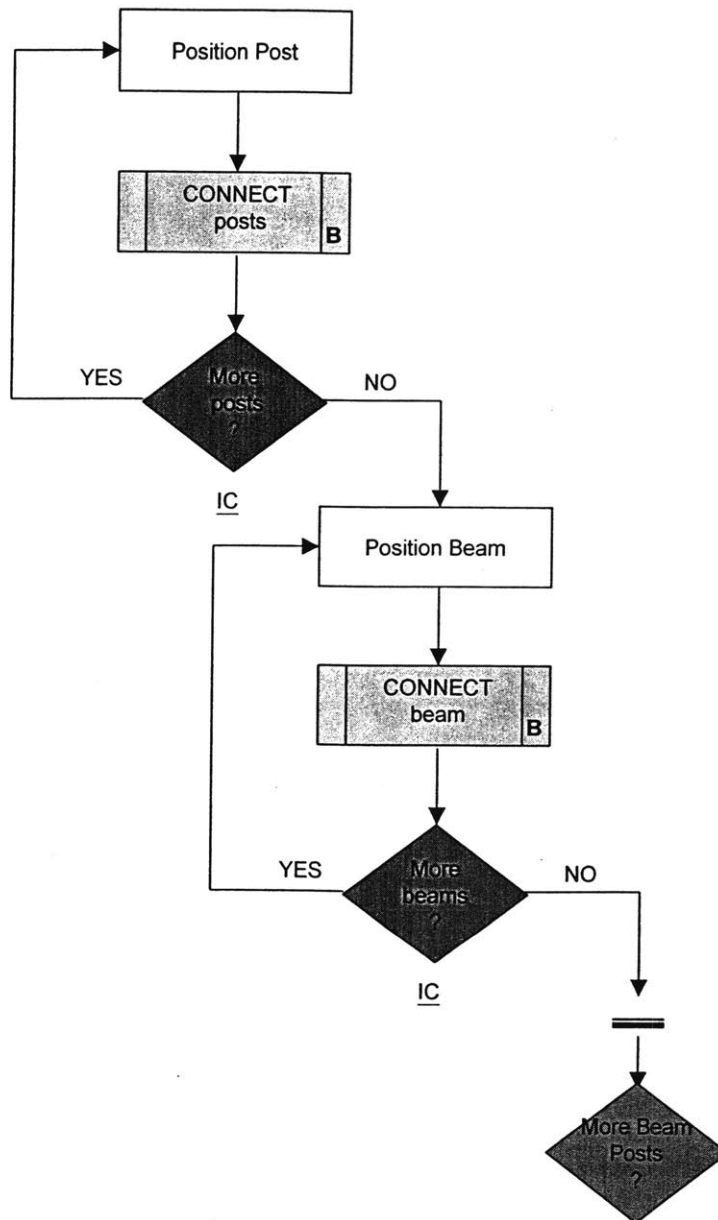


**4**

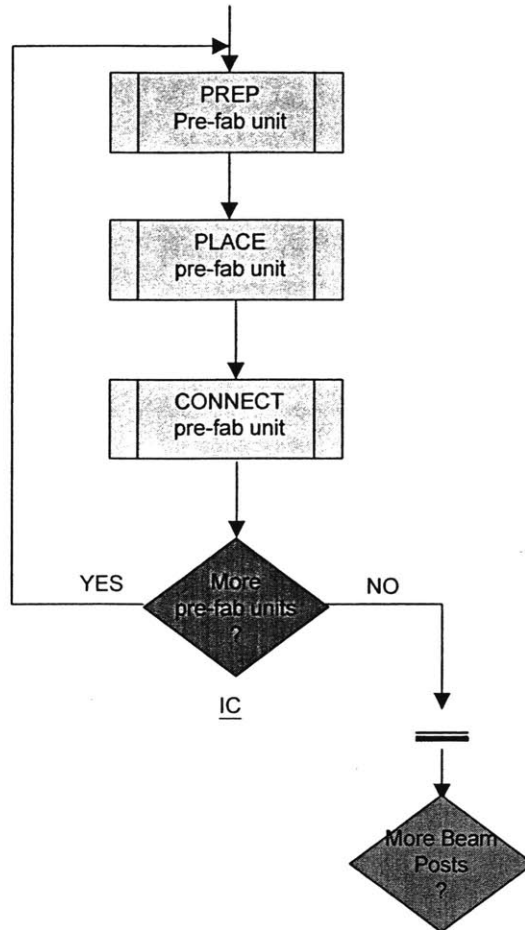
**b: Prep Beams**



## 4 b: Place Beams & Posts

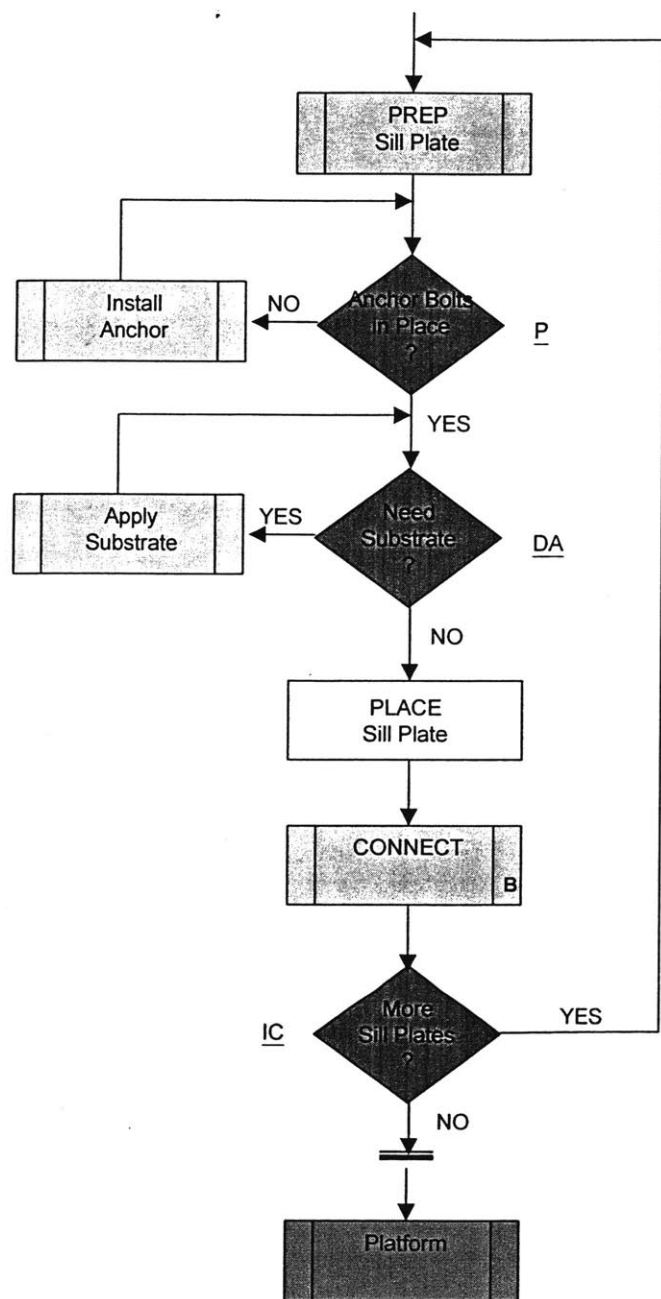


### 3 b: Pre-fab Platform

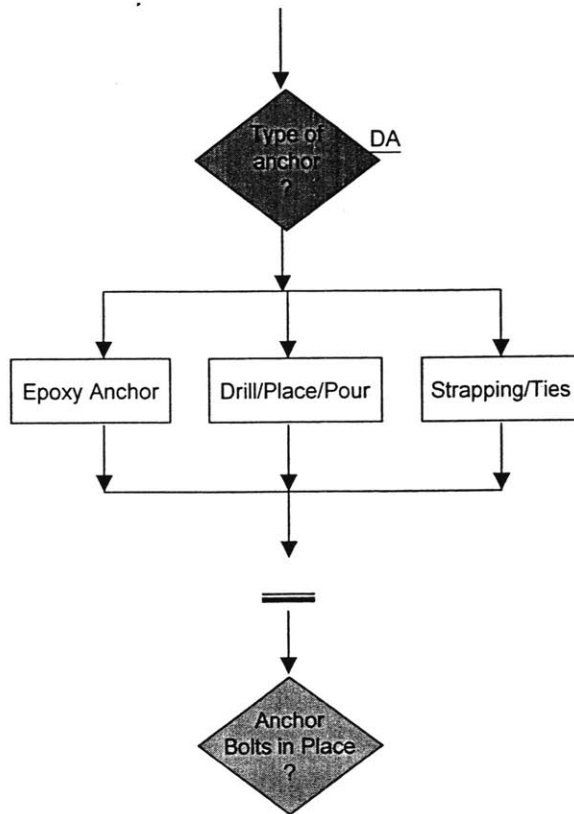




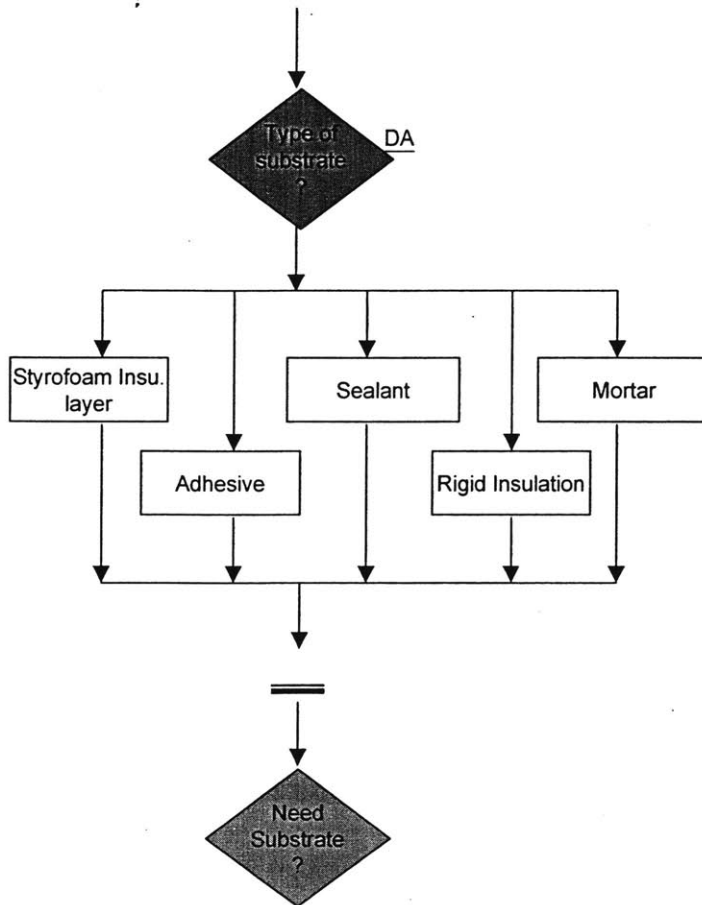
### **3** b: Install Sill Plate



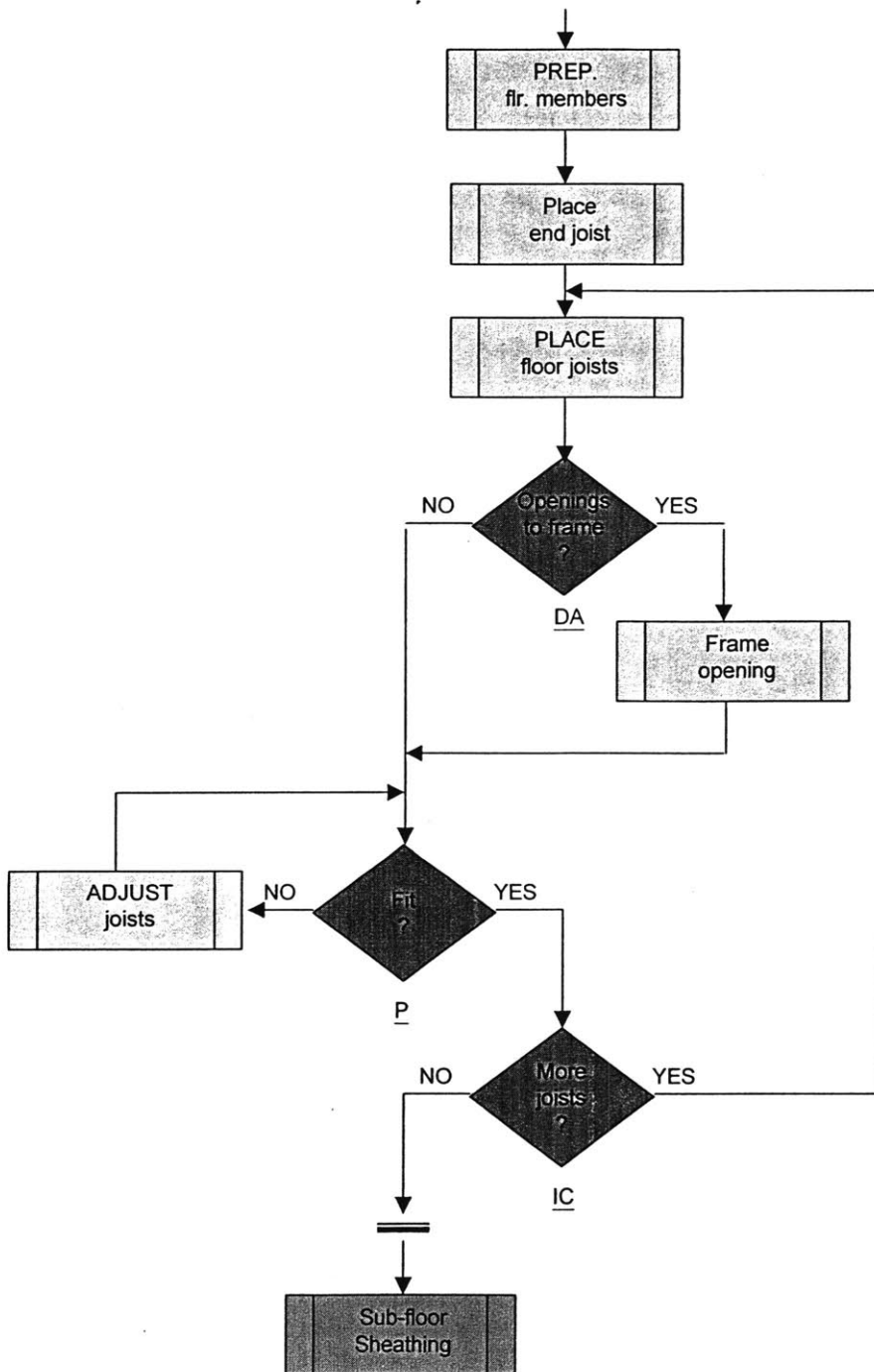
## **4 b: Install Anchor**



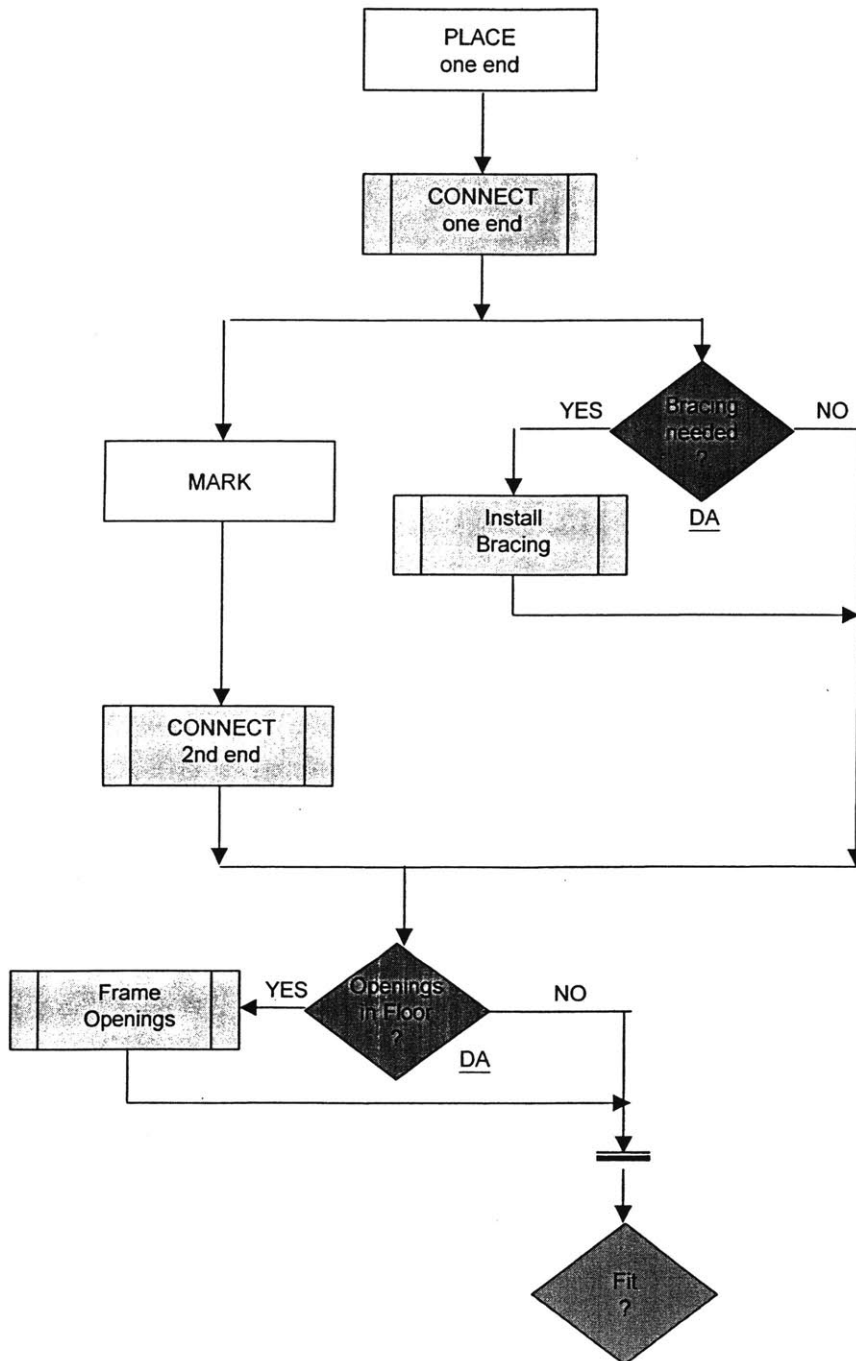
## **4 b: Apply Substrate**



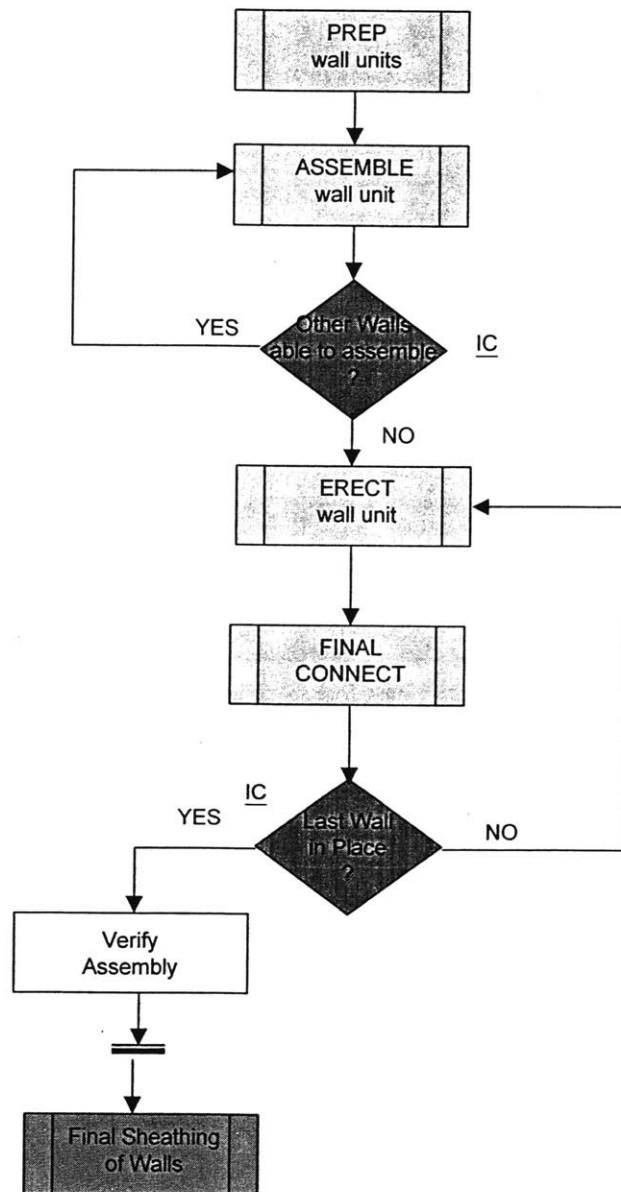
### **3** b: Install Joists



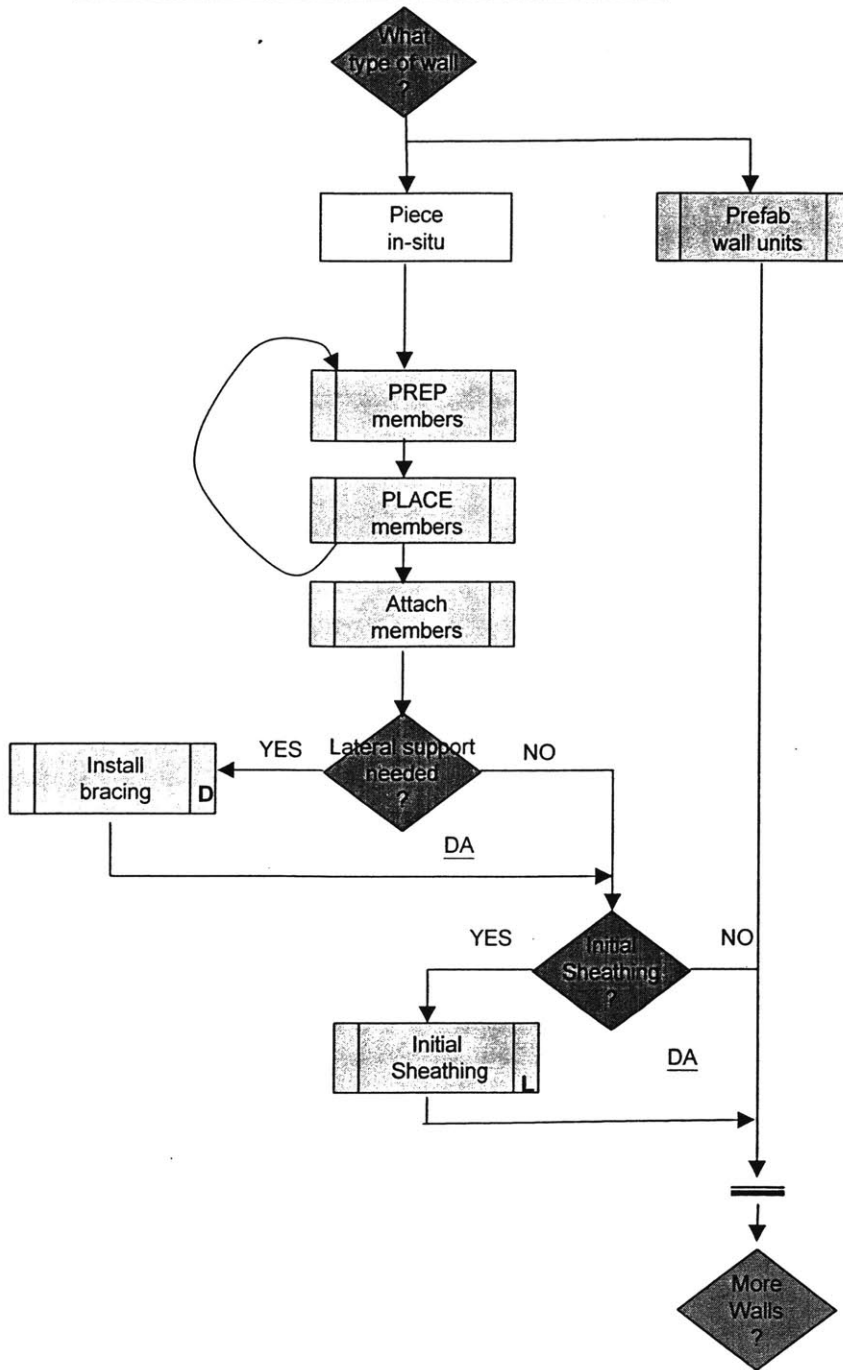
## 4 b: Place Floor Joists



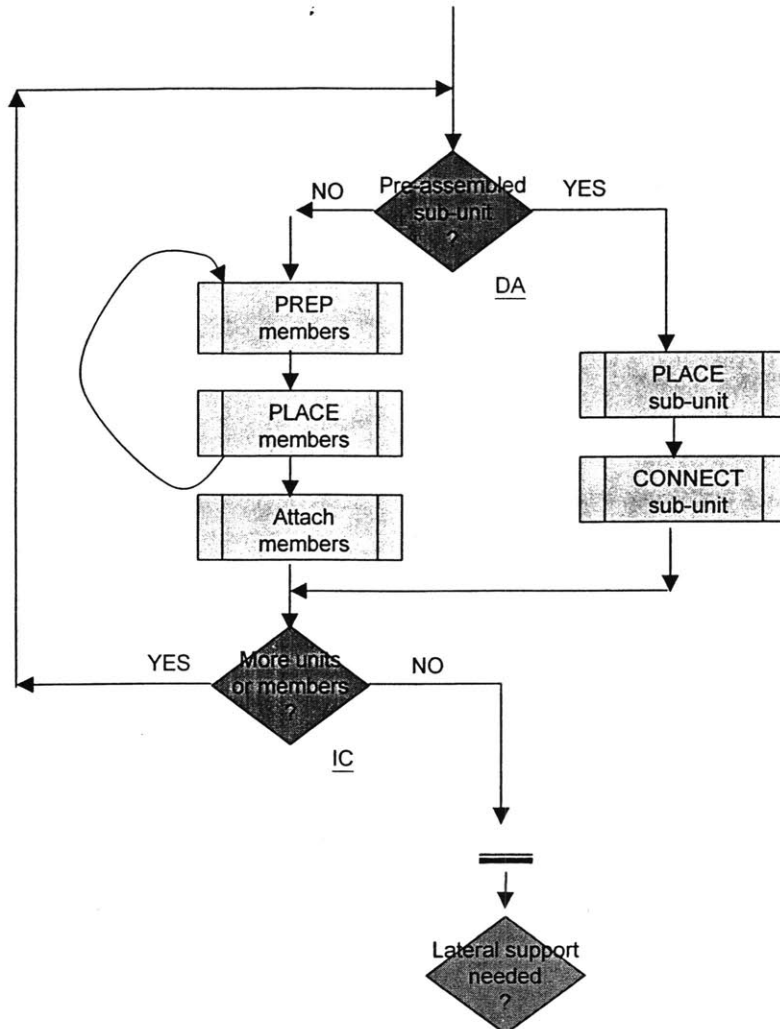
## 2c: Walls - load bearing/non-load bearing



### 3 c: Assemble Wall Unit



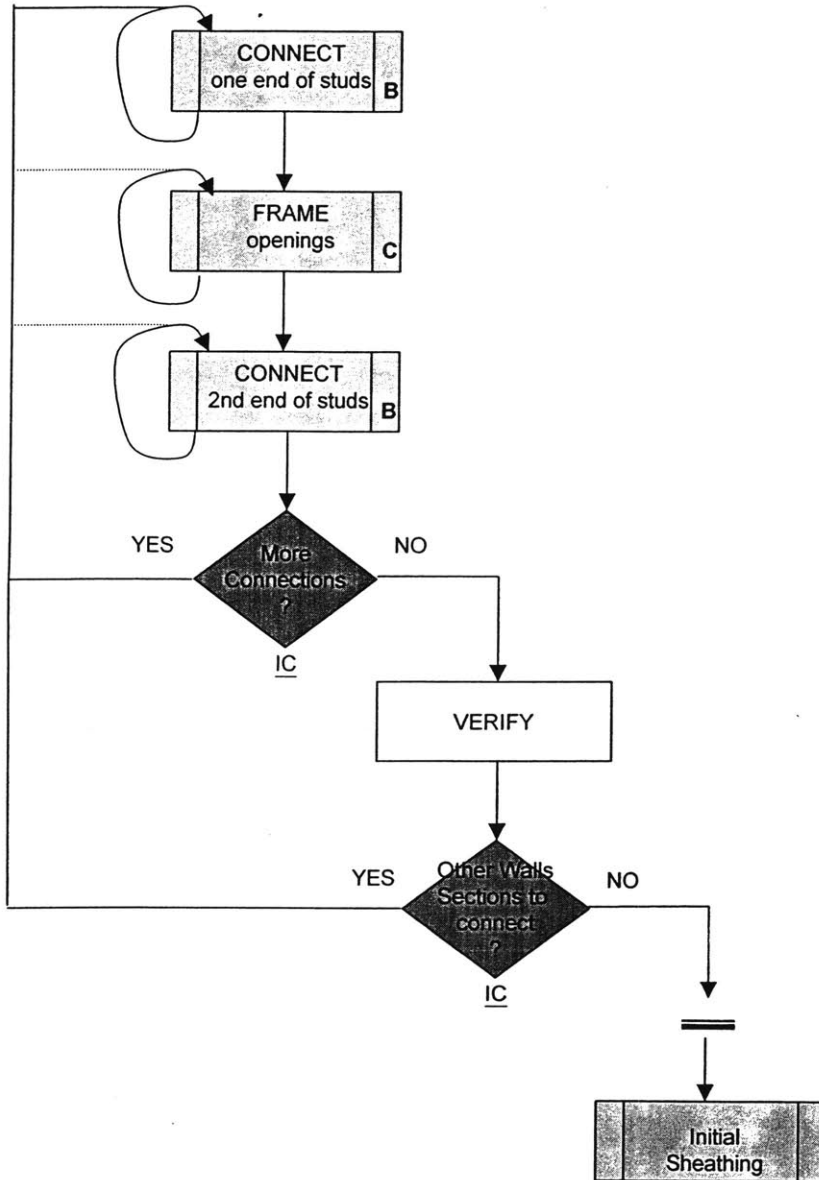
## 4 c: Site Pre-assembled



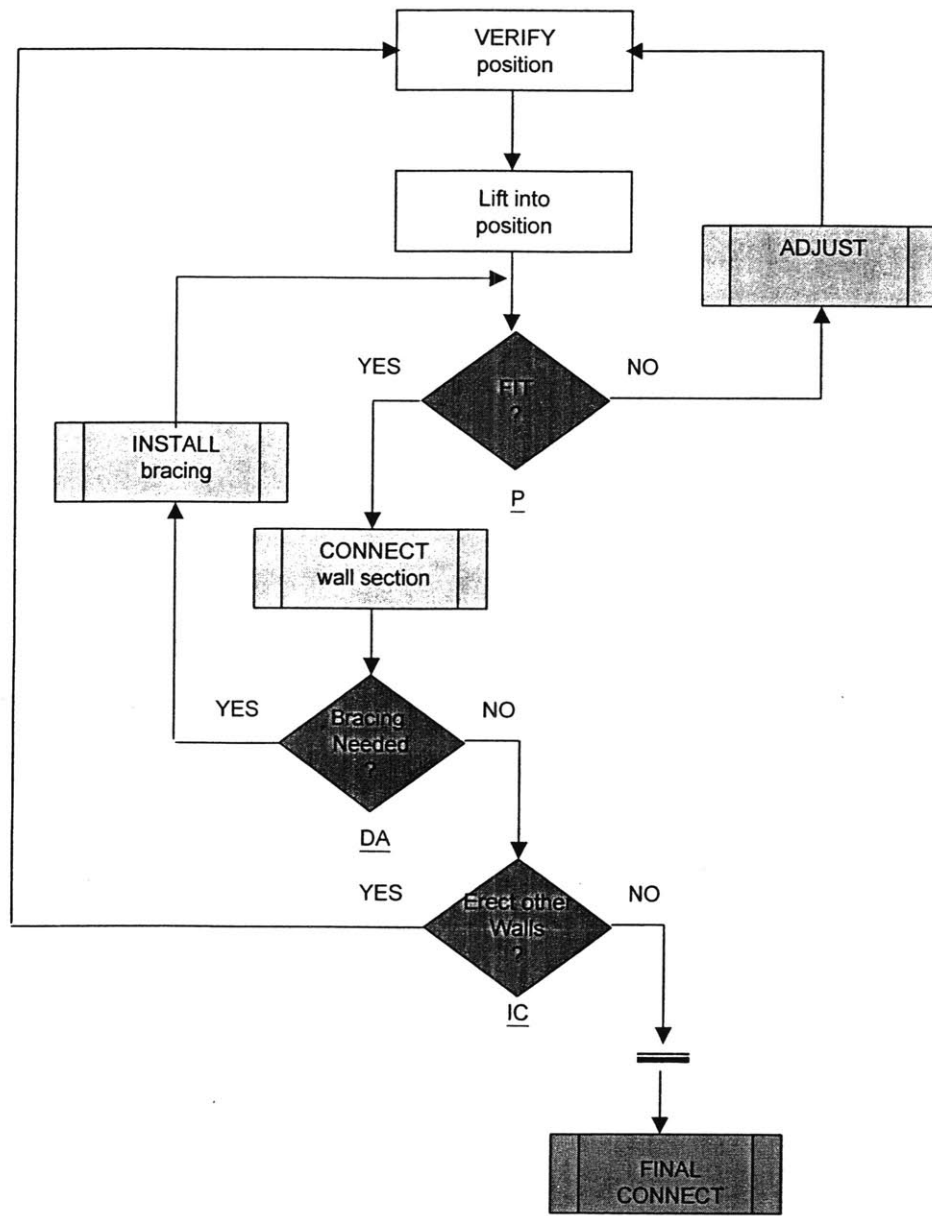


**4**

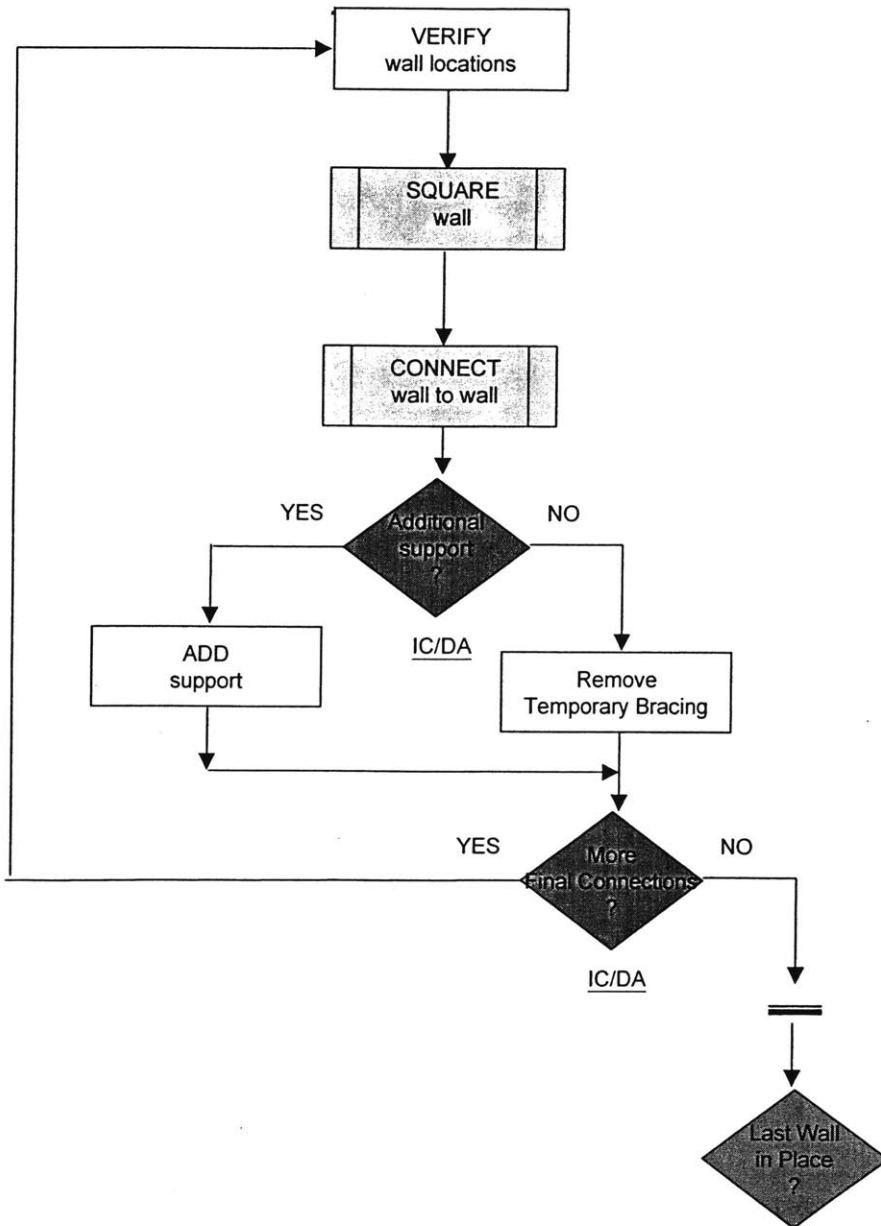
**c: Attach Members**



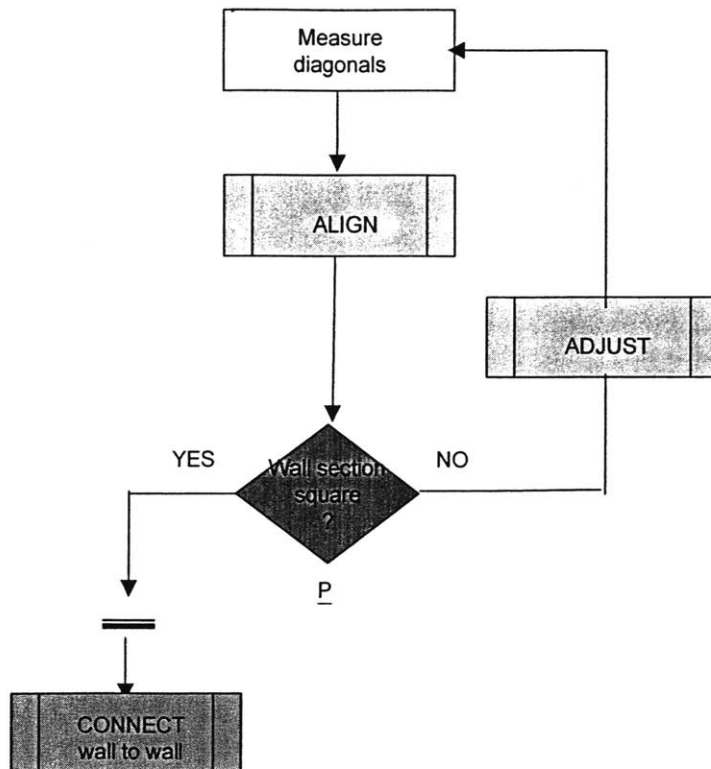
### 3 c: Erect Wall



### 3c: Final Connect

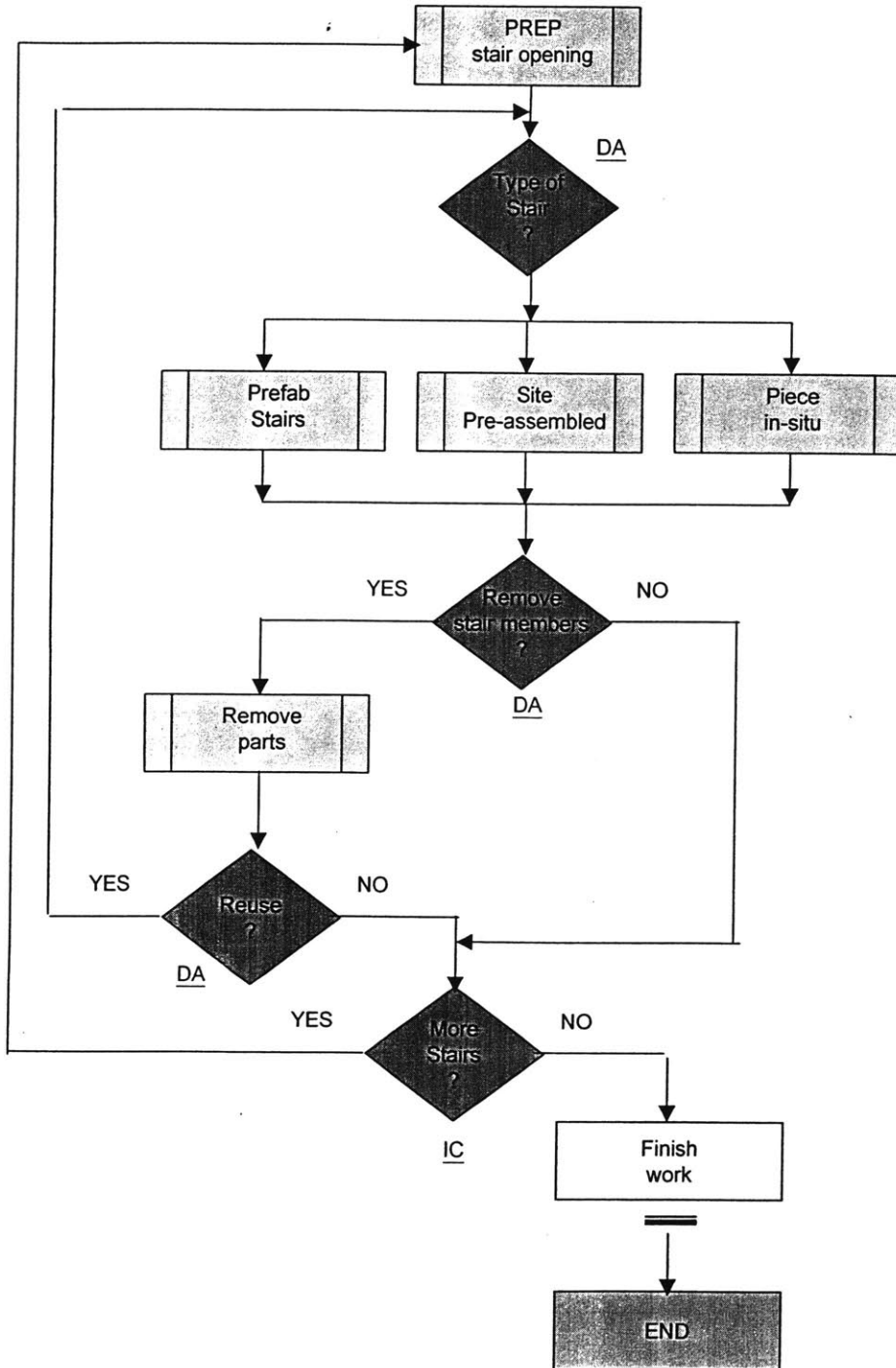


## 4 c: Square Wall

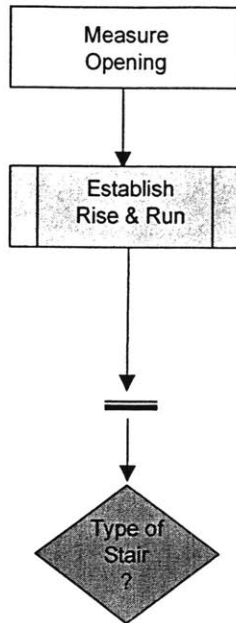


**2**

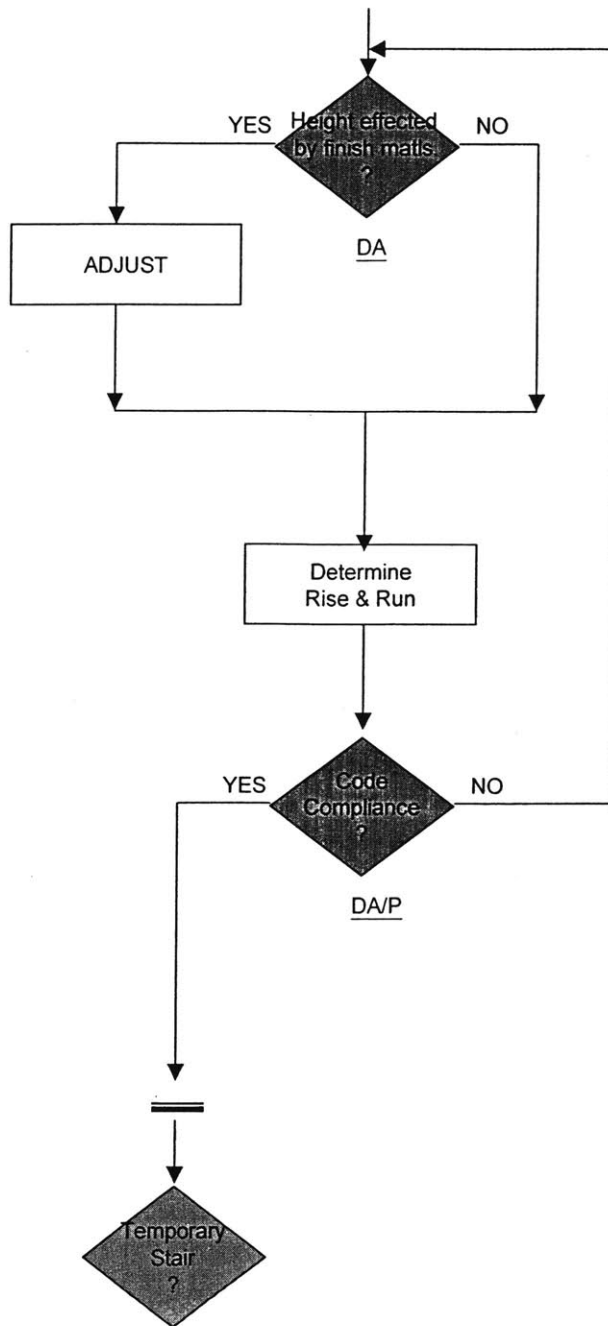
**d: Stairs**



### 3 d: Prep Stairs

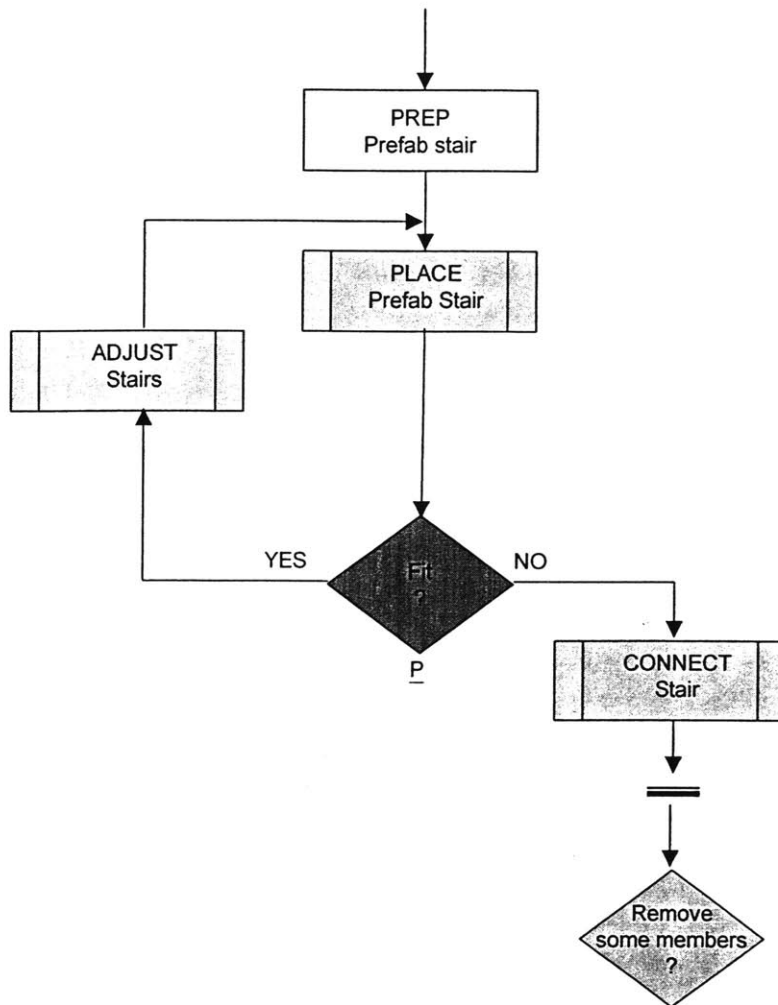


## 4 d: Establish Rise & Run



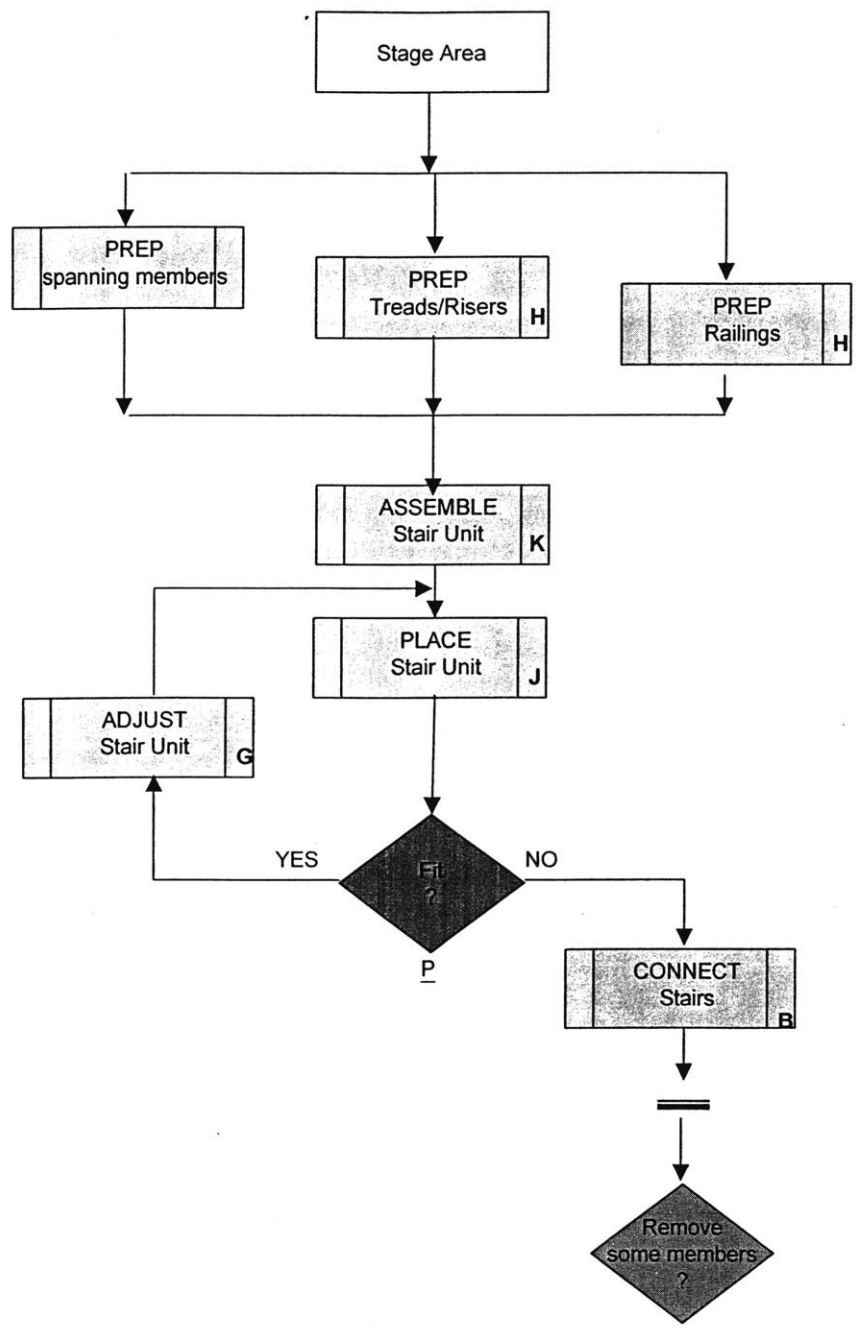
**3**

**d: prefab stair**

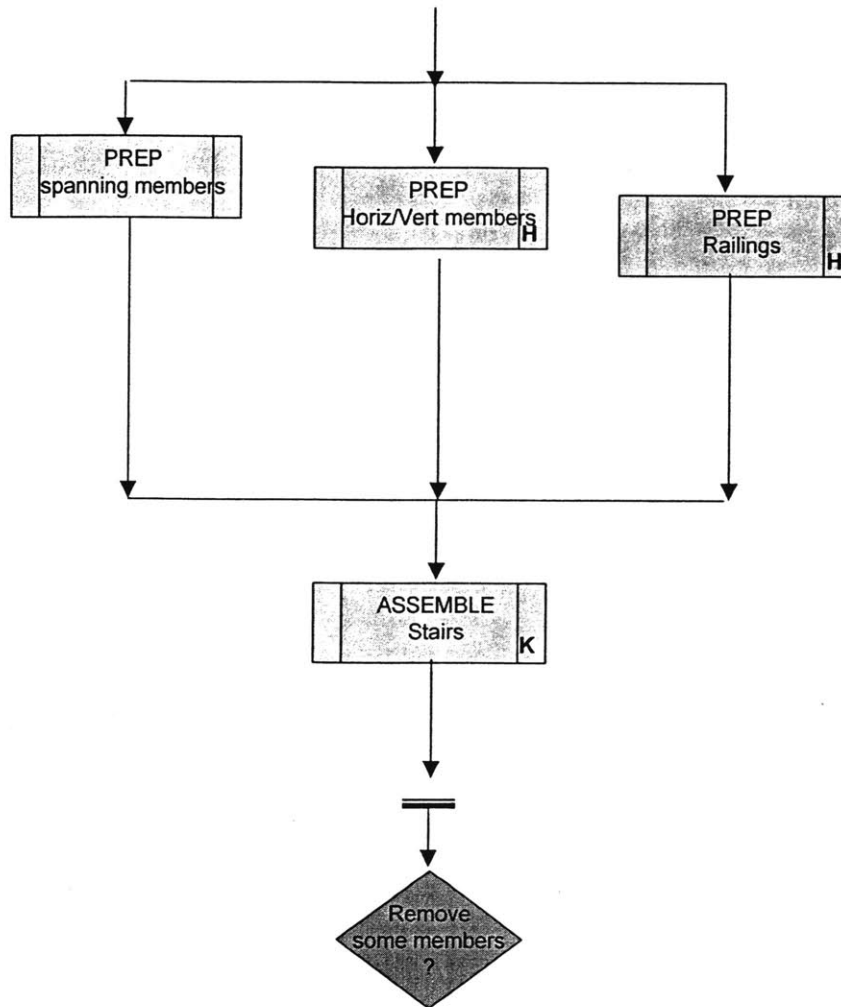




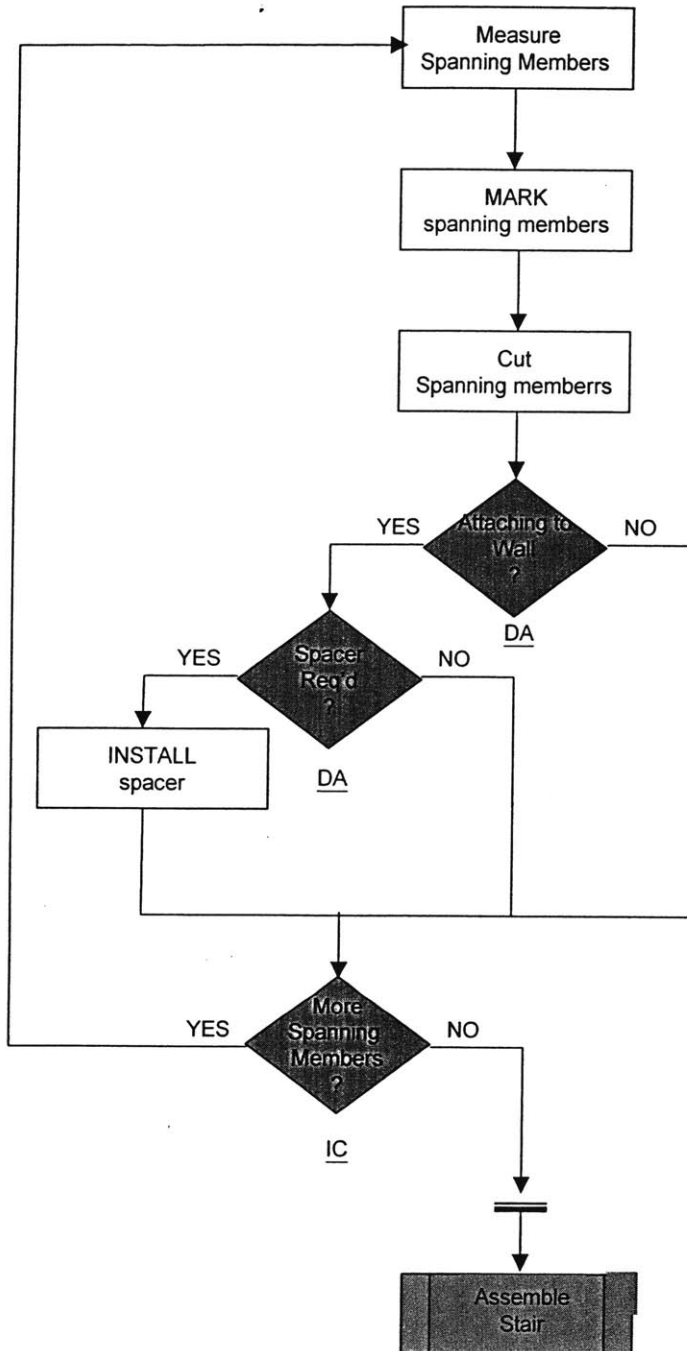
### **3** d: site pre-assembled stair



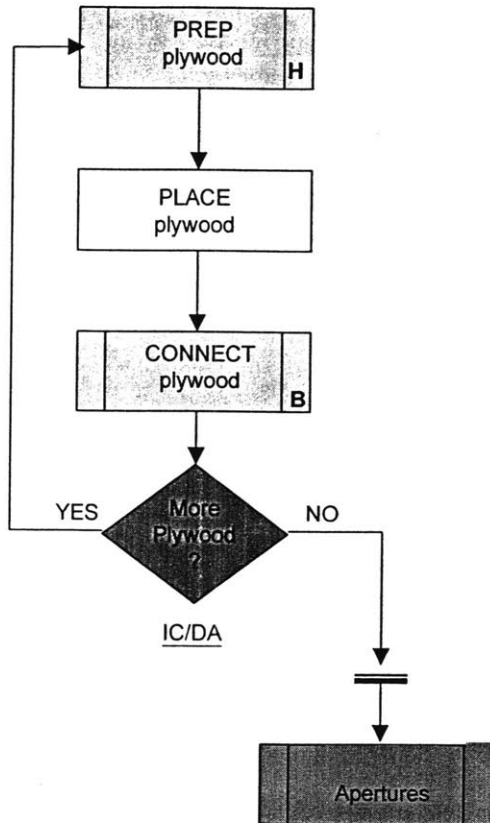
### 3 d: piece in-situ stair



## 4 d: Prep Spanning Members

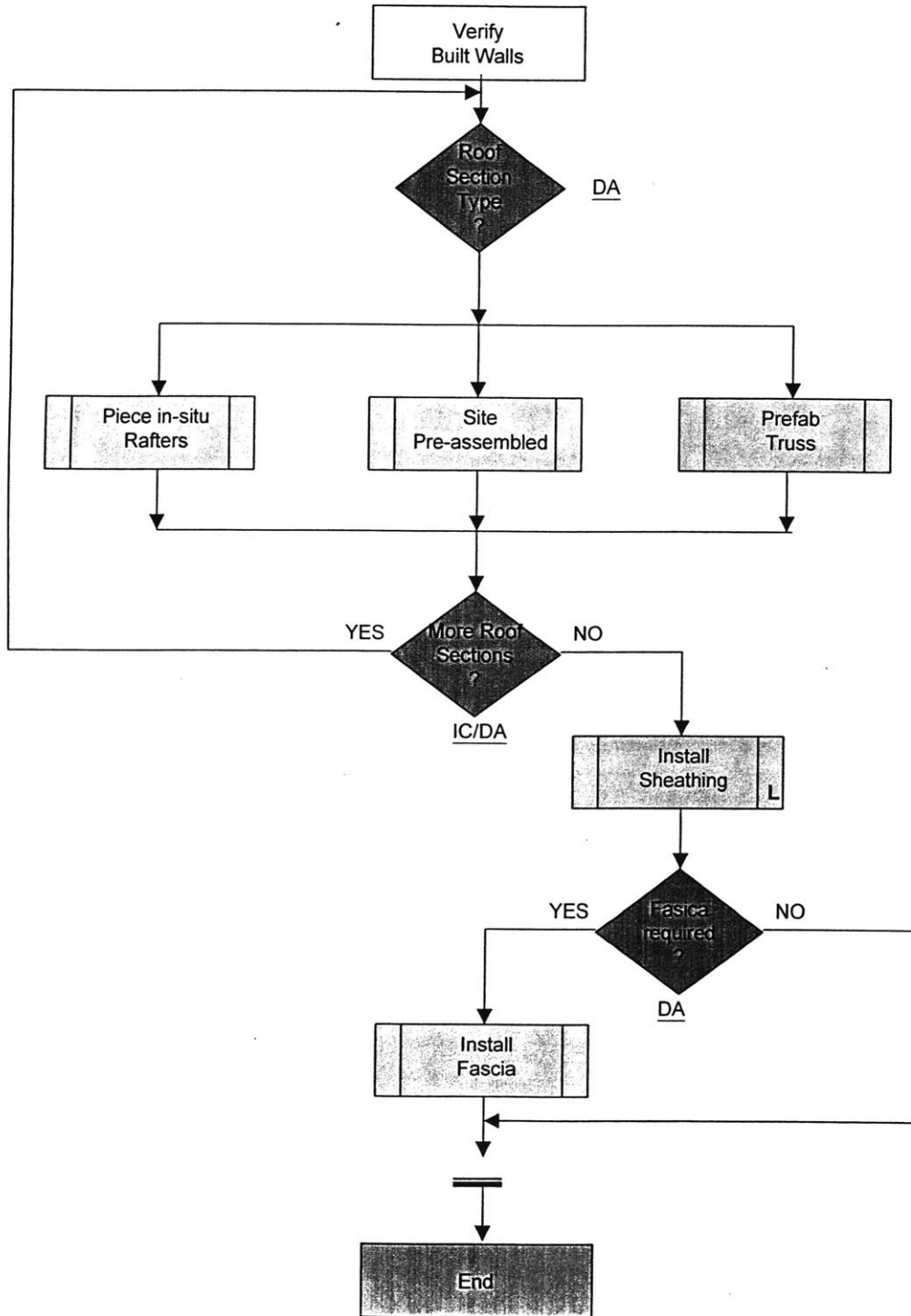


## 2 e: Final Sheathing of Walls

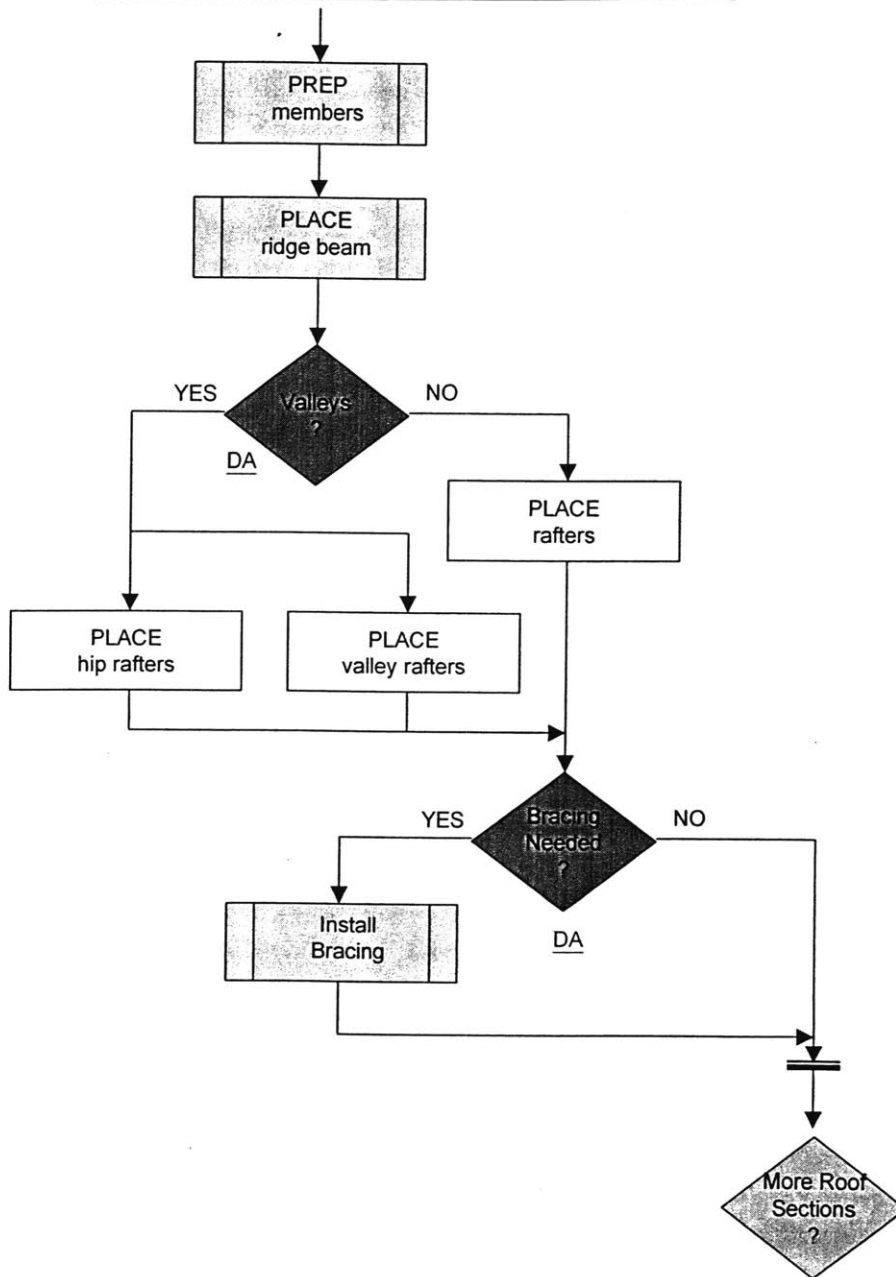


**2**

**f: Roof**

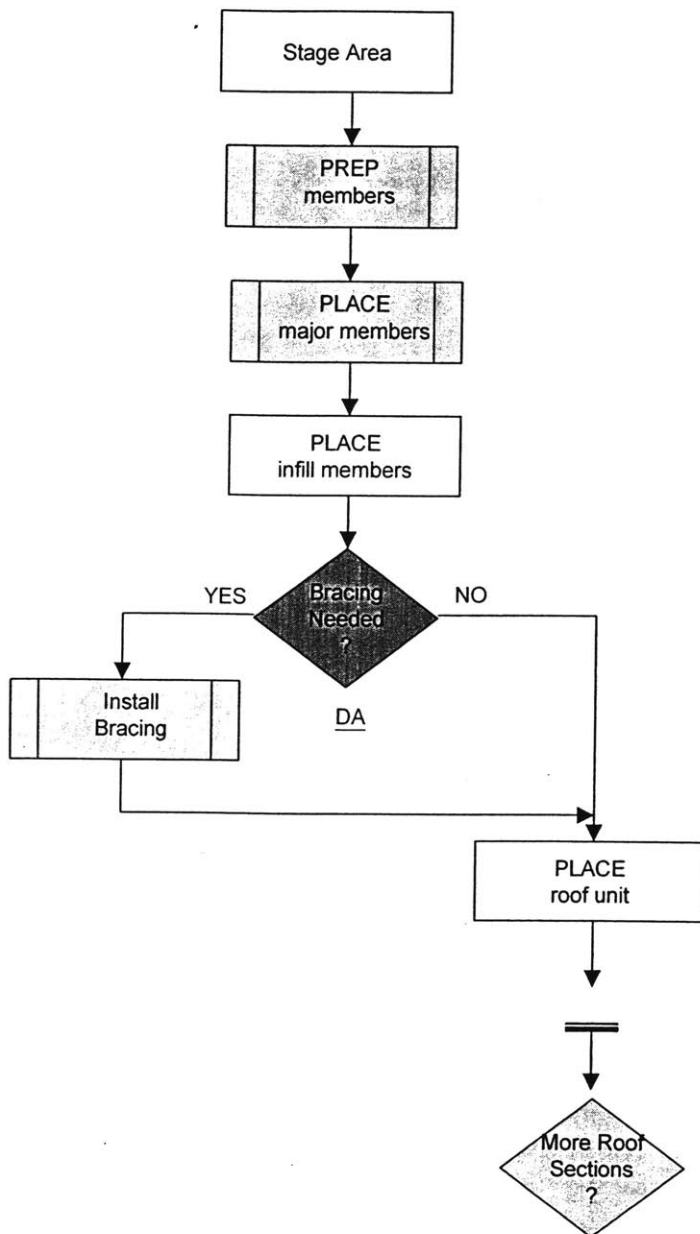


### 3 f: Piece In-Situ Rafters



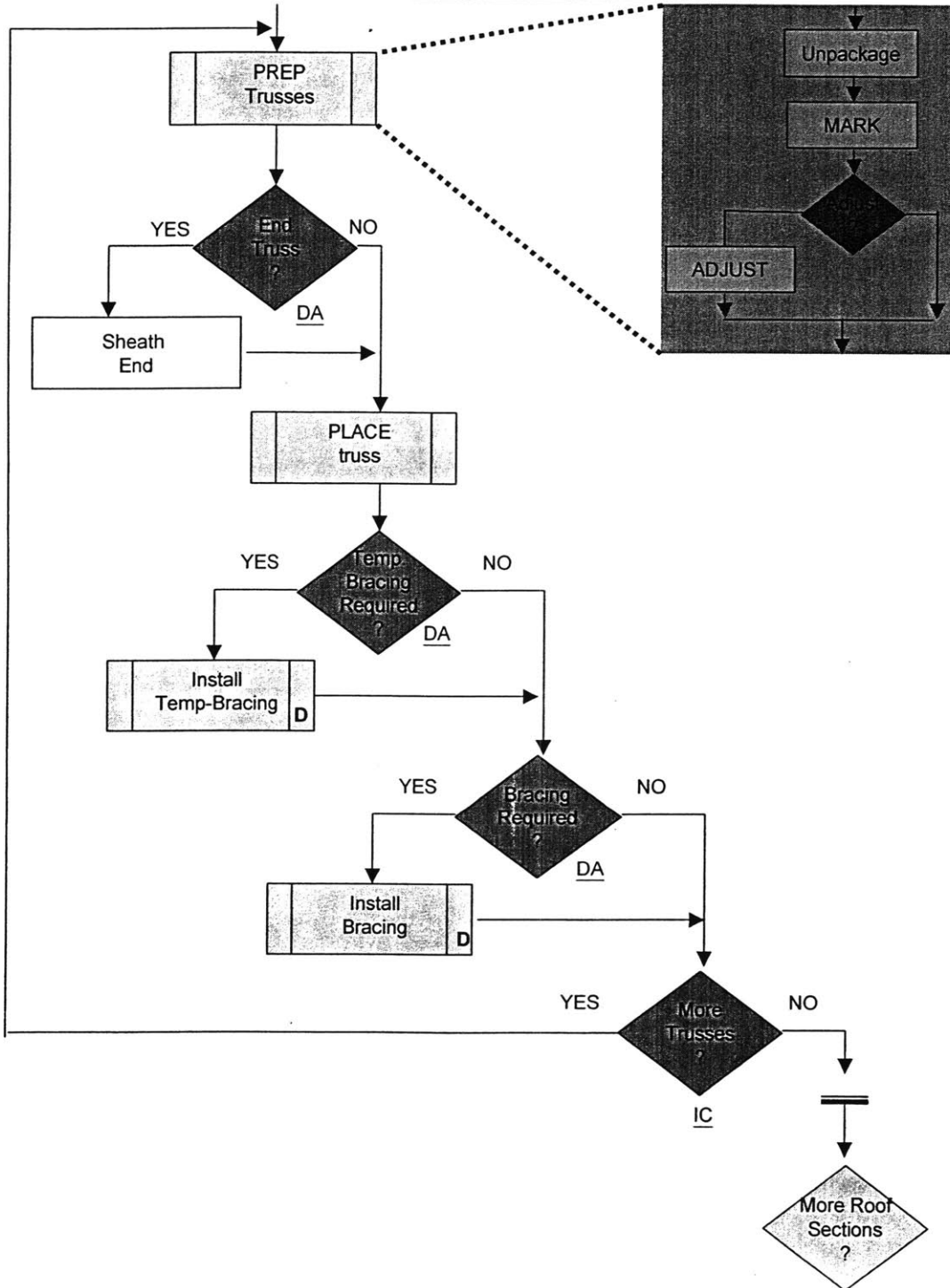
**3**

**f: Site Pre-assembled**



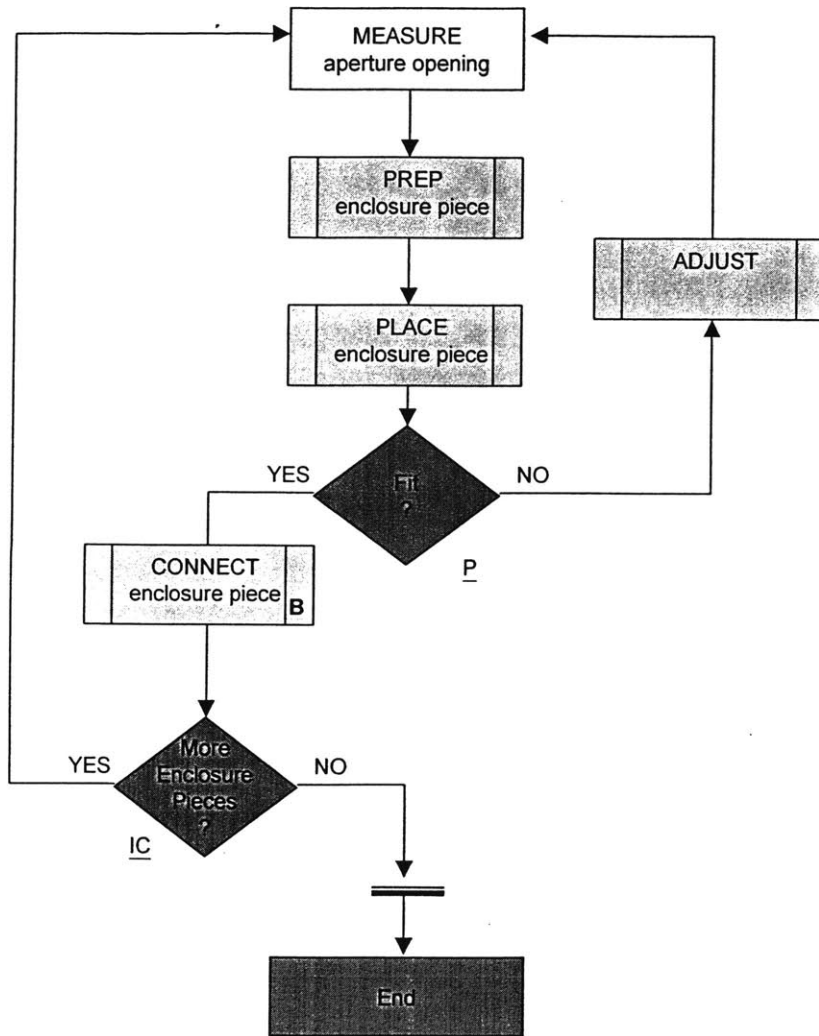
### 3

## f: Prefab Truss





## 2 g: Apertures



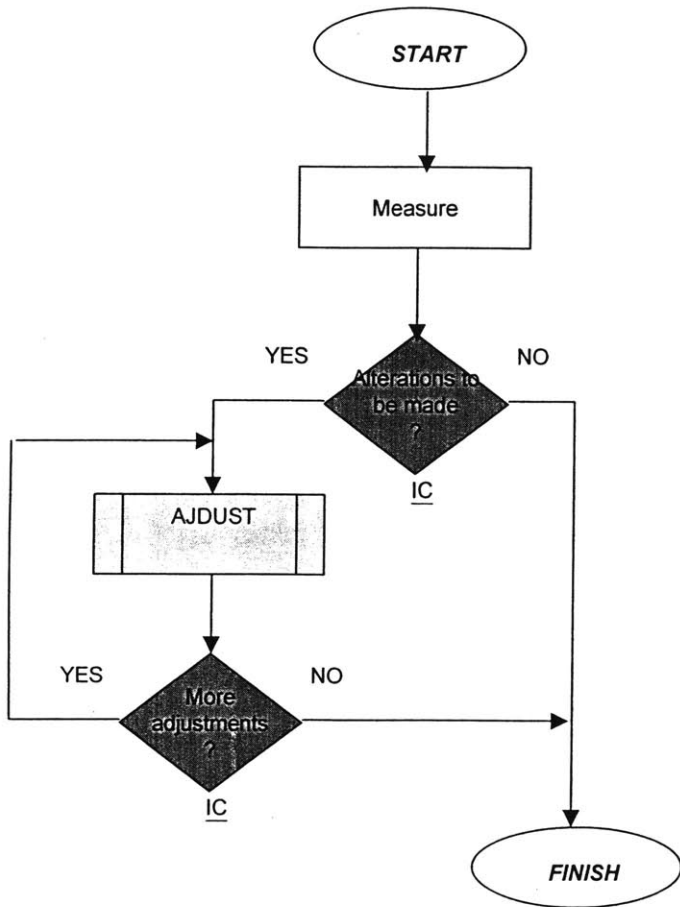
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# Reoccurring Tasks/Activities

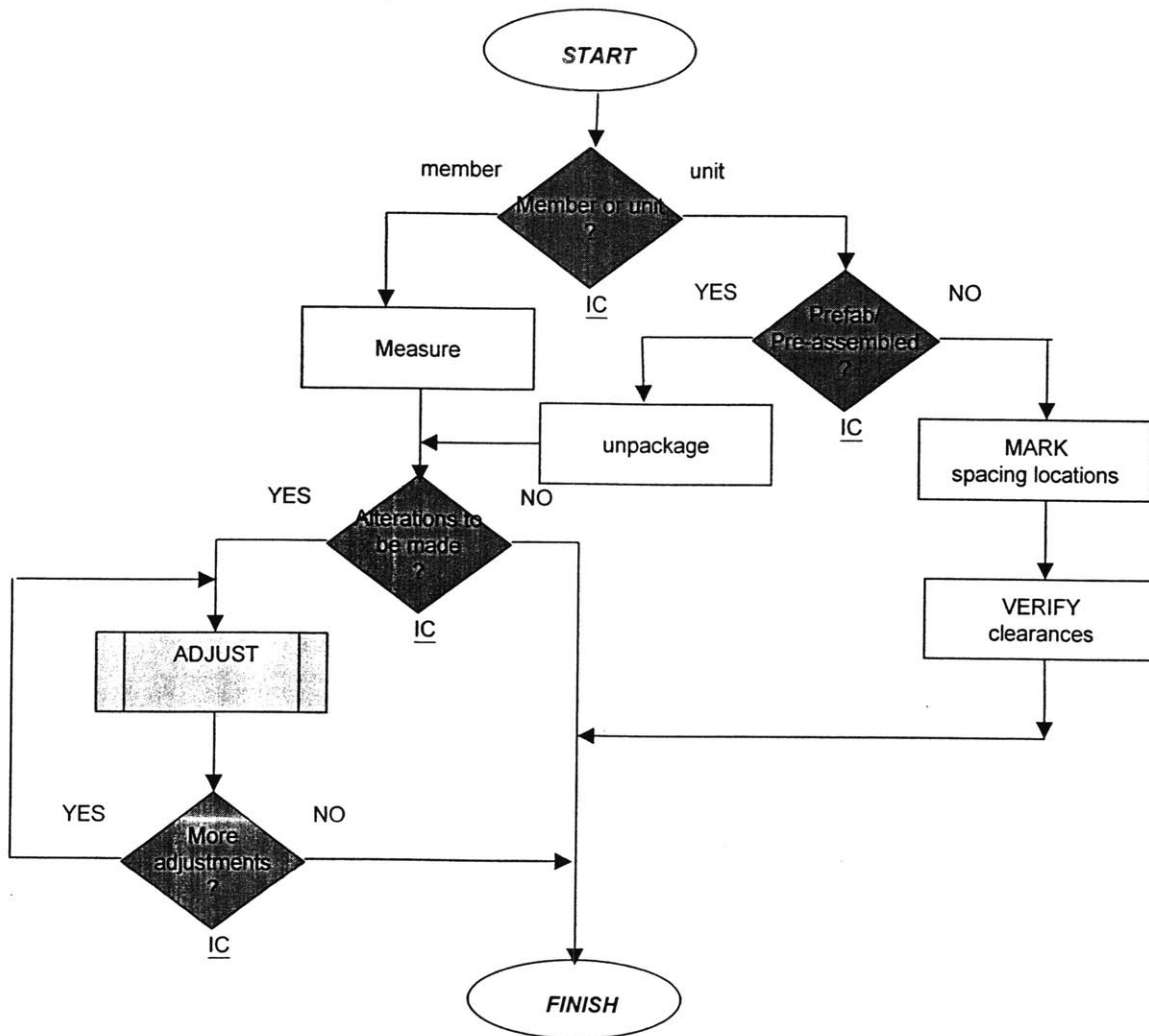
Prep  
-Cut  
-Build-up  
Place  
Align  
Adjust  
Connect  
-Pre-Connect  
-Temp-Connect  
Assemble  
Frame Opening  
Install Sheathing  
Install Bracing

These tasks reoccur and map into the flow at various levels throughout and relate to the customization and differential of in-situ to pre-fab construction as it deals with floor, walls, roof, etc.

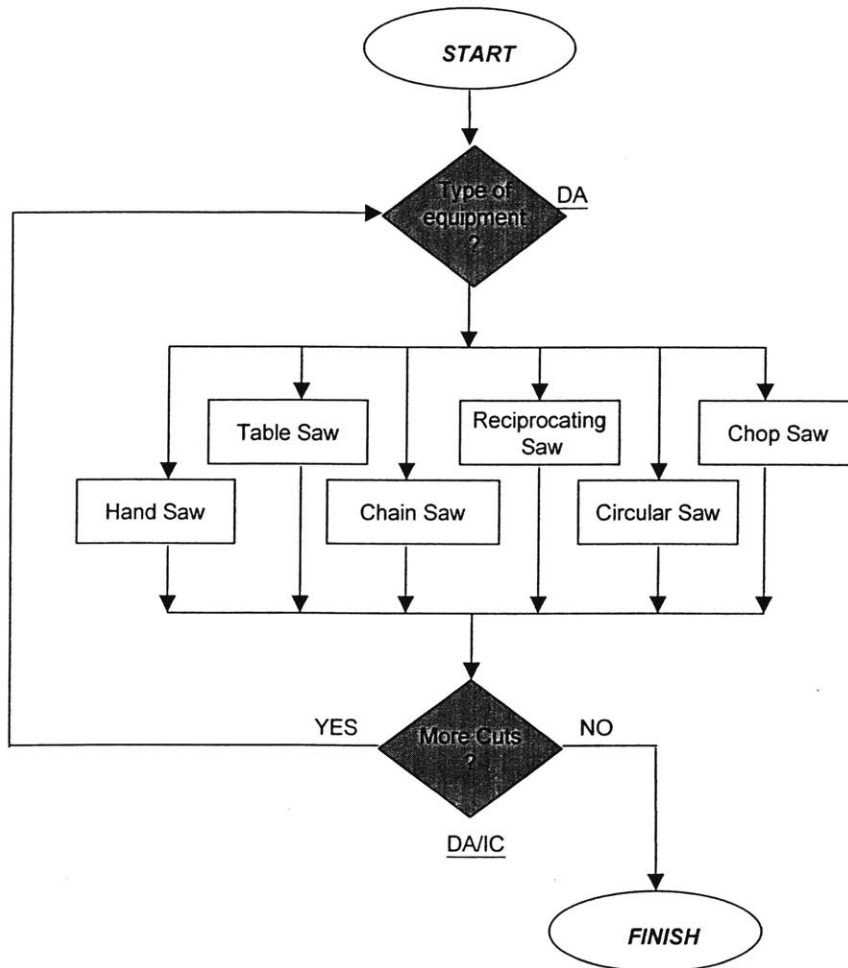
# PREP



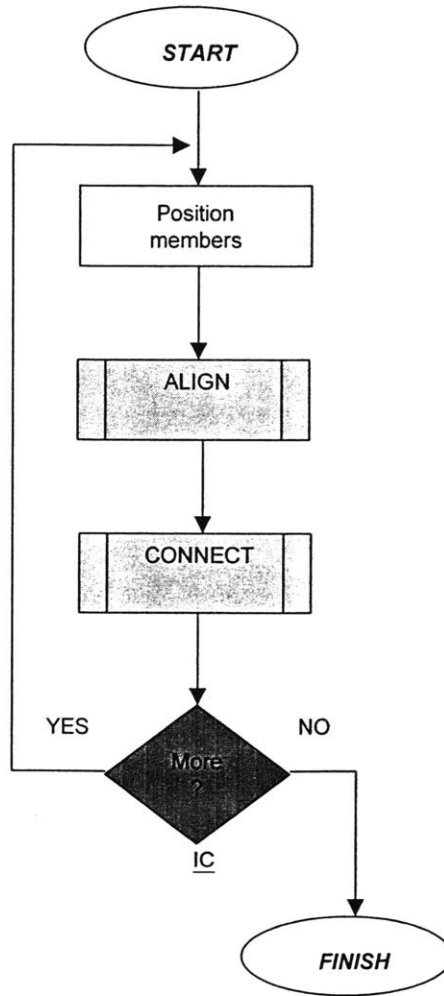
## PREP: unit or member



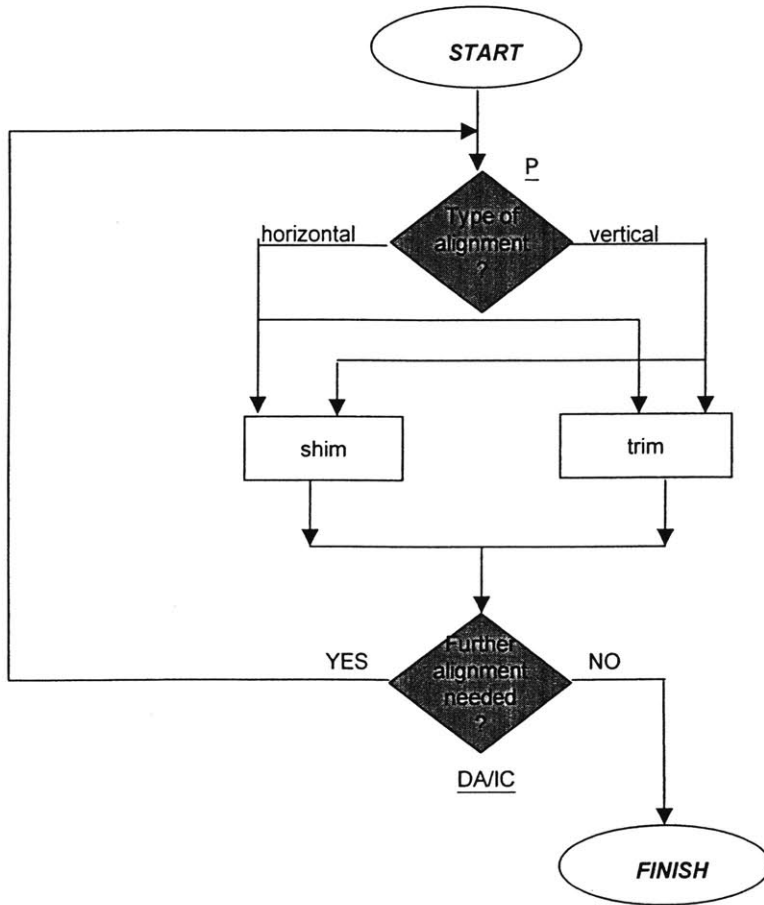
# CUT



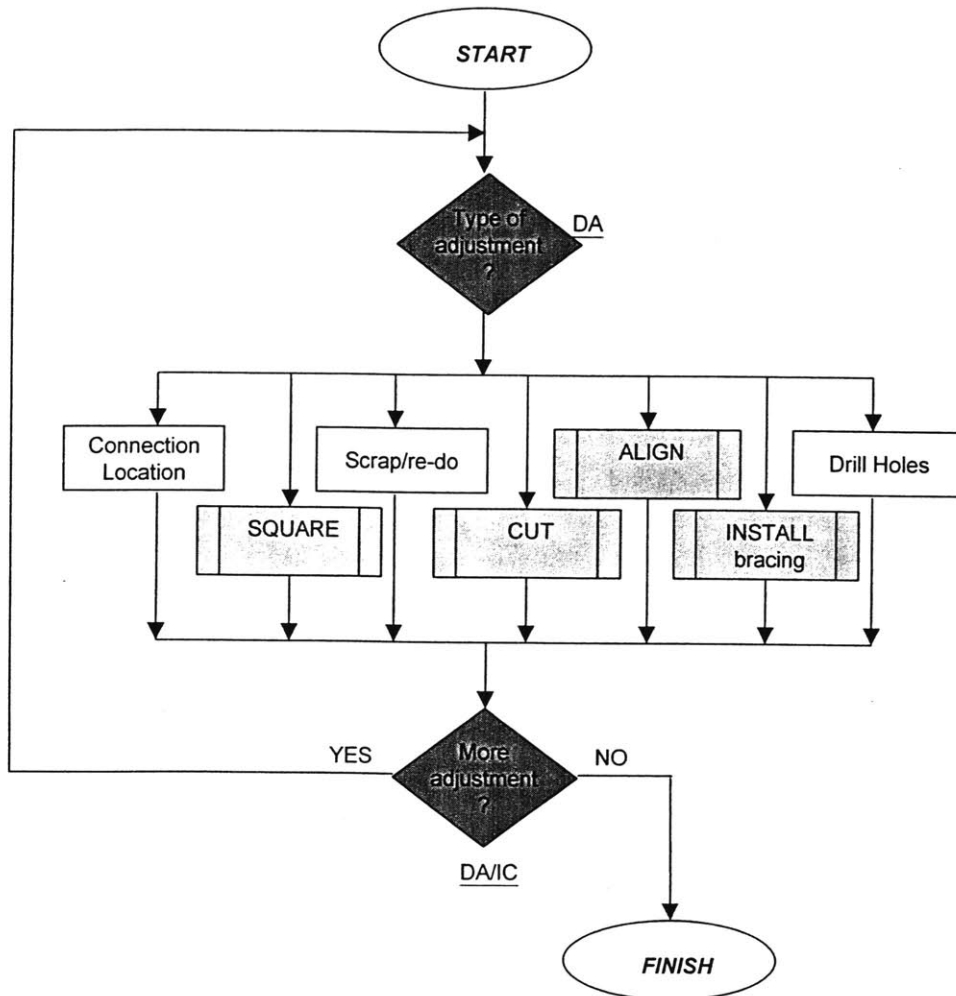
## **BUILD-UP MEMBER**



# ALIGN

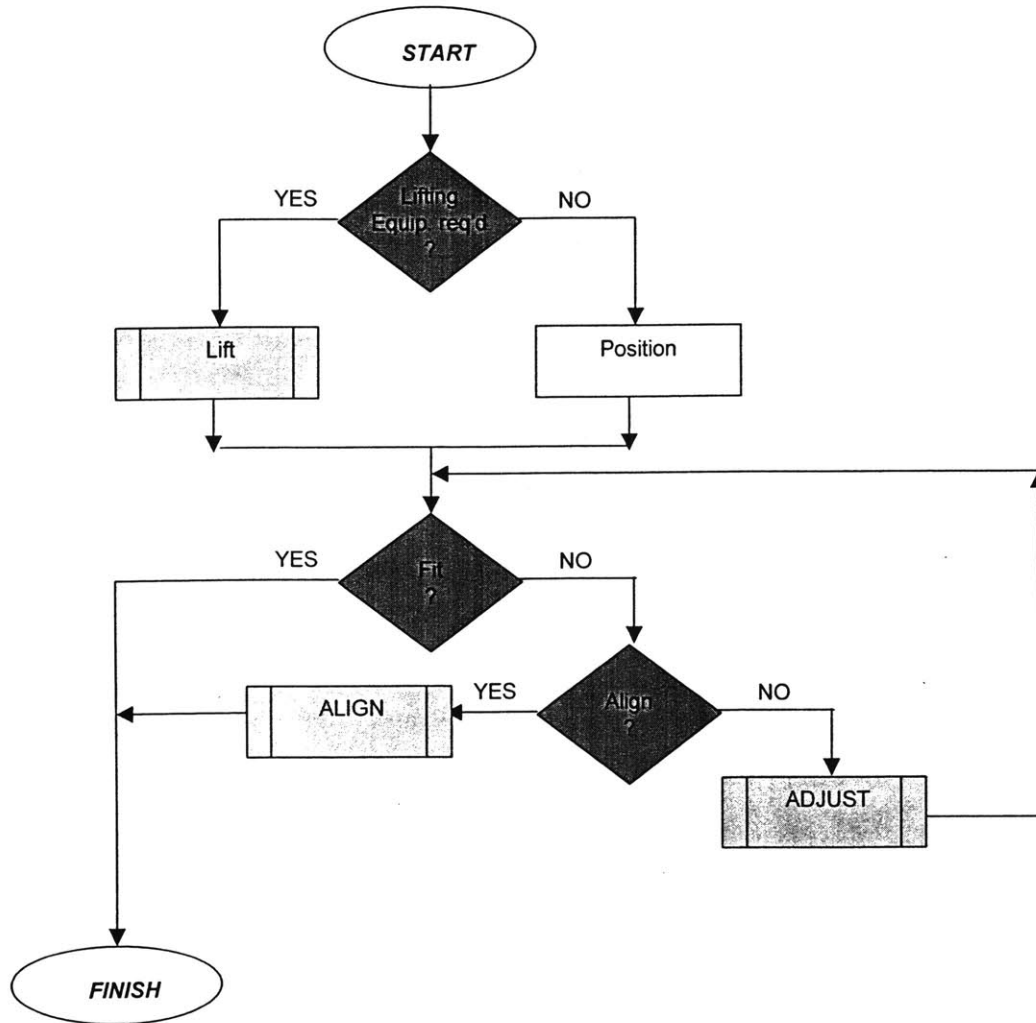


# ADJUST

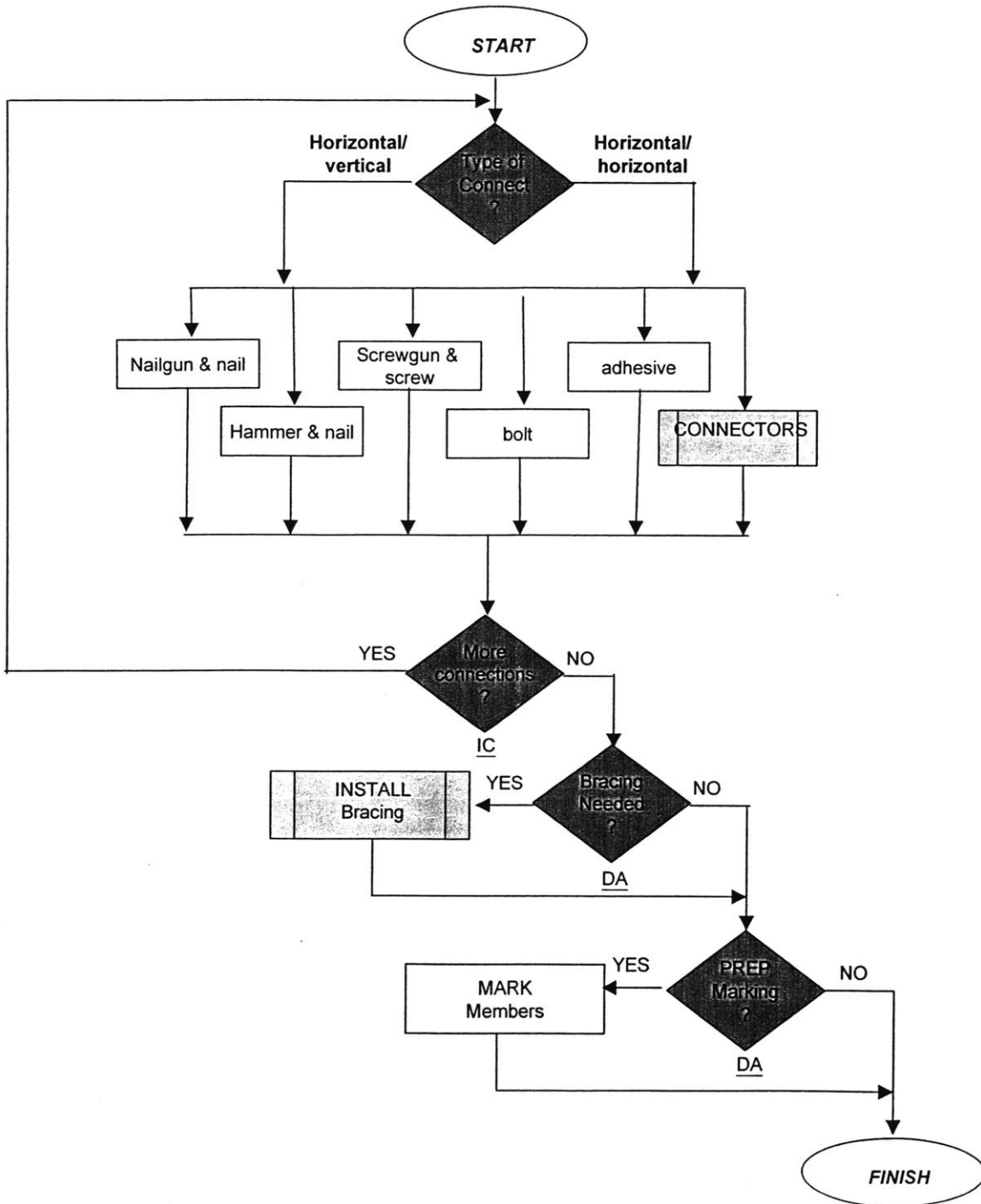




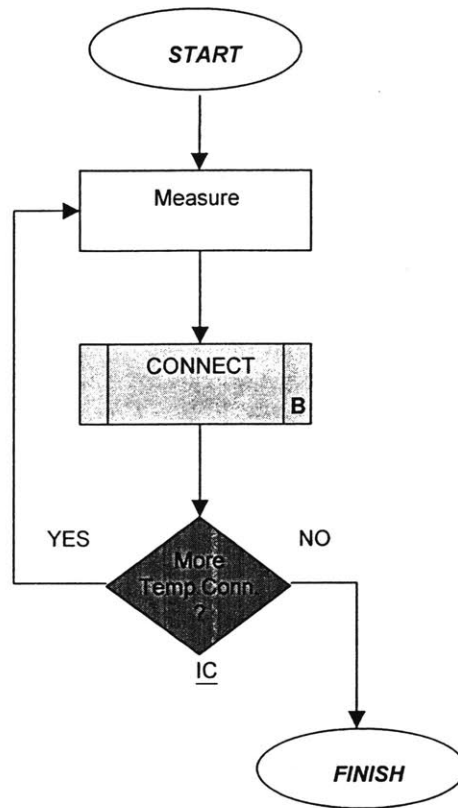
## Place



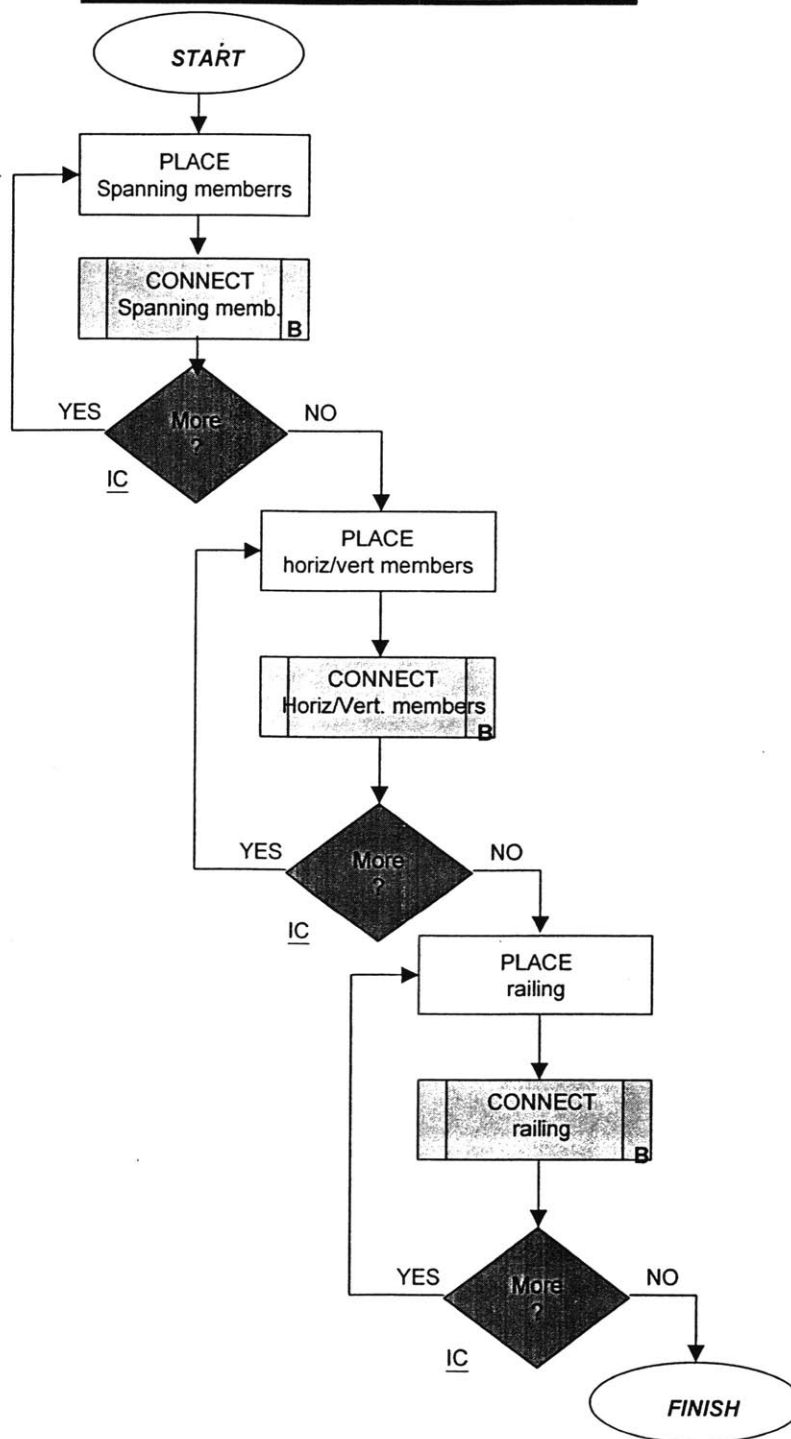
# CONNECT



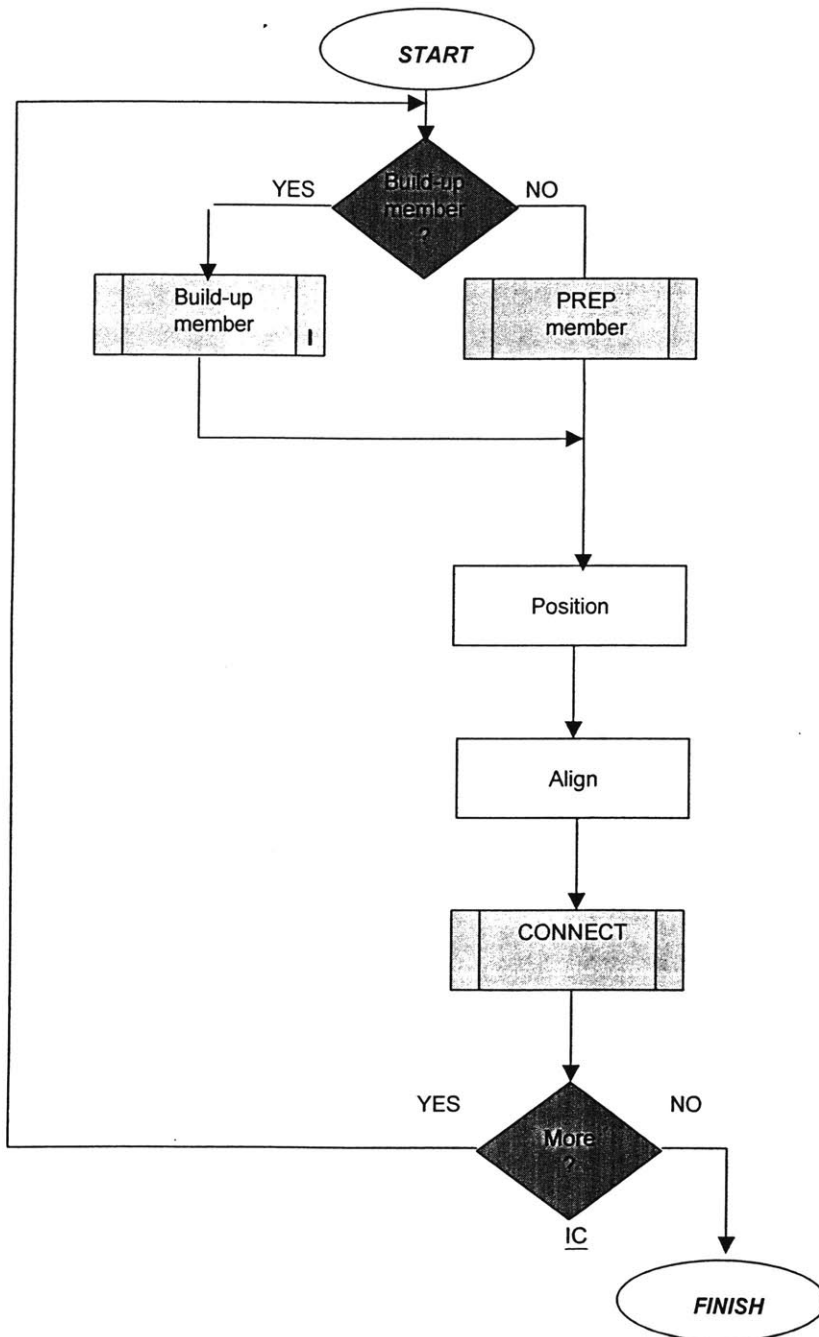
# **PRE-CONNECT**



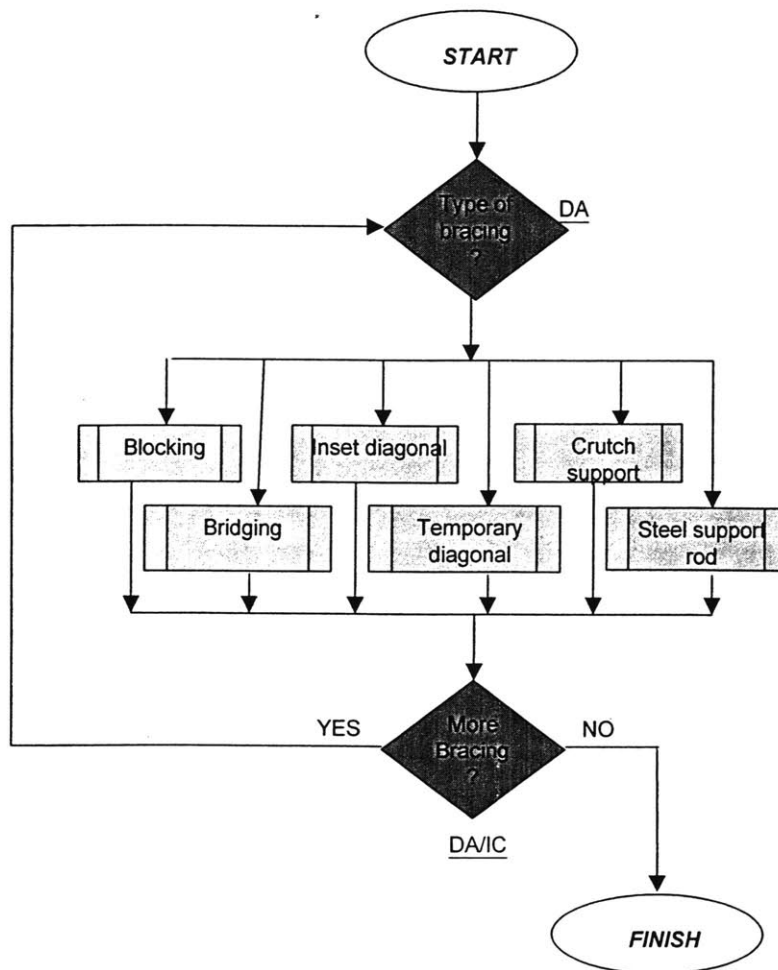
# ASSEMBLE STAIR



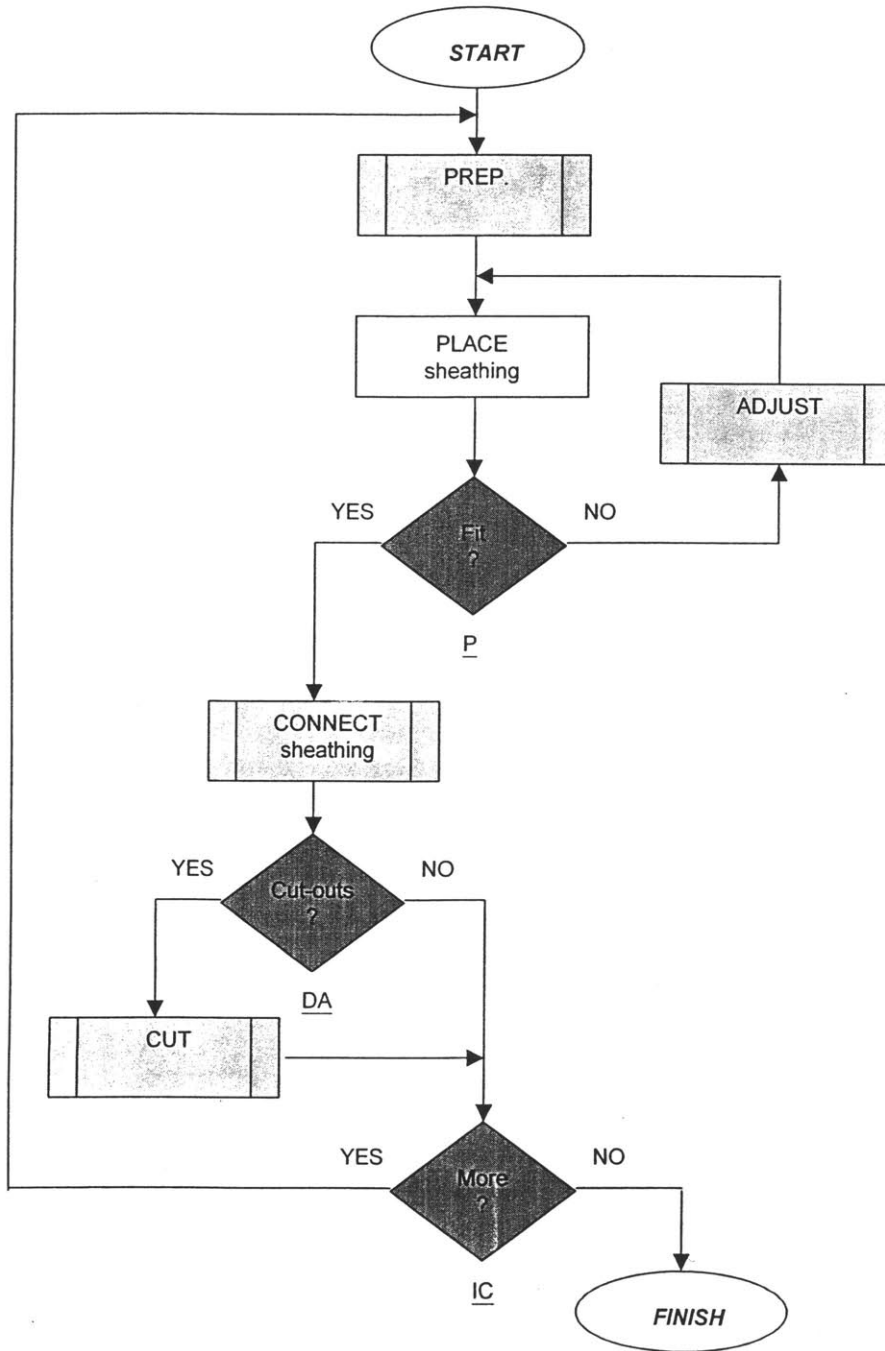
# FRAME OPENING



# INSTALL BRACING



# INSTALL SHEATHING









# Appendix D

Site Visits  
Site Visit Photographs (a selection)  
Design Attributes  
Resources



## Cambridge, MA

1. Buckingham #1 -- Renovation/Addition S + H Construction  
This house, which is on the historical register, was basically having the rear half removed and reconstructed, in addition to a garage with an attic apartment added to the rear of the site.
2. Buckingham #2 -- Renovation/Addition S + H Construction  
Another early 1900's residence having extensive renovation done including an addition and finishing out the basement. The house was having a radiant floor heating system installed as well as a "smart devices system".
3. Brattle #1 -- Renovation/Addition S + H Construction  
Same style as the two previous mentioned, but the renovation involved integrating the construction with other types of construction, such as steel due to the spans required by the design, past and present.
4. Green St. #1 & #2 - New Condominiums Hammond Realty  
A total of (7) 3-bedroom condos were constructed in two separate three-story buildings on a tight site. A single framing crew that utilized pre-fab components as well as stick construction completed the framing.
5. Apartment #1 -- New Apartment Complex  
A total of four new apartment complex buildings in North Cambridge following the text of standard construction. The project was at the point of aperture installation and final connections.
6. Boston University Boat House Walsh Brothers  
A new boat house built in the footprint of the recent boat house that was condemned and torn down. The project was a combination of steel, heavy timber and stick construction. A crew of between 8-10 workers were used and provided an interesting comparison to carpenter framing crews.
7. Allston #1 -- 2-family home  
Demolition of a previous home provided space for this new 2-family residence to be constructed in tight confines in a densely built area. Standard 2x6 wood construction with the interesting characteristics of a complex roof form and pre-fab outlooker units that were incorporated into the roof.

## Newton, MA

8. Ridge Ave. -- Addition Stefcro Construction  
A two-story home on a steep slope was having a 3-story addition completed with a garage on the 1<sup>st</sup> level and bedrooms and living spaces on the other two levels. The addition was increasing the square footage of the home by about 40%.

## Andover, MA

9. Andover #1 -- New Commercial  
A 3-story mixed use commercial building with retail on the first floor and office space above. The project was a combination of steel and wood construction that used wood trusses for the roof.



---

## North Andover, MA

### 10. N.Andover #1 -- Assisted Living Units

An addition of 270 assisted living units for elderly individuals to an existing complex. The building is in the form of units spaced over 3-stories.

## Saugus, MA

### Birch Pond Estates

This site is being developed by Walnut Street Trust and when completed will have 24 new houses constructed. The homes are all of a similar mold (two-story, 2,000 + sq. ft., forms of gable roofs), but do have interesting differences in shapes, styles and work crews. Four different contractors are doing the construction of the individual houses.

### 11. Estate #1 -- New Residence

The residence incorporated an entry stair that was hung from the second floor, which differs from normal framing techniques. The roof was of a shape that incorporated multiple dormers and due to the massing and slope of the roof created long spans of rafters on the north side, which were surprisingly not blocked.

### 12. Estate #2 -- New Residence

The residence incorporated a large gable end wall, which under normal conditions could be raised by 5-6 workers, but due to the windy conditions on site that day become difficult for 10 workers. One comparison within this house and the one next door was the on-site building of the lookouts for the roof versus a component element.

### 13. Estate #3 -- New Residence

The framing was complete and the aperture enclosures had begun to be installed. The industry standard window installment of vinyl double-paned windows with a fin extending out in all four directions was observed.

### 14. Estate #4 -- New Residence


The framing was near completion when visited, but provided some insight into the interesting methods that some builders will use to brace and temporarily brace structures.

### 15. Estate #5 -- New Residence

The largest residence in the development with a garage space that was a two-story plus volume providing large vertical stud spans. The stud walls were required to be diagonally braced as well as intermittently blocked due to the height.

### 16. Estate #6 -- New Residence

The basement of the residence incorporated steel columns for the intermediate supports of the members shaping the garage and rooms behind. Temporary wood stud columns were used as placeholders until the steel columns appeared on site.



### **Chase St. cul-de-sac**

A development of eight homes, four of which are complete and three previously under construction. However, only two are beyond the point of foundations. The homes are similar in type to those at the Birch Pond Estates.

#### 17. Chase #1 - - New Residence

Another two story residence with a basement that incorporated large windows on the lower level to the east requiring an interesting framing solution due to the load lines from the floors above.

#### 18. Chase #2 - - New Residence

A residence observed at the initial stages of framing, prior to the platform being framed. Insight was provided to the initial steps that the framer must go through prior to beginning.

### **Pembroke, NH**

#### 19. Epoch Corp. Manuf. Home Builder

Epoch Corp. is a traditional manufactured home builder that produces large finished units of the home that are then shipped and configured on site. A typical example is two to four units per house. They have a limited palate for the range that these can be customized. The visit to their manufacturing facility and talking with workers and representatives provided the counter view to wood construction that occurs within the factory rather than on site.

### **Other Areas**

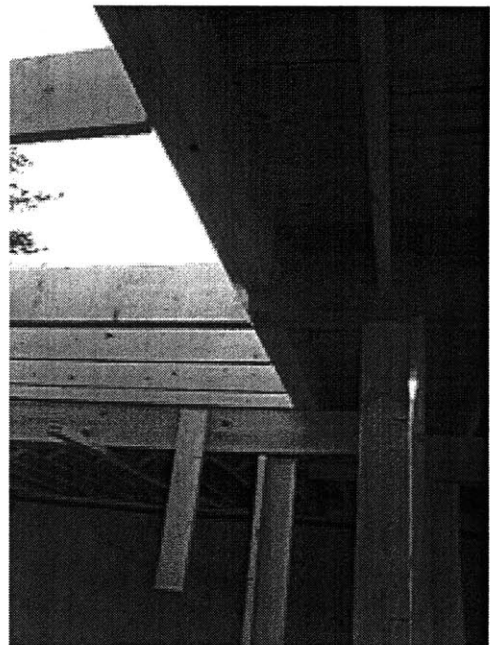
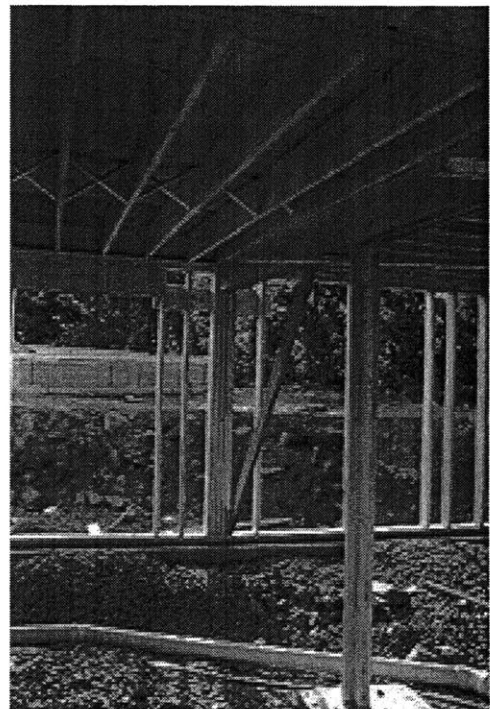
#### 20. Deck House/Acorn House

Visiting the manufacturing facility, display homes, and construction sites of homes being assembled of this pre-fab home manufacturing company. Deck/Acorn House is a step or two in quality above Epoch Corporation (mentioned above) and are one of the few companies that provide a kit of parts for home construction which has the ability to be customized in a number of ways.

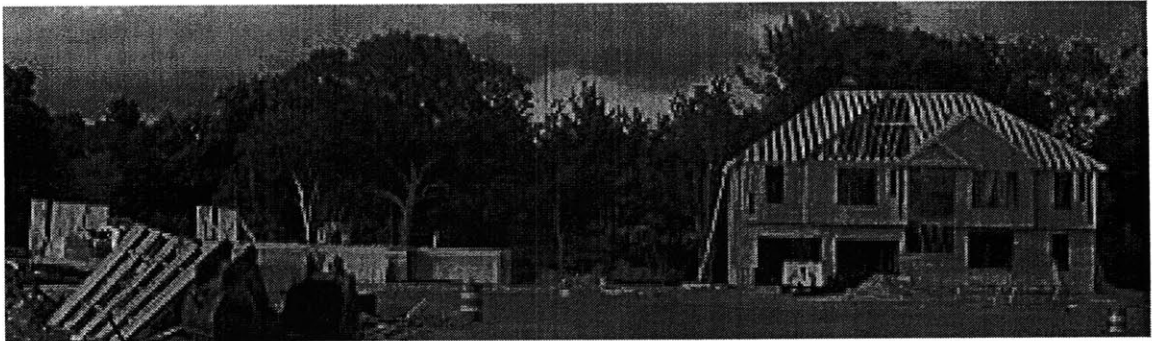
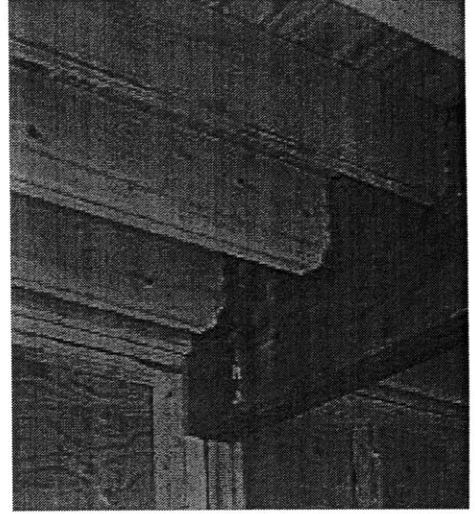
#### 21. Manchester by-the-sea, MA

##### Keefe Residence - - New Residence

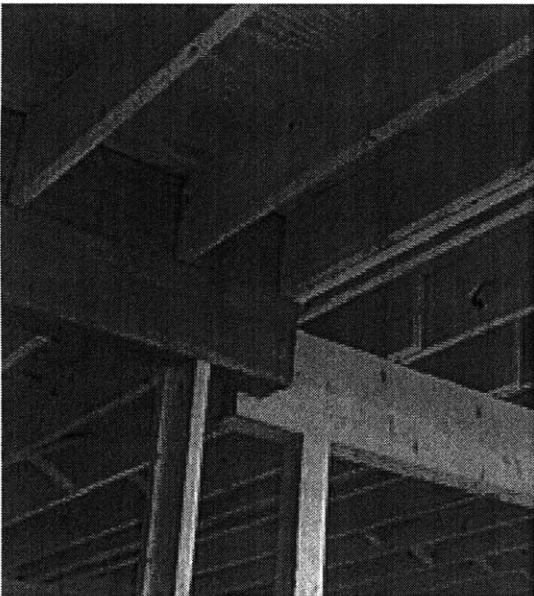
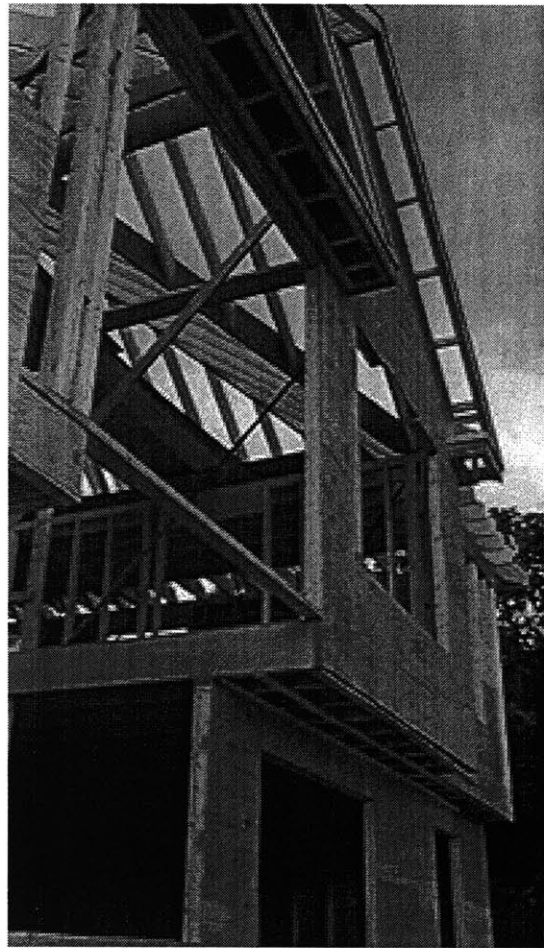
This project is a large customized home being constructed for an architect as a current second home and a future retirement home. The project is a combination of light wood construction and heavy timber trusses serving to create large volumes of highly detailed space. It will provide a good balance to the production time estimates as they relate to custom residential construction.



Site Photos  
Chase Residence #1







## Resources

Crew: 2-4 carpenters, 1 foreman

### Basic Framing Tools

- Chalk line & refill bottle
- Tape measure
- Hammer
- Ratchet wrench with sockets
- Pencil and keel
- Awl
- Dryline
- Screw driver – standard & Phillips
- Allen wrenches
- Tin snips
- Pliers and sidecutters
- Chisel
- Utility knife
- Duct tape
- *Hand plane*
- *Hand saw*
- *Nail set*
- *Speed square*
- *Putty knife*
- *Tool box*

### Additional Tools

- Level
- Triangular rafter square
- Framing square with stair gauge
- T-square
- Nail pulling bar – “cat’s paw”
- Sledgehammer
- 5-gallon bucket
- crow bar
- *Adjustable or open end wrench*
- *Caulk guns (2 sizes)*
- *Transit*
- *Shovels*
- *Feet/inch calculator*
- *3” hand planer*
- *12” board planer*
- *extension chords*

### Power tools

- chop saw
- circular saw – heavy-duty model w/ 7-1/4” blade or worm gear driven
  - skyhook attachment
  - chain-saw attachment
- radial arm saw
- pneumatic nailers and air compressors
- reciprocating saw (saw-z-all)
- drill
- chain saw
- beam saw
- table saw
- *auto laser level devices*
- *sliding compound miter saw*
- *powder actuated fastener gun*
- *auto feed screw gun*
- *cordless drill, drill bits, hole saw bits*
- *jig saw*

### Framer’s attire

- Ear protection
- Leather Gloves
- Tool belt
- Protective eye-wear
- Steel-toed boots
- Knee-pads
- Hard hat
- Dust mask or respirator

### Safety equipment

- First aid kit
- Harness with tie-off





### Customized Site-Built Tools

- bolt hole marker
- homemade "T"
- layout stick
- corner and channel markers
- plumb-stick
- sawhorses
- scaffolding
- ramps & ladders
- story pole
- rafter guides
- general guides
- *site built ladders*

### Larger or special equipment

- Bobcat
- Crane
- Forklift
- *Generator*
- *Trailer or other job site storage*
- *Ladders*
- *Gang boxes*
- *Wall jacks*
- *Beam lift*
- *Come-a-long*
- *Pickup truck*

---

## ***Design Attributes***

### **Building**

Number of floors  
Number of rooms each floor  
Number of stairs each floor  
Floor to floor height  
Roof type

### **Foundation**

*Foundation type (pilings, pier, cont. perimeter)*  
*Height of foundation above grade*

### **Walls**

Number of walls  
Type of wall (load vs. non-load bearing)  
Length of wall  
Height of wall  
*Amount of shear wall needed (calculation)*  
Number of openings  
Type of openings (window, door)  
Height of openings  
Width of openings  
*Stud size*  
*Stud type*  
Stud spacing  
Temporary erection support  
Type of sheathing  
Timing of sheathing  
Type of connections  
Number of connections/member

### **Floors**

*Type of Floor Section*  
*Type of Beams (built-up, LVL, PSL, Glulam, flitch, steel)*  
Number of beams  
Size of beams  
Connection type for beams  
Length of Sill  
Substrate for Sill  
Number of Floor Sections  
Type of Floor Section(full span, intermediate support)  
*Joist type*  
Joist Spacing  
Length  
Width  
Number of openings  
Type of openings (stair, atrium)  
Type of sheathing  
Type of Blocking or Bridging  
Type of connections  
Number of connections/member

### **Roof**

Number of sections  
Type of sections (dormer, valley)  
Type of member (rafter, truss)  
Spacing  
Temporary erection support  
Length  
Height  
Number of openings  
Type of openings (skylight, hatch)  
Type of sheathing  
Type of connections  
Number of connections/member



---

## **Stairs**

Number of sections  
Type of sections (single run, scissor, spiral or curving)  
Number of temporary units  
Number of members  
Types of members (stringer, riser, tread, railings)  
Length  
Width  
Height  
Type of connections  
Number of connections/member

## **Decks**

*Number of decks*  
*Square footage of deck (length, width)*  
*Type of Floor Section*  
*Type of Beams (built-up, LVL, PSL, Glulam, flitch, steel)*  
Number of beams  
Size of beams  
Connection type for beams  
Number of Floor Sections  
Number of Levels  
Type of Floor Section (full span, intermediate support)  
*Joist type (built-up, LVL, PSL, Glulam, flitch, steel, dimensional)*  
Joist Spacing  
Slope of Deck  
Number of openings  
Type of openings (jacuzzi, pool)  
Type of Blocking or Bridging  
Type of connections  
Number of connections/member  
Number of stairs related to deck

## **External Features - -**

### **Dormers, Skylights, etc.**

Number of dormers, skylights, etc.  
Size  
Orientation  
Shape  
Type of members  
Type of connections





## Appendix E

### Test Chamber Design

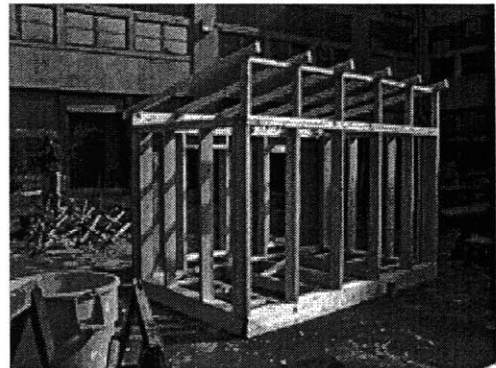
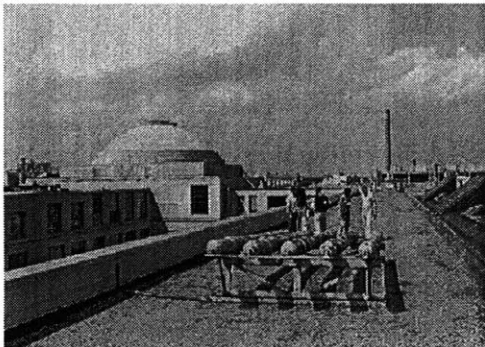
## Appendix H – Test Chamber

### Test Chamber Background

The concept of using test cells also known as test chambers, guarded heat boxes, is to measure the performance of wall panels in an isolated environment where the panel is the only perceived variable has been practiced for numerous years. 1975-1985 and the early 1990's are two periods where large government supported projects at Los Alamos[2] and the Lawrence Berkeley Lab[3] began using multiple test cells.

Constant scrutiny has revolved around the results and the conclusions made from these test cells[5]. The main issues relating to data validity are type of construction, context, and scaling. Each new test cell project that was developed seemed to be of a new construction type, whether it is a single-envelope, double-envelope, single chamber, or multiple chambers in one, causing problems for the comparison of the results of each facility. The complexity is increased when the issue of material use is brought into the equation. Scaling, however, is the most important issue, and is based upon the assumption that scaled models provide valid results. The problem is that elements such as airflow and mass can not be scaled down due to numerous factors, and even the best results are merely educated guesses.

The purpose of the Mobile Window Thermal Test (MoWiTT) [6] was to provide accurate, full-scale, dynamic thermal performance testing of various types of window systems when exposed to real weather conditions, and to measure solar gain. The description above is of highly precise test cells with sophisticated sensors and monitors, providing results with the reliability to shape or support a standard.



### Test Chamber- Data Collection

The first step was to collect general data about the site and begin calibrating each chamber to evaluate and identify the differences between each. Unfortunately, due to external factors and timing, this calibration did not occur until after a series of data was collected upon a few component types. From this point, refinements were made to the chamber to suit the type of component tests run.

The majority of the measurements were taken through the use of devices, provided within the Vital Signs Toolkit. The Vital Signs program developed at the University of California, Berkeley by Cris Benton.[Vital] The purpose was to empower students to begin to question and find answers on how built structures perform once they are constructed. MIT had obtained the rights to use the toolkit through an accepted proposal written by our research group. The devices, such as the Raytek surface temperature gun and the Hobo Light intensity sensor, (pictured at right) collected data pertaining to long term, short term and instantaneous measurements. Data was collected on the exterior of the test chamber, within the first control zone, and within both of the second control zones. Temperature, Light and Relative Humidity were measured in various capacities.

With the calibration complete, testing of the various configurations could begin. The initial concept was to test:

- 1) *each material in isolation*
- 2) *partnerships of materials*
- 3) *at least one complete configurations*
- 4) *alternatives*

to develop a larger family of comparable data.

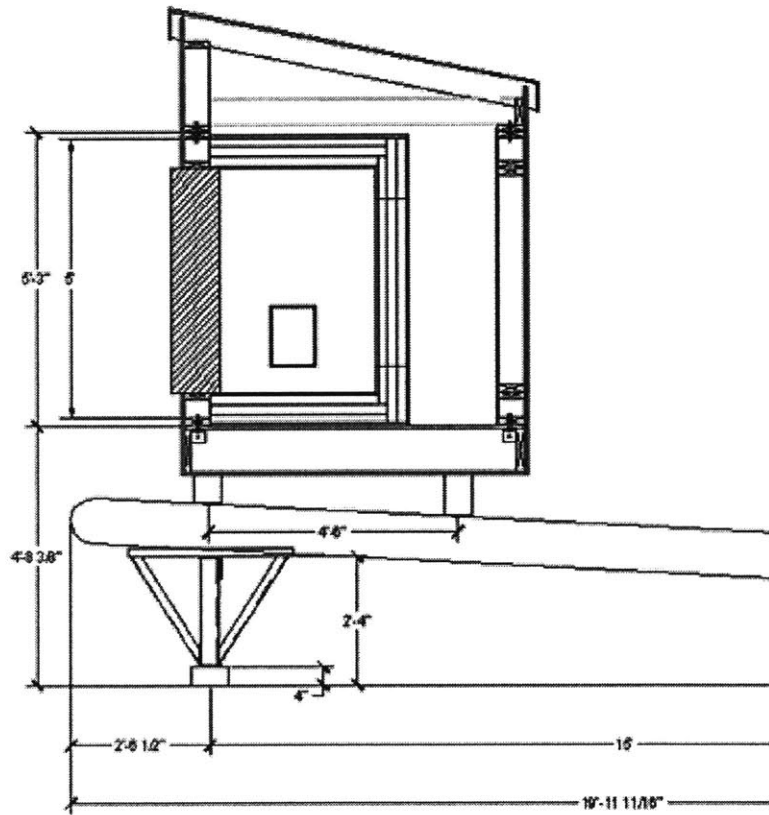




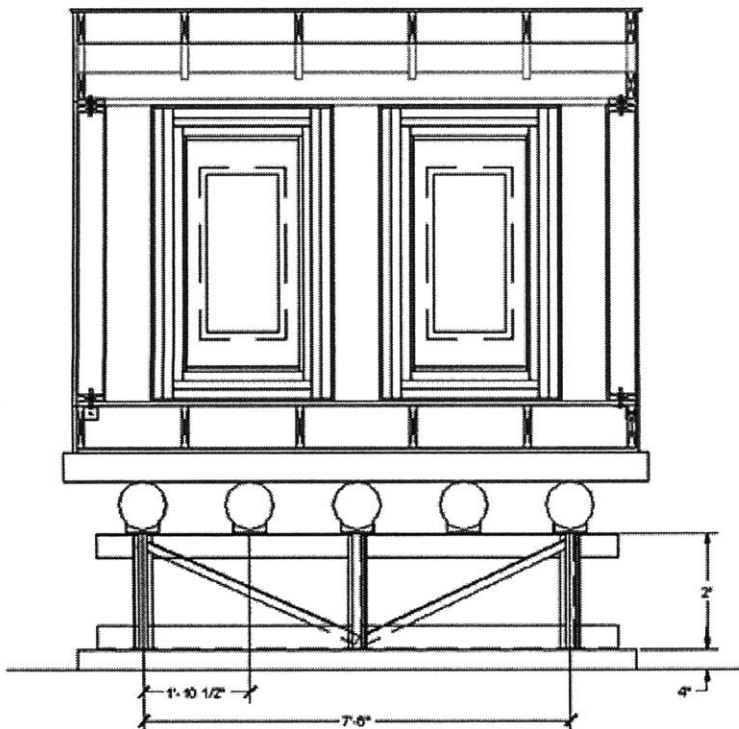





Section looking east

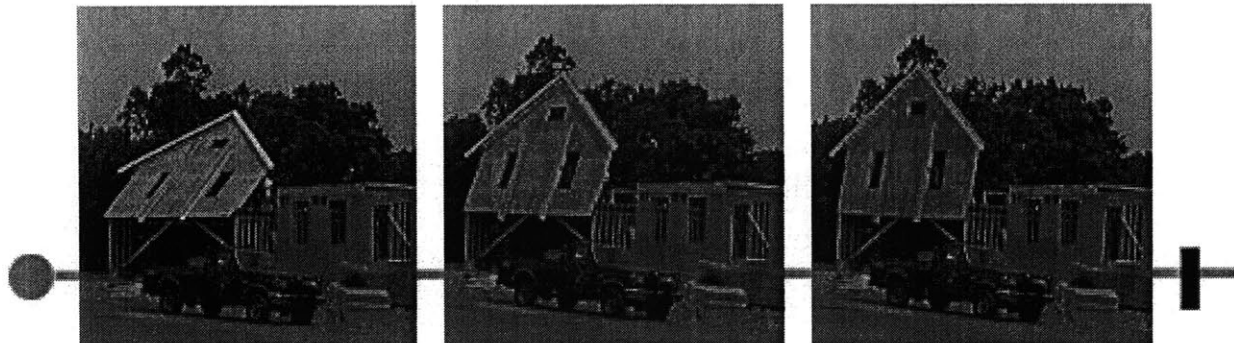


Section looking south





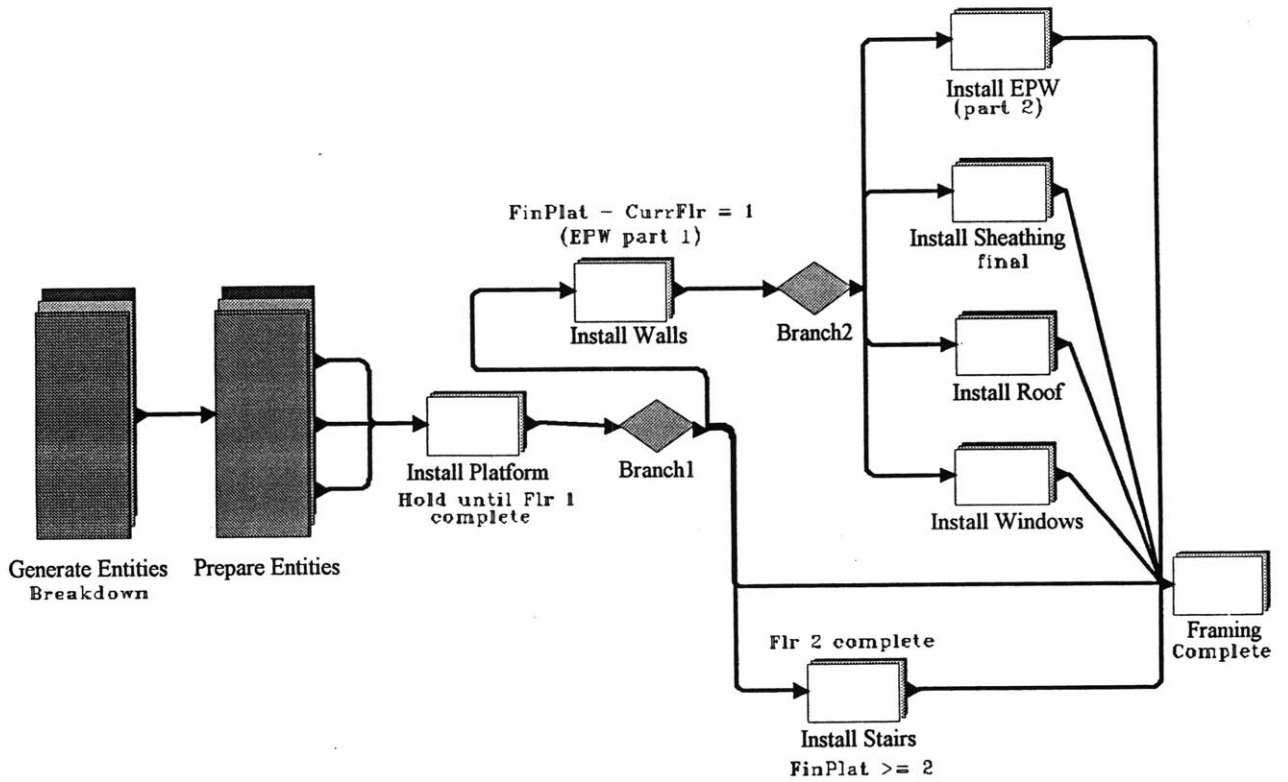
The data gathered within the settings of the test chamber were inconclusive and did not have significant influence upon refinement of material selection and layer configurations. The inability to obtain the necessary materials to bring the experiment into the realm of comparison and the method of monitoring the units, with the equipment utilized, created significant room for error, even with orders of magnitude as the target. Base cases of a standard wall section, a standard double-glazed window, a translucent insulation material and others listed in Appendix B were placed within the test chamber. However, the level of assumptions and the simplifications made due to the two factors mentioned, made the influence upon the framework fall into the categories of aesthetic and process, rather than operational. The level of reliability was not high due to a large range and high variance of results and the difficulties in fine tuning the environment of the test chamber. Basic ideas could be assessed, but not to the point of influencing the calculations. However, this stated the spillover benefits into other areas relating to the frame and component construction and insight into the system links and requirements for the equipment associated with the photovoltaic units proved invaluable to the overall concepts and did have significant qualitative effects.



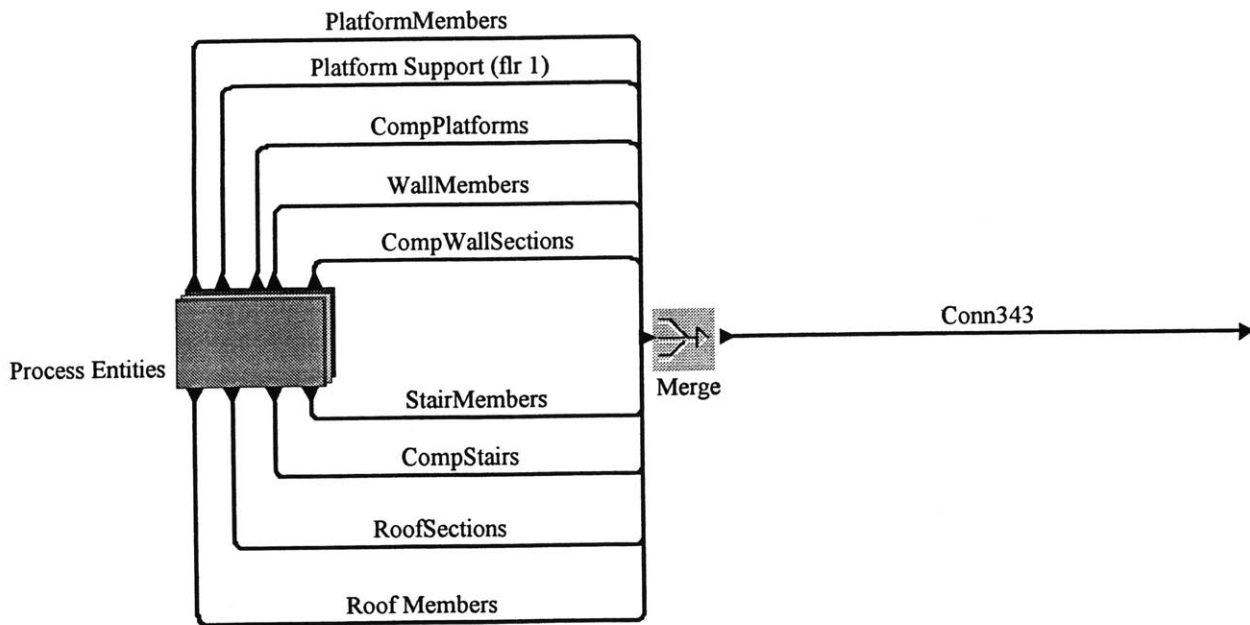
## Appendix F

### Dynamic Process Model for Light Wood Frame Construction (DPM-LWF)

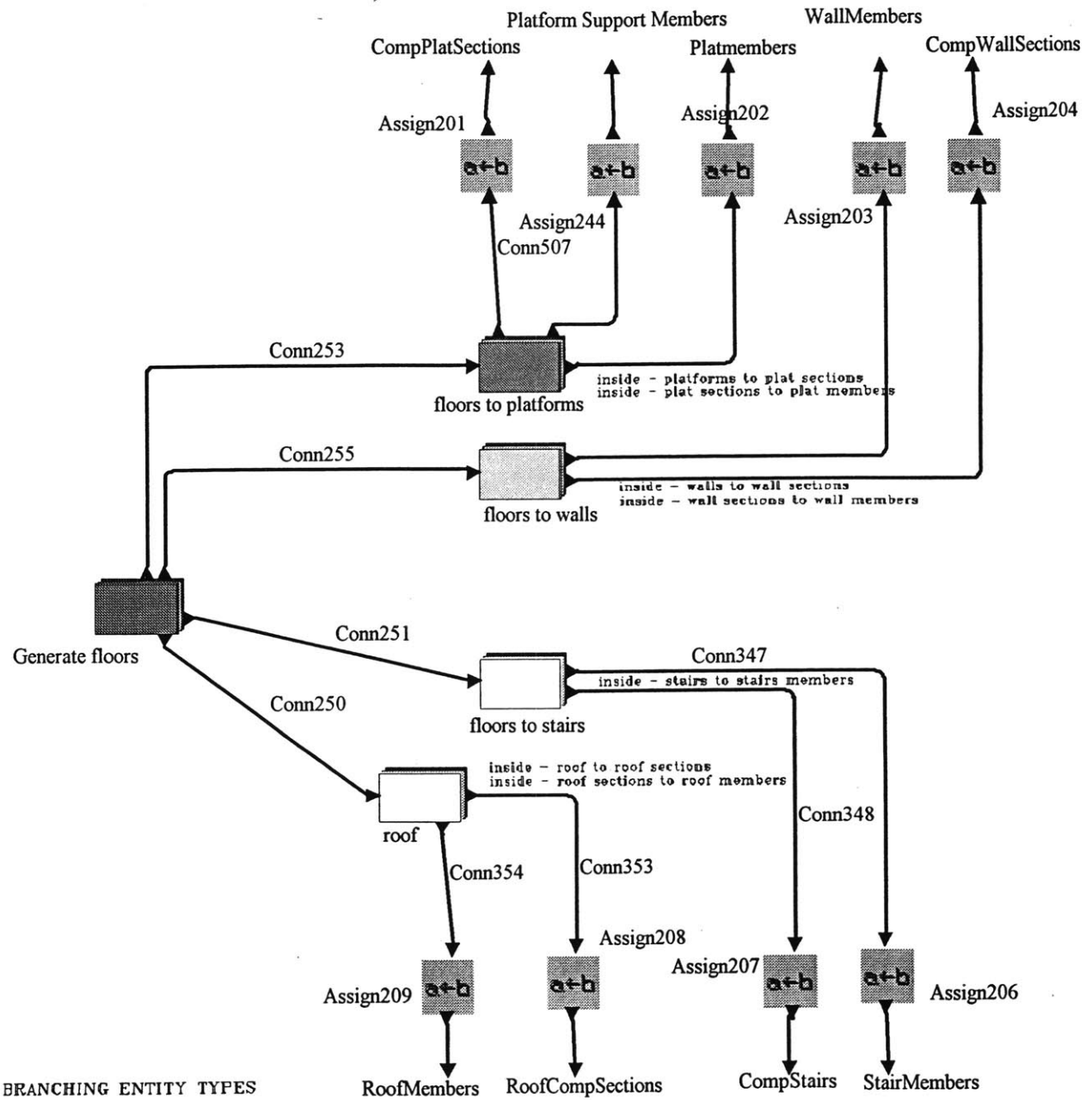
Diagrams from SIMPROCESS of higher level diagrams within the process.  
All of the diagrams within the model are not included



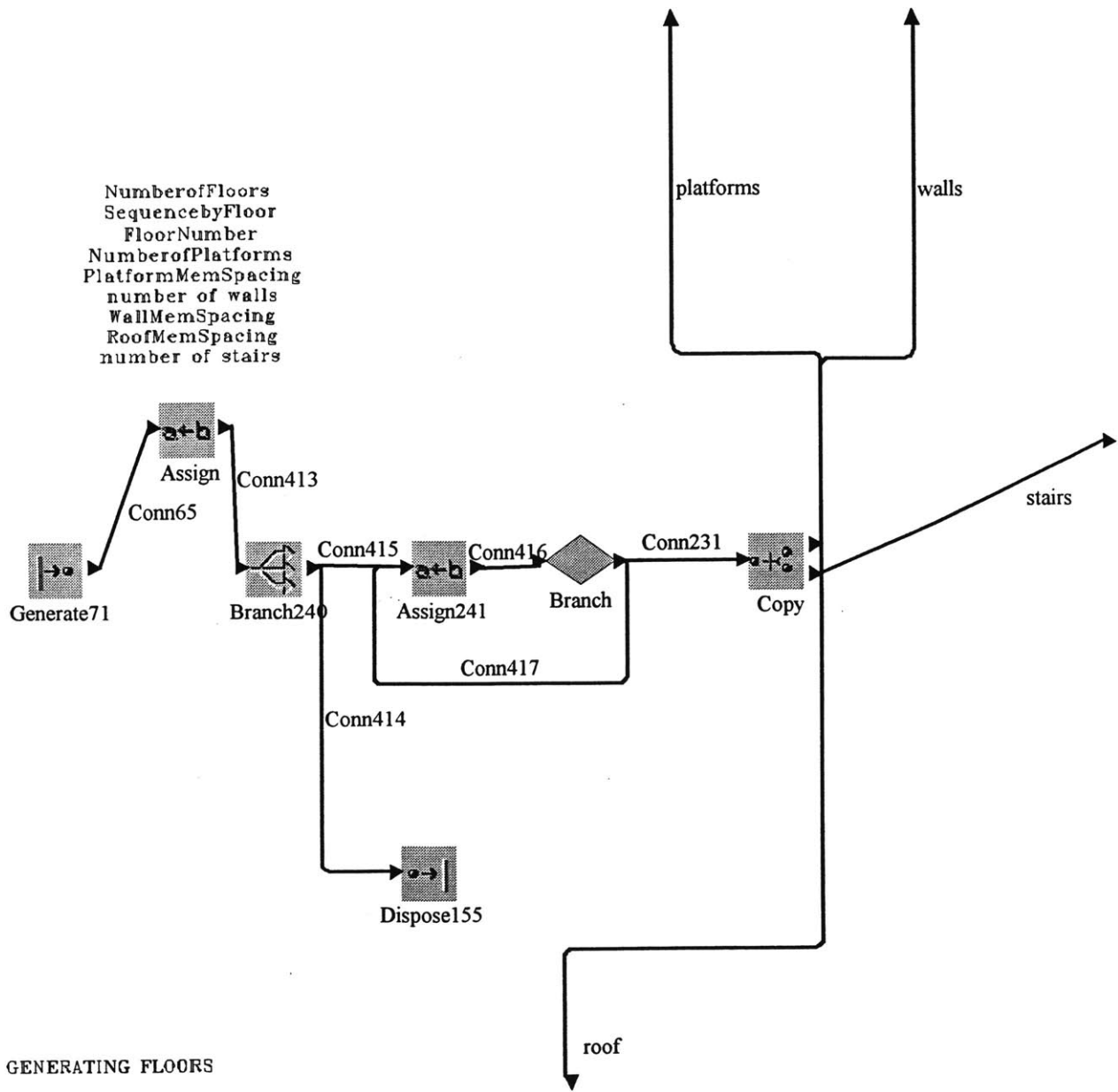
# Appendix I

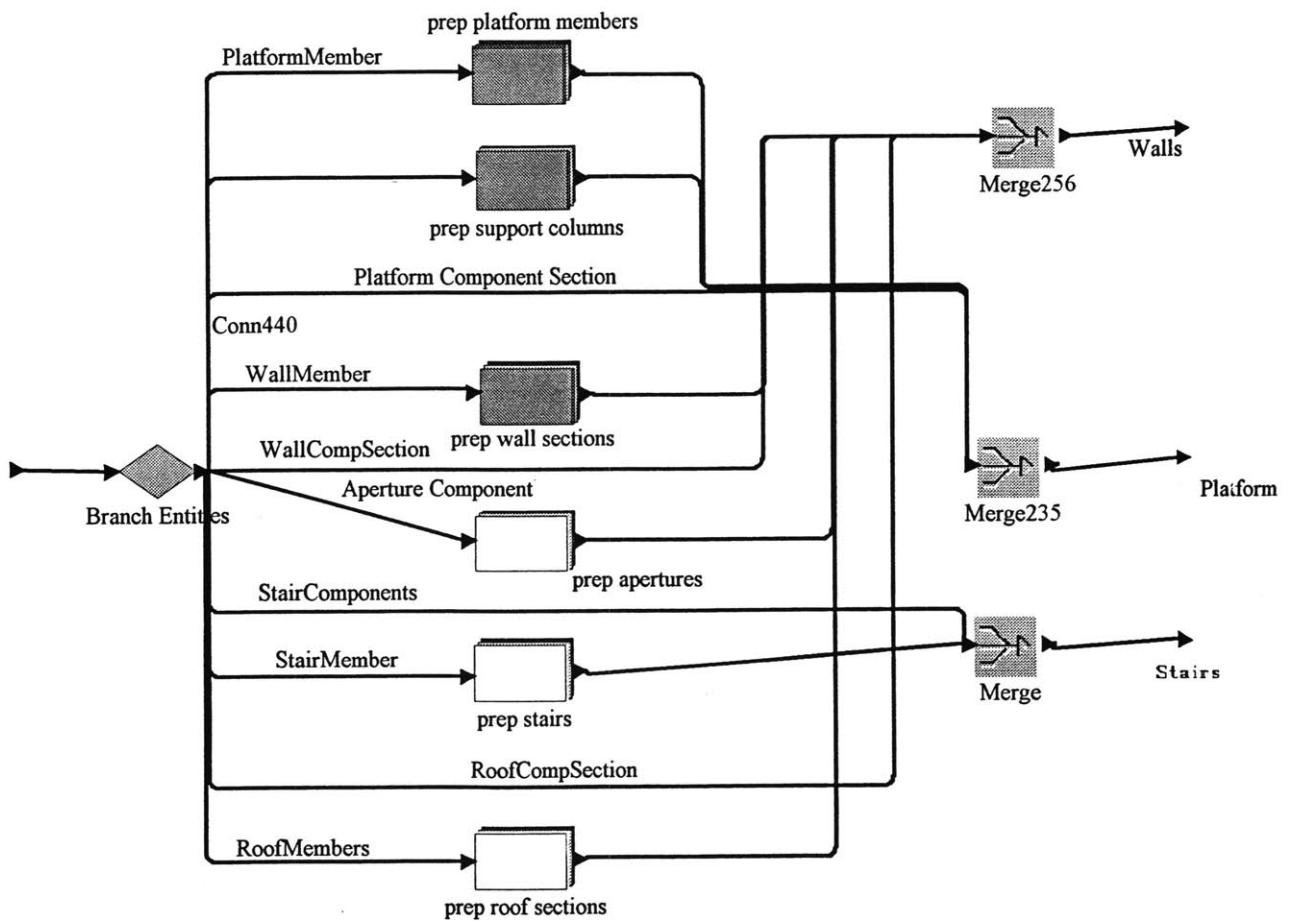


BRINGING ENTITIES TOGETHER PRIOR TO INSTALLATION

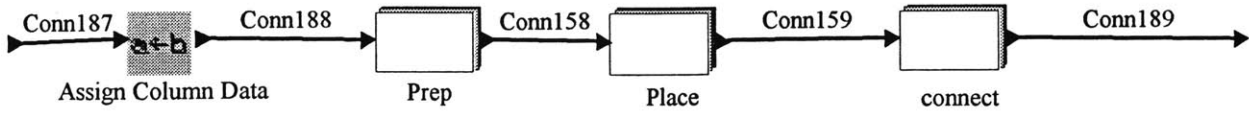


BRANCHING ENTITY TYPES



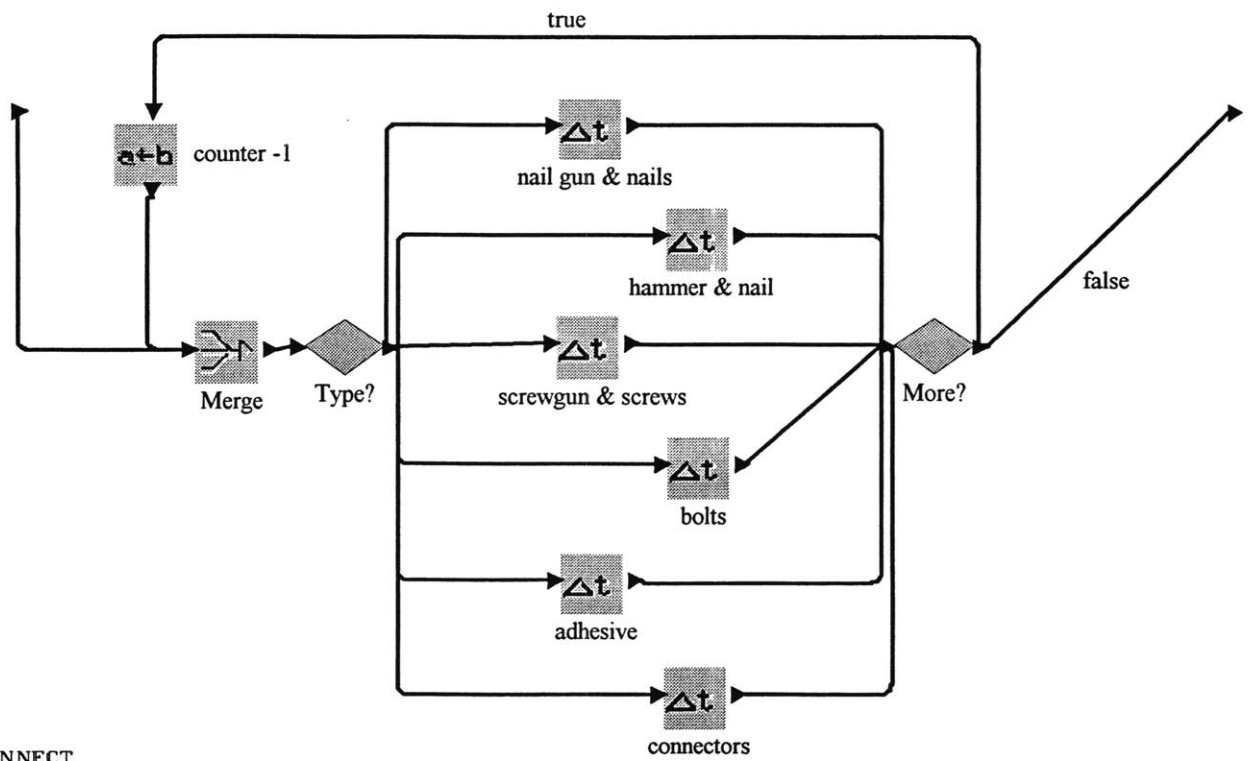






```
open data file  
read data file info  
EntityColumnNumber=count  
Entity.counter=Entity.numberofcolumnouts  
Entity counter=Entity numberofcolumnconnects  
Close Data File
```

SUPPORT COLUMNS



CONNECT





## **Appendix G**

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