ABSTRACT OF DISSERTATION

EXPLORING THE USE OF VIRTUAL CONSTRUCTION TO CAPTURE KNOWLEDGE AND REDUCE WASTE FOR RESIDENTIAL PROJECTS

Construction lags behind manufacturing in productivity, occupational safety, and construction quality is considered to be insufficient (Koskela, 2000). Additionally, cost has continued to increase faster than the rate of inflation preventing many Americans from realizing home ownership (Shiller, 2006). Many of the advancements in manufacturing can be traced to the Lean production techniques developed by Toyota Motors (Ohno, 1988; Womack, 1996). A current line of research in the construction industry is focused on infusing Lean production principles into construction. Lean construction has not been significantly diffused in the construction industry primarily because it is a set of guiding principles or theory rather than an established set of practices. Few project management tools have been developed on the foundation lean principles.

Producers of most manufactured products experienced breakthrough advances in productivity due to the digital-based convergence of 3-D CAD representations and production processes. The 3-D model serves as the medium for communication and collaboration among project participants. Products are digitally created and produced seamlessly from concept through production (Kolarevic, 2003).

This study used a mixed methods sequential exploratory design (case study and quasi-experiment) to investigate waste in the residential on-site framing process. A new set of construction documents founded on lean principles was developed and tested for effectiveness to reduce waste. Much of the waste in the residential framing process is associated with the information poor traditional construction documentation. This study provided insight into the waste activities associated with residential framing by identifying four information categories associated with the waste. These categories are, preference information, conflicting information, insufficient information, and hard to find and/or confusing information.

A set of traditional construction documents (TCD) was compared to a set of new construction documents (NCD) produced from a 3-D model on construction time, construction quality (including accuracy), and framing experience. The results of the quasi-experiment showed a significant reduction in time and an increase in accuracy when using the NCD. The results also showed that quality (not including accuracy) was a function of experience. Overall, it was found that when crews used the NCD produced from a 3-D model, waste was reduced.

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CHAPTER 1: INTRODUCTION AND BACKGROUND

Introduction

The housing industry has yet to realize the breakthrough productivity advances witnessed in the past decade by the manufacturing industry and similar product-oriented industries (Kieran & Timberlake, 2004). As part of these advances, we have seen improved quality and added value with lower relative cost to customers (Mapes, Szwejczewske, and New, 2000). Construction lags behind manufacturing in productivity, occupational safety, and construction quality is considered to be insufficient (Koskela, 2000). Additionally, cost has continued to increase faster than the rate of inflation preventing many Americans from realizing home ownership (Shiller, 2006). Recognizing this problem, the National Association of Home Builders (NAHB) promised to commit efforts and resources to create stronger, more efficient home production delivery systems (National Association of Home Builders & Freddie Mac, 2004).

Many of the advancements in manufacturing can be traced to the Lean production techniques developed by Toyota Motors (Ohno, 1988; Womack, 1996). Lean techniques rely on bottom-up management to capitalize on production worker expertise/experience and empower them to continually improve productivity and quality (Spear & Bowen 1999). This approach appears particularly appropriate for the affordable housing sector because of multiple builds of a given model. Additionally, the need to reduce cost and improve quality through process improvement for entry level homes continues to be an important issue.

A current line of research in the construction industry is focused on infusing Lean production principles into construction. Much of current research in Lean construction theory and practice is conducted by researchers in universities and groups such as the International Group for Lean Construction and the Lean Construction Institute. The Lean Construction Institute is a non-profit research organization founded in August 1997 by Glenn Ballard and Greg Howell. As stated on their website:

> LCI's purpose is to reform the management of production in design, engineering and construction for capital facilities. LCI developed the Lean Project Delivery System™ (LPDS) that applies principles pioneered in manufacturing to construction. LPDS tools facilitate planning and control, maximizing value and minimizing waste throughout the construction process. (Lean Construction Institute, n.d.).

The International Group for Lean Construction (IGLC) was founded in 1993. This group "makes up a network of professionals and researchers in architecture, engineering, and construction (AEC) who feel that the practice, education, and research of AEC have to be radically renewed in order to respond to the challenges ahead (the International Group for Lean Construction, n.d.)."

A fundamental principle of lean production, also known as the new production system (NPS) and world class manufacturing, as summarized by Womack and Jones (2003 p.15) is providing ways "to do more and more with less and less – less human effort, less equipment, less time, and less space – while coming closer and closer to providing customers with exactly what they want." Fundamental to this principle is waste reduction. Waste in the context of lean has been defined as "any human activity which absorbs resources but creates no value" (Womack and Jones, 2003 p.15).

Additionally, value and non-value adding activities have been defined by Koskela (1992 p.17) as follows:

- Value-adding activity: Activity that converts material and/or information towards that which is required by the customer.
- Non value-adding activity (also called waste): Activity that takes time, resources or space but does not add value.

Construction, like much of the manufacturing industry before lean production principles were introduced, is founded in the transformation model of production. The transformation model, simply put, is the process of transforming input (materials, labor and knowledge) into an output (product). Traditional and current construction management practitioners' view construction as a set of activities (transformations) necessary for project completion (output) (Koskela 1992). Little attention is given to flow in the transformation production model. In addition to transformation, lean production focuses on flow as a way to reduce or eliminate waste (non value-adding activities). Lean production including the concept of flow has been described by Koskela (1992) as follows:

> Production is a flow of material and/or information from raw material to the end product (Figure 1). In this flow, the material is processed (converted), it is inspected, it is waiting or it is moving. These activities are inherently different. Processing represents the transformation aspect of production; inspecting, moving and waiting represent the flow aspect of production.
> Flow processes can be characterized by time, cost and value. Value refers to the fulfillment of customer requirements. In most cases, only processing activities are value-adding activities. For material flows, processing activities are alterations of shape or substance, assembly and disassembly.

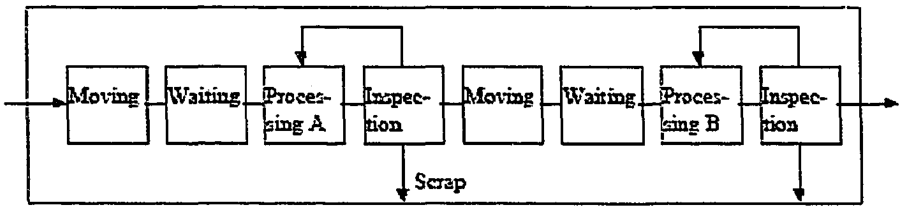

Figure 1-1. Production as a flow process: simplistic illustration. The shaded boxes represent non value-adding activities, in contrast to value-adding processing activities. (p.15)

Not only are these non value-adding activities not sufficiently addressed in traditional construction management practice, additional waste is caused by poor design, errors in quantity takeoff, delays in shipment, and fabrication errors requiring rework (Choo, 2002). All of these activities and causes of waste increase the variability in the production/construction system. This variability itself is a significant contributor to waste.

Lean construction has not been significantly diffused in the construction industry primarily because it is a set of guiding principles or theory rather than an established set of practices. Few project management tools have been developed on the foundation of lean principles largely because of the differences between construction and manufacturing. As stated by Koskela (1992 p.51) "The idiosyncrasies of construction, like unique, one-of-a-kind products, site production, temporary project organizations and regulatory intervention necessitate an industry-specific interpretation of the general principles of the new production philosophy, which currently exist only in outline." One lean construction management technique developed by Ballard and Howell (Ballard, 2000) is the Last Planner System or LPS. It has been the premier implementation tool used by the LCI and construction companies involved in Lean (Intri-Conte, 2002). LPS is based on three levels of a project schedule. The most detailed "plan level" is defined by a project's "Last Planners" (those closest to the work) in weekly face-to-face meetings, where the group determines the tasks for the next week. Even though some success has been realized through the use of the LPS, much of the success has been focused on plan or schedule reliability. In order to increase plan reliability utilizing the LPS, "last planners" are required to identify prerequisite or predecessor activities to be completed in order to release the planned work (Ballard, 2000). In other words, only activities available to be scheduled (all prerequisite work completed) are allowed to be scheduled. With the LPS focus on the schedule to improve plan reliability, there is still much variability and waste, within and between the activities, available to be removed or minimized.

Much of the waste associated with the current methods of construction management and practice is related to the uncertainties that plague the construction process. Variation comes in many forms and is found in many aspects of a production system. Each type of variation has the potential to impact quality, schedule and/or budget. Tommelein (2000) suggests that there are two major forms of variability in production systems, product and process. She points out that the first step in engineering a product and process that will be least impeded by variability is to identify some of the causes of variability. Next is to work on eliminating the most significant causes, and identifying the causes allowed to remain.

One of the tools utilized by the manufacturing industry to reduce waste is three dimensional (3-D) computer aided design (CAD), at the component level. Producers of most manufactured products (e.g., airplanes, ships, cars, consumer products) experienced breakthrough advances in productivity due to the digital-based convergence of 3-D CAD representations and production processes. Products are digitally created and produced seamlessly from concept through production (Kolarevic, 2003). In many of these industries, design (including engineering) and production departments have been combined into one where teams come together to meet customer needs (Kieran and Timberlake, 2004).

Three-dimensional models have also been used successfully on complex construction projects to communicate and coordinate construction activities (Kolarevic, 2003). Currently research is being done on the use of 3-D CAD to improve constructability (through analysis of the virtual model) and to generate construction documents (including the 2D drawings and specifications). The fourth dimension (time) has been added to aid in scheduling. And what some are calling the fifth dimension (linking cost and product data to the model) could inform the estimate. The sixth dimension deals with the management of the building throughout the life of the building. Many research institutions and industry professionals as well as software companies have focused their attention on these technologies. Building information modeling or BIM is the term that is being used in the AEC industry to describe the use of the third through sixth dimensional models for building construction. Three-dimensional CAD is the tool that will be used for this research to serve as a common visual language to plan production, and is a language that may be able to capture, preserve, and precisely reiterate detailed production knowledge using processes compatible with Lean principles.

Statement of the Problem

The overreaching problems addressed by this research are the high and rising cost (Shiller, 2006), as well as the poor quality of housing in today's market (Koskela, 2000). One of the significant contributors to these problems is the waste inherent in the traditional method of home construction and design. Another factor includes a shrinking skilled labor force in conjunction with the high cost associated with a craft industry (Barlow 1999).

One of the problems with design is the poor communication among design, engineering and building professionals. These professionals work almost independently to produce increasingly complex projects. Not only are separate documents produced by these organizations (often in non-compatible formats) but this documentation contains conflicting, confusing, and missing information. As stated by Tommelein and Ballard (1998), "it is seldom the case that contract documents including design drawings and specifications are unambiguous and sufficiently detailed to be of direct use to specialty contractors." The practice of producing "shop-drawings" for production purposes is common in commercial construction. For residential construction, even the term "shop-drawings" is rarely used. The closest thing to shop-drawings for most residential construction projects is a detailed plan for cabinets (a manufactured component).

In spite of this information-poor documentation, the residential and to a large extent the other sectors of the industry have been able to function using a skilled management and labor force that are expected to interpolate the information on construction documents in order to complete their respective work. These interpolations often equate to waste in the forms of fabrication errors, poor product quality, and material discrepancies including a lack of needed materials and delivery of inappropriate materials (Choo, 2002).

In an effort to increase profit and improve relations, highly skilled workers attempt to learn from their mistakes over subsequent builds to gain efficiency and improve coordination. Although not explicitly stated as such, these improvements are an undocumented effort at reducing non-valued added activities that include such things as optimizing their work for the next trade. In spite of these improvement efforts, craftsmen will attest that even though they are building the same house repeatedly, houses are seldom if ever built the same way twice. Many of these craftsmen do not have a system to document waste reduction and value adding activity enhancements documentation that could be continuously improved to reduce waste (Folkestad, 2006).

This reliance upon a skilled labor force has been a luxury that may be coming to an end. The Bureau of Labor Statistics (US Department of Labor: Bureau of Labor Statistics, n.d.) has predicted a skilled labor shortage the beginning of which has been recognized by the Construction Industry Institute as an area of significant concern (Construction Industry Institute, n.d.). Additionally, with many construction workers coming from non-English speaking countries, language/literacy barriers exist among project personnel. Thus, in addition to the absence of an effective process for documenting learned valued added activities, there are not enough skilled laborers who fluently speak or understand the language used by design and project management professionals. These additional factors add to the waste that contributes to the overall problems of high and rising cost of poor quality homes.

In spite of the significant problems in the housing industry, much of the technology development by software companies, including that for BIM has been focused on commercial projects. Some of the leading BIM solutions (Autodesk Revit, Bentley Systems Inc., VICO software, Constructor) claim the ability to quickly create more accurate 2D drawings with fewer mistakes, improve the accuracy and reliability of the schedule and estimate, and increased collaboration through visualization. The 2D drawings, even though more accurate, still are information-poor when it comes to the ability of front-line workers to use the information for construction. Additionally, the focus has not taken into account the skilled labor shortage. In other words, the information produced by these programs is not sufficient for front-line workers, many of whom are not skilled craftsman. The work performed by these skilled or non-skilled personnel can be a major source of waste in the form of variability. Lean production/construction recognizes variability as a main producer of waste. Thus, variability reduction is a significant method utilized for waste reduction. Koskela (1992) identifies two reasons for reducing process variability. First, from the quality perspective, a uniform product is better quality. Second, variability increases waste in the form of non value-adding activities. Given these two reasons, variability reduction in production product and process must be an intrinsic goal (Sullivan 1984). And as stated by Schonberger (1986) "Variability is the universal enemy."

BIM software solutions have focused on improving current construction project management techniques (grounded in the transformation production model) which are driven by a critical path schedule (CPM). These solutions have largely failed to investigate how the lean production principles such as flow management including variability reduction, and process improvement can be applied to construction.

Three-dimensional models were utilized for this research to investigate how a new production process founded in lean principles can be used for the construction of single family homes. These virtual models were the clearinghouse for design, engineering and building information. Because the 3-D model is a representation at the component level of the actual building, information from all relevant project documentation is contained in the model. Additionally, a process for collecting and distributing information in a language that will be more universally understood was tested. One of the challenges with using a 3-D model is the ability to distribute the information to the field workers in a format that contains the most relevant information. Even though the information may be contained in the model, it may not be in a form that can be utilized by those in the field.

In summary, the overreaching problems of high cost and questionable quality are in part the result of waste caused by variability resulting from current construction methods. Some of this variability is the result of insufficient information in the documentation in conjunction with the use of a craft labor force. Additionally, the effects of the documented skilled labor shortage in the industry are beginning to be seen and are resulting in increased variability resulting in additional waste.

Research Questions

The project began as an exploratory case study to investigate the usefulness of three dimensional models to improve construction of on-site wood-framed residential homes. The exploratory project was conducted because of a lack of prior research in this specific area. Through this study it was found that a 3-D model of a home frame could be generated using a 3-D parametric modeling software that has traditionally been used to design manufactured products. Additionally, it was found that certain types of information could be captured by the 3-D model. This exploratory study lead researchers to a general theory upon which this study is founded and was the basis for the following research questions. The overall research question explored by a case study and answered by the formal research questions was: How can a three dimensional model of a residential home frame be utilized to reduce variability and minimize waste in the residential framing process. Answers to subsequent questions assisted in answering this overriding question.

1) What are the non value-adding activities (waste) contained in the residential on-site framing process?
   a) How are the non value-adding activities different in the virtual and physical building processes?
2) What information (eg. documentation, explicit knowledge, tacit knowledge) needs to be communicated to front line workers to reduce variability and minimize waste?
3) What information found to be pertinent in research question 2 can be communicated using a three dimensional model?

From the original case study came the development of a new set of construction documents generated directly from a complete 3-D model of the home frame. These documents were utilized as part of the case study to improve usability of the new documents. The new documents went through several iterations before an acceptable solution was found. Once a usable form of the new documents was realized, several additional research questions arose. The following research questions were answered using a quasi-experimental design:

4) Does framing time differ when a crew uses construction documents produced from a 3-D model as apposed to when traditional construction documents are used?
5) Does frame quality differ when a crew uses construction documents produced from a 3-D model as apposed to when traditional construction documents are used?

6) If a difference is found for question 4, does a more experienced framing crew differ from a less experienced crew on the time difference
7) If a difference is found for question 5, does a more experienced framing crew differ from a less experienced crew on the quality difference

Delimitations

There are many aspects of the residential construction process including design, engineering, and construction that could be investigated as part of this research. Based upon exploratory research conducted at Colorado State University (CSU) and prior residential construction experience of the researcher, on site wood framing was chosen as the area of study.

The exploratory research found that the frame informed, and was central to every other system in a home. The frame is one of the first major systems to be installed for a home with the exception of the foundation and underground plumbing. It was found in the exploratory study that errors in underground plumbing, as well as the foundation and structural slab, were corrected to fit the frame. It should be noted; for most custom home construction and for some production builders, the frame is adjusted to fit the foundation. However, for the case under investigation the framing plans had precedence. It was also found that efforts were made to change the frame to meet the needs of the mechanical, electrical, and plumbing systems. Overall it was found that realizing and perfecting the frame had a profound impact on the other systems. These findings were in concordance with the researcher's prior experience.

There are many software programs available that have the ability to generate three dimensional models. SolidWorks is the tool that was chosen for this project. This decision was based upon the exploratory research which was conducted at Colorado State University where several tools were considered and evaluated for function and usability. As these tools continue to develop, it may be found that another tool could be more effective in accomplishing the goals of this project. Toward the end of the research project, it was found that a Colorado based company (Keymark) has been working toward the same goals as the researchers for several years.

Limitations

This project is limited to a single development of single family homes near Denver, Colorado. The homes in this development are constructed on-site using somewhat unique wood frame and foundation systems. The other systems are fairly typical for homes in this region of the United States but different than other regions or countries. The frame is unique in that the engineering allowed for the walls to be constructed in a slightly different manor than usual. The framing process, which is central to this investigation, may also be somewhat unique to the crews and framing subcontractor employed for this project. Additionally specific methods and means employed by the developer as well as code requirements of the governing municipality, although similar to other developers and municipalities, are unique.

Once the new construction documents were realized as part of the case study, a convenience sample of students enrolled in the construction management program at CSU was selected. These students were chosen based upon prior framing experience.

The study was conducted in a lab building at CSU and only utilized three walls per home. Interaction with other systems such as the foundation, plumbing and floor truss system was absent. The first time the participants had worked together was while working together on the experiment.

The case study investigation only included the first few builds of each of the home plans. Results of the case study may have been different if it had been conducted later in the maturation process of the development. Additionally, crews used for the quasi-experiment had not been exposed to the plans prior to construction. This is both a limiting factor as well as a control.

Definition of Terms

The construction industry has several different sectors as well as similar terms that are used within and between these sectors that may have significantly different meanings. Some of these terms and there operational definitions are included here to clarify the scope of this project.

- *Framer(s):* Carpenters who specialize in constructing single family home wood frames.
- *Framing*: on site wood frame of residential single family homes including structural and non-structural components.
- *Process Variability:* The variation associated with the flow from one activity to the next. Dealing with the whole production process from design to use or completion. (project level)
- *Product Variability:* The variation associated with product components and their assemblies. (Activity level)

- *Typical onsite framing process:* The process of using two dimensional construction drawings created by an architect, and/or engineer, and/or draftsman including floor plans, roof plan, foundation plan, elevations, and associated details to frame a home. Additionally, the process of clarifying and collecting the necessary information for completing the frame is part of the process. Framing errors and rework associated with errors are also part of the process.
- *Waste:* Any non value-adding activity. Sometimes waste is the result of variability.
- *Value-adding activity:* Activity that converts material and/or information towards that which is required by the customer.
- *Non-value adding activity*: Activity that takes time, resources or space but does not add value.
- *Variability:* able or apt to vary : subject to variation or changes (Merriam-Webster Online Dictionary, 2006)

CHAPTER 2: REVIEW OF LITERATURE

Lean Theory

Daniel W. Halpin, the recipient of The Peurifoy Construction Research Award in his acceptance speech to the American Society of Civil Engineers emphasized the need for a Theory of construction that focused on process technology at the production level (Halpin, 1992). He recognized the need for a theory or framework for construction within which fundamental research could be conducted. Koskela in his foundational works (Koskela, 1992; 2000) has made a significant effort towards describing a theory of production and its application to the construction industry. He describes the functions of a theory of production as follows (Koskela, 2000 p.25-26):

> Firstly a theory of production has the same functions as theories in general. On the basis of discussion above, these can be summarized as follows:
>
> - *Explanation.* A theory provides an explanation of observed behavior, and contributes thus to understanding.
> - *Prediction.* A theory provides a prediction of future behavior; in the case of production, especially of the contribution of action to goals.
> - *Direction.* A theory pinpoints the sources of further progress.
> - *Testing.* When explicit, it is possible to constantly test the theory to prove its validity.
>
> Secondly, however, the functions of theory are more wide-ranging in the case of production management than in the case of natural and behavioral sciences. It will not only serve to research but also to practice. An explicit and adequate theory of production will provide the following functions, in addition to those presented above
>
> - *Tools for decision and control.* On the basis of a theory, tools for analyzing, designing and controlling production can be built (Kochikar & Narendran 1994).

- *Communication.* A theory, when shared, provides a common language or framework, through which the co-operation of people in collective undertakings, like a project, firm, etc., is facilitated and enabled (Heim & Compton 1992).
- *Learning.* A theory can be seen as a condensed piece of knowledge: it empowers novices to do things that formerly only experts could do (Fenves 1996).
- *Transfer.* Innovative practices can be transferred to other settings by first abstracting a theory from that practice and then applying it in target conditions (Lillrank 1995).

Much of this section of the review of literature comes from Koskela's work.

Many of the advancements in manufacturing can be traced to Lean production techniques developed by Toyota (Ohno, 1988; Womack, 1996). Lean techniques rely on bottom-up management to capitalize on production worker expertise/experience and empower them to continually improve productivity and quality (Spear & Bowen 1999). Womack and Jones (2003) Identify five principles for lean production as follows:

1. Specify value for the product
2. Identify the value stream by product
3. Make value flow
4. Let the customer pull value from the producer
5. Pursue perfection through continuous improvement

These principles fit well with Koskela's (2000) Transformation, Flow, and Value(TFV) theory of production.

A fundamental principle of lean production, also known as the new production system (NPS) and world class manufacturing, as summarized by Womack and Jones (2003 p.15) is providing ways "to do more and more with less and less – less human effort, less equipment, less time, and less space – while coming closer and closer to providing customers with exactly what they want." Fundamental to this principle is waste reduction. Waste in the context of lean has been defined as "any human activity which absorbs resources but creates no value" (Womack and Jones, 2003 p.15). Additionally, value and non-value adding activities have been defined by Koskela (1992 p.17) as follows:

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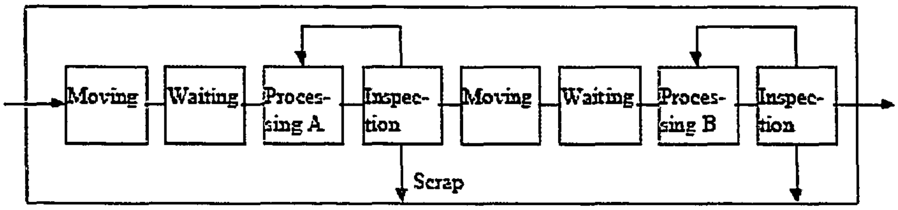

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Not only are these non value-adding activities not sufficiently addressed in traditional construction management practice, additional waste is caused by poor design, errors in quantity takeoff, delays in shipment, and fabrication errors requiring rework (Choo, 2002). All of these activities and causes of waste increase the variability in the production/construction system. This variability itself is a significant contributor to waste.

Lean construction has not been significantly diffused in the construction industry primarily because it is a set of guiding principles or theory rather than an established set of practices. Few project management tools have been developed on the foundation lean principles largely because of the differences between construction and manufacturing. As stated by Koskela (1992) "The idiosyncrasies of construction, like unique, one-of-a-kind products, site production, temporary project organizations and regulatory intervention necessitate an industry-specific interpretation of the general principles of the new production philosophy, which currently exist only in outline." One lean construction management technique developed by Ballard and Howell (Ballard, 2000) is the Last Planner System or LPS. It has been the premier implementation tool used by the LCI and construction companies involved in Lean (Intri-Conte, 2002). LPS is based on three levels of a project schedule. The most detailed "plan level" is defined by a project's "Last Planners" (those closest to the work) in weekly face-to-face meetings, where the group determines the tasks for the next week. Even though some success has been realized through the use of the LPS, much of the success has been focused on plan or schedule reliability. In order to increase plan reliability utilizing the LPS, "last planners" are required to identify prerequisite or predecessor activities that need to take place in order to release the planned work (Ballard, 2000). In other words, only activities available to be scheduled (all prerequisite work completed) are allowed to be scheduled. With the LPS focus on the schedule to improve plan reliability, there is still much variability and waste, within and between the activities, available to be removed or minimized.

Much of the waste associated with the current methods of construction management and practice is related to the uncertainties that plague the construction process. Variation comes in many forms and is found in many aspects of a production system. Each type of variation has the potential to impact quality, schedule and/or budget. Tommelein (2000) suggests that there are two major forms of variability in production systems, product and process. She points out that the first step in engineering a product and process that will be least impeded by variability is to identify some of the causes of variability. Next is to work on eliminating the most significant causes, and identifying those allowed to remain.

Variability Reduction

Manufacturing, and to some degree construction have had a continuing effort to achieve high levels of operating performance across a wide range of measures. For construction these measures have traditionally been budget, quality, schedule, and safety. In manufacturing a list as given by Mapes, Szwejczewske and New (2000) included: quality consistency, quality specification, lead time, delivery reliability, cost, flexibility, and innovativeness. It could be argued that even though, flexibility, and innovativeness are important, they are somewhat related to schedule, budget, and quality which make the performance measures very similar in both construction and manufacturing.

It has been the common sense in both manufacturing and construction that high levels of performance in one area will come at the expense of lower performance in another. Skinner (1974) explains these trade-offs in manufacturing as follows:

> These measures of manufacturing performance necessitate trade-offs – certain tasks must be compromised to meet others. They cannot all be accomplished equally well because of the inevitable limitations of equipment and process technology. Such trade-offs as cost versus low inventory investment are fairly obvious. Other trade-offs while less obvious, are equally real.

The Project Management Institute, (1996) a leader in construction project management training, have suggested that similar trade-offs exist in construction. Many practitioners in the construction industry state in reference to schedule, budget, and quality that to improve one, another must be sacrificed.

The common sense related to trade-offs is being challenged both in manufacturing and construction. Schonberger, as surmised by Mapes, et al. (2000) "has been one of the most notable of these critics, stating that, for the modern manufacturing company, trade-offs no longer exist. He argues that the factors leading to excellent performance on one factor also lead to excellent performance on other factors. Therefore, world class companies are able to out-perform their competitors on every aspect of performance."

Many researchers in construction believe that the recent advances witnessed in manufacturing can be realized in construction. As stated by Koskela (1992): "The implications of the new production philosophy for construction will be far-reaching and broad, as they are in manufacturing." Many construction researchers and practitioners believe that by using the principles employed by high performing manufacturing companies, construction companies can improve project quality and reduce schedules and cost at the same time.

Ferdows and De Meyer (1990) followed by Roth (1996) have suggested that high performance is achieved in succession. They argue that the first focus should be on quality improvement. Once quality improvement is under way and results are being achieved, then efforts should be made to make the production process more dependable. Speed is the third step in the process, not forgetting quality and dependability. Once speed efforts have been implemented then efforts at cost reduction should be implemented. Other researchers state that time or low throughput is the most important factor. They argue that initiatives that reduce throughput are in turn beneficial to cost and quality (Mapes, et al. 1996). Improvement efforts for construction are similar in that they focus on cost reduction, schedule reliability, and quality improvement.

Even though each of the aforementioned steps is important to becoming a high performing company, one of the root causes of low performance in each of the areas is variability. Mapes et al. (1996) state that:

> These ... actions are likely to be associated with the development in high-performing plants of operating systems that are much more stable and reliable than those in low-performing plants. This will lead to less stock and shorter manufacturing lead times in the high-performing plants. This will, in turn, lead to faster, more reliable delivery, greater quality consistency and lower unit costs. In other words, the fundamental drivers that lead to simultaneous improvements in productivity, customer lead time, delivery reliability and quality consistency are all aspects of reduced variability and uncertainty within the operating system.

Many others have identified variability as a key component to improved reliability and productivity in production systems (Koskela 1992, 2000) (Tommelein, Riley, and Howell 1999) and many others that will be referenced later.

Lean production/construction recognizes variability as a main producer of waste. Thus variability reduction is a method of waste reduction. Koskela (1992) identifies two reasons for reducing process variability. First, from the quality perspective, a uniform product is better quality. Second, variability increases waste in the form of non value-adding activities. Given these two reasons, variability reduction in production product and process must be an intrinsic goal (Sullivan 1984). And as stated by Schonberger (1986) "Variability is the universal enemy."

Variability and Variation

Variation comes in many forms and is found in many aspects of a production system. Each type of variation has the potential to impact quality, schedule and/or budget. Tommelein (2000) suggests that there are two major forms of variability in production systems, product and process. She points out that the first step in engineering a product and process that will be least impeded by variability is to identify some of the causes of variability. Next is to work on eliminating those that are most significant, and identifying those that are allowed to remain. Tommelein further defines product variability by asserting that components and their assemblies are the subjects of concern. Four categories of product uncertainties are identified by Tommelein as follows:

1. **Configuration:** Includes the components contained in the design along with the spatial arrangement and connectivity.
2. **Dimensional Tolerances:** Including the tolerances of the pre-manufactured parts as well as the parts produced on site. Many times the on-site components are subject to greater variation with reliance upon filler materials such as caulking, shims, and trimming excess material. These tolerances may be compounded to cause problems as construction progresses.
3. **Dimensional variance (degeneration):** Changes in form and size of product due to wear of tools.
4. **Location and Layout:** Again when deciding on the location and layout of the different components there is opportunities for variation depending on the area. Coordination of the parts in addition to the selection of those parts is key to this source of variance.

Process variability is concerned with the activities that are part of the design or construction. Tommelein describes five categories of process variability as follows:

1. **Scope of work:** Including work that is to be performed that is not found in the contract documents; scope gap, overlap, or changes; design mistake corrections; unforeseen site conditions; differing or changing building regulations; material availability.
2. **Duration and timing:** Variation in activity duration causes uncertainty in the flow of project.
3. **Quality:** Some causes include variation in quality due to differing skill levels of workers, differing or changing methods. Inspections will determine if quality is acceptable or if rework is necessary.
4. **Resource assignment:** Deals with the planning and execution of resources for project activities. Includes the planning to ensure that each process has the proper resources for the most predictable duration budget and quality.
5. **Flow path and sequencing:** Looks at the sequencing of activities to optimize flow. Tommelein mentions that decisions concerning flow and sequencing may need to be made during the construction process because of uncertainty.

Others have similarly classified locations or types of variability within a project by showing a continuum from product to process variability. They place product oriented variability at the subtask or method level and process oriented variability at the project level (Thomas, Horman, de Souza, and Zavrski 2002).

Abdelhamid and Everett (2002) summarize the causes of variability in the construction industry by stating: "sources of variability include late delivery of material and equipment, design errors, change orders, equipment breakdowns, tool malfunctions, improper crew utilization, labor strikes, and environmental effects." Additionally they identify an indirect source of variability as the physical demand of work. Hopp and Spearman describe the causes of variability in manufacturing environments as:

- Natural variability: variability, which includes minor fluctuations in process time due to differences in operators, machines, and material,
- Random outages
- Setups
- Operator availability
- Recycle: Rework due to quality issues.

Even though the causes are stated and classified differently, they are similar in nature in that they come from similar sources and have similar effects.

Hopp and Spearman (2001) from the perspective of manufacturing environments make a distinction between process time, and flow variability. Process time variability is concerned with the time variance at individual work stations. Flow variability is concerned with the effect of the process time variation on other stations and the production line as a whole. Abdelhamid and Everett (2002) make a similar distinction by using the terms intra-process and inter-process performance. This fits with Koskela's TFV theory of production with process time and intra-process performance being part of the transformation, and flow variability as well as inter-process performance being associated with flow.

Even though there are differing terms and somewhat different classifications for sources of variability, there are striking similarities among researchers. Each researcher seems to agree that there are different levels of variability, one being at the workstation or activity level and the other at the process or project flow level. Table 1 shows the terms used by each of the aforementioned researchers to classify variability.

Table 1

Terms used to classify types of variability by researcher

Researcher	Activity level	Project level
Tommelein	Product	Process
Thomas et al.	Product	Process
Abdelhamid and Everett	Intra-process	Inter-process
Hopp and Spearman	Process time	Flow
Koskela	Transformation	Flow

Methods of Variability Reduction

If "Variability is the universal enemy" then understanding ways to reduce it is imperative. Much like there are many different ways to classify and describe the different causes of variability, there are also many different approaches to variability reduction. Additionally, each approach may focus only on one type of variability and may not address others. Koskela (2000) states that "the practical approach to decreasing variability … consists of finding and eliminating the root causes." Others argue that the ability to eliminate variability is difficult and that it is "often more cost effective to manage variability than to eliminate it" (Thomas, Horman, de Souza, and Zavrski 2002). Several methods have been given for variability reduction but only a few have been formalized. Most researchers and authors give a variety of often overlapping methods with no real formal way of implementation.

The Last Planner System™.

One of the most developed and leading methods for variability reduction in construction is the Last Planner System (LPS) developed by Ballard and Howell (directors of the Lean Construction Institute (LCI)) (Ballard 2000). It has been called the premier implementation tool used by the LCI and construction companies involved in lean (Intri-Conte, 2002). The LPS is designed to reduce workflow variability by improving plan reliability, and through continuous improvement.

One of the problems identified in construction is that schedules or plans are not adhered to. Variability in the form of not meeting a scheduled deadline has been shown to cause increased variability for the rest of the project. It has also been shown that the earlier the variability is introduced into a project the greater the impact. One of the major tenets of the LPS is shielding production. This term is used to describe a method of planning that minimizes the surprises of missed schedule deadlines. The LPS is based on three levels of a project schedule- the master schedule, look-ahead schedule and a weekly work plan. The most detailed "weekly work plan" is defined by a project's "Last Planners" (those closest to the work) in weekly face-to-face meetings, where the group determines the tasks for the next week. In order to increase plan reliability, "last planners" are required to identify prerequisite work or predecessor activities that need to be completed in order to release the planned work (Ballard, 2000). In other words, only activities available to be scheduled (all prerequisite work completed, and all necessary equipment and material is available) are allowed to be scheduled (Thomas et al. 2002). The quality characteristics of the weekly work plan as identified by Ballard and Howell (1994) are:

- Work is selected in the right sequence
- The right amount of work is selected
- The selected work can be done

Often what is found on the master schedule and also on the look-ahead schedule may not be the right sequence or even possible. The weekly work plan utilizes the experience of the field personnel to help sequence the work to meet the needs of the workers while still maintaining project objectives. To ensure the shielding of downstream work, only work that is able to be completed (given available resources) is scheduled. Several principles of the LPS have been given as follows:

1. Assignments should be sound based upon prerequisite work, material, and equipment

2. Performance should be monitored concerning the completion of scheduled assignments on the "weekly work plan". The term percent plan complete (PPC) is used to monitor performance.
3. When the "work plan" assignments are not met, causes are identified and investigated to prevent reoccurrence (continuous improvement).
4. Maintain a buffer of tasks which are available to be performed in case assignments turn out to be impossible to complete.
5. Prerequisites of future assignments are actively made ready in keeping with project goals (Koskela 2000).

This method of variability reduction has shown some success with a reported 30% improvement in productivity for piping crews with a PPC above 50% compared to crews with PPC below 50% (Ballard and Howell 1994). Thomas et al. (2002) point out that "while these data are useful, this is hardly conclusive. More analysis is needed to confirm the causal link between reductions in workflow variability and improvements in project performance."

The LPS is focused on reducing variability at the project level. The sources as identified by Tommelein (2000) addressed by the LPS are scope of work, duration and timing, resource assignment, and flow path and sequencing. The sources identified by Hopp and Spearman (2001) addressed by the LPS are natural variation, random outages, setups, operator availability, and to some degree recycle or rework. Even though the sources of variability identified by Hopp and Speaman are more manufacturing oriented, they are similar and commonalities can be found in construction.

Implementation of Lean Principles

As stated previously, lean production principles are designed to reduce waste. Variability is a major source and form of waste in manufacturing and construction. Thus, it stands to reason that the implementation of lean principles into an organization would be a method of variability reduction. In fact, a tenet of lean is variability reduction. Some of the key variability reducing principles of lean include:

- Simultaneous or concurrent engineering
- Continuous improvement (product and process)
- Simplify by minimizing the number of steps and parts

Each of these principles are designed to work together to improve the production process, thus there will be overlap among the principles when describing how they reduce variability.

Simultaneous or concurrent engineering.

Simultaneous or concurrent engineering has many names and varieties. Some additional names include; design for production, design for manufacturing, and work structuring (a term used by many in the lean construction camp). Many of the problems that cause variation in the production system are caused by missing, inaccurate, or misunderstood information in the design, Tsao, Tommelein, Swanlund and Howell (2004) state:

> Designers often leave interface resolution, such as dealing with issues of scope gap and scope overlap, to the builders. They leave tolerance management to installers because they assume that the pieces they have designed will be relatively simple to identify and fit together. By viewing a project as an aggregation of parts, designers may not realize that they can—and, we think, should—design the project as an assembly of interacting pieces all the way from design through construction. While the design of each part may appear to be reasonable and logical upon inspection (MCAA 2003), the design of the overall assembly may actually be far from optimal. Not only may it fail to take advantage of overlapping disciplines, the uncertainties and errors created upstream (e.g., during design) may prove to be detrimental to performance downstream (e.g., during installation) (Tommelein, Riley, and Howel 1998). (p.781)

It stands to reason that many players, including specialty contractors such as mechanical, electrical and fabricators should be involved in the design of the product and production process to take advantage of their knowledge to improve efficiencies and reduce variability (Tommelein and Ballard 1997).

It is important to understand that this approach to design can reduce cycle times. It also enables redesign opportunities that can decrease capacity requirements and simplify production. This is a holistic approach to design with an opportunity to improve and simplify the systems and the process (Herrmann and Chincholkar 2000).

Using this approach to design has the opportunity to reduce variation in every form and category mentioned previously. Both activity and project variability should see improvement with this approach. In spite of the significant benefits of this approach, few in the construction industry have made the effort to implement it. A couple reasons for the slow adoption include contractual relationships and tradition. However, adoption is happening especially in the area of design-build where contractual relationships place the designer and the builder on the same team.

Continuous improvement.

Continuous improvement is a principle that crosses most if not all boundaries in the lean paradigm. Improvements are to be made in design, in process, in quality and in many other areas of the production system. Koskela (1992) states:

> The effort to reduce waste and to increase value is an internal, incremental, and iterative activity, that can and must be carried out continuously. There are several necessary methods for institutionalizing continuous improvement:
> - Measuring and monitoring improvement.
> - Setting stretch targets (e.g. for inventory elimination or cycle time reduction), by means of which problems are unearthed and their solutions are stimulated.
> - Giving responsibility for improvement to all employees; a steady improvement from every organizational unit should be required and rewarded.
> - Using standard procedures as hypotheses of best practice, to be constantly challenged by better ways.

- Linking improvement to control: improvement should be aimed at the current control constraints and problems of the process. The goal is to eliminate the root of problems rather than to cope with their effects.

L. P. Sullivan (1984) in an article titled *Reducing Variability: A New Approach to Quality* discusses continuous improvement and the importance of striving for perfection. He highlights the difference between being within specs (which was typical for the day) and being very close to the target. The article points out that the closer a product is to the target, the less variation there is and the greater the profit can be through reduced labor, time, and greater customer satisfaction. An example of a car door fitting into a frame is given to illustrate the point. If a car door is manufactured consistently on the small end of the specification and the opening that the door will go into is consistently on the large end, extra cost is incurred. Extra labor will be expended to shim or rework the door at the expense of time and money. Customer satisfaction will be less if the door does not close properly or if it leaks.

Marosszeky, Karim, Perera, and Davis (2005) investigated quality control mechanisms as a means to improve work flow reliability on a multistory timber framed refurbishment project. Implementation of quality control mechanisms is a continuous improvement initiative. Their research showed that as time between completion of defective work to discovery of defect increased, so did the cost of fix. It also showed that defective work had a negative impact on the project by increasing the variability among the activities. They found that the use of a "trade startup checklist" showed significant improvement in defect avoidance. The checklist used in this research was completed by downstream trades. In other words, work was checked by successive trades for quality, before the successive trades began their work. As quality increased in the form of fewer defects, variability was reduced.

Simplification.

On the topic of simplification, it seems that concurrent engineering and continuous improvement efforts are a means to simplification. As project operations and systems become more complex, they become more time consuming and costly (Koskela 1992). This complexity and increased specialization add to the silo effect, making it more difficult to respond to the variability as it emerges, thus requiring additional resources for project completion (Thomas et al. 2002). Simplification is accomplished by reducing the number of components in a part or assembly and/or reducing the number of steps or activities in an assembly or process (Koskela 1992). Simplification has implications in both activity and project variability reduction.

Several construction organizations have made efforts to implement lean principles into their organizations with reported success. The successes include reports of lower cost, shorter construction time and lower accident rates. However, as stated by Bertelsen and Koskela (2002) "there is still no single project having all aspects. And no formal reporting has yet taken place." To the authors knowledge this statement still holds true.

Additional Methods

Mapes et al. (2000) list what they call the "main ways of achieving reduced variability and uncertainty" as follows:

- Increased adherence to schedule
- Reduced process time variability

- Increased reliability of supplier deliveries
- Reduced process output variability

Each of these is very similar to ideas already discussed. Increased adherence to schedule is substantially covered by the LPS as well as by continuous improvement, concurrent engineering and simplification. Reduced process time is achieved through continuous improvement efforts and simplification. Increased reliability of supplier deliveries is partially included in the LPS and continuous improvement. The reduction of process output variability is realized largely through continuous improvement but also finds some benefit from concurrent engineering and simplification. It is important to note that each of these methods is covered in the methods described previously.

The Product Development Cycle

As mentioned previously, the earlier the variation is introduced into the production process the greater the negative impact. Thus, it stands to reason that the earlier methods of variation reduction are introduced into the process, the greater the positive impact could be. In this section, each method of variation reduction will be assessed for its location in the product development cycle and the potential impact that this location might have.

From a manufacturing perspective, the product development cycle *is* the company, given that the resources necessary to accomplish the cycle are all part of the company. As defined by Slade (1993) the product development cycle"is the engine that drives the corporation, generates revenue, determines profit, and supplies customers with what they want." Slade further describes two aspects of the cycle by making a distinction between the management or organizational process, and the content of the work necessary to develop strategies, technologies, design, and produce a product. This distinction points out the importance of the organizational structure and its impact on the ability of an organization to be a high performer. If an organizational structure is not conducive to the collaborative process then many if not all of the variability reducing strategies would not be possible.

The product development cycle has many different but similar descriptions. Slade (1993) identifies the "program phases" as concept, definition, design, develop, produce, launch, and support. Fleck (2002) gives the phases as ideation, concept development, product definition, product design, product development, and product launch. These are just a couple of the many versions of the cycle. Ballard (2000) gives his version of the product development cycle in what he calls the Lean Project Delivery System™ (LPDS). The phases in this cycle consist of project definition, lean design, lean supply, lean assembly, and use. Given that this research is construction related, Ballard's model of the product development cycle is used for comparison. Table 2 shows each phase in the LPDS along with each of the methods for variability reduction. It shows to what degree the method is used or employed for each of the phases.

Table 2

Variability reduction method by phase in the LPDS product development cycle

Method	Project Definition	Lean Design	Lean Supply	Lean Assembly	Use
Last Planner System™		Low	Medium	High	
Concurrent Engineering	Medium	High	High	Medium	
Continuous Improvement	Medium	Medium	Medium	High	Medium
Simplification	Medium	High	Medium	Medium	

The level of use for each method is from the author's perspective and could be debated. However, the description of the methods and their logical applications, support the author's perspective.

From the information in Table 2 it could be argued that concurrent engineering, continuous improvement and simplification may have the greatest impact on variability reduction as a whole. Even though continuous improvement does not have high use as early as simplification and concurrent engineering, it has medium and high application across the whole cycle. The LPS, the most defined and described among lean construction firms and researchers seems to have the least amount of possible impact because it is designed specifically for assembly which is late in the development cycle. It could also be argued that simplification is inherent in concurrent engineering and is not a separate process. However, Simplification is not only a concurrent engineering process.

Variation Concluding Ideas

Variation has many negative implications for design and production/construction systems. It seems apparent that the ability to reduce this variability would give a significant competitive advantage to an organization. There are many forms of variability as well as many methods of variability reduction. Only the most defined forms of variability reduction have been described in this research. Also, just as one type of variability can lead to, or be affected by other types, variability reduction methods can work together or affect each other, often in positive ways. In other words, utilizing more than one strategy for variability reduction can have a synergistic effect. It should also be pointed out that looking at the implementation of only variability reducing methods is insufficient for an organization to be successful. It is also necessary to look at the structure, relationships, culture, and knowledge of the organization. However accomplished, variability reduction will be a key to the survival of future organizations.

Implications of Design

When we find a problem with an artifact "we have the option of concluding that the flaw was in "the design"."(Bell 2000). This sentence characterizes the importance of, and responsibility that designers have when conducting their work. Before we examine the implications of design we must first explore the definitions of design including how it is accomplished.

Definitions of Design

There are many different definitions and models for design. These depend greatly upon the context (industry or practice) in which the term is being used. They also depend upon the specific perspective of the designer or the person using the design. Roozenburg and Eekels (1995) make this point when they stated:

> Many factors have to be considered when designing a product. Consumers look upon a product as something to be bought and used. To the design engineer it is a technical-physical system that has to function efficiently and reliably. An industrial designer considers the product to be an object that functions in a psychological sense and embodies cultural values. Production engineers have to manufacture it, often in large numbers, preferably fast, cheaply, accurately and with the lowest possible number of faults. A marketer considers it a commodity with added value, something that people are prepared to buy. Entrepreneurs invest in new products and count on the attractive return. People that are not directly involved may seem above all the reverse side of the coin: the undesirable and often even harmful side-effects of the production and use.

For any design, there are many different perspectives about what the design should be and what information should be included in the design documents. The Merriam-Webster Online Dictionary (2006) gives the following definition of design:

> **1 :** to create, fashion, execute, or construct according to plan **:** DEVISE, CONTRIVE
> **2 a :** to conceive and plan out in the mind <he *designed* the perfect crime> **b :** to have as a purpose **:** INTEND <she *designed* to excel in her studies> **c :** to devise for a specific function or end <a book *designed* primarily as a college textbook>
> **3** *archaic* **:** to indicate with a distinctive mark, sign, or name
> **4 a :** to make a drawing, pattern, or sketch of **b :** to draw the plans for
> *intransitive senses*
> **1 :** to conceive or execute a plan
> **2 :** to draw, lay out, or prepare a design

A definition for design from an architectural perspective is as follows: "To design is an activity – to devise, contrive, intend, indicate, plan, arrange, strategize, scheme, sketch, or the like." Additionally, design includes "actions to implement "the design", and results produced by the design (Bell, 2002)." Dym (1994) defines design from an engineering perspective as:

> the systematic, intelligent generation and evaluation of specifications for artifacts whose form and function achieve stated objectives and satisfy specified constraints. Roozenburg and Eekels (1995) state: "Products are artifacts conceived, produced, transacted and used by people because of their properties and the functions they may perform. Product design is the process of devising and laying down the plans that are needed for the manufacturing of the product. ….. designing of a product is much more than drawing. First and foremost it is a goal-directed thinking process by which problems are analyzed, objectives are defined and adjusted, proposals for solutions are developed and the quality of those solutions is assessed.

Another aspect of design as described by Bell (2002) is that the design is not only about what people use, but it has an impact on who people are. He States: "Do we dare speak a story in which, in the process of designing structures in which others live, we are designing them, their possibilities, what they attend to, the choices they will make, and so forth?" An interesting thought that increases the gravity of the concept of design.

Levels of Design

There are different levels of design depending on the innovativeness of the product. What Bell (2002) calls levels I, II, and III of design, Haik (2003) calls adaptive design, development design, and new design. Adaptive design or level I consists of making slight changes or modifications to existing designs. For level II or development design, a designer begins with an existing product and in the end has a product that is significantly different or improved. New or level III design is just as the name implies, a completely new idea or product that performs a new function. It is noted that very few designs are new designs.

Design definitions and models used in manufacturing and the architecture, engineering, and construction (AEC) industry are here considered. It has been argued that there are many similarities between these two industries with only a few differences (Koskela, 1992, 2000). First, the similarities as well as the differences will be discussed. Next some of the models from each industry will be described. Finally these models will be compared and classified, followed by a discussion of the implications of design for each industry.

Peculiarities of Construction

Manufacturing and the AEC industry are similar in many ways. Each follows a similar product development cycle. For example, each has an identified need or want to be filled. The need is then developed and described. There is then a design of the product followed by production/construction, then service and/or maintenance. In his research

Koskela (1992, 2000) compares manufacturing to construction (within the context of lean) by identifying three "peculiarities of construction" (one-of-a-kind production, site production, and temporary organization). Each of these has an impact on all aspects of the product development cycle including the design. Much of the following discussion of each of these peculiarities comes from Koskela's aforementioned work.

One-of-a-kindness.

It has been argued that each project in construction is one of a kind that will not be duplicated exactly. Given that each project is on a different site with peculiar conditions this may be somewhat true. One-of-a-kindness in AEC is often caused by varying needs of owners, differing site conditions, varying code requirements, and views of designers on best design solution. Although it is given as a peculiarity of construction, it should be pointed out that it is not significantly different than some sectors of manufacturing where manufactures produce small batch sizes of various products.

Even though the complete projects are mostly one-of-a-kind, many aspects of each project are usually similar to other projects. For example, placing masonry on one structural steel building will be similar to placing masonry on a completely different structural steel building.

Two distinct characteristics of one-of-a-kind production are that design is an integral part of production, and there is uncertainty often in the form of customer order acceptance (Koskela, 2000). Because each project is one of a kind, the design basically starts from scratch for each project. And, because the owner is typically commissioning the design of the project, owner approval and acceptance of the design throughout the process is necessary.

It should be mentioned that one-of-a-kindness is not completely true for residential construction. Often a single home model is built many times in a single subdivision. Even though a home is built several if not hundreds of times, there are usually options including different elevations that make each home somewhat unique. It could, however, be argued that these options are all part of the original design much like variations of an automobile model.

Site production.

Unlike many manufacturing processes, much of construction is not carried out in a factory and then delivered to the customer. With the exception of manufactured housing, construction is conducted directly on the site that the product will be used. Some characteristics of site production outlined by Koskela are as follows:

- Site as a resource: the site is a necessary input resource for production.
- Lack of shelter: There is usually little protection against elements or intrusion, rendering operations prone to interruptions.
- Local resources and conditions: local material and labor input often has to be used, potentially adding to uncertainty; other areas of uncertainty include site geology and other environmental factors.
- Creating the production infrastructure: the production infrastructure (machines, manpower, etc.) has to be planned procured and set up on site.
- Space needed by production (workstations move on the product): the spatial flow of workstations (teams) has to be coordinated (in contrast to a factory, where only material flow through workstations is planned.)

This aspect of construction is similar to only a few other industries like agriculture and mining. Design of the production process is quite different because of this peculiarity.

Temporary organization.

Construction organizations are typically established only for the duration of a given project. Many companies including design professionals, trade organizations, and construction management (including general contracting) firms, come together to complete a project. These companies may or may not have worked together before. Additionally, they have varying contractual arrangements from organization to organization and from job to job. This peculiarity again has implications on the design of the product.

Models of Design in Manufacturing

Manufacturing has seen a progression of design that has been driven by the steadily increasing level of complexity of products, the need for speed, customer requirements for quality, and a competitive environment that requires all this at the least cost. The following progression is summarized from Koskela (2000). Until the Second World War, much of design was carried out by small groups or single designers. Products and processes were relatively simple with no need for elaborate design management methods. Design for this era has been termed "design as craft".

During the War more elaborate systems of management were established that could handle a sophisticated design. The complexity of the systems being produced increased, along with the need to produce at a faster rate (Yazdani and Holmes, 1999). Following the war, the different design experts were grouped into different departments and work was passed from one department to the next ("sequential engineering"). During the 1980's with the continued increase in complexity and the need for shorter lead times, the concept of "concurrent engineering" (a term coined by the Institute for Defense Analysis) began to gain interest.

It has been argued that in manufacturing, design is more then just the aesthetics, form, and function of a solution. From the literature there is a prevailing notion that design today is infused in almost all aspects of the product development process (PD) (Roozenburg & Eekels, 1995). There are many different definitions of the product development cycle with just as many iterations of the steps included. Yazdani and Holmes (1999) give the following steps of PD as follows: marketing, concept design, detail design, prototyping, process design, process manufacture, and lastly production. The difference between the models tends to be found in the level of interaction between the specialists, the departments involved in the process, and the location of the interaction among departments within PD.

Sequential design / engineering.

As mentioned previously, sequential design was the prevailing method of design in manufacturing following the Second World War up until the 1980s and 90s. This model with its different departments, utilizes little or no collaboration among the different functions of PD. Each of the steps as outlined by Rozenburg and Eekels are completed one after the other or in a sequential manner as the name implies. It has been stated that that the process or protocol for transfer of information in this model is usually limited so the information transfer is less then smooth or seamless.

Another characteristic of this approach is that the prototyping is not done until the detail design is completed. At this stage of PD, changes are very costly and time consuming. No collaboration among departments usually translates to a greater number of changes. Thus, this method of design has proved to be unsatisfactory given today's industrial pressures.

Design centered model.

Many organizations have realized that utilizing the sequential model can be costly due to changes after design is finalized and production has begun. Because of this, several tools have been developed to minimize the risk of changes by considering the manufacturing process during design (Prasad 1997). In the design centered model; concept design, detail design, and analysis are completed somewhat simultaneously. Design tools such as finite element analysis, life cycle costing, design for environment, design for assembly, and design for manufacture are utilized during the detail design portion of the PD to minimize changes during production. The utilization of these tools does not necessarily involve collaboration among departments, but at least the downstream needs are considered during detail design. In this model, prototyping is still not completed until detail design is completed, but the confidence in the model is improved. (Yazandi & Holmes, 1999).

Yazdani and Holmes (1999) believed that "the design center approach can be observed in most Western-style engineering companies..... The western culture and education systems tend to support and be geared towards the sequential and design centered models of product definition." A belief that the literature suggests is changing.

Concurrent engineering and design.

With the continued increase in complexity of projects and need to shorten time to market, it has become increasingly difficult to compete using the design centered model of PD. Additionally, with the increased complexity, the tools utilized in the design centered model are not adequate. Expertise involvement in design from downstream departments and activities has become necessary for most organizations (Yazdani & Holmes, 1999).

Possibly the first definition of concurrent engineering given in a report by the Institute for Defense Analysis is as follows (Carter and Baker 1992):

> Concurrent Engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacturing and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from concept through disposal, including quality, cost, schedule, and user requirements.

Later definitions emphasize the overlapping of processes in PD. This overlap happens in the concept design, detail design, prototyping, process design, and process manufacture stages of PD (Yazdani & Holmes, 1999). Multi-functional or cross-functional teams are used to enable the overlap. (Prasad, 1997). As teams of experts work together they are able to take the knowledge that they have about earlier processes and begin their respective work. They are also able to give early input on how a particular aspect of design will impact their respective processes.

Design is a highly iterative process that is most efficient when many experts work together to find the optimal design solution for the whole of PD. The number and magnitude of the iterations is reduced through concurrent engineering processes.

Additional savings come from fewer iterations following prototyping. This process is partly what has given many manufacturing organizations a competitive advantage.

Dynamic definition model.

Concurrent engineering is seen as a significant advantage over both sequential and design centered methods. The overlapping of stages in addition to the cross-functionality of the teams showed a significant advantage in reducing time to market. However, there was still a lag from one department to another leaving a significant amount of work to be accomplished before the next set of experts become involved. As pointed out earlier, the further along in the PD process, the more expensive and difficult it is to make changes. These realizations prompted a system that enables communication and collaboration from the beginning stages of PD. This process is truly concurrent as all product development activities begin at the same time (excluding production).

Using the dynamic model can prove difficult for organizations that do not have a fully dedicated multi-functional team with high levels of business and technical expertise. These teams need to be empowered to make decisions at the working level. Another important enabler of using this model is the ability to communicate among departments using a single medium. In other words, as one activity is completed the next department in the process needs to be able to take what has been developed and add to it (not re-create it), and so on until the design is complete. This technical challenge can be a significant barrier to adoption if not considered completely (Yazdani & Holmes, 1999).

A significant enabler to this method of design is the use of three dimensional (3-D) computer aided design (CAD), at the component level. The 3-D model serves as the medium for communication and collaboration among project participants. Producers of most manufactured products (e.g., airplanes, ships, cars, consumer products) experienced breakthrough advances in productivity due to the digital-based convergence of 3-D CAD representations and production processes. Products are digitally created and produced seamlessly from concept through production (Kolarevic, 2003). In many of these industries, design (including engineering) and production departments have been combined into one where teams come together to meet customer needs (Kieran, 2004).

Manufacturing Models Compared

The previously described models are given in chronological order. Each of the models is still in use today in some form or fashion. Figure 1 shows each of the four models and there respective configurations of the PD process. It can be seen that cycle time is shortened for each successive model.

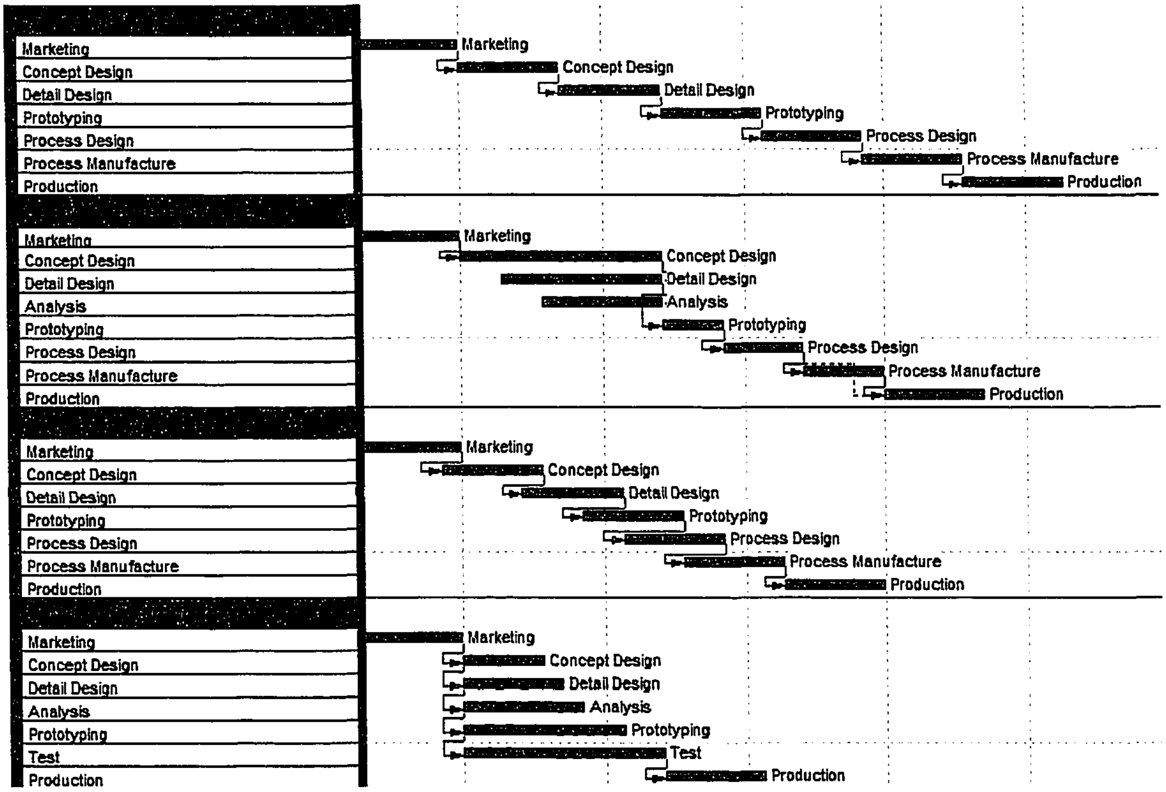

Figure 1 Comparison of manufacturing models on time

Yazdani and Holmes (1999) compared the four models of design definition on such things as product driver for new product, time, cost, and design quality. Table 1 is a summary of their findings. From this we see that Dynamic Definition is the fastest model with high quality and low cost. At the time of their study, the dynamic definition model was only being practiced in Japanese companies.

Table 3

Comparison of identified models of manufacturing design

Variable	Sequential design	Design Centered	Concurrent Engineering	Dynamic Definition
Top driver for new product	Cost/Quality	Cost/Quality	Quality Time	Time
Time	Slow	Medium	Medium	Fast
Cost	High	Medium	Medium/Low	Low
Design Quality	Low	High	Medium	High

Adapted from Yazdani and Holmes (1999)

Models of Design in AEC

Like manufacturing, there is a historical progression of design models in AEC. Prior to the 20th century, master builders were hired to design, engineer and construct a project for an owner. As the 20th century progressed, changes in technology and complexity of buildings required specialization of design and construction services. This separation continued to the point that communication between the designer and builder was virtually nonexistent until design was complete. In the 1970s and 80s the construction manager was introduced into the process to bring some collaboration between designers and builders. Recently the need to involve many different construction specialists in design has brought an even more integrated approach to the AEC industry. Much of the change has been driven by complexity, and a desire to reduce schedule and cost (Konchar, & Sanvido, 1998).

The literature suggests that the primary model used in AEC is very similar to the Sequential model previously described. Often the non-collaboration in manufacturing is due to the physical and social separation of the different departments involved in PD. In AEC these departments are separate companies that have been brought together to complete a project (temporary organization) (Koskela, 2000). As stated by Luiten, Tolman, & Fischer, (1998):

> The AEC industry is very fragmented with many cultural and legal barriers between the disciplines, even if the different departments are part of the same company. There is often much distrust between the clients (or project management advisers), architects, structural engineers, contractors, sub-contractors, suppliers and facility operators. The disciplines often have conflicting interests. For example, minimizing design effort might be interesting for architects and structural engineers, but conflicts with maximizing constructability and maintainability for contractors and operators. The relationships between the disciplines are predominantly short-term, only for the

current project, and therefore often rather cost-based than quality based. These cultural and legal barriers are not easy to overcome.

Because of this fragmentation and general lack of collaboration, design is often completed from a single perspective. Thus, much information needed for downstream users is missing. As design is focused on maximization for each designing entity, opportunities may be missed to design for overall project performance (Tsao, Tommelein, Swanlund, & Howell, 2004; Ballard, & Koskela, 1998). Additionally, for many AEC projects, contractors are brought into the temporary organization late in the design process and have little control over design. Constructability problems identified by contractors are found late in the process when changes are very time consuming and costly. This concept is further described by Halpin (1992) when he asserts that in AEC the designer is concerned with the "what" leaving the builder to figure out the "how".

In their work to map the process of design during the conceptual phase of building projects Macmillan, Steel, Kirby, Spence, and Simon (2002), put together a list of criticisms of the different design models in AEC. The list includes the following:

- Most describe a sequence of phases which, typically, imply iteration within phases but not between one phase and another.
- Most imply starting with an analysis of requirements before the generation of possible solutions (although much design work involves the modification of existing solutions, not the invention of new ones.
- Most set out only what should be undertaken, not why or how it should be performed
- Most do not define what is to be carried out separately by different team members and what needs to be performed in collaboration.
- Most limit their concerns to the problem requirements and their solution, and do not address the social aspects surrounding team-working, such as the selection and involvement of team members at various stages, the exchange of information, or the promotion of effective collaboration.

These criticisms have a central theme of design as an independent function focused on the project requirements instead of a collaborative team evaluating previous solutions to meet project requirements.

Following are several models of design for the AEC industry. Much like manufacturing, design in AEC is tied closely to the project development cycle, or method of project delivery, thus the terms used to describe the models are those used to describe the main methods of project delivery in AEC. Due to the large variety of definitions and variations of delivery methods, two primary sources of definition and descriptions of the delivery methods will be used. One of these sources is *the Primer on Project Delivery* authored by The Joint Committee of The American Institute of Architects and the Associated General Contractors of America (2004). And the other is a research article titled *Comparison of U.S. Project Delivery Systems* (Konchar, & Sanvido, 1998). These resources were chosen based upon the leadership of the authors of the Primer and the thorough nature of the comparison. A goal of the primer is "To create definitions broad enough that all hybrids fall within the three primary delivery methods". Additional resources will be used and noted.

Design-bid-build.

Design-Bid-Build (DBB) has been the primary delivery method in the U.S. for many years. Public projects have traditionally used this method as a mater of law. It has been the common belief that using price as the primary or only selection criteria for awarding projects, would best protect the interest of the public. This belief is rapidly changing with many states and federal agencies allowing some form of the other two project delivery methods. A succinct definition of DBB is given as follows:

> Design/bid/build is the traditional project delivery system in the U.S. construction industry where the owner contracts separately with a designer and a constructor. The owner normally contracts with a design company to provide "complete" design documents. The owner or owner agent then usually solicits fixed price bids from construction contractors to perform the work. One contractor is usually selected and enters into an agreement with the owner to construct a facility in accordance with the plans and specifications.

Defining characteristics for DBB are given as follows:

- Three prime players – owner, designer, builder
- Two separate contracts – owner-designer, owner-builder
- Final contractor selection based on lowest responsible bid or total contract price

Typical characteristics of DBB include the following:

- Three linear phases – design, bid, build
- Well established and broadly documented roles
- Carefully crafted legal and procedural guidelines
- A lowest responsible bid that provides reliable market price for the project
- Contract documents that are typically completed in a single package before construction begins, requiring construction-related decisions in advance of actual execution
- An opportunity for construction planning based on completed documents
- Complete specifications that produce clear quality standards
- Configuration and details of finished agreed to by all partied before construction begins

This method of project delivery has many negative implications for design. Even though designers may have experience with prior projects, they are often more concerned with aesthetics, form, and function and are not as concerned or familiar with cost and schedule including constructability. Mokhtar (1998) gives some common types of errors due to a lack of coordination and collaboration:

- Inconsistency in design information: For example, the location of a specific column is not identical when comparing the architectural and the structural drawings.

- Mismatch between connected components: For example, heating, ventilating and air conditioning (HVAC) ducts dimensions, which are given in the mechanical drawings, do not match the dimensions of the related pass-holes in the structural beams, which are given in the structural drawings.
- Components malfunction: For example, electric supply in a room designed to serve a classroom activity while architectural drawings indicate that the same room has been re-designed as a computer lab. (p. 82)

Often projects are not awarded because design is not possible within budget. When this happens contractors provide "value engineering" options to bring the project within budget. These options require additional design work that could have been avoided if construction personnel were involved earlier. Many of the problems with DBB are similar to the problems of sequential design in manufacturing.

Construction management at risk.

The inherent problems with DBB became apparent to many in the AEC industry. To rectify these problems an alternative method evolved known as Construction Management at Risk (CM@R). This delivery method is similar to DBB especially in that two contracts still exist, one between the owner and designer, and one between the owner and CM@R contractor. The main difference is that the CM@R contractor provides preconstruction services (including design consulting) and is involved in the process at an earlier stage (Kenig, n.d.). The definition of CM@R is given as follows:

> CM@R is a project delivery system where the owner contracts separately with a designer and a contractor. The owner contracts with a design company to provide a facility design. The owner selects a contractor to perform construction management services and construction work, in accordance with the plans and specifications, for a fee. The contractor usually has significant input in the design process.

The following defining characteristics identify CM@R:

- Three prime players—owner, designer, CM@R
- Two separate contracts—owner to designer, owner to CM@R
- Final provider selection based on aspects other than total cost

Typical characteristics of the CM@R approach include the following:

- Overlapping phases—design and build (fast track)
- Hiring of the construction manager during the design phase
- Preconstruction services offered by the constructor (such as constructability review, bid climate development and bid management)
- Specific contractual arrangement determines the roles of players
- Clear quality standards produced by the contract's prescriptive specifications

As mentioned in the typical characteristics previously, fast tracking or overlap of phases is possible with CM@R. This is enabled through the collaboration of the design and construction firms. It has been seen that projects using this type of method can be completed faster and at less cost. This is possibly due to a higher quality design with fewer changes after design completion.

Design-build.

Luiten et al. (1998) observe: "Traditionally, the relationship between designers (architects, HVAC advisors, and structural engineers) and constructors (general contractors and their subcontractors) has been adversarial in nature. .....The requirement from the market that design and construction should be dealt with by the same contractual partner, aligns the interests of designers and constructors. This opens the way for improving the relationship structurally." Even though CM@R is an attempt to align design and construction by having construction consultants work with the designer early on, the adversarial and trustless relationships that have existed for many years create significant barriers. Additionally, no contract exists between design and construction in CM@R. A significant difference found in design-build (DB) is that the owner hires the design-builder who is responsible for both the design and construction of the project. A definition for DB was given as follows:

> Design/build is a project delivery system where the owner contracts with a single entity to perform both design and construction under a single design/build contract. Contractually, design/build offers the owner a single point of responsibility for design and construction services. Portions or all of the design and construction may be performed by a single design/build entity or selected specialty work, or in some cases, all may be subcontracted to other companies.

The following defining characteristics identify design-build delivery:

- One contract—owner to design-build entity

Typical characteristics of the design-build approach include these:

- Project-by-project basis for establishing and documenting roles
- Continuous execution of design and construction
- Overlapping phases—design and build (fast track)
- Two prime players—owner, design-build entity
- Carefully crafted legal and procedural guidelines for public owners
- Some construction-related decisions after the start of the project
- Overall project planning and scheduling by the design-build entity prior to mobilization (made possible by the single point of responsibility)
- Either cost or solution as the basis for selection of the design-build entity

Design-build firms are typically led by either an architect or general contractor. In either case the project team is a team where failure of one entity means failure for everyone. If the owner's expectations are not met, the design-builder fails. When considering all methods of project delivery, collaboration is realized most significantly in DB.

AEC Models Compared

One of the most significant differences in delivery methods is the collaboration among design and construction entities (from DBB with little or no collaboration, to DB with complete collaboration). A term used by DB firms that signifies this collaboration is co-location. This term is used when designers and constructors are physically in the same office. Co-location is considered necessary among leading DB firms. Another significant difference is the contractual relationships of the different methods. Both DBB and CM@R have two separate contracts; one between the owner and the designer, and one between the owner and the contractor. DB utilizes one contract between the owner and the design/builder. Some design-build firms are fully integrated, meaning that they have the personnel to perform both the design and the build. Others hire a designer or builder depending on what type of organization is leading the project and/or the type of project to be completed.

Two of the delivery methods (CM@R and DB) are more suited to fast tracking or overlap of the phases due to collaboration during the design phase. DB however should be more capable of successful fast tracking because of the difference in contractual relationships. Konchar et al. in their research compared the three delivery systems utilized in the AEC industry and in their conclusion wrote:

> this research collected data from 351 U.S. building projects, verified the data through the use of nonresponse sampling techniques, and built multivariate linear regression models for cost and schedule metrics using nearly 100 response, explanatory, and interacting variables. On a univariate basis, this study also ranked turnover and facility system quality based on data collected from owner interviews.
>
> Project delivery literature indicates clearly the distinctions between design/build and its procurement peers. This research, however, puts an empirical face on the fact the projects administered using design/build project delivery can achieve significantly improved cost and schedule advantages, In addition, design/build projects produce equal and sometimes more desirable quality performance than construction management at risk and design/bid/build projects.

Much like the dynamic definition in manufacturing, DB with collaboration from the beginning of the project shows advantages in time, cost, and sometimes quality.

Comparing Manufacturing and AEC Models of Design

Models in both AEC and manufacturing have had a progression of models driven by similar factors of complexity and speed, driven by competition. These progressions are similar in that improvements have been realized through collaboration of activities or phases in the respective project development cycles. This collaboration is focused predominately on design with the recognition that design is an iterative process that has an influence on every aspect of a product lifecycle (Rosenman and Gero, 1996). As mentioned at the beginning, if there is a problem with the product it is probably a problem with the design.

A significant difference in design between manufacturing and the AEC industry is that much more planning is done to manage flow or process of manufacture or assembly. This may be in part because of the peculiarities of construction described previously. It is believed that the one-of-a-kindness of a large complex construction project does not lend itself to what is perceived as an exorbitant amount of time in preplanning construction processes. However, many have recognized this lack of preconstruction planning as a major shortfall and contributor of project failure (Tommelein, 1997).

One difference between manufacturing and AEC is in the technology utilized in design. For many years manufacturing has used three-dimensional models as a common design tool to enable collaboration among different departments. This method of design provides a visual common language that enhances communication. This design tool is also much more useful in the detection of constructability problems, interactions among different systems, and variability reduction. Luiten et al. have stated that "One of the areas needing improvement is communication: migrating from paper-based document exchange to computer aided information and knowledge sharing." This topic will be discussed further in this chapter.

Design is an integral part of any type of product that has or will be developed. The methods and models will continue to improve, and I believe will continue to improve quality and reduce relative cost, all with a shorter lifecycle. The future is bright for those who have aspirations to improve the process of design and construction in the AEC industry. Many improvements are possible and needed.

Modeling in Architecture Engineering and Construction

Three-dimensional models have also been used successfully on complex construction projects to communicate and coordinate construction activities (Kolarevic, 2003) (Folkestad, and Sandlin, 2005). Currently research is being done on the use of 3-D CAD to improve constructability (through analysis of the virtual model) and to generate construction documents (including the 2D drawings and specifications). The fourth dimension (time) has been added to aid in scheduling. And what some are calling the fifth dimension (linking cost and product data to the model) could inform the estimate. The sixth dimension deals with the management of the building throughout the life of the building. Many research institutions and industry professionals as well as software companies have focused their attention on these technologies. Building information modeling or BIM is the term that is being used in the AEC industry to describe the use of the third through sixth dimensional models.

Much of the technology development by software companies, including that for BIM has been focused on commercial projects. Some of the leading BIM solutions

(Autodesk,s Revit, Bentley Systems Inc.'s Microstation, Graphisoft's Archicad and Constructor) claim the ability to quickly create more accurate 2D drawings with fewer mistakes, improve the accuracy and reliability of the schedule and estimate, and increased collaboration through visualization. The 2D drawings, even though more accurate, still are information-poor when it comes to the ability of front-line workers to use the information for construction. Additionally, the focus has not taken into account the skilled labor shortage. In other words, the information produced by many these programs is not sufficient for front-line workers, many of which are not skilled craftsman. The work performed by these skilled or non-skilled personnel can be a major source of waste in the form of variability. Lean production/construction recognizes variability as a main producer of waste. Thus, variability reduction is a significant method utilized for waste reduction. Koskela (1992) identifies two reasons for reducing process variability. First, from the quality perspective, a uniform product is better quality. Second, variability increases waste in the form of non value-adding activities. Given these two reasons, variability reduction in production product and process must be an intrinsic goal (Sullivan 1984). And as stated by Schonberger (1986) "Variability is the universal enemy."

Craft Production and AEC

The term craft production typically invokes thoughts of an archaic method of production largely replaced by mass production followed by lean and other modern production systems. Craft production is identified by highly skilled craftsman producing unique or one-of-a-kind products (Cusumano, 1991). Residential construction (as well as the other sectors of the construction industry) has largely remained somewhere within the craft production paradigm. Barlow (1998) places residential construction in the UK somewhere between craft production and mass production. Although many of the parts used to construct a home are produced using a manufacturing process, the parts are assembled using "craft" workers.

Problems with Craft Production

Some of the reasons for this inability to move completely away from craft production were identified by Koskala (1992, 2000) as the three "peculiarities of construction" (one-of-a-kind production, site production, and temporary organization). Additionally, design in AEC does not provide sufficient information to enable a shift from craft labor to assembly labor. The same problems that cause variation in construction may be the same problems that are forcing the use of a craft workforce. These problems have to do with the information-poor documents which are riddled with missing, inaccurate, or misunderstood information in the design. Tsao, Tommelein, Swanlund and Howell (2004) state:

> Designers often leave interface resolution, such as dealing with issues of scope gap and scope overlap, to the builders. They leave tolerance management to installers because they assume that the pieces they have designed will be relatively simple to identify and fit together. By viewing a project as an aggregation of parts, designers may not realize that they can—and, we think, should—design the project as an assembly of interacting pieces all the way from design through construction. While the design of each part may appear to be reasonable and logical upon inspection (MCAA 2003), the design of the overall assembly may actually be far from optimal. Not only may it fail to take advantage of overlapping disciplines, the uncertainties and errors created upstream (e.g., during design) may prove to be detrimental to performance downstream (e.g., during installation) (Tommelein, Riley, and Howel 1998).

In spite of information-poor documentation, currently in use in AEC, the industry has been able to function using a skilled management and (craft) labor force that are expected to interpolate the information on construction documents in order to complete their respective work. These interpolations often equate to waste in the forms of fabrication errors, poor product quality, and material discrepancies including a lack of needed materials and delivery of inappropriate materials (Choo, 2002).

In an effort to increase profit and improve relations, high skilled workers attempt to learn from their mistakes over subsequent builds to gain efficiency and improve coordination. Although not explicitly stated as such, these improvements are an undocumented effort to reduce non-valued added activities that include such things as optimizing their work for the next trade. In spite of these improvement efforts, craftsmen will attest that even though they are building the same house repeatedly, houses are seldom if ever built the same way twice. Many of these craftsmen do not have a process to document waste reduction and value adding activity enhancements, documentation that could be continuously improved upon to reduce waste (Folkestad, 2006).

Labor Shortage in AEC

The reliance upon a skilled labor force for the AEC industry has been a luxury that may be coming to an end. The Bureau of Labor Statistics (US Department of Labor: Bureau of Labor Statistics, n.d.) has predicted a skilled labor shortage the beginning of which has been recognized by Construction Industry Institute as an area of significant concern (Construction Industry Institute, n.d.). Additionally, with many construction workers coming from non-English speaking countries, language/literacy barriers exist among project personnel. Thus, in addition to the absence of explicit production documents and an effective process for documenting learned valued added activities, there are not enough skilled laborers who fluently speak or understand the language used by design and project management professionals. These additional factors add to the waste that contributes to the overall problems of high and rising cost of homes and poor quality.

CHAPTER 3: METHODOLOGY

Research Design

This study began from a pragmatic perspective (Creswell, 2003) as an exploratory case study to investigate the use of virtual construction to improve the construction process for residential homes. As stated by Glasser and Strauss the goal of an exploratory case study "may justifiably be to discover theory by directly observing a social phenomenon in its raw form" (as quoted in Yin, 2003 p.6). According to Yin (2003), a case study methodology should be used when the research questions focus on the "how and why" when researchers have little control over the behavioral events and when the focus is on contemporary events.

As the study progressed, several findings began to emerge as well as the recognition that the theory of lean construction fit well with the problems observed during the investigation. The emergent nature of the study facilitated evolution of the research questions and thus, the methods of data collection. As outlined in figure 2 a sequential mixed methods approach was utilized to investigate solutions to the perceived problems (Creswell, 2003).

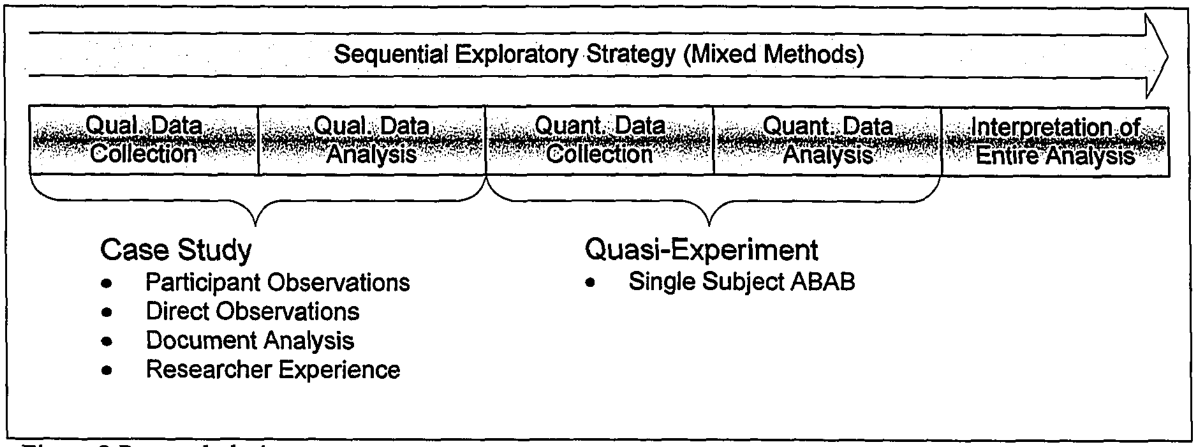

Figure 2 Research design

Even though much was learned during the initial case study, additional exploration was completed using a single subject ABAB design quasi-experiment to collect additional and different data to verify the results of the case study (Gliner and Morgan, 2000). These multiple sources of evidence were collected over an extended period of time for the purposes of triangulation (Stake, 1995; Yin, 2002).

Case Study Methods

Participants and Site

The case investigated the production processes (primarily the framing production) of a single family home development northeast of Denver, CO. This development was typical in that the materials and methods were similar to the majority of homes built in the area as well as the United States. The project utilized on-site wood framed homes with a somewhat unique engineering/design. The unique engineering does not make the project atypical based upon the fact that each framer/builder/developer/designer etc. has unique ways in which they prefer a home frame to be completed. Thus, framers are accustomed to framing homes slightly different for each project.

Much of the data collected are related to the traditional construction documents (TCD) produced for the project. As explained by the developer (the person overseeing the entire development), the budget for the project is very tight. In an effort to keep costs down, an inordinate amount of preconstruction planning was utilized for this development. These efforts included design meetings between the developers and designers to minimize waste in both material and methods.

Later in the design process, the design meetings were expanded to include major subcontractors such as excavation, foundation, plumbing, electrical, heating ventilating and air conditioning (HVAC), framing, drywall and other subcontractors. Considerable effort was made to design for optimization by considering the different construction systems and how those systems interact. At the completion of design, prototypes of each of the six home plans were constructed and analyzed during a coordination walk with all major designers, subcontractors, and developers present. During the coordination walk, the drawings were to be red-lined to facilitate what was to be the last update of construction documents before the development was to go into full production mode. This process of design, although somewhat common for medium to large size production builders, was given high priority for this project.

The development offered homebuyers six different home plans with optional upgrades on a total of 1300 lots. The developer's interest in using 3-D technology to improve production translated into funding for the initial project. A case study where several subunits are investigated has been termed an embedded case study (Yin, 2002; Scholz & Tietje, 2002). The subunits included in this embedded case study include framing crews and framing processes and the framing product.

Data Collection

The data used for the case study were collected as part of a funded research project conducted by faculty and a graduate student at Colorado State University. The purpose of the project was to investigate the benefits of virtual construction for improving physical construction processes. The existing data were analyzed to answer research questions pertaining to this project. Even though data were collected as part of a previous project, methods for data collection are included to provide clarity.

Multiple data collection methods were utilized as part of the case study. The following describes these methods in relation to the research questions. One of the first goals of this research was to identify the waste in the typical onsite framing process (questions 1). Four sources of evidence were used to aid in the identification of non value-adding activities (waste). These sources included: participant observation, direct observation, document analysis, and researcher experience. Succeeding sections will describe each source in detail.

Participant observation.

Researchers began working on this project after many of the design meetings had been completed. Researcher participation included development of a 3-D model of each of the homes. Through model development it was determined that a new set of construction documents could be generated directly from a fully realized 3-D model. This realization led researchers to develop a new set of construction documents. Through the development of the 3-D models, as well as the new construction documents (NCD), researchers interacted with and participated in many aspects of the construction process. The work produced by researchers was used to facilitate design changes as well as aid in construction.

Direct observation.

Several direct observations were made throughout the course of the project. Due to the significant role of the researchers in this study, it became difficult to distinguish direct observations from participant observations. Often, during the direct observations, researchers were pulled into the process by other participants. Due to the nature of the funded study, researchers were obligated to participate in the process when prompted. The direct observations made during the course of the case study included:

- Post-construction observations of prototypes
- Observations of the framing process for both prototypes and early production
- Observation of the coordination walk
- Observation of a follow up coordination meeting

The types of evidence collected during the observations include post-construction errors, production sequencing leading to waste, and information related to typical construction coordination.

Document analysis.

As part of the study, the traditional construction documents were analyzed for effectiveness. These data were collected during the virtual build as well as during the direct observations. Although these documents were updated several times, it became apparent that the documents were still information-poor.

Researcher experience.

Two researchers conducted the majority of the research. One had significant residential construction experience and the other had expertise in manufacturing technology. The researcher with construction experience had many years of residential framing experience both as an owner/operator of a subcontracting firm (specializing in residential framing and finish carpentry) and a residential general contracting firm. This experience provided first hand knowledge of the challenges facing the industry related to framing and construction processes especially as it compares to manufacturing. The findings in the case study were validated by researcher experience from both a construction and manufacturing perspective.

Data associated with the case study did not include recorded durations for the activities classified as waste. Observations were not continuous but were made either during the framing process or ex-post-facto to identify errors and omissions. The first two physical iterations of each of the six models were observed as well as several additional iterations of some of the physical models.

Treatment of Data

All four sources of evidence were used to answer the research questions 1 through 3. First, the data were analyzed to identify the most common types of waste activities (question 1). This was done by reviewing researcher notes including: participant observation notes and direct observation notes. To answer research question 1-a a table showing each waste activity by build type was created.

Early in data analysis, researchers realized that much of the waste, as evidenced by mistakes, was directly related to information. To aid in analysis and organization, four categories of information were determined. The data analysis was organized largely by these information categories. To provide further insight, a table was created for each information category showing examples of waste activities for each build type (physical and virtual) by mistake or lack of optimization.

To answer research question 3 each activity identified as waste was evaluated to determine the associated information as well as the information source. Sources included architectural drawings, engineering drawings (also called structural drawings), specifications (written and unwritten), and truss shop-drawings. Once the specific information/knowledge tied to the waste was identified, efforts were made to capture this information in the virtual model of the frame. The ability to capture information or knowledge using the 3-D model was also documented on the previously mentioned tables.

The above outline of data collection and treatment make up a significant portion of a "case study protocol". The purpose of a protocol is to act as a guide to the researcher throughout the study and to increase reliability (Yin 2003). Additionally the successive nature of the research questions and the structure of the study provide a "chain of evidence" increasing reliability and supporting construct validity (Yin, 2003). It has been argued that external validity for case study research has been a major barrier. To overcome this barrier for single case studies (as utilized in this study) it is recommended that the investigator strive to generalize a specific set of results to a broader theory. The theory that will be generalized to for this research is the theory of lean (Yin, 2003).

External validity is also strengthened by the addition of the quasi-experiment used to verify the findings of the case study.

Quasi-Experiment Methods

As part of the original case study a new set of construction documents (NCD) were created directly from a parametric 3-D model of the home frame. These documents were developed by researchers and pilot tested during the case study. The NCD were used by framers in conjunction with traditional documents for several builds. Through an iterative process where feedback was provided by both framers and project management personnel the NCD were continually improved to increase usability. Several iterations were developed before an acceptable solution was found. Once a usable form of the new documents was realized, several additional research questions became apparent.

A quasi-experiment was conducted to answer the following research questions:

4) Does framing time differ when a crew uses construction documents produced from a 3-D model as apposed to when traditional construction documents are used?
5) Does frame quality differ when a crew uses construction documents produced from a 3-D model as apposed to when traditional construction documents are used?
6) If a difference is found for question 4, does a more experienced framing crew differ from a less experienced crew on the time difference
7) If a difference is found for question 5, does a more experienced framing crew differ from a less experienced crew on the quality difference

The purpose of the experiment was to identify the differences in the framing process when framers build from the traditional construction documents as apposed to building from the plans generated from the 3-D model. The null hypothesis for the experiment was: the duration to construct and the quality of construction including accuracy will be the same for walls framed using the traditional and new construction documents. Figure 3 shows the layout of the experiment.

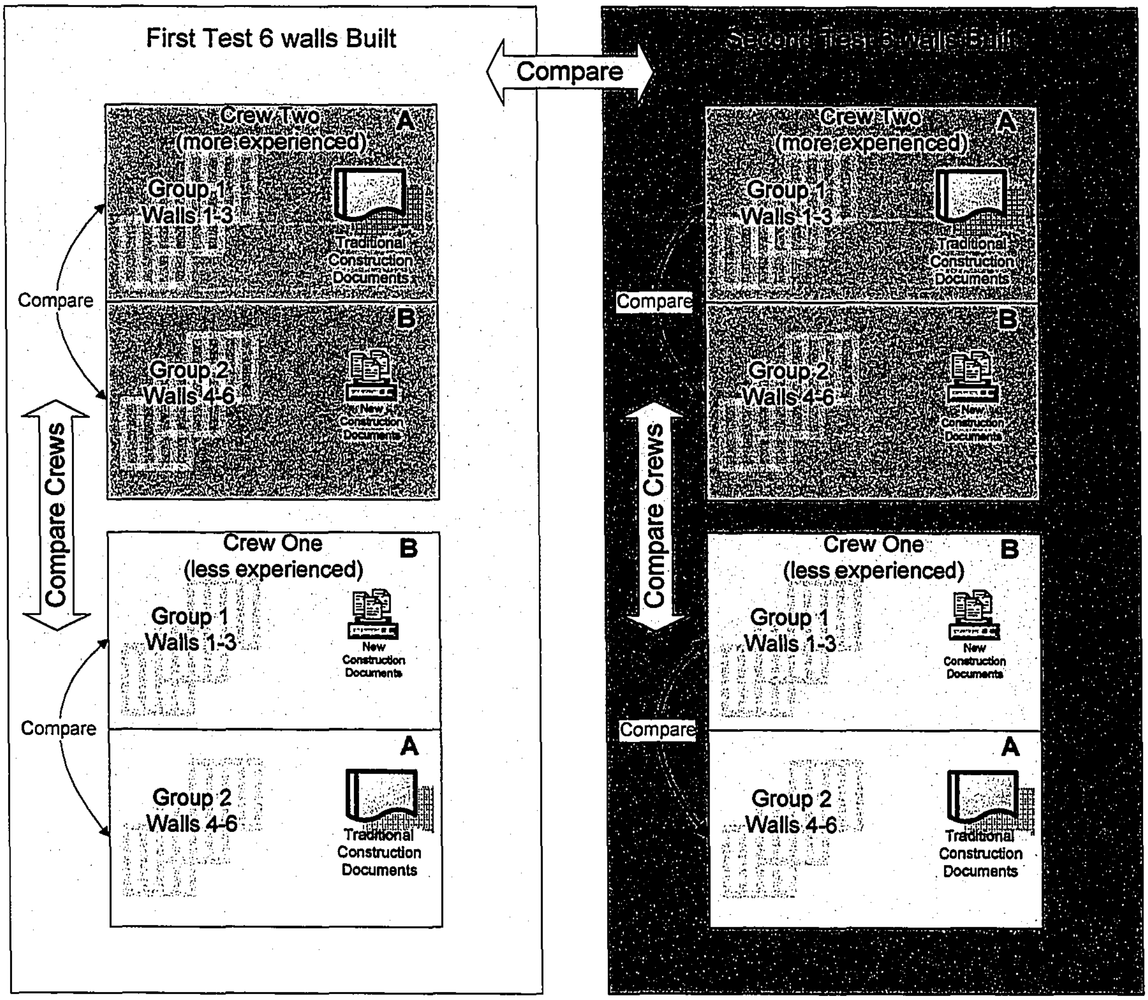

Figure 3 Design of quasi-experiment (adapted single subject ABAB design)

Participants and Site

A purposeful convenience sample of framers living in Colorado at the time of the study was used. Participants were chosen from undergraduate and graduate students working toward a degree in construction management at Colorado State University. Final selection of willing participants was based upon student level of residential framing experience as determined by a qualifications survey. The experiment was conducted in a construction lab located on the Colorado State University campus.

The crews utilized in the experiment were different from many crews working in the field by formal education level and first language. First language is germane because many working in the construction trades speak English as a second language. This heterogeneity of crews in the field and experiment was believed to be acceptable as researchers held that differences observed during the experiment would be less for crews with English as a first language. In other words, the hypothesized advantages of improved quality and time would be greater for a crew who would have difficulty reading the traditional construction documents in English, their second language. The new construction documents contain only pictures and numbers. First language as an independent variable was beyond the scope of this study thus, the effects of primary language were not measured. Further research could address first language as a variable.

Recruitment Plan

Two crews were utilized for the experiment each consisting of a foreman and three carpenters including one alternate carpenter. A purposeful convenience sample was selected from Graduate and undergraduate students working toward a degree in Construction Management at Colorado State University (approximately 1,000 students enrolled). Students were asked to participate via a series of emails from the Construction Management Department Administrative Assistant. Emails were sent until 16 potential participants were identified. A plan was in place to utilize an outside person (not employed by the Construction Management department) to recruit in construction management classes if the email recruitment was not effective in recruiting enough qualified participants. The use of a recruiter was not necessary. A copy of the recruitment email can be found in appendix A.

As part of the recruitment email, students were informed of the compensation (two $20 restaurant gift certificates) and requirements for participation. Because of the inaccurate estimate of the time needed to complete the experiment, participants compensation was doubled. The four requirements for participation were:

1. Student must be currently enrolled in or had completed MC 151 Construction Materials and Methods (requirement for undergraduate students only)
2. The student must have at least 6 months of residential framing experience (wood frame)
3. The student must be able to read a framing layout
4. Student must be comfortable using typical framing tools (circular saw, reciprocating saw, miter saw, pneumatic nail gun, and other hand tools)

These requirements were developed to increase safety for the experiment and strengthen the ability to infer results to the target population. Participation in and completion of MC 151 ensured the undergraduate participants had some formal safety training as lab 1 in MC 151 is dedicated to safety. Framing experience provides experience using framing tools. Thus, the requirement for framing experience also increased safety. The requirement for experience as well as the ability to read a framing layout increased participants' similarity to the target population. Participant comfort with framing tools increased both safety and similarity to the target population.

Each volunteer was asked to complete a qualifications questionnaire (see appendix B) to aid in participant selection. The two crews were selected based upon qualifications survey scores, with one crew being more experienced than the other. Upon selection, participants attended a briefing session where they were asked to sign a consent form which briefly described participation in the study including the risks and benefits. All selected volunteers participated in the whole experiment. The use of alternates was not required. The consent form and methodology for the quasi-experiment were approved by the Colorado State University Regulatory Compliance Human Research Committee. A copy of the approval letter can be found in appendix C.

Data Collection

It could be argued that if differences exist in time and quality for the experiment, these differences could be diminished as a framing crew builds multiple iterations of the same house plan. In other words as a crew frames a home multiple times, the crew is able to improve on time and quality of the frame using TCD through learning and experience. To control for some of this learning, each crew was asked to participate in two iterations of the same experiment (single subject ABAB design). These iterations were completed approximately two to three weeks apart. This would be comparable to the time between builds if the same crew were to build the same home consecutively. Even if a crew happens to build the same home multiple times, frequently a different model would be built between same home builds thus, minimizing carryover. Additionally, changes in crew members as well as changes in crews or subcontractor would require the learning process to begin again.

A total of six walls of varying complexity were chosen from the homes built as part of the case study. The six walls were separated into two groups of three. Each wall in group one (WG1) had a similar (size, and complexity) wall in group two (WG2). To eliminate any carryover from one set of construction documents to another, walls from WG1 were selected from one home and walls for WG2 from another similar (size and complexity) home. To mimic the natural framing process, directions were not given as to the order of wall framing or even if they were to be framed sequentially.

Each crew participated in the study on two separate occasions. The start time for each experiment was between the hours of 7 am and 5 pm. Each participant received the same instructions and directions. An excess of framing material was provided in the same location for each experiment (A, B, A, B). Tools and equipment were also provided including a skill saw, a miter saw, a reciprocating saw, and two pneumatic nail guns with a compressor. Tool bags and non-electric hand tools were also provided if necessary as well as safety glasses and hard hats. Before the experiment began, safe use for each tool was demonstrated and safety was emphasized.

As is traditional in the framing process, a person (researcher) was identified as the construction manager or superintendent for the project. This person was available to answer questions throughout the process. However, the crews were told to act as if the superintendent was not on site. They were requested to act as if they were working on a real site. They were told that they should only ask questions if they would call and ask the superintendent on a real site. Two researchers watched to ensure that safe practices were maintained at all times. If an unsafe practice was observed, it was stopped immediately.

To begin the first timed portion of the experiment, the crew was given a set of TCD with WG1 highlighted on the drawings. As shown in figure 3, crew two built WG1 using the TCD first (A). Upon completion of the first half of the first test, framers were either given a 15 minute break, or a time was scheduled to return to complete the second half of the first test. Following the break framers were given training on the use of the NCD. Once the training was complete, the second timed portion of the project began by giving the crew a set of NCD with WG2 highlighted on the drawings (B). Crew one went through a very similar process with the exception of using the NCD on WG1 first and then building WG2 using the TCD.

Each crew repeated the experiment two times for reasons previously explained. For the second measure, crews were given (prior to beginning to build each WG) a list of errors made during measure one for each wall group. The list was not wall specific and did not indicate how many times a specific error was made.

The documents used in the experiment (both TCD and NCD) had gone through several iterations as part of the case study. The TCD had been red-lined and updated several times by the architect, engineer, and truss designer. These updates were informed by the prototypes, including the coordination walk and a follow up coordination meeting. These documents are believed to at least as accurate if not more accurate than a typical set of TCD. The NCD went through the same process and are believed to be very accurate. A reduced size set of one of the TCD used for the experiment can be found in an envelope attached to the back cover of the dissertation. One set of the NCD documents used for the experiment can be found in appendix D.

Treatment of Data

As outlined in the research questions, the three independent variables are: document type, crew experience, and measure. Each independent variable has two levels. For document type the two levels are the NCD and the TCD. Crew experience was determined by the purposeful selection of two crews; one crew more experienced than the other crew. The two levels for measure are a result of the repeated measures design (AB-AB for each crew).

The two dependent variables are construction time and quality. Construction time is operationalized for this study to mean: the total amount of time for a crew to build three walls. Construction time began when the construction documents were given to the crew. Construction time concluded when the crew stated that the last wall was complete. Quality was measured using two instruments. At the completion of each build, walls were scored for accuracy using an error evaluation rubric (Appendix E). The score from the error evaluation rubric provided an error score for each wall. Grading was completed by a researcher who compared what was actually built to what should have been built. In addition to the error evaluation rubric, walls were scored for quality of cuts, quality of connections and overall quality of appearance. This scoring was done using a 5 point likert scale with 5 being high quality and 1 being low quality. Each wall was scored and these scores were averaged together for each wall group by measure and crew. This partly subjective evaluation was also conducted by a researcher.

Construction time and the error score were added together to create an additional variable used for comparison. The reason for combining these scores is to provide a more complete picture of the findings. To illustrate: If a wall is built in the same amount of time by two crews yet one is accurate and the other has multiple mistakes, comparisons on time only would not provide an accurate assessment. Additionally, if the same two walls were built by two crews at the same level of accuracy yet construction time was very different for the crews, comparisons on accuracy would not provide an accurate assessment. Combining error score and construction time provide a more complete and accurate depiction of the results.

Multiple comparisons were made on each variable. Some of the comparisons are represented as arrows in figure 3. These comparisons include within and between crews as well as between measures. Other comparisons included comparing the differences within crews, by crew and measure. Descriptive statistics using charts and tables are used to present the findings and for analysis. A graphical analysis using 3D bar charts was also conducted.

Summary

This sequential exploratory design will add to the body of knowledge surrounding the use of technology to infuse lean principles into construction. As mentioned earlier, few tools have been developed or defined to facilitate lean construction practices. With the current problems facing the home building industry, it is imperative that researchers look to the successes of other industries (such as manufacturing) for solutions. This research does just that!

CHAPTER 4: FINDINGS

As outlined previously in figure 2 chapter 3, a sequential exploratory strategy was utilized in this investigation. The findings in this chapter follow the structure outlined in this strategy by presenting data from the case study followed by results of the quasi-experiment. The sequence of findings is also in keeping with the order of the research questions.

Case Study

Introduction

The exploratory research found that the frame informed and was central to every other system in a home. The frame is one of the first major systems to be installed for a home with the exception of the foundation and underground plumbing. It was found in the exploratory study that errors in underground plumbing, as well as the foundation and structural slab, were corrected to fit the frame. It should be noted; for most custom home construction and for some production builders, the frame is adjusted to fit the foundation. However, for the case under investigation, the framing plans had precedence. It was also found that efforts were made to change the frame to meet the needs of the mechanical, electrical, and plumbing systems. Overall it was found that realizing and perfecting the frame had a profound impact on the other systems. These findings were in concordance with the researcher's prior experience.

Data were collected from the four sources of evidence concurrently. This simultaneous data collection allowed researchers to triangulate even during data collection. In other words, data from one source of evidence were often cross checked with another source for verification. This concurrency of data collection supports simultaneous reporting of findings for data sources.

Waste Activities

One of the first goals of the case study was to identify the waste in the residential on-site framing process for both the virtual and physical builds. Research questions 1 and 1-a are as follows:

1) What are the non value-adding activities (waste) contained in the residential on-site framing process?
   a) How are the non value-adding activities different in the virtual and physical building processes?

These questions are founded in lean theory. A principle of lean is to eliminate waste and variability in the production/construction process. From the case study data, it was found that much of the waste and variability in the framing process is caused by mistakes made in the frame or other systems like plumbing or foundation. Additionally, often systems are installed correctly but are not optimized for future systems. For this case study, the most common types of non value-adding activities associated with these mistakes and lack of optimization include:

1) Time spent building the item wrong
2) Time spent removing inaccurate components
3) Time spent reinstalling or reworking components
4) Time spent trying to determine the right way to build (interpreting plans, waiting for information)
5) Time spent working around previously installed systems
6) Extra time spent installing components with inferior tools
7) Time for demobilization and remobilization

Additionally, Often material (M) is wasted as a result of the mistakes.

The answer to research question 1-a is primarily found in table 4 which describes the differences between the previously specified waste activities by build type (physical and virtual 3-D) Mistakes resulting in waste are made whether building virtually or in reality. However, the impacts of these mistakes are significantly different for multiple reasons. One reason for the difference is that the building processes are much different. For example, the way a 2x4 is sized appropriately is different for each build type. If a 2x4 @ 97"long is needed in the physical build, a 2x4 that is longer then 97" would be found, measured, marked, and cut to 97". In the virtual build, the 2x4 is either built from a 2x4 sketch and extruded to the proper length, or another 2x4 (longer or shorter) is resized to the proper length. Once a particular component (say a 2x4 @ 97") has been created virtually, it can be used wherever and whenever a component of that size is needed. It does not need to be recreated for every instance (unlike in the physical building process)

The purposes for each build type are also different. For the physical build the purpose is to produce an end product to be sold. Thus, some mistakes may not be corrected (example to follow). The purpose of the virtual build is to produce an accurate and optimized home frame from which captured information can be transferred to field workers in an effort to minimize waste. Thus errors in the virtual build were always corrected. When an error is found, either virtually or physically, the ability to capture the correct information and then transfer the information to the field workers for the next build has been largely ineffective. Thus, many of the waste activities are perpetuated throughout multiple builds. This perpetuation of waste has largely been an accepted part of the home building process.

Table 4

Comparison of specified waste activity type by build type

Waste activity number	Physical build	Virtual build
1	Waste includes only time spent producing the parts of the assembly that are wrong. Or time beyond what it would have taken if done right	Similar to physical build. However, processing and connecting materials virtually is handled differently and is quicker overall
2	Can be a significant factor. Often damaging other correct components.	Usually an easy fix. Common method is to select component and press delete.
3	This activity is equivalent to time if built right the first time. Other activities such as 5 and 6 may be added to 3.	Same as physical build but again the building process is quicker virtually.
4	This activity is largely participant specific and is probably related to experience and access to outside information. This may also include time waiting for information.	Mostly the same as the physical build.

5	This activity is specific to a lack of optimization. Often work takes more time due to a lack of forethought about how a previous system could have been changed to allow quicker install of future systems. It also includes extra time to fix a component built wrong.	Very similar to physical build. If no thought is taken during planning, the work-around remains. The benefit of the 3-D model is that optimization can be explicitly documented and utilized.
6	Often when returning to install a missing or incorrect component, not all tools are used because of demobilization and mobilization time, or the fact that the tools are being used by the rest of the crew on the next job.	Not a big factor in the virtual build because a specific assembly can be worked on independent of the rest of the model.
7	Extra time related to loading up equipment and materials, transporting to another job, and unloading equipment and materials.	Much different in the virtual build. This process only includes locating, finding, and opening the appropriate file. All tools and materials are there.

Results by Information Category

The findings of the case study support the notion that much of the waste in the process is related to information. Problems associated with the information often lead to errors or lack of optimization which in turn lead to rework, work-arounds and/or wasted material. As outlined in the literature, these activities are inherent waste in the largely craft production process. To gain a further understanding of the problems with information, several categories of information were determined to aid in the organization of the data. These categories include:

1) Preference information
2) Conflicting information
3) Insufficient information
4) Hard to find and/or confusing information

Written examples from the case study will follow for each information category. Additionally, a table showing common instances of mistakes or lack of optimization for each information category will be provided. These tables (5 through 8) are not complete lists of errors found during the case study; but are representative examples of the types of errors caused by each information type. These tables will also include the associated waste activities for the physical and virtual build, as well as the information source, and ability to capture the information in the 3-D model. Research question 1 through 3 will be answered using information provided in these tables. Questions 2 and 3 are as follows:

2) What information (eg. documentation, explicit knowledge, tacit knowledge) needs to be communicated to front line workers to reduce variability and minimize waste?
3) What information found to be pertinent in research question 2 can be communicated using a three dimensional model?

Preference information.

Involvement in this project began for researchers as participants. Researchers were sent a late iteration of the construction documents (prior to prototype construction) from which the 3-D models were constructed. At the onset of this process it became apparent that framing experience and knowledge (knowing the craft) were absolutely necessary to complete the 3-D virtual frame. This experience was required to fill in the gaps of missing information found in the traditional construction documents (TCD). As the following examples of preference information will illustrate, just filling in the gaps with previous knowledge may not produce the desired result. In other words building virtually using similar craft skills often results in the same types of waste.

As is the case for much of construction, there are numerous ways to construct a system. It is often a matter of preference as to which method is used (preference information). Sometimes the preference is left to the subcontractor and other times the developer dictates. Other times still, the code official has a preference even though it is not explicitly outlined in the code books. In other words, the "right way" to construct each system is often context specific, driven by multiple participants in the construction process including the owner, developer, code officials, and subcontractors. The "right way" is either driven by the participant with the most clout or most convincing argument for their preference. This preference information is often not included in the TCD.

To illustrate the preference information category, an example of wall backing for intersecting walls is described. There are multiple appropriate ways to *back out* for wall intersections. Some common methods include, "channel backing", "ladder backing", and the "California corner" method (see figure 4 for backing types). For this project, ladder backing was verbally specified by the developer. However, for the first few homes built, the framers utilized the channel and solid backing method (the solid backing method is not common because of the unnecessary use of material as well as a reduced R value for exterior walls). Once this was discovered by the developer, the framers were informed that ladder backing was specified. After a few homes had been built using the ladder backing method, the code official challenged the method and mandated an alternate method be used. After arduous discussions between the developer, code officials, and the drywall contractor, it was determined that the ladder method was acceptable and would be used for the project.

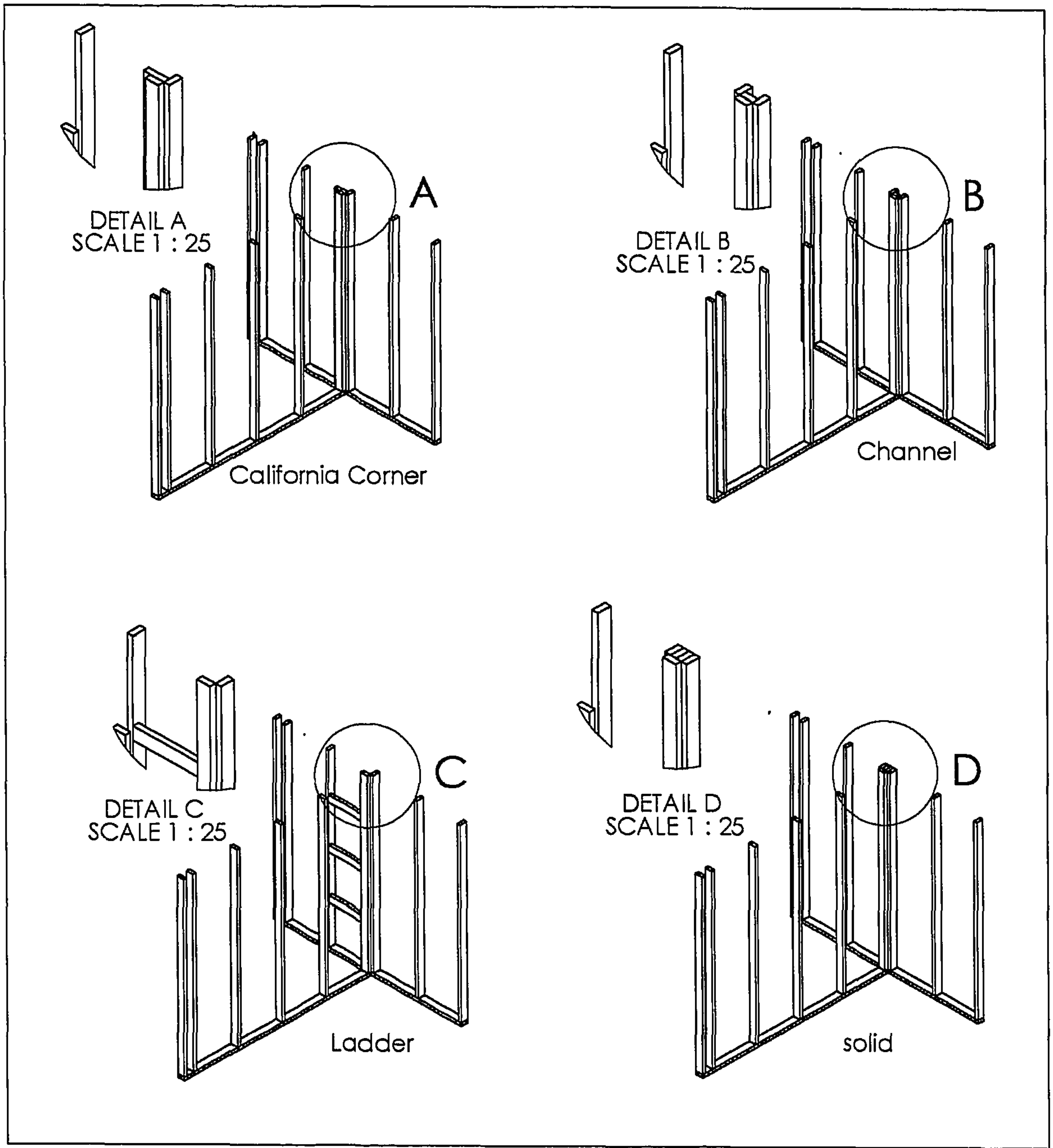

Figure 4 Wall intersection backing types

Table 5, provides four instances of waste activities associated with preference information. The first mistake listed is using the wrong corner. For this mistake, the table shows the physical build only incurring one waste activity (activity 4 which is time spent trying to determine the right way to build including; interpreting plans, and/or waiting for information) and some wasted material (M). Even though activity 4 is shown, it may be that very little time was spent trying to determine the correct method. Often for preference information, craft workers just move forward with a known, or their own preferred method. Often mistakes made in the physical build, related to preference information, are not corrected. This is due to the fact that even though material may have been wasted, or the method used may not be the preferred method of the person with the most clout, the fact is, it will still work. Once discovered, these mistakes are frequently not fixed but are not repeated on future builds.

For the virtual build, this mistake caused multiple waste activities (1-Time spent building the item wrong, 2-Time spent removing inaccurate components, 3-Time spent reinstalling or reworking components, 4- Time spent trying to determine the right way to build including; interpreting plans, and/or waiting for information, and 7-Time for demobilization and remobilization). Since the virtual model is designed to be used for many builds, it needs to be changed to reflect what should be done in the future. The next column in table 5 indicates that the information source for corner type is US or an unwritten specification, specified by the developer in this case. The last column indicates that this information was able to be captured in the 3-D model.

The instance in table 5 of pulling common stud layout from the wrong end is a good example of when the system could be optimized. Say for example, a wall has several door and window frames included. Pulling layout from one end may require additional studs to be installed as apposed to pulling layout from the other end. As shown in table 5, extra time was spent building the wall wrong by installing more materials than necessary (1, M). As with the other example, if this mistake is caught, it would likely not be changed. However, there would be a desire to change the layout direction on the next build to save both time and material. This information can be examined and captured in the model. Another benefit to the virtual build is that no materials are wasted in the process.

Table 5

Observed problems with preference information by waste activity type, information source, and ability to capture in the 3-D model

Mistake or lack of optimization	Waste activity type(s) physical	Waste activity type(s) virtual	Information Source(s)	Captured in 3-D
Used wrong corner type	4,M	1,2,3,4,7	US	Yes
Used wrong type of backing for wall intersections	4,M	1,2,3,4,7	US	Yes
Configuration of window assembly wrong	4,M	1,2,3,4,7	US	Yes
Layout from wrong end of wall	1,M	1,2,3,4	Model	Yes

Guide to Tables 5 through 8

Waste Activity Types:
1) Time spent building the item wrong
2) Time spent removing inaccurate components
3) Time spent reinstalling or reworking components
4) Time spent trying to determine the right way to build (interpreting plans, waiting for information)
5) Time spent working around previously installed systems
6) Extra time spent installing components with inferior tools
7) Time for demobilization and remobilization
M) Material waste
(see table 4 for differences between build types)

Information Sources:
A) Architectural drawings
S) Structural /engineering drawings
T) Truss Layout
US) Unwritten specification
Model) captured only in the model

Captured in 3-D:
Yes) Information was able to be captured in the 3-D model
No) Information was not able to be captured in the 3-D model

Many times throughout the process of building the 3-D models, production was stopped due to a lack of preference information because researchers knew that if it was built wrong in the model it would have to be changed. Several things were changed once researchers determined they had made preference decisions found to be contrary to the preference of another project participant. Had this information been explicitly shown or stated in the TCD, these issues may have been resolved much earlier in the design process and completed correctly the first time homes were built both virtually and physically. This type of missing preference information has a significant impact on the virtual frame but much less of an impact on the physical build.

As indicated by table 5, this type of information is often an unwritten specification. For the direction of layout, the model is specified as the information source because this is the only place an attempt would be made to effectively capture this information. All information provided in table 5 can be captured in the model and should be communicated to front line workers. However, it is even more important to provide this information to those building the 3-D model because the waste activities are more significant.

Conflicting information.

One of the most dramatic cases of this type of information included data from the documents, participant observations, and direct observations. During the early stages of production of the 3-D models, researchers found a discrepancy between the foundation plan and the framing plan for one of the home models. It showed the concrete slab misaligned with the party wall between the house and the garage. When the two assemblies were first brought together in the virtual environment, it was believed that a mistake had been made in one of the 3-D assemblies. The misalignment was verified by the pertinent documents and brought to the attention of the construction management (CM) team prior to actual construction of the home foundation or frame. Because of the newness of this process and technology to construction, the CM team did not trust the model was accurate and ignored the information. A few weeks later during a site visit, we observed a crew removing the portion of the slab that protruded into the garage. This experience alone helped the CM crew begin to trust the technology.

Table 6 shows that almost every specified waste activity (1,2,3,4,5,7,M) was associated with the foundation and frame misalignment. For this mistake these activities were:

1. Installing the foundation wrong (Time beyond what it would have taken if done right)
2. Removing the extra misplaced concrete
3. Reinstalling the concrete correctly (only time it would have taken if done right first)
4. Verifying the misalignment once noticed and determining a fix
5. The extra activities related to working around walls that had been built near the misalignment including removal and reinstall of the framed wall at the misalignment
7. Two crews had to demobilize and remobilize to this job (foundation and framing crews).
M. Concrete material was wasted.

For the virtual build, only activities 1,2,4 and 7 were associated with this misalignment. For this mistake, these activities were:

1. Modeling the foundation wrong
2. Resizing the foundation
4. Verifying the misalignment on TCD once discovered.

7. Navigating to the correct foundation file and opening it.

For this mistake, the physical build incurred much more waste than the virtual build. For the virtual build, only one person was required to perform the work in a relatively short amount of time. The physical build required multiple workers from at least two separate crews. Table 6 also indicates this information was able to be captured in the 3-D model; and the sources of information for this example included the structural and architectural drawings.

Table 6

Observed problems with conflicting information by waste activity type, information source, and ability to capture in the 3-D model

Mistake or lack of optimization	Waste activity type(s) physical	Waste activity type(s) virtual	Information Source(s)	Captured in 3-D
Foundation and frame mismatch	1,2,3,4,5,7,M	1,2,4,7	A, S	Yes
Wrong beam size used	1,2,3,4,5,6,7,M	1,2,3,4,7	A,S	Yes
Header sizes wrong	1,2,3,4,5,6,7,M	1,2,3,4,7	A,S,US	Yes
Beam pocket in the wrong location	1,2,3,4,5,6,7,M	1,2,3,4,7	A,S,T	Yes

Guide to Tables 5 through 8

Waste Activity Types:
1) Time spent building the item wrong
2) Time spent removing inaccurate components
3) Time spent reinstalling or reworking components
4) Time spent trying to determine the right way to build (interpreting plans, waiting for information)
5) Time spent working around previously installed systems
6) Extra time spent installing components with inferior tools
7) Time for demobilization and remobilization
M) Material waste
(see table 4 for differences between build types)

Information Sources:
A) Architectural drawings
S) Structural /engineering drawings
T) Truss Layout
US) Unwritten specification

Captured in 3-D:
Yes) Information was able to be captured in the 3-D model
No) Information was not able to be captured in the 3-D model

Another significant example of conflicting information came after the prototypes had been built, and second iterations of the homes were under construction. A Researcher was on site working with one of the lead developers for the project to resolve some previously identified conflicts. During this meeting, a new set of shop drawings for the floor trusses was brought into the office. As is common, during our meeting the developer had to tend to some critical issues allowing the researcher time to update the floor truss system from the newly obtained documents. Upon completion of floor truss update in the virtual model, it became apparent that several of the trusses were going to be too long if built according to the shop drawings (See figure 5). With the truss designer and developer in the office, the researcher brought this to their attention. The truss designer was skeptical stating that the trusses were right. He stated that these trusses were on site and were to be installed that very afternoon. Researcher, developer, and truss designer walked to the construction site to field verify the trusses. It was determined that the trusses were in fact built too long and needed to be modified. These examples illustrate the types of conflicting information that are common in the residential construction industry.

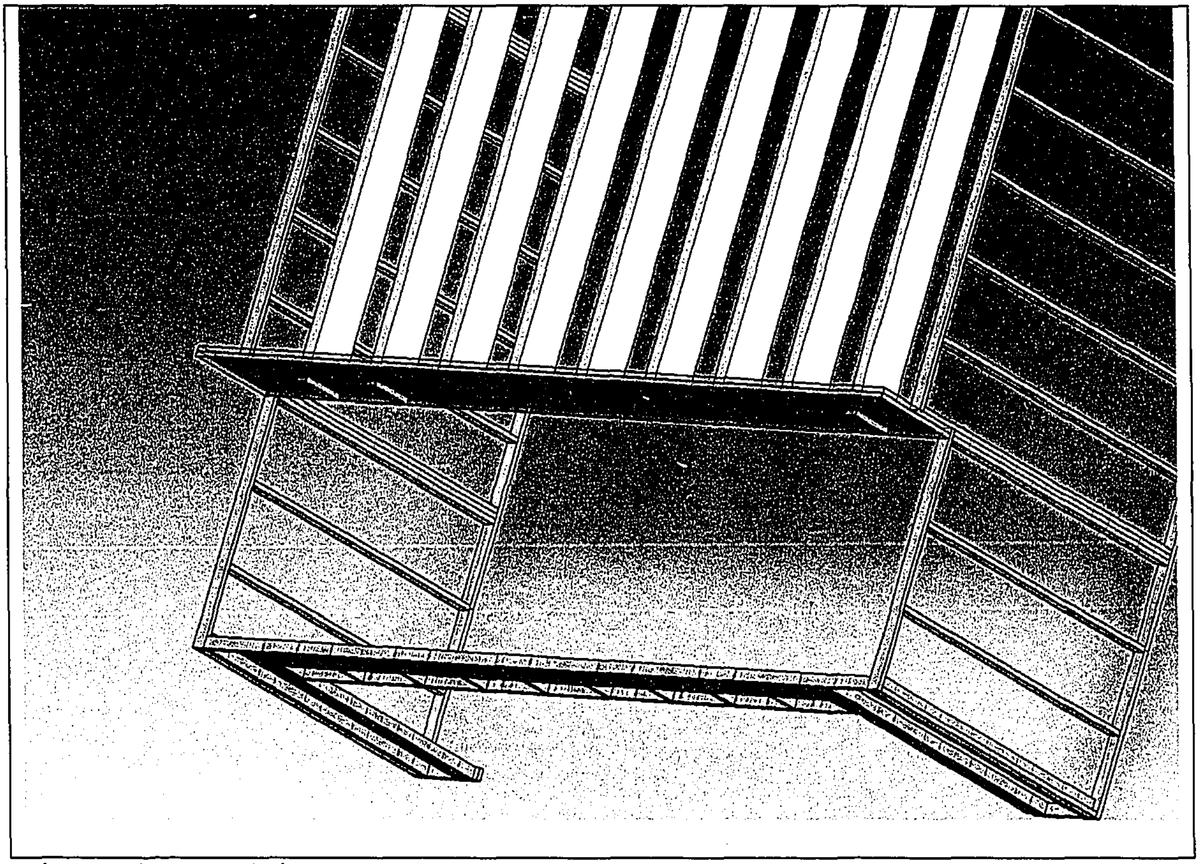

Figure 5 Floor truss design error

Table 6 shows that the associated waste activities are very similar for each item. Activities 1,2,3,4,5,7, and M are present in the physical build for all examples. Activity 6 which is the extra time spent using inferior tools is associated with all but one item. Activity 6 happens often when the fix is perceived as minor. Often crews will remobilize with only necessary tools (hammer instead of a nail-gun) to complete the fix (see table 4 for further explanation). Activities 1,2,4, and 7 are present for each example in the virtual build. Activity 3 is present for all but one of the examples. This activity is not included for the foundation misalignment because the foundation was simply resized; activities 2 and 3 happened simultaneously. The differences between the physical and virtual build for most examples include waste activity numbers 5 and 6. These differences deal with the working environment including the tools used. For the physical build, working on a standing wall can pose significant challenges as apposed to working with a wall that is laying on the ground. Additionally, often an intersecting wall is in the way making it more difficult to replace or modify a component. In the virtual environment these items do not pose a challenge. Again, waste activities take much less time to fix virtually than physically. Similar to preference information, all of the information included in table 5 can be captured in the 3-D model and should be communicated to front line workers to reduce waste. Unlike the examples of preference information, the waste for conflicting information is much more significant for the physical build than for the virtual build.

Insufficient information.

It could be argued that Problems with preference information may be due to insufficient information. However, often information that is not sufficient is related to items that are more than a matter of preference e.g. (specific structural or architectural information). Additionally, preference information may be intentionally left off the TCD precisely because it is a matter of preference. Information in this category will include information that should be explicitly defined in the TCD and not left to preference.

Often problems with insufficient information are found during the construction process. Evidence suggests these problems surface whether the build is virtual or physical. One example of insufficient information came during the virtual build of the garage walls for one of the homes. It quickly became apparent that a significant beam was required to hold up the floor trusses. The size of the beam had been specified but it had to rest on another significant beam that spanned the garage door opening. Not only did the drawings not indicate how the connection between beams was to be made, the elevation of the beams was also not specified. Additionally, it was determined that if the beam was to sit below the floor trusses (as specified by the truss shop-drawings), the garage door would not have room to open. This issue was brought to the attention of the developer who required the structural engineer to determine an appropriate fix. By the time a fix had been determined, the garage walls as well as the trusses had already been built (activity 1,4). Beam pockets had to be added (activities 2,3, and 5), another beam had to be moved (activities 2,3 and M), and the trusses had to be modified by a crew from the truss plant (activities 2,3,6, 7, and M). For this example, every specified waste activity took place for the physical build (see also table 7). For the virtual build only activity 4 was a factor. This is because once the lack of information was determined, the virtual build for this area of the home stopped. For this example, the information was able to be captured in the 3-D model; and the sources of information were the architectural, structural, and truss shop-drawings.

Another instance of insufficient information came when researchers were virtually framing the floor truss system in relation to the stair opening for one of the models. For this home, researchers were framing concurrently with the actual framing crew. In other words, virtual and physical builds were happening simultaneously. In the process of the virtual build it became apparent that information was lacking and needed to be defined.

Table 7

Observed problems with insufficient information by waste activity type, information source, and ability to capture in the 3-D model

Mistake or lack of optimization	Waste activity type(s) physical	Waste activity type(s) virtual	Information Source(s)	Captured in 3-D
Beam location in garage not specified	1,2,3,4,5,6,7,M	4	A,S,T	Yes
Floor and beam system around stair opening not specified	1,2,3,4,5,6,7,M	3,4	A, S,T	Yes
Backing for tub and tub plumbing fixture not installed	4,5,6,7	7	A	Yes
Location for water stub up wrong	1,2,3,4,5,6,7,M		A	Yes

Guide to Tables 5 through 8

Waste Activity Types:
1) Time spent building the item wrong
2) Time spent removing inaccurate components
3) Time spent reinstalling or reworking components
4) Time spent trying to determine the right way to build (interpreting plans, waiting for information)
5) Time spent working around previously installed systems
6) Extra time spent installing components with inferior tools
7) Time for demobilization and remobilization
M) Material waste
(see table 4 for differences between build types)

Information Sources:
A) Architectural drawings
S) Structural /engineering drawings
T) Truss Layout
US) Unwritten specification

Captured in 3-D:
Yes) Information was able to be captured in the 3-D model
No) Information was not able to be captured in the 3-D model

During their next visit to the site, researchers decided to go into the home to see how it had been constructed physically. Upon entering the home, researchers met the developer with the structural engineer talking over the exact issue that had been found in the virtual build. The physical frame had been completed incorrectly and required rework. Researchers can only guess the amount of time framers spent trying to determine how to build this section of the home. For this example, the waste activities are again significantly different for the physical and virtual builds (1,2,3,4,5,6,7,M compared to 3,4 respectively).

Included in table 7 are the two examples previously mentioned as well as two other problems caused by insufficient information. As shown in the table the waste activities associated with this type of information is significantly different for the physical and virtual builds. Part of the reason for the difference is researchers stopped production for most systems once the lack of information was determined. When a solution was determined, the systems were built correctly. For the second item in the table, the trusses had been built previously and had to be altered.

For the tub backing, researchers did not include any backing in the walls until the information concerning location was determined. The water stub up locations were completed virtually only because it was a significant cause of waste in the prototypes and other builds. This item deserves further exploration.

As mentioned previously the water stub location was a significant cause of waste for the prototypes. The only document used to determine locations for plumbing stubs is the architectural drawings. From the information on these drawings, the plumbers determine the location for the stubs. These stubs are often placed to be inside a wall once the frame is complete. To determine these locations, plumbers add chains of dimensions to determine future wall locations (a common source for mistakes). When researchers offered to provide a drawing showing dimensions from outside foundation wall to center of stubs, the plumbers politely declined the offer stating that once they had installed plumbing in one home, they would get it right for the rest. During the second build of each home, it became apparent that this remained a significant issue with most homes having plumbing stubs in wrong locations a second time.

During a site visit, researchers found a piece of drywall upon which the locations of the stubs in relation to the foundation was sketched. Several adding mistakes had been made causing several of the stubs to be placed in the wrong location. This prompted researchers to develop a new model driven document with site specific plumbing stub locations. Figure 6 is an example of a plumbing stub location drawing.

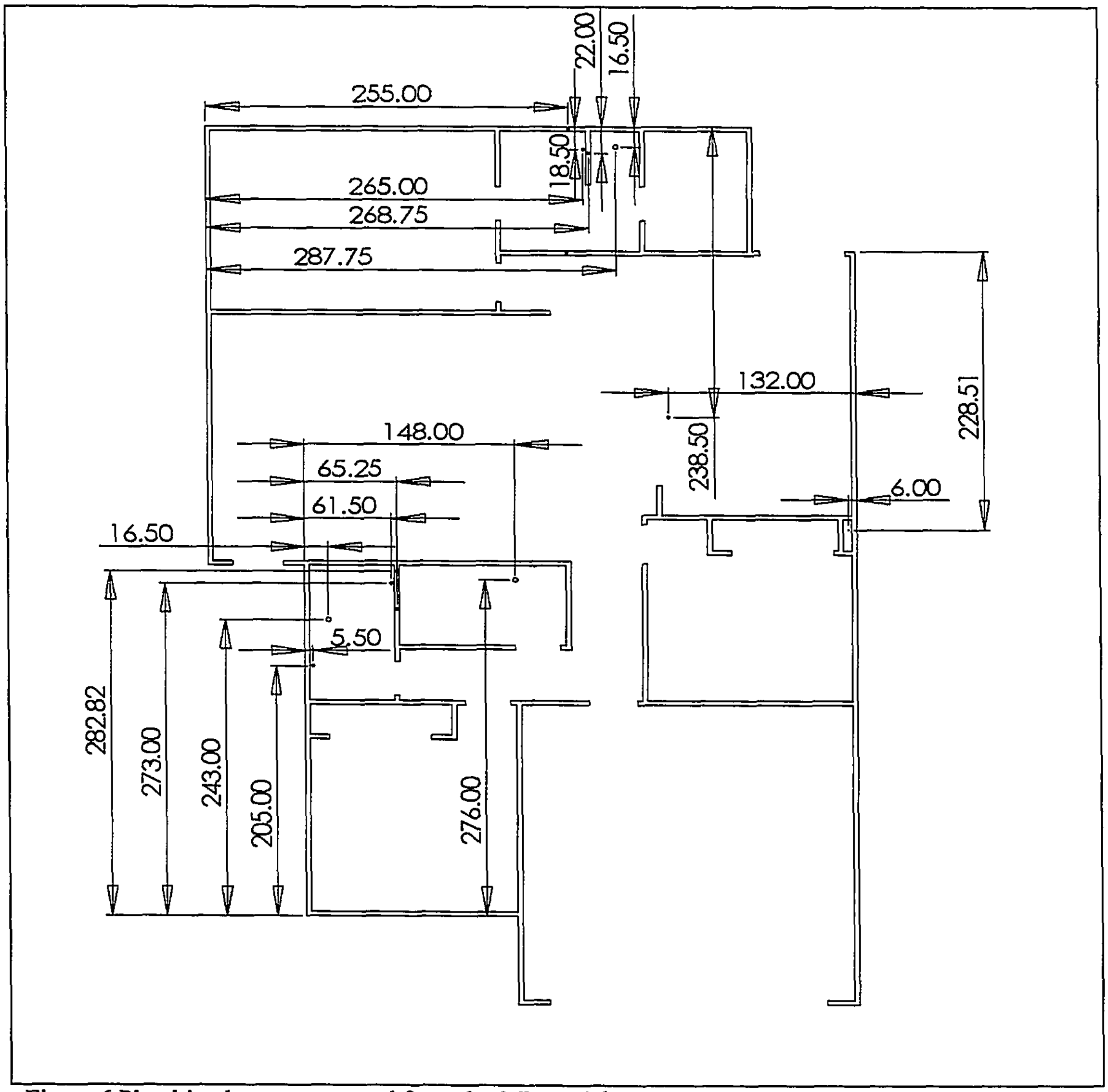

Figure 6 Plumbing layout generated from the 3-D model

Hard to find and/or confusing information.

Again, preference information could fall into this category. As with insufficient information, some of the information that is hard to find or confusing is more than just a matter of preference. However, preference information could be placed into this category if the information is included in the TCD but just hard to find or understand. This type of information is more difficult to classify than the other categories because it is relative to the user. In other words, what may be difficult information to understand for one person, may be perfectly clear to another. Researchers included information in this category if: 1. the TCD included information related to the items, and 2. the items were not installed or were installed incorrectly during the original build of the wall or system. It could be argued that it is a matter of preference whether or not to install certain components at the time of original build. However, researchers argue that the reason these components are left out is because it is not clear to the worker how or where to install the component. Additionally, it often takes longer to add components after the fact, thus increasing the amount of waste in the system.

Hard to find and/or confusing information may be the most common cause of waste. Additionally, the waste caused by this category is perhaps the most often repeated. Observations (both participant and direct) indicate that many items are built contrary to what is indicated in the TCD. These mistakes would be placed into this category of information.

Researcher experience indicates less waste if all pertinent components are installed at the appropriate time. To illustrate; if a wall is being framed while laying on the ground where it is easy to work with, it seems plausible that installing all necessary components would take less total time than leaving components out to be installed later. Often, omitted components are forgotten only to be remembered when another system is being installed. Thus, requiring either the original framer or some other worker to change direction and install the component.

The direct observations provide several examples of components left out during original wall frame. Table 8 lists several examples of problems related to hard to find and/or confusing information. These examples indicate the number of waste activities is fewer for this type of information than the others. However, these types of mistakes were found on builds several iterations beyond the prototype.

The first example listed (beam pocket missing) happened for both build types (physical and virtual). The sources for this information include the architectural drawings, structural drawings, and often the truss shop-drawings. The fact that information is scattered throughout several documents, in and of itself, makes the information hard to find and/or confusing. When this mistake was identified (either in the physical or virtual build) the beam pocket was correctly identified and installed (activities 3, and 4) requiring demobilization and remobilization (activity 7). The physical build also included time spent working around the previously installed system in less favorable circumstances as well as the use of inferior tools (activities 5, and 6).

Table 8

Observed problems with hard to find and/or confusing information by waste activity type, information source, and ability to capture in the 3-D model

Mistake or lack of optimization	Waste activity type(s) physical	Waste activity type(s) virtual	Information Source(s)	Captured in 3-D
Beam pocket missing	3,4,5,6,7	3,4,7	A, S, T	Yes
Point load for truss system left out	4,5,6,7	4,7	A, S, T	Yes
Extra studs in wall because of wrong stud spacing	1,4,M	1,2,4	S	Yes
Not enough studs in wall because of wrong stud spacing	3,4	3,4	S	Yes

Guide to Tables 5 through 8

Waste Activity Types:
1) Time spent building the item wrong
2) Time spent removing inaccurate components
3) Time spent reinstalling or reworking components
4) Time spent trying to determine the right way to build (interpreting plans, waiting for information)
5) Time spent working around previously installed systems
6) Extra time spent installing components with inferior tools
7) Time for demobilization and remobilization
M) Material waste
(see table 4 for differences between build types)

Information Sources:
A) Architectural drawings
S) Structural /engineering drawings
T) Truss Layout
US) Unwritten specification

Captured in 3-D:
Yes) Information was able to be captured in the 3-D model
No) Information was not able to be captured in the 3-D model

A specific example from the case study of hard to find or confusing information provides insight. During one of the participant observations in the field, a researcher was observing the framing process of a home that had been physically built at least once. The researcher had completed the virtual build and had updated the 3-D model to correct errors found during prototype build. The researcher observed a wall being built without a required beam pocket. When this was brought to the lead framers attention he said "no, we will get it in after" the researcher then explained that a stud, if built as they were planning, would have to removed and replaced with the beam pocket. As stated earlier, researcher experience in conjunction with observations indicates that these types of items are left out in an effort to not slow the process. In other words, if the framer was to include the beam pocket in the initial build of the wall, the precise size and location of the pocket would have to be determined. Often from the framers perspective, this would slow wall production.

Summary of Case Study Findings

Research Question 1.

From the case study data, it was found that much of the waste and variability in the framing process is caused by mistakes made in the frame or other system such as plumbing or foundation. Additionally, often systems are installed correctly but are not optimized for future systems. For this case study, the most common types of Non value-adding activities associated with these mistakes and lack of optimization include:

1) Time spent building the item wrong
2) Time spent removing inaccurate components
3) Time spent reinstalling or reworking components
4) Time spent trying to determine the right way to build (interpreting plans, waiting for information)
5) Time spent working around previously installed systems
6) Extra time spent installing components with inferior tools
7) Time for demobilization and remobilization

These activities provide the answer to research question 1 by defining some of the most common non value-adding activities in the onsite framing process observed during the case study. Other non value-activities were certainly present but were not captured in the case study data. These other waste activities likely include additional activities related to moving, inspection, and waiting (Koskela 1992).

Research question 1-a.

The differences in waste activities between the physical and virtual builds are related to the purpose for the build and the differences in the building processes. Table 4 describes the nature of each waste activity by build type. Tables 5 through 8 provide additional insight into how the numbers of waste activities differ per build type for each information category. Table 9 provides further insight by indicating the average number of waste activities for each build type by information category. This information is taken from tables 5 through 8 which include a sample of problems associated with each information type. These examples were not selected randomly nor are the lists complete. However, each example came from data collected during the case study and were selected from these data in the order they appeared until each information category had 4 examples. Furthermore, data was collected for only the first few builds of each home. How this information might change over time is not known. Researchers have no reason to believe that the examples are not representative of the problems for each information category at least for the first few builds.

It is also important to note that the number of waste activities is not a true comparison because the nature of the activity changes based upon the build type. Thus, an activity with the same number of waste activities by build type, would not likely contain the same amount of waste. As stated previously, waste activities are typically much shorter in the virtual build as compared to the physical build.

Only the preference information category shows fewer waste activities for the physical build (see table 9). As stated previously, this is because errors related to preference information must be changed (captured) in the virtual build so as to not perpetuate the problem. These same mistakes likely will not be changed in the physical build (as observed in the case study).

Table 9

Average number of waste activities for each build type and difference by information category

Information category	Average number of waste activites (physical)	Average number of waste activites (virtual)	Difference
Preference information	2	4.75	2.75
Conflicting information	7.75	4.75	3
Insufficient information	7	1	6
Hard to find or confusing information	3.5	2.5	1

The difference in the average number of waste activities in the conflicting information category were mainly due to the activities related to the working environment and the tools used (activities 5 and 6). The difference in the insufficient activity information category is a result of construction stopping for the virtual when the conflict was found. For the physical build, items were often built wrong. The hard to find or confusing information category shows the least difference. However, the difference again is probably activities 5 and 6.

Research questions 2 and 3.

The findings of the case study support the notion that much of the waste in the process is related to information. Problems associated with the information often lead to errors, or lack of optimization which in turn lead to rework, work-arounds and/or wasted material. To gain a deeper understanding of the problems related to information, several categories of information are proposed which provide additional clarity to the problem of waste. These categories include:

5) Preference information
6) Conflicting information
7) Insufficient information
8) Hard to find and/or confusing information

Each category is described previously using examples from the case study. Researchers contend that information of any type leading to waste activities should be communicated to front line workers. All examples of information described previously (see tables 5through 8) were able to be captured in the 3-D model. Researchers believe this information can be communicated effectively through the NCD produced from the model. This belief was tested in the quasi-experiment.

Quasi-Experiment

Introduction

The exploratory case study provided the foundation for the quasi-experiment in two significant ways. First, from the case study came the identification and deeper understanding of the waste associated with the typical on-site framing process. Second, as part of the case study the new construction documents were developed. The findings of the case study support the notion that much of the waste in the process is related to information. Problems associated with the information often lead to errors, or lack of optimization which in turn lead to rework, work-arounds and/or wasted material. The purpose of the quasi-experiment was to test the effectiveness of the NCD on time and quality (including an accuracy measure, and a subjective quality measure).

Participants

Qualified volunteers were divided into two crews based upon scores from a qualifications survey. Table 10 shows scores from the qualifications survey along with crew selection. From the sixteen volunteers only eleven completed the qualifications survey. From the eleven who completed the survey, two were not qualified and one was not available to complete the study. This left enough qualified and available participants to form two crews of four including one alternate for each crew.

As part of the design, crew one had less experience than crew two. The average qualification score for crew one and crew two were 32 and 38 respectively. The average years of experience were 1.4 for crew one and 3.9 for crew two. Alternates were not used for the experiment. Thus, qualifications survey data for alternates were not included in the preceding findings. As shown in table 10, the foreman for crew one had more experience than the crew members for crew two. This was done to ensure a person qualified to perform plate layout was on the less experienced crew. The foreman for crew one had 3 years 5 months of framing experience; and the foreman for crew two had 8 years of framing experience. The difference in experience between the crews was evident from observations made during the experiment.

Table 10

Qualifications survey score and crew selection

Qualifications survey score	Crew Selection	Qualifications survey score	Crew Selection
47	Crew two foreman	29	Crew one
45	Crew two alternate	25	Not available
37	Crew one foreman	24	Crew one alternate
34	Crew two	12	Not qualified
33	Crew two	6	Not qualified
30	Crew one		

Construction Time

Several comparisons were made to determine the answer to research questions 4 and 6. Question 4 is: Does framing time differ when a crew uses construction documents produced from a 3-D model as opposed to when traditional construction documents are used? Total construction time (both crews and both measures combined) was shorter when using the NCD (an overall reduction of 28%). Table 11 shows the difference in framing times and percent reduction for each measure by crew.

Table 11

Framing times for each document type used, time difference, and percent difference by crew and measure

Crew and measure	Duration using Traditional documents (minutes)	Duration using new documents (minutes)	Difference	Percent difference
C1 M1	143	111	32	-22%
C2 M1	152	89	63	-41%
C1 M2	119	69	50	-42%
C2 M2	89	92	-3	3%

Note: M1 = first build, M2 = second build

Since the data indicate a difference in framing times by document type, research question 6 is applicable. Question 6 is: If a difference is found for question 4, does a more experienced framing crew differ from a less experienced crew on the time difference? The total time difference for document type by crew (both measures combined) indicates the less experienced crew had a slightly larger difference (31% to 25%). A comparison of the time difference by measure provides additional insight (see figure 7). For the first measure, both crews were able to frame quicker using the NCD. Crew one realized a 22% time reduction, and crew two had a 41% reduction in time. For the second measure only crew one showed a reduction in time when using the new documents (42% reduction). The reduction for crew one on the second measure was very similar to the reduction for crew two on the first measure (42% vs. 41%).

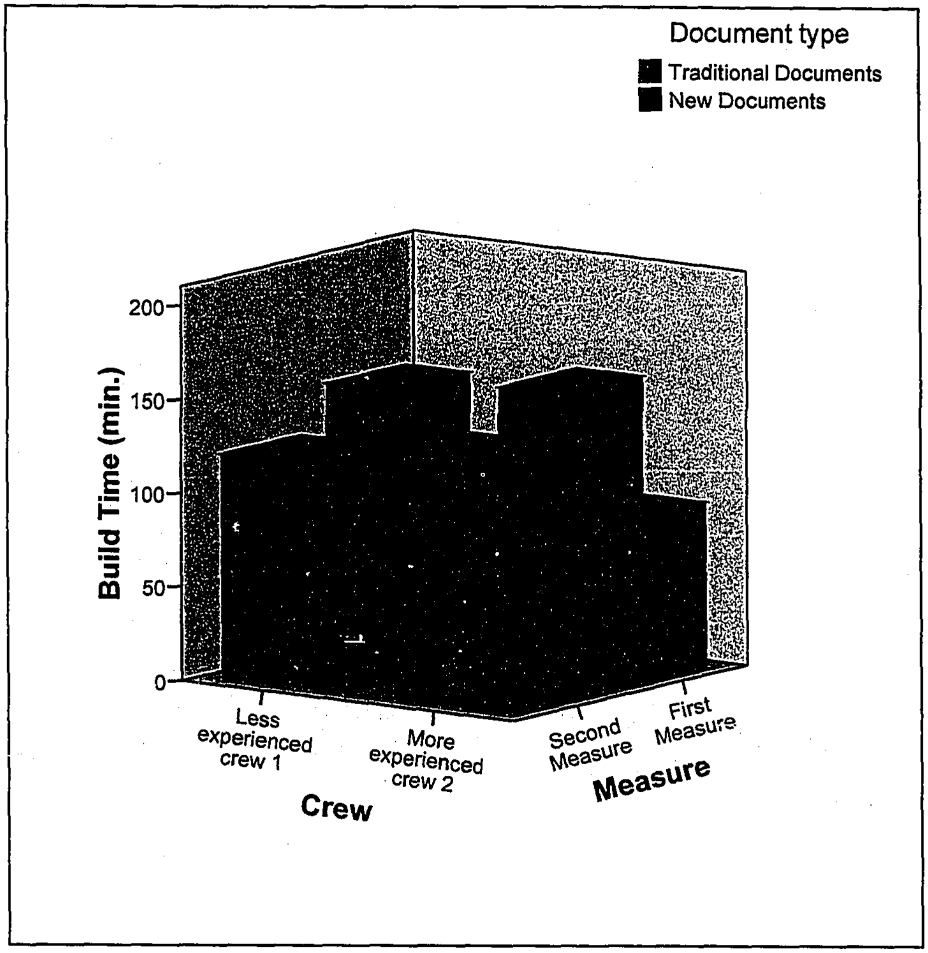

Figure 7 Build time by crew and measure

Another interesting difference (as shown by figure 7) is related to the repeated measures factor. For crew one, framing time was decreased for both document types from measure 1 to measure two. For crew two, framing time decreased from measure 1 to measure 2 for only the traditional documents. Time remained constant for the NCD between builds.

Overall, these data show that crews in the experiment using the NCD were able to frame the three walls in less time than when TCD were used. The differences between crews were inconclusive with the more experienced crew framing both wall groups in nearly the same amount of time during the second measure. The total framing time by crew (A+B+A+B for each crew) showed the more experienced crew framing all walls slightly quicker (422 minutes vs. 442minutes)

Construction Quality

Two instruments were used to measure quality. Results from both instruments will be used to answer research questions 5 and 7. The first instrument is an error evaluation rubric used to determine error scores. Using the rubric, researchers analyzed each error to determine: the level of error, Estimated time to fix the error, and cost of wasted material caused by the error. Errors for each wall were added to determine a wall error score. Wall error scores were then combined to determine error scores for each wall group organized by crew, document type, and measure. For example, a single error score was determined for the three walls built by crew one using the **NCD** during measure 1. A separate error score was determined for the three walls built by crew one using the **TCD** during measure 1. The second instrument used a five point Likert scale to judge each wall on the quality of cuts, quality of connections, and the overall quality of appearance. Quality scores were organized similar to the error score except the scores for each wall were not added together but averaged together by crew document type and measure.

Error evaluation rubric.

Question 5 is: Does frame quality differ when a crew uses construction documents produced from a 3-D model as apposed to when traditional construction documents are used? Table 12 shows the difference in error scores and percent difference for each measure and crew. Total error score (both crews and both measures combined) was significantly less when using the NCD (an overall reduction of 95%). The percentage differences are fairly similar from one crew to the next and from one measure to the next with the error scores for walls built using the TCD much higher than the scores for walls built using the NCD.

Table 12

Error Score for each document type used, score difference, and percent difference by crew and measure

Crew and measure	Traditional documents (error score)	New documents (error score)	Difference	Percent reduction
C1 M1	146	5	141	97%
C2 M1	52	5	47	90%
C1 M2	165	0	165	100%
C2 M2	63	10	53	84%

Since the data indicate a difference in error scores by document type, research question 7 is applicable. Question 7 asks: If a difference is found for question 5, does a more experienced framing crew differ from a less experienced crew on the quality difference? The percent difference of error scores combined by crew (both measures included) indicate the less experienced crew saw a greater difference between document types (98% vs. 87%).

Other differences by crew are revealed in figure 8 which shows error scores by crew and measure. The error scores for the less experienced crew when using the TCD are much higher than error scores for the more experienced crew when using the TCD (311 vs. 115). Error scores when using the NCD are very similar for both crews for both measures combined (5 and 15); however, it is interesting to note that the less experienced crew had a slightly lower error score than the more experienced crew when using the NCD. Figure 8 and table 12 also show the error scores slightly increasing from measure 1 to measure 2 for both crews. For crew one, the error score for measure 1 is 146 compared to 165 for measure two. The corresponding scores for crew two are 52 and 63 respectively.

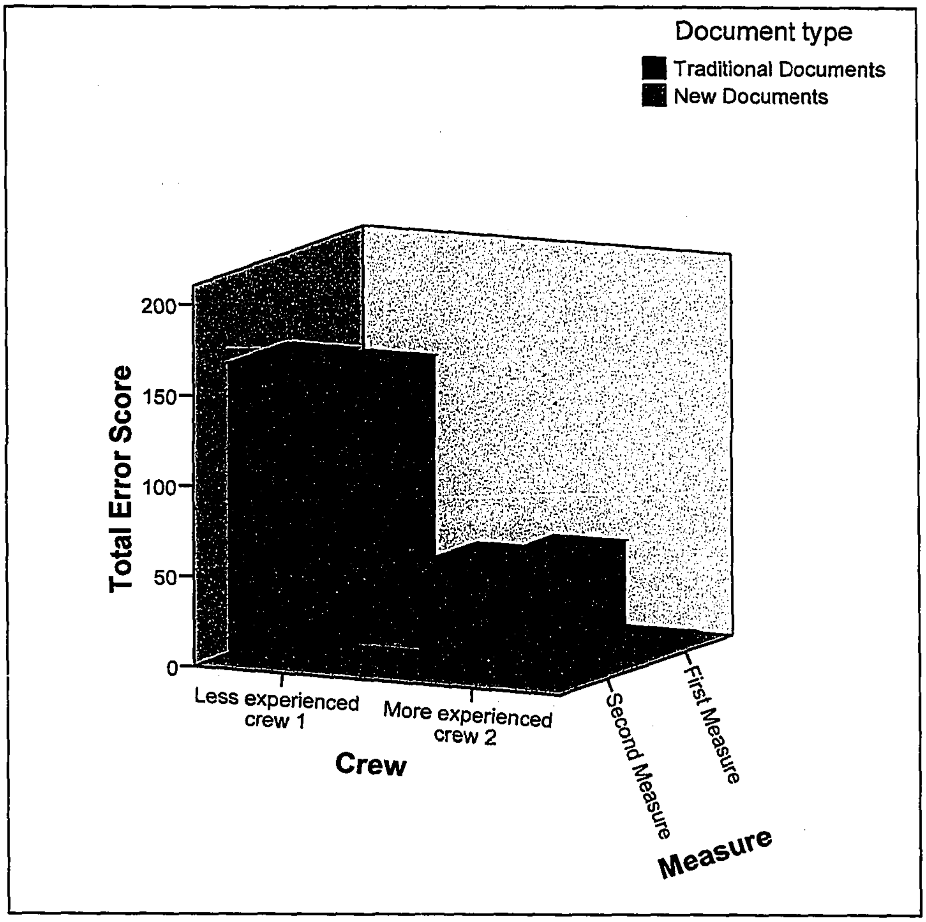

Figure 8 Error score by crew and measure

Quality score.

Table 13 provides the quality score for each document type by crew and measure. The data in the table indicate no significant difference between document type with only three comparisons indicating a difference in score. Two comparisons showed a slight increase in score for the walls built using the NCD (5% and 8%); and one comparisons showed a slight increase in score for the walls built using the TCD (7%).

Table 13

Quality Score for each document type used, score difference, and percent difference by crew and measure

Crew and measure	Traditional documents (quality score)	New documents (quality score)	Difference	Percent difference
C1 M1	3.78	3.5	0.28	7%
C2 M1	4.11	4.33	-0.22	-5%
C1 M2	3.75	4.06	-0.31	-8%
C2 M2	4.53	4.58	-0.05	-1%

Figure 9 provides a visual of the quality scores by crew and measure. The data represented in figure 9 and table 13 indicate the more experienced crew had higher scores than the less experienced crew. The data also indicate the second build had slightly higher quality scores for each crew.

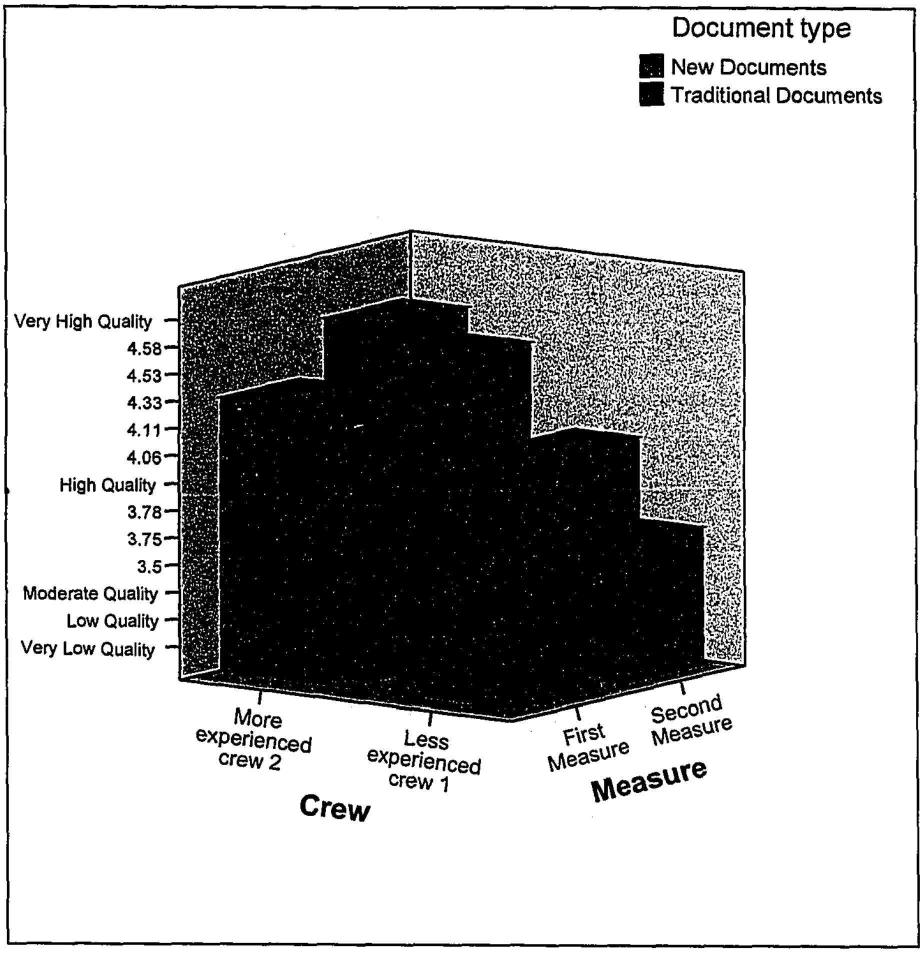

Figure 9 Quality score by document type, crew, and measure

Time and Quality Combined

Previous findings have shown by using NCD, walls were built in less time and with fewer errors. Combining these variables for multiple comparisons provides a more complete view of the findings. Table 14 shows significant differences for combined scores when compared by document type. The percent difference ranges from 33% to 76%.

Table 14

Construction time plus error score for each document type used, score difference, and percent difference by crew and measure

Crew and measure	Traditional documents (construction time + error score)	New documents (construction time + error score)	Difference	Percent difference
C1 M1	289	116	173	60%
C2 M1	204	94	110	54%
C1 M2	284	69	215	76%
C2 M2	152	102	50	33%

Figure 10 in conjunction with table 14 indicate the less experienced crew had a larger difference on the combined score (both measures combined) than the more experienced crew. The total percent difference for crew one was 68% compared to a 45% total percent difference for crew two. This difference is a result of higher scores on the TCD for the less experienced crew as the scores on the NCD were very similar for each crew (185 for crew one and 196 for crew two). It is interesting to note the combined score is slightly higher for the more experienced crew on the NCD. Also, the more experienced crew had a lower score for the second measure when using the TCD and the less experienced crew's score is very similar for both measures. However, the less experienced crew has a lower score on the NCD for the second build and the more experienced crew's score is similar for both measures.

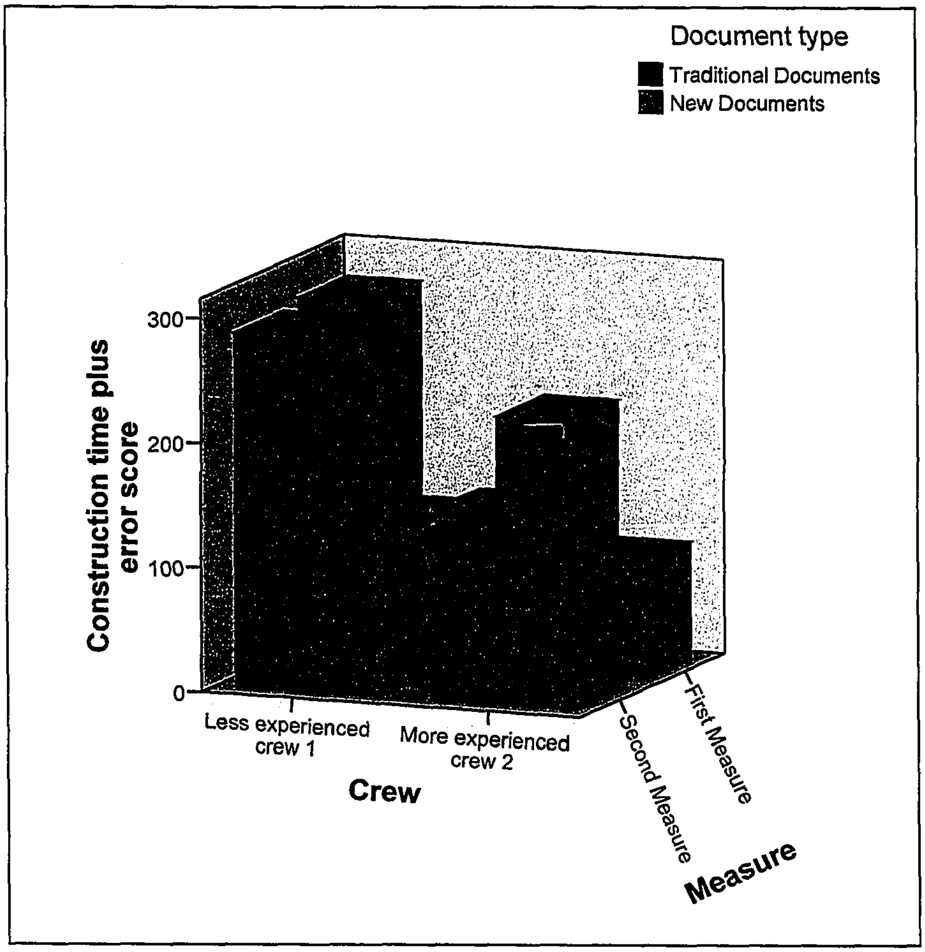

Figure 10 Construction time plus error score by document type, crew, and measure

Errors and Information Type

The findings from the case study provided four different categories of information associated with waste activities. The quasi-experiment provided additional examples of errors that cause waste. Each error from the quasi-experiment was evaluated to determine the associated information category. A total of 48 errors were made on 24 walls built during the experiment. Of the 48 errors, 40 were associated with hard to find or confusing information. In other words, the information was in the documents but was either not found or misunderstood. Two errors were associated with preference information, 3 were associated with missing information and 3 were not associated with any information type but were errors due to poor quality. The NCD accounted for only 3 of the 48 errors.

Summary of Quasi-experiment Findings

Overall the findings show crews building walls in less time and more accurately when using the NCD. Walls built by the more experienced crew were built quicker and were more accurate then the walls built by the less experienced crew when using the TCD. Total construction time was very similar for both crews, yet the more experienced crew had a much less combined score of construction time and error score. A comparison of the crews when using the NCD shows little difference in build time plus error score. The only difference when using the NCD is the subjective quality measure.

CHAPTER 5: DISCUSSION AND SUMMARY

Findings in the Context of Lean Theory

Introduction

This project began as an exploratory study to investigate the use of virtual construction to improve the construction process for residential homes. The initial goal was to develop a 4-D model (the fourth dimension being time) of six home plans. The belief was the 4-D model could provide an accurate visual schedule for construction/production purposes. The first step was to develop a parametric 3-D model of the home. During early stages of virtual model development, researchers came to four significant conclusions. First, developing a parametric model of all components in the home would not provide sufficient value. For example, modeling every piece of exterior siding is a slow process in this virtual environment and would likely not add value to the process. Second, the fourth dimension of time combined with the 3-D model did not add significant value for this residential project. A computer generated schedule can provide sufficient information for typical residential projects. Producing a parametric model of all components in a home tied to a schedule represents significant effort with the end result providing little benefit. Third, the residential construction process is full of waste, much of which is the result of information-poor traditional construction documents

(TCD). Fourth, the home frame was a key system in the home. As stated in chapter four: It was found that realizing and perfecting the frame had a profound impact on the other systems. Research questions one through three came out of these four findings.

The case study provided the answer to research questions 1 through 3 in addition to providing the foundation for the quasi experiment. For reasons previously stated, the majority of the case study focused on frames of six different home plans. This focus provided significant insight into the waste activities associated with the home frames (question 1), the differences in the waste activities associated with the physical build versus the virtual build (question 1-a), and the information associated with the waste activities including the ability to capture information in the virtual build (questions 2 and 3). Additionally, a new set of construction documents (NCD) were developed and pilot tested during the case study.

From the findings of the case study along with the development of the NCD came research questions (questions 4 through 7). Researchers believed framers could construct home frames in less time (questions 4 and 6), and with higher quality (questions 5 and 7) through the use of the NCD. The quasi-experiment was the research method used to answer the last four questions.

As the quasi-experiment is an extension of the case study, the findings are closely related. Thus, the case study and the quasi-experiment are discussed concurrently in this section. The discussion will be organized by major topic area which closely follows the order and content of the research questions. Additionally, the discussion will be grounded in Lean theory using references from chapter two.

Waste Activities Associated with Residential Framing

A tenet of Lean theory is the reduction of waste. Waste in the context of lean has been defined as "any human activity which absorbs resources but creates no value" (Womack and Jones, 2003 p.15). Koskela (1992 p.17) further defines value and non-value adding activities as follows:

- Value-adding activity: Activity that converts material and/or information towards that which is required by the customer.
- Non value-adding activity (also called waste): Activity that takes time, resources or space but does not add value.

For this case study, the most common types of waste activities associated with residential framing include:

1) Time spent building the item wrong
2) Time spent removing inaccurate components
3) Time spent reinstalling or reworking components
4) Time spent trying to determine the right way to build (interpreting plans, waiting for information)
5) Time spent working around previously installed systems
6) Extra time spent installing components in more difficult circumstances or with inferior tools
7) Time for demobilization and remobilization

M) Wasted Material

A common cause of waste as defined in Lean theory is variability. Koskela (2000) states "the practical approach to decreasing variability … consists of finding and eliminating the root causes." The root cause for all of the waste activities identified in the case study is poor information provided to framers. This finding is in harmony with the findings of Tsao, Tommelein, Swanlund, and Howell (2004) who state:

> Designers often leave interface resolution, such as dealing with issues of scope gap and scope overlap, to the builders. They leave tolerance management to installers because they assume that the pieces they have designed will be relatively simple to identify and fit together. By viewing a project as an aggregation of parts, designers may not realize that they can—and, we think, should—design the project as an assembly of interacting pieces all the way from design through construction. While the design of each part may appear to be

> reasonable and logical upon inspection (MCAA 2003), the design of the overall assembly may actually be far from optimal. Not only may it fail to take advantage of overlapping disciplines, the uncertainties and errors created upstream (e.g., during design) may prove to be detrimental to performance downstream (e.g., during installation) (Tommelein, Riley, and Howel 1998). (p.781)

In this statement, these researchers indicate the problem is the lack of design detail, specifically interface resolution. The lack of detail is supported by the findings of this study. However, the problem is much more than a lack of design. Even if designers were to go to the lengths described in the statement and "design the project as an assembly of interacting pieces all the way from design through construction" the current documentation is not capable of communicating the information in an effective manner. In other words, the problem is not just poor design; the problem is the inability to communicate design information in a manner that can be easily understood.

Information and Waste

The findings of the case study support the notion that much of the waste in the process is related to information. Problems associated with the information often lead to errors or lack of optimization which in turn lead to rework, work-arounds and/or wasted material. As described previously, these activities are inherent waste in the largely craft production process. To gain a further understanding of the problems with information, several categories of information were determined to aid in the organization of the data. These categories are:

1) Preference information
2) Conflicting information
3) Insufficient information
4) Hard to find and/or confusing information

The findings of this study indicated that each specified information type contributed significantly to the waste and variability in the construction process. Organizing the data into these categories for analysis provided greater understanding of the causes of waste in the framing process. It is likely if other systems were studied in a similar manner, the waste related to the poor information could be similarly categorized. Additionally, it is believed the waste by category would be similar to the waste associated with residential framing.

Traditional Construction Documents

Researcher experience indicates waste from the first three categories of information will be significantly minimized over time. As framers build the homes multiple times, preference information will be learned and followed; conflicting information will eventually be corrected in the TCD; and insufficient information will be included in the traditional documents in some fashion. In spite of this reduction in waste from information categories one through three, it is believed that much waste will remain in the construction process as long as the TCD are used in their current form because the information is still hard to find, and confusing.

Due to the inherent problems with the TCD, researchers believe the waste from the fourth category of hard to find and/or confusing information is perpetuated throughout the duration of the project. Some of the reasons for the confusion include: a lack of detail, multiple sources of information (e.g. architect, engineer, and truss shop drawings), and scattered information. For example, the information necessary to appropriately size and locate a beam pocket may be found on three different drawing sets, and possibly multiple sheets for each set. This scattered information is difficult to accurately determine. The notion that information in the TCD is hard to find and/or confusing, and is perpetuated throughout the project is supported by the findings of the quasi experiment.

The TCD used for the quasi-experiment had been updated several times to eliminate errors found during the first few physical and the virtual builds of the home plans. Most of the conflicting and insufficient information had been corrected or added. In other words, these documents were as accurate as could be expected for traditional documents. In spite of the largely complete and accurate state of the TCD, the walls built using these documents had many errors. The findings of the quasi-experiment showed that approximately 89% of these errors were related to hard to find or confusing information. This in conjunction with researcher experience indicate the waste caused by hard to find and/or confusing information is most lasting and difficult to eliminate for residential frames for homes to be built multiple times. For projects to be built only once or a few times, all information categories are significant sources of waste.

Researchers believe, even the waste associated with hard to find and/or confusing information will be reduced over time. Framing crews will become familiar with the documents, and through trial and error, learn to build the homes with fewer mistakes thus, less waste. However, as is typical for production home builders, each home plan has three elevations and several options causing changes to the frame and other major systems. In other words, each home is likely to be slightly or significantly different than any previous build of the same plan. Due to the difficulty of reading the TCD along with the changing options for each home plan, mistakes from poor information will continue to be a large source of waste. Additionally, if framing crews change or if a different framing subcontractor is hired (as is typical for production builders), the amount of waste will spike for the first few builds. This increase in waste for a new crew would likely be related to the hard to find and/or confusing information as well as preference information.

From the preceding discussions, it is apparent that much of the waste in the residential framing process is associated with the traditional construction documents. As a result of information-poor documentation currently in use in AEC, the industry has continued to require a skilled management and (craft) labor force that are expected to interpolate information found on construction documents to complete their respective work. This method of construction has been categorized as being somewhere between craft production and mass production which has the inherent problems of poor and inconsistent quality as well as significant variability and waste (Barlow 1998). The lack of detail in design, along with the inability to effectively communicate the design information when using the TCD, keeps the industry in this outdated state.

New Construction Documents

The advances in manufacturing are in large part, due to the reduction of product and process variability which are leading causes of waste. Lean production has provided several methods of variability reduction. The major methods are: concurrent engineering or the dynamic definition model of design, continuous improvement, and simplification. For these methods to be successful, effective communication is essential. As outlined in the following sections, 3-D parametric modeling is a significant communication tool that enables each method of variability reduction. This study shows that this same communication tool can be used in construction with similar results.

Concurrent engineering or dynamic design.

The dynamic definition of design is truly concurrent as all product development activities begin at the same time (excluding production). These activities are concept design, detail design, analysis, prototyping, and testing. As previously explained, a significant enabler to this method of design is the use of 3-D computer aided design (CAD), at the component level. Producers of most manufactured products (e.g., airplanes, ships, cars, consumer products) experienced breakthrough advances in productivity due to the digital-based convergence of 3-D CAD representations and production processes. The 3-D model serves as the medium for communication and collaboration among project participants. Products are digitally created and produced seamlessly from concept through production (Kolarevic, 2003). In many of these industries, design (including engineering) and production departments have been combined into one where teams come together to meet customer needs (Kieran, 2004).

The closest equivalent to concurrent or dynamic design in AEC is the design-build method of project delivery. A major benefit of the design-build delivery method is collaboration during design. In this model, the contractor is involved in the design to provide input into the methods means and cost of the project. Designers are kept in check from a budgeting and constructability standpoint. Although this method encourages collaboration among the project participants, the same tools of design are used, and the result is still information-poor documentation.

To a large extent, the design-build delivery method is used by many production home builders. Designers are either hired by the builder/developer to design homes, or design is completed by in house architects. The findings of this study support the notion that even when design-build type collaboration is utilized, a significant amount of waste remains in the construction/production process.

Although, 3-D technology has been used for complex construction projects (Folkestad and Sandlin, 2005), only selected systems are modeled and often not at the level of detail to provide production information. Modeling for production of onsite wood frames is rare. Toward the end of this study, a company was found that has been developing the software and a process for dynamic design of residential framing for many years. The technology and process are in final development stages and have not been scientifically tested. The results of this study could inform and support the efforts of this company by providing evidence of the benefit of 3-D modeling for residential framing. Although the models built for this study were not used specifically for design, the results of this study strongly suggest that significant benefits can be realized by using 3-D modeling to design and produce production documents for onsite residential framing. It is believed that this technology should be developed and used for other systems in all sectors of construction.

Continuous improvement and simplification.

Continuous improvement and simplification are principles that cross most, if not all boundaries in the lean paradigm. Improvements and simplification efforts are to be made in design, in process, in quality and in many other areas of the production system.

The 3-D model and the corresponding NCD make the methods of variability reduction possible. Without a way to analyze and capture improvement and simplification information, the efforts are largely fruitless. A developer may find significant ways to improve and simplify the construction product yet, if these ways cannot be communicated effectively, the result may be an increase in waste.

The case study provides a good example of continuous improvement/simplification efforts having a negative impact on production when using the TCD. As described previously, the home frame and foundations were somewhat unique. The uniqueness of these systems was the result of an attempt to simplify the system and improve the construction process by eliminating material and steps. However, because of the inability of the TCD to communicate the information correctly, evidence showed an increase in waste. Researcher observation, along with some of the comments made by participants, indicated the unique design resulted in a number of errors made during the quasi experiment. Researcher observations during the case study indicated the same.

The quasi-experiment showed an extreme difference in error scores when walls were compared by document type. These stark differences indicate that the information, including information related to the simplification/improvement efforts, was able to be communicated through the NCD produced from the 3-D model. Continuous improvement and simplification efforts are enabled by the use of a 3-D model as a communication tool to identify and document the changes. Documentation produced from the 3-D model (NCD) is effective in communicating this information to framers.

Time, Quality, Experience, and a Skilled Labor Shortage

Several items merit discussion related to build time, build quality (including accuracy), crew experience, and how these items relate to the skilled labor shortage. Most of the discussion in this section is related to the findings of the quasi-experiment. Several observations made during the experiment will be discussed as they qualify some of the findings. Additionally, findings will be discussed for their implications for practice. These discussions will follow a quick recap of the quasi-experiment findings.

Overall crews were able to build walls in less time and more accurately when using the NCD. Walls built by the more experienced crew were built quicker and were more accurate then the walls built by the less experienced crew when using the TCD. Total construction time was very similar for both crews, yet the more experienced crew had a much lower combined score of construction time and error score. A comparison of the crews when using the NCD shows little difference in build time plus error score. The only difference when using the NCD is the subjective quality measure which shows experience increases quality (not including accuracy).

Figure 7 chapter 4 shows the more experienced crew realized a significant reduction in time when using the NCD for the first measure. Observations of the quasi-experiment indicate this large time reduction was in part due to this crew finding and fixing errors during the build. One wall was built three times to fix significant errors found during the build. These errors were a result of the more experienced crew beginning construction before understanding how the walls were to be built. After construction had begun, the crew foreman continued to study the plans and found the items that needed to be changed. This extra time building the wall multiple times almost certainly reduced the error score for this wall and thus, the wall group.

The less experienced crew spent very little time changing walls due to error detection when using the traditional construction documents. Even though a significant amount of time was spent looking over the documents, the less experienced crew was less capable of identifying the correct way to build the walls. Once wall construction began, the documents were not checked to verify accuracy. To recap, the extra time spent rebuilding the walls when using the TCD for the more experienced crew correlated to a lower error score. For the less experienced crew, build time was slightly less for the first measure but the error score was significantly higher.

Figure 10 chapter 4, and table 14 chapter 4, show a significant finding. When using the NCD, build time plus error scores (combined score) are very similar for both crews. In fact, the less experienced crew had a slightly lower combined score than the more experienced crew when using the NCD (185 for crew one and 196 for crew two). This finding supports the idea that the NCD enable less experienced or lower skilled workers to produce walls of the same accuracy, and in the same amount of time as a more experienced crew. Additionally, the less experienced crew using the NCD was able to frame walls faster and with more accuracy than a more experienced crew when using the TCD (combined scores of 185 and 356 respectively). With the predicted skilled labor shortage in the construction industry, the preceding findings have significant implications for residential construction as well as other sectors of the industry. The findings support the notion that 3-D technology and medium for communicating construction/production information (NCD) could allow a less skilled labor force to construct home frames quicker and with more accuracy than a more skilled labor force using the TCD.

One factor not impacted by document type is the subjective measure of quality. As shown in table 13 chapter 4, and figure 9 chapter 4, the more experienced crew consistently had higher quality scores. This factor was measured by quality of cuts, quality of connections, and quality of overall appearance. Experience in this case did make a difference. However, this was really a measure of quality of assembly. The skills required for this factor are the skills of cutting, connecting (including nailing), and overall appearance which included framing component alignment. These skills are very different than the skills needed for framing accurately when using the TCD which include, the ability to find and interpret the information in the TCD; and the skill of being able to fill in the gaps with prior framing knowledge when using the TCD. The skills required for accuracy when using the TCD require significant experience. In conclusion, the skills required for accuracy are not a factor when using the NCD. The skills required for assembly can be taught relatively quickly thus, difference in quality by crew experience could be reduced with minimal training.

Limitations of the Findings

The findings of this study provide strong evidence that indicate the use of the NCD derived from a 3-D model of home frames provide significant benefit by minimizing waste through increased accuracy and quicker building times. However, caution should be exercised when making generalizations to the residential framing population. This section identifies some of the reasons cautionary measures should be taken when considering the findings of this study.

The findings cannot be statistically generalized to the target population for several reasons. The reasons include: method of sample selection (purposeful, convenience sample), small sample size, (two crews of 3participants each), and heterogeneity of sample to the population (current students, mostly former framers, had never worked together before). In spite of this inability to statistically generalize to the population, this study provides strong evidence that utilizing parametric 3-D technology at the component level can provide significant benefit. The study also provides a foundation upon which further research can be conducted.

As specified in the methodology, and by design, the quasi-experiment participants had not seen either the NCD or the TCD prior to the first measure. It could be argued that a framing foreman would have time to "get to know the drawings" before the build which would have increased the accuracy of the walls when using the TCD. In response to this argument, this time to "get to know the drawings" could have been spent once the documents were given (at the beginning of the experiment). However, any time spent prior to the build studying the drawings is considered waste if it is not necessary when using a new set of construction documents. Additionally, the day of the first experiment was the first time any participant had seen a full set of NCD. Some of the students had been shown single pages of the NCD during researcher presentations; and they had all been shown an example of the NCD during the brief training prior to the experiment. The example used for training was a ranch style (single story) home and the homes used for the experiment were two story homes. Additionally, none of the participants had built from the new construction documents.

It could also be argued that much time was spent in completing the 3-D model thus requiring significant preconstruction cost to produce the NCD. This is true, however, it is important to realize these documents are, as the name implies, new to construction and cost of documents was not a factor for the study. It is anticipated the technology will be developed which will allow the 3-D to be the design tool used for communication, collaboration, and documentation eliminating the need to produce the TCD. In manufacturing, it has been found that time and money spent in planning can produce significant dividends. It is believed that the same can be true for construction.

The case study was conducted at the beginning of the project starting with the prototypes. This had both positive and negative implications. Due to the project timing, researchers were able to observe the waste associated with project startup. Researchers were also able to observe the final stages of the design process. However, the findings might have been different, had the study been conducted half way through, or at the end of the project.

Another limitation is the lack of interaction with the other systems in the home. Participating crews built three independent walls which were not connected to the foundation or slab on grade, and did not interface with the floor truss or other systems. Had the walls interacted with other systems during the first measure, the error scores may have been reduced for the second measure. The list of errors provided to the framers prior to the second measure was an attempt to see if the framers could identify the errors using the construction documents. Providing this list did not seem to help as the error scores were slightly higher for the second measure using the TCD. In light of this limitation, it is interesting to note that the crews were not negatively impacted by the inability to interact with the other systems when using the NCD. The interactions had been worked out virtually prior to the physical build and the walls were built correctly in spite of the lack of interactions with other systems. If walls are built as shown on the NCD, all other walls and systems will work with the walls.

As stated in the methodology, the data collection including subjective quality evaluations and error scores were completed by the researchers. This part of the methodology increases the possibility of researcher bias. Researchers recognized this possible weakness in the study and made a conscious effort to make fair evaluations. The effort to be fair likely caused researchers to render evaluations in favor of the TCD. The differences in the error score were so significant that any bias in either direction would have caused little difference in the findings.

Recommendations for Further Research

During the course of the study, several ideas have surfaced for additional research projects. Some have been alluded to in the previous sections and chapters and others will be discussed in this section for the first time. The strength of the findings, as well as the potential implications for practice, justify additional research.

Homogeneity of Sample to the Population

A logical next step would be to conduct an experiment using actual framing crews. The study could be conducted in a controlled environment or in the field using actual projects. An important methodological aspect of this project would be to only provide one document type at a time. When the NCD was pilot tested, crews used both document types. As with any change, the crews had a hard time trusting the new documents, and spent extra time verifying the accuracy of the NCD by looking at the TCD.

Diffusion Study

A change of this nature and degree is difficult to implement. The challenge is likely magnified by the nature of the population into which the technology is to be diffused. The construction industry as a whole has been criticized for its unwillingness to change, especially when it comes to technology. A study investigating the best way to implement or "sell" this technology to the industry would be important if the benefits are to be realized. The importance of a diffusion study is related to the potential benefits of the study which are far-reaching as described previously.

Framing Processes Compared: Differences between TCD and NCD

During the quasi-experiment, it was observed that differences in framing processes existed. Identifying the differences in process as well as time spent in each different process would provide additional insight. Such items as time spent looking at the documents, time spent standing around, and differences in the way the crew performs the tasks could be observed. As part of this future study, items related to specific areas of confusion when looking at the plans could be investigated.

New Construction Document Improvements

As part of the case study, iterations of the NCD were tested for usability and changes were made according to the feedback and observations. Additional improvements could be made to the NCD to advance their effectiveness in communicating pertinent information. Different mediums could be tested including an interactive 3-D computer model on a laptop.

Quasi-experiment with Non-framers

This research has shown that the NCD are more effective than the TCD in communicating the production/construction information to former framers. Additionally, it was found that when using the NCD the less experienced crew was able to perform as well as the more experienced crew on all factors except the subjective quality measure. A follow-up study could include a crew of participants with no framing experience. It would not be necessary to include the TCD as the benefit has already been shown. This study should include training on the use of tools and skills necessary for proper assembly.

This research provides a foundation upon which the previously described future projects may be founded. The significance of the findings and their implications for practice provide a strong argument for continuing this line of research. It is anticipated that the technology described in this project as well as the theoretical concepts will eventually make their way into the construction industry. However, the diffusion process is anticipated to be difficult.

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APPENDIX

Appendix A

Dear construction management Student,

My name is Brad Johnson from the Colorado State University, department of Construction Management and I am writing to invite you to participate in my graduate research study. This research investigates the use of virtual construction for residential projects. You are receiving this invitation to participate because you are enrolled in the CM program at CSU. We are looking for candidates who meet the following qualifications to participate in the study:

1. Are currently enrolled in or have completed MC 151 (Construction Materials and Methods)
2. Have at least 6 months of residential framing experience (wood frame)
3. Can read a framing layout
4. Are comfortable using tools used for framing (circular saw, reciprocating saw, miter saw, pneumatic nail gun, and other hand tools)

If you decide to participate in this study, you will be asked to take part in two sessions each lasting from 2 to 4 hours. The sessions will be approximately three weeks apart and will be completed before the end of the spring semester 2007. For your participation you will receive a $20 gift certificate to a local restaurant at the conclusion of each session (a total of $40 if you participate in both sessions). The framing portion of each session will be audio/video recorded. These recordings will be used to enable the researchers to more accurately document the observed data. Remember, this is completely voluntary. You can choose to be in the study or not. If you'd like to participate please respond to this email stating such. If you have any questions about the study, please email or contact the researchers using the information below:

Brad Johnson
Office: (970) 491-7960
bradlyt@colostate.edu

James Folkestad
Office (970) 491-7823
Folkestad@CAHS.Colostate.edu

Thank you very much.
Sincerly,
Brad Johnson

Appendix B

Qualifications Survey

Volunteer Name______________________

1. Are you currently enrolled in or have you completed MC 151 Construction Materials and Methods? Yes No (circle one)

2. Are you comfortable using framing tools (circular saw, reciprocating saw, miter saw, pneumatic nail gun, and other hand tools)? Yes No (circle one)

3. How many years/months of residential wood framing experience do you have? Years_____Months_____

4. During your time as a framer did you have responsibility for plate layout? Yes No (circle one)

5. If you answered yes to question #4, how many years/months were you responsible for plate layout? Years_____Months_____

6. Please define or explain the following markings utilized in framing layout

   a. X or K____

   b. C ____

   c. T or O ____

7. What is the actual size of a 2x4? ________________________________

8. What is the actual size of a 2x10?________________________________

9. Have you ever successfully completed the layout for a stair stringer? Yes No (circle one)

10. A plumb cut on a roof rafter is:
    a. Perpendicular to the rafter on a pitch roof
    b. Parallel to the rafter on a pitch roof
    c. Perpendicular to the exterior wall sheathing
    d. Parallel to the exterior wall sheething

11. Are you available during the normal work day (8am to 5pm) until the end of the fall 2007 semester to participate in the study. Yes No (circle one)

12. If yes to answer 11, is am or pm more convenient? am pm either (circle one)

Colorado State University

Notice of Approval for Human Research

Office of Regulatory Compliance
Office of Vice President for Research
Fort Collins, CO 80523-2011
(970) 491-1553
FAX: (970) 491-2293

Principal Investigator: James Folkestad, Construction Management, 1584
Co-Principal Investigator: Brad Johnson, Construction Management, 1584
Title: Exploring the Use of Virtual Construction to Capture Knowledge and Identify Variability and Waste for Residential Projects
Protocol #: 07-069H **Funding Source:** N/A
Number of Participants/Records: 8 student participants
Committee Action: **Approval Date:** April 4, 2007 **Expires:** March 29, 2008
HRC Administrator: Janell Meldrem

Consent Process:
The above-referenced project was approved by the Human Research Committee with the condition that safety training is provided and the attached consent form is signed by the subjects and each subject is given a copy of the form. *NO changes may be made to this document without first obtaining the approval of the Committee.*

Investigator Responsibilities:

- It is the PI's responsibility to obtain this consent form from all subjects.
- It is the responsibility of the PI to immediately inform the Committee of any serious complications, unexpected risks, or injuries resulting from this research.
- It is also the PI's responsibility to notify the Committee of any changes in experimental design, participant population, consent procedures or documents. This can be done with a memo describing the changes and submitting any altered documents.
- Students serving as Co-Principal Investigators must obtain PI approval for any changes prior to submitting the proposed changes to the HRC for review and approval.
- The PI is ultimately responsible for the conduct of the project.
- A status report of this project will be required within a 12-month period from the date of review. Renewal is the PI's responsibility, but as a courtesy, a reminder will be sent approximately two months before the protocol expires. The PI will be asked to report on the numbers of subjects who have participated this year and project-to-date, problems encountered, and provide a verifying copy of the consent form or cover letter used. The necessary continuation form (H-101) is available from the RCO web page www.research.colostate.edu/rcoweb/.
- Upon completion of the project, an H-101 should be submitted as a close-out report.
- If approval did not accompany a proposal when it was submitted to a sponsor, it is the PI's responsibility to provide the sponsor with the approval notice.
- **Should the protocol not be renewed before expiration, all activities must cease until the protocol has been re-reviewed.**

This approval is issued under Colorado State University's OHRP Federal Wide Assurance 00000647.

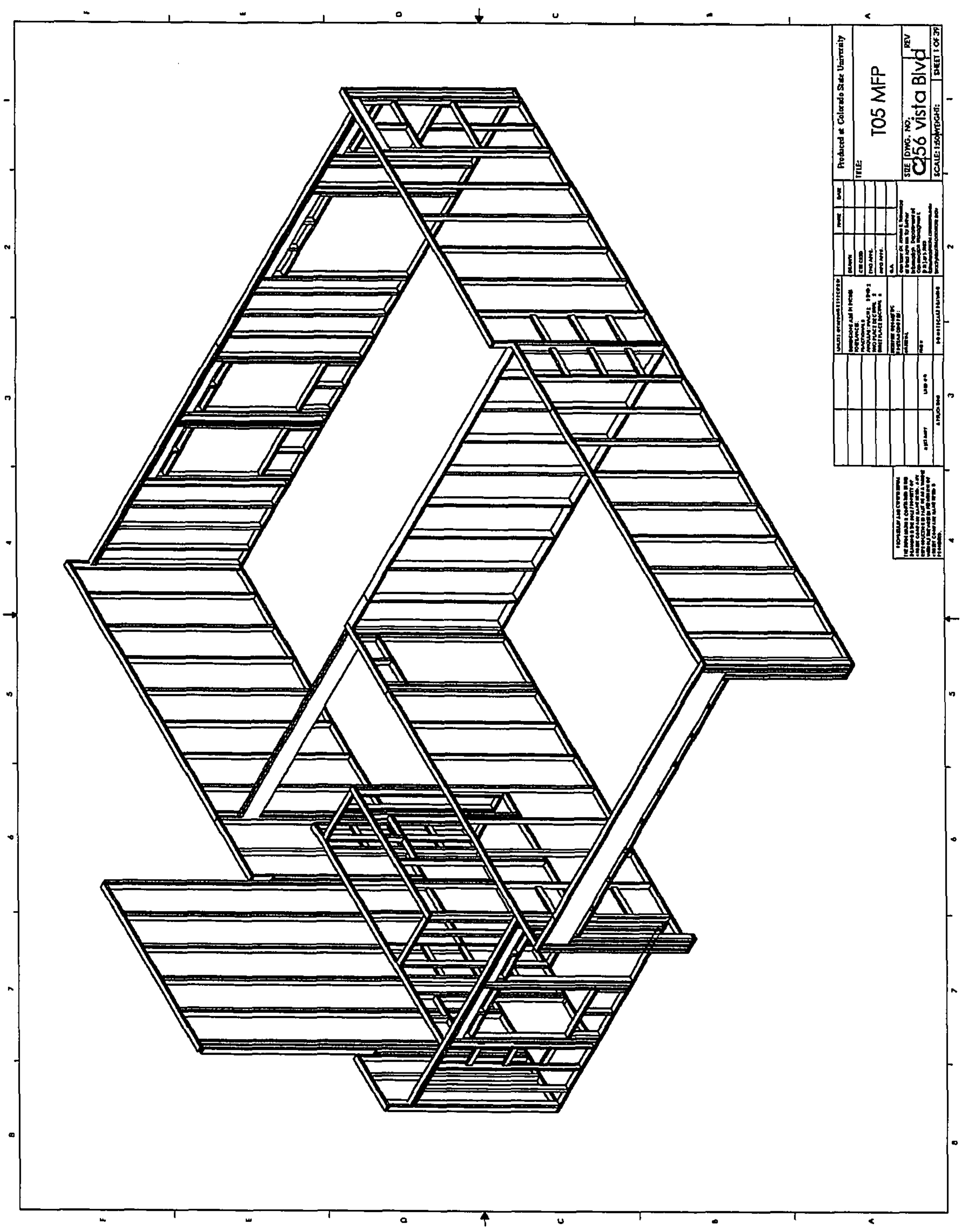
Please direct any questions about the Committee's action on this project to me for routing to the Committee.

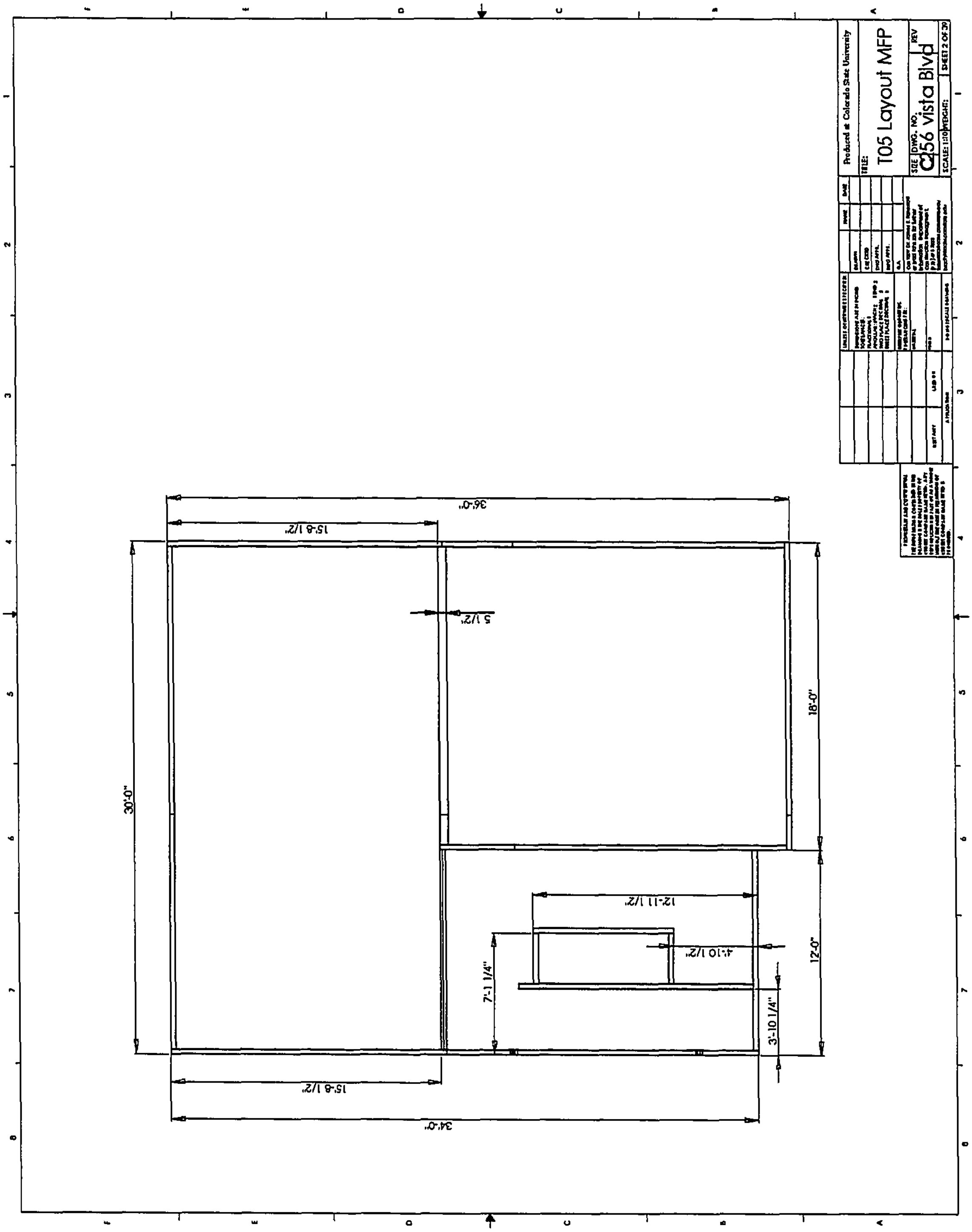
Attachment Date of Correspondence: April 11, 2007

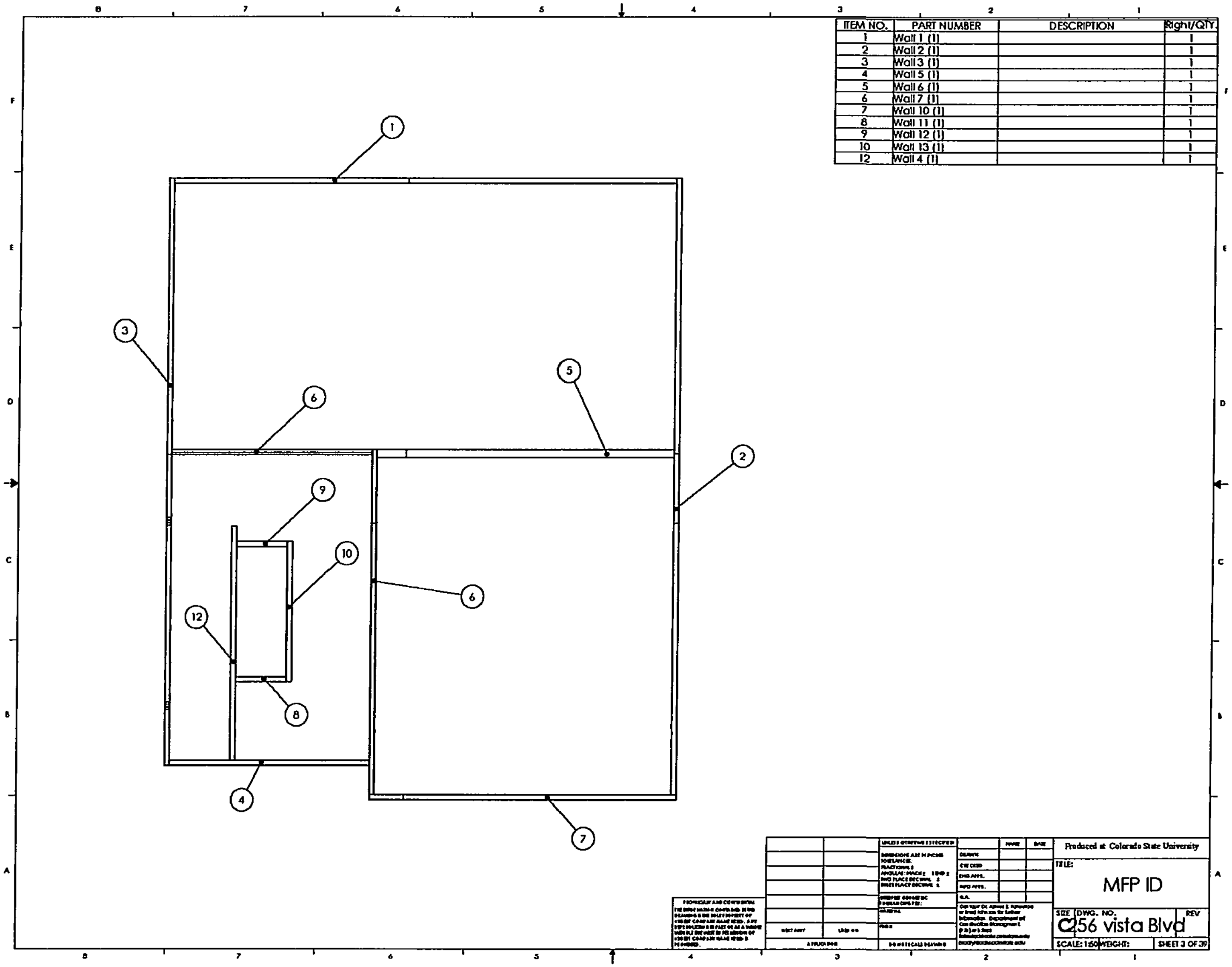
Animal Care and Use · Drug Review · Human Research · Institutional Biosafety
321 General Services Building · www.research.colostate.edu/rcoweb/

Appendix D

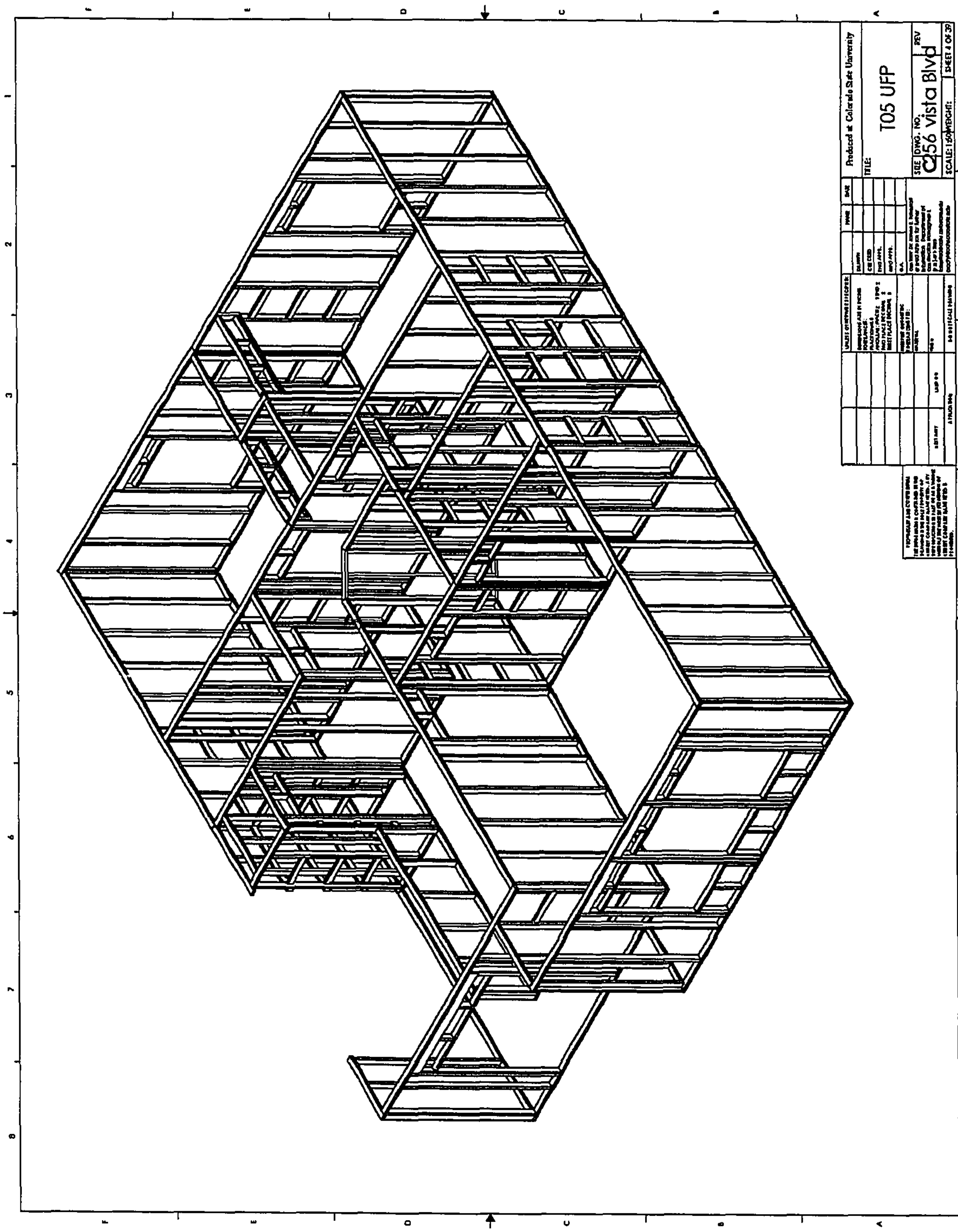
New Construction Documents

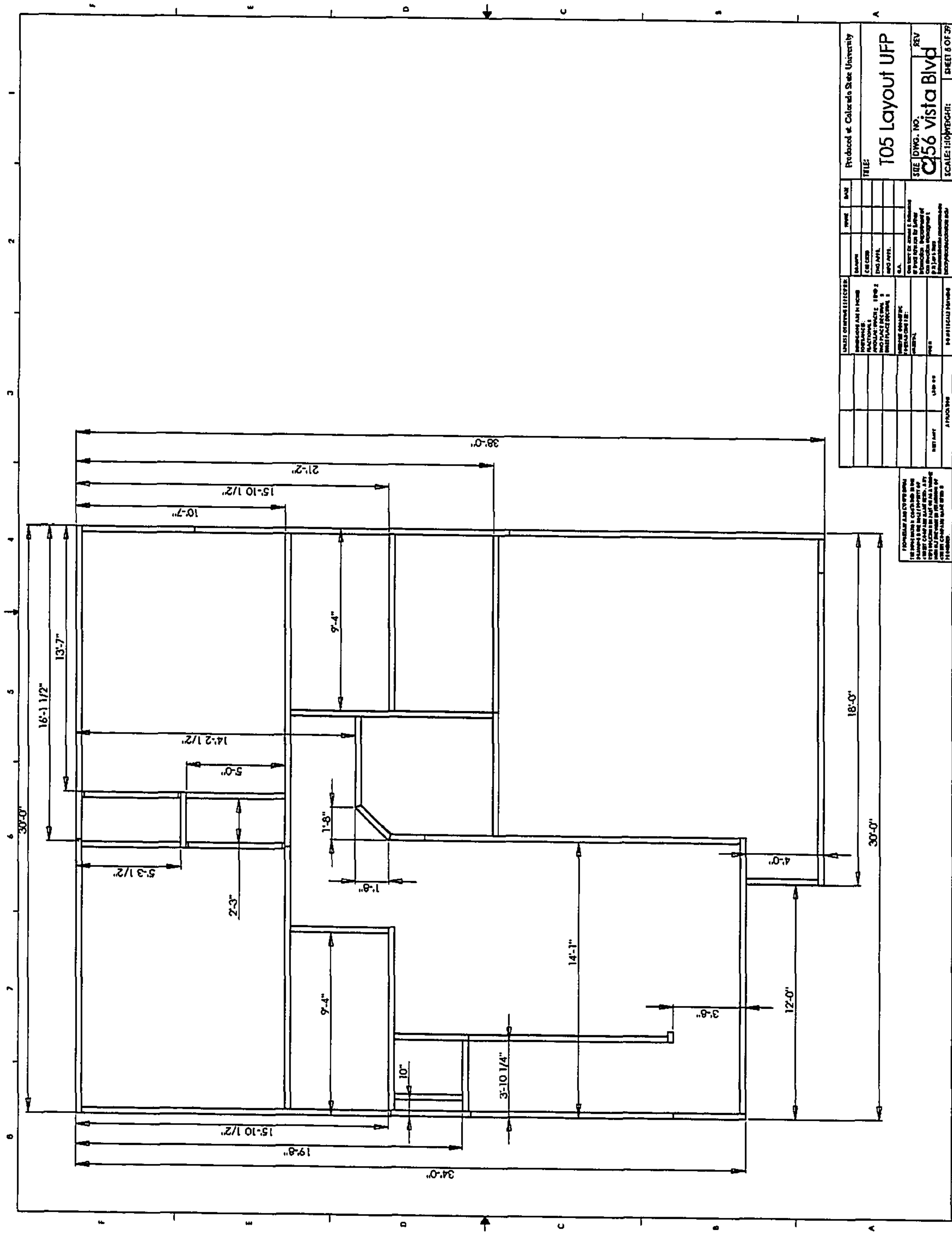

Produced at Colorado State University
T05 MFP
C356 vista Blvd

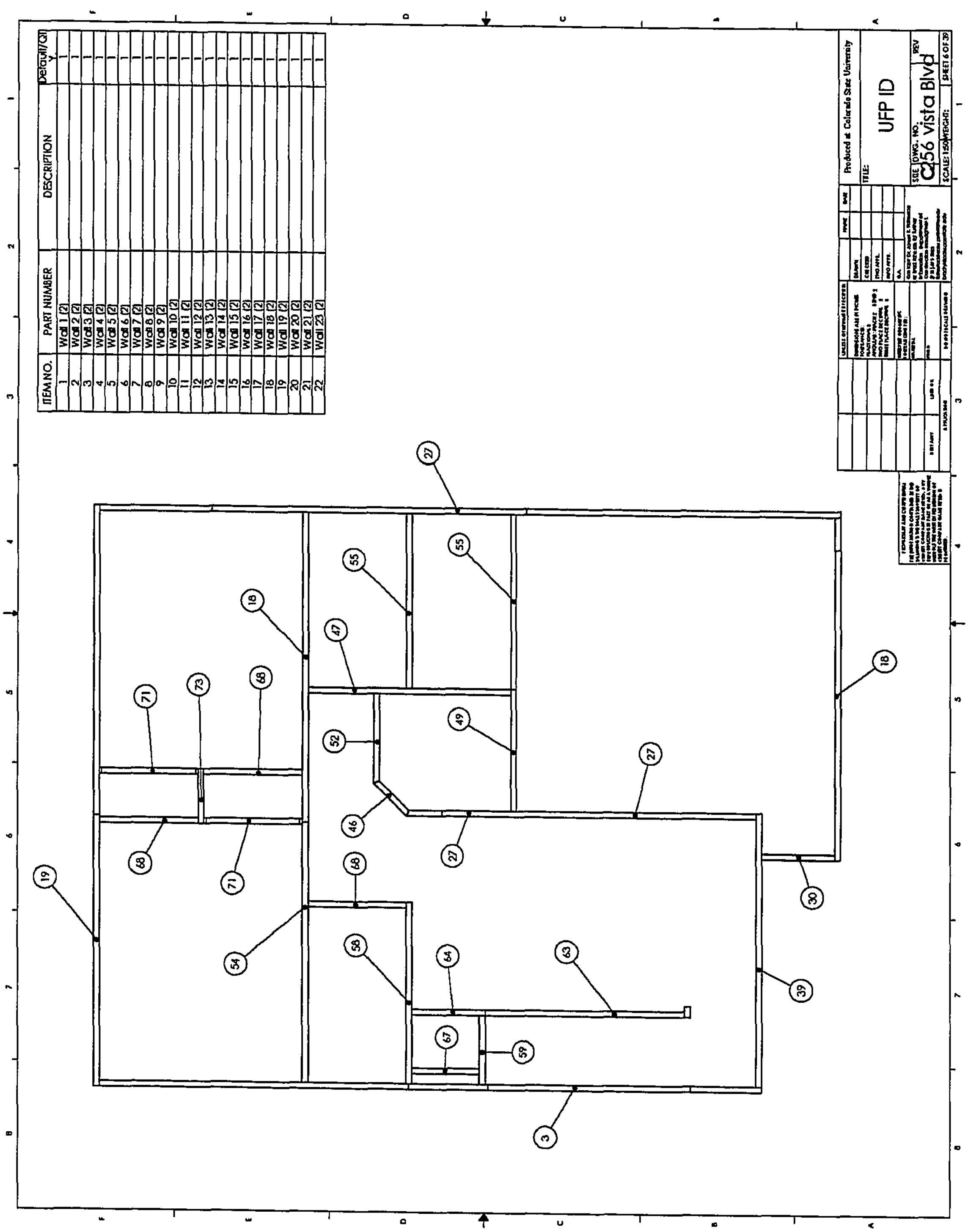

Produced at Colorado State University
TITLE:
T05 Layout MFP
SIZE DWG. NO.
C 256 vista Blvd
REV
SCALE: 1:10 WEIGHT:
36'-0"
15'-8 1/2"
5 1/2"
18'-0"
30'-0"
12'-11 1/2"
4'-10 1/2"
12'-0"
7'-1 1/4"
3'-10 1/4"
15'-8 1/2"
34'-0"



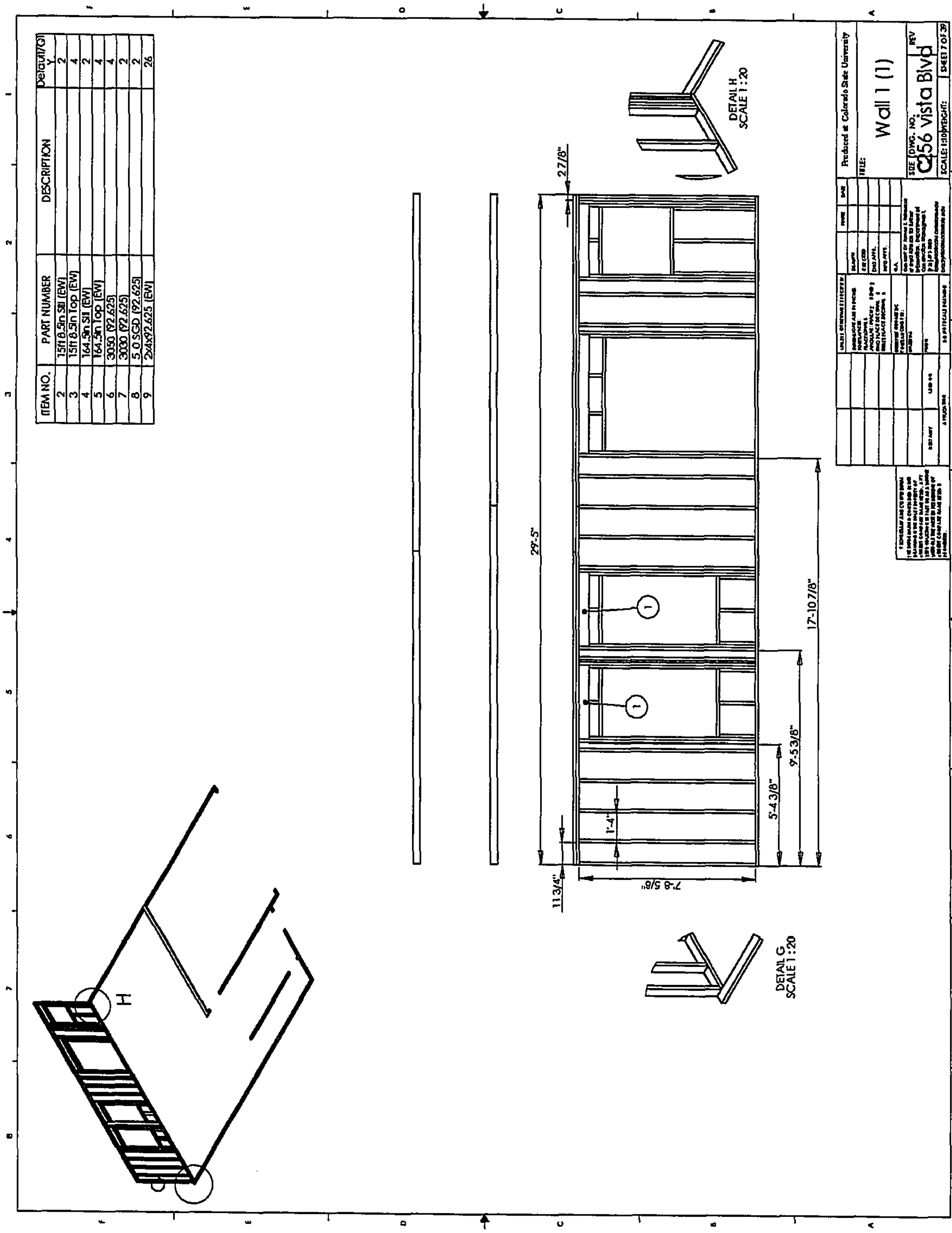
ITEM NO.	PART NUMBER	DESCRIPTION	Right/QTY.
1	Wall 1 (1)		1
2	Wall 2 (1)		1
3	Wall 3 (1)		1
4	Wall 5 (1)		1
5	Wall 6 (1)		1
6	Wall 7 (1)		1
7	Wall 10 (1)		1
8	Wall 11 (1)		1
9	Wall 12 (1)		1
10	Wall 13 (1)		1
12	Wall 4 (1)		1


Produced at Colorado State University
T05 UFP

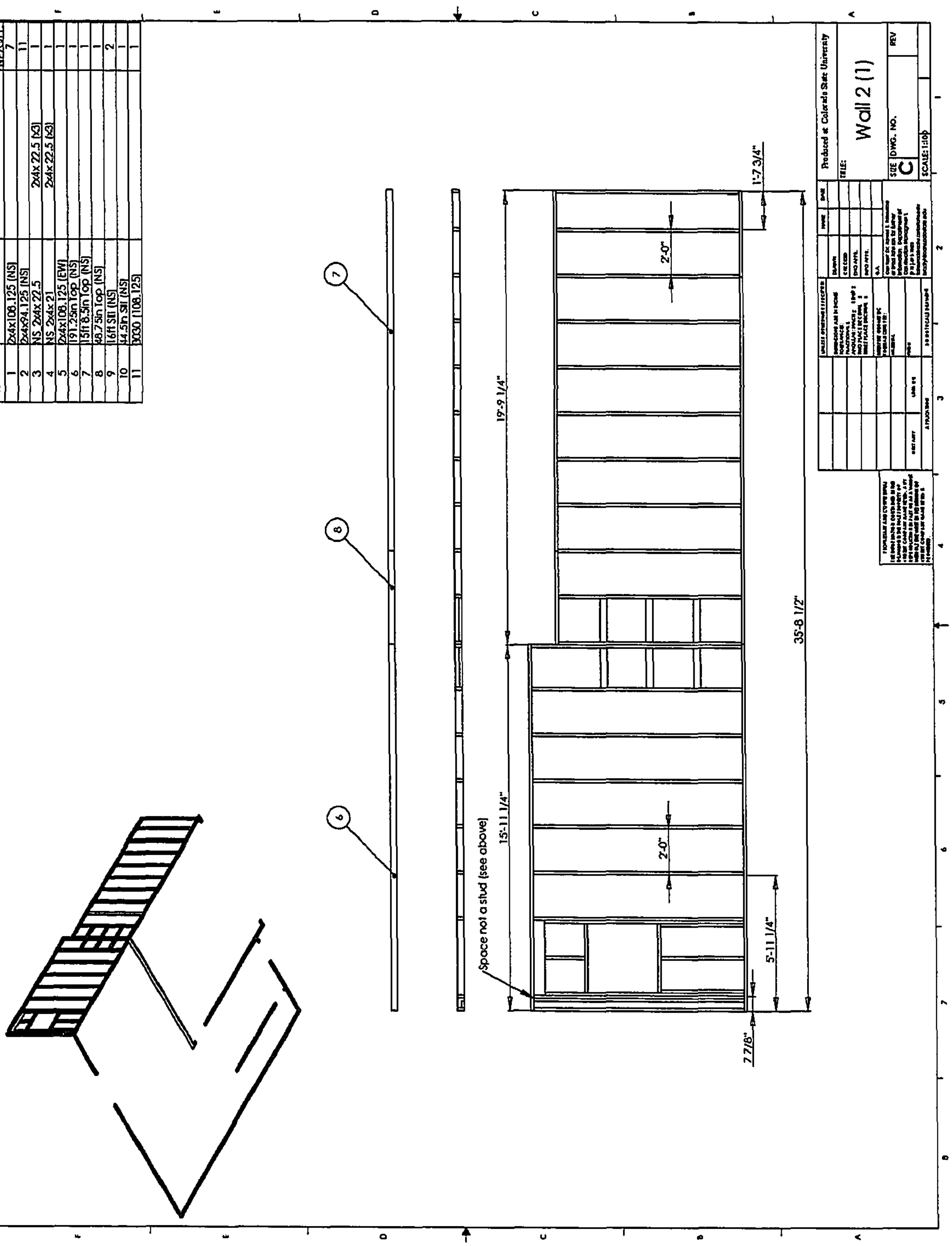

Produced at Colorado State University
T05 Layout UFP
G56 Vista Blvd



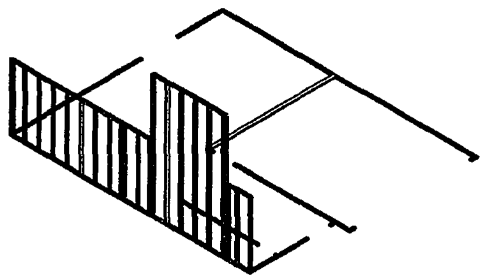
ITEM NO.	PART NUMBER	DESCRIPTION	Default/QTY.
1	Wall 1 (2)		1
2	Wall 2 (2)		1
3	Wall 3 (2)		1
4	Wall 4 (2)		1
5	Wall 5 (2)		1
6	Wall 6 (2)		1
7	Wall 7 (2)		1
8	Wall 8 (2)		1
9	Wall 9 (2)		1
10	Wall 10 (2)		1
11	Wall 11 (2)		1
12	Wall 12 (2)		1
13	Wall 13 (2)		1
14	Wall 14 (2)		1
15	Wall 15 (2)		1
16	Wall 16 (2)		1
17	Wall 17 (2)		1
18	Wall 18 (2)		1
19	Wall 19 (2)		1
20	Wall 20 (2)		1
21	Wall 21 (2)		1
22	Wall 23 (2)		1



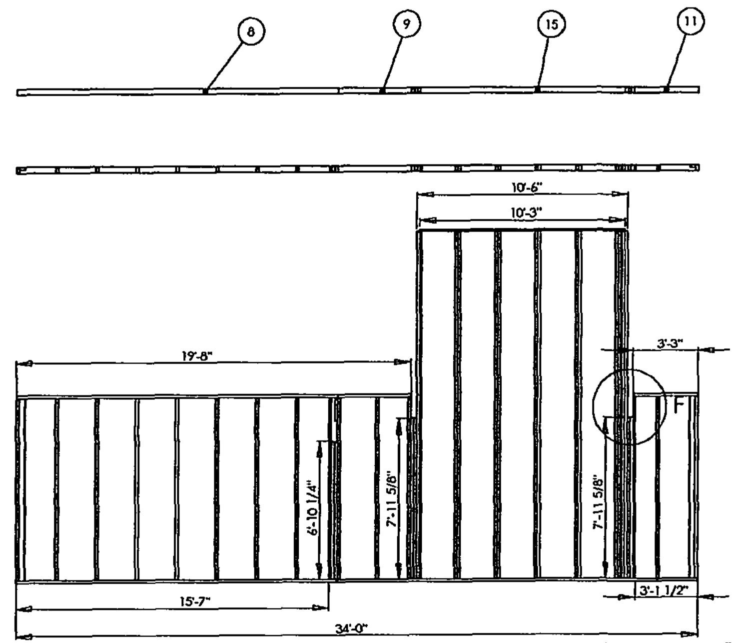
ITEM NO.	PART NUMBER	DESCRIPTION	Default/QTY
2	15ft 8.5in Sill (EW)		2
3	15ft 8.5in Top (EW)		4
4	164.5in Sill (EW)		2
5	164.5in Top (EW)		4
6	3050 (92.625)		4
7	3030 (92.625)		2
8	5_0 SGD (92.625)		2
9	2x4x92.625 (EW)		26

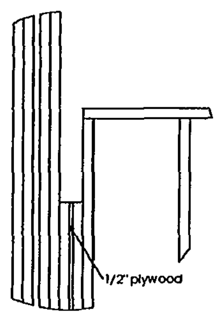


ITEM NO.	PART NUMBER	DESCRIPTION	R NP/QTY.
1	2x4x108.125 (NS)		7
2	2x4x94.125 (NS)		11
3	NS 2x4x22.5	2x4x22.5 (X3)	1
4	NS 2x4x21	2x4x22.5 (X3)	1
5	2x4x108.125 (EW)		1
6	191.25in Top (NS)		1
7	15ft 8.5in Top (NS)		1
8	48.75in Top (NS)		1
9	16ft Sill (NS)		2
10	44.5in Sill (NS)		1
11	3030 (108.125)		1



ITEM NO.	PART NUMBER	DESCRIPTION		Right NP No Door/QTY.
2	2x4x108.125 (NS)		[illegible]	15
3	2x4x108.125 (EW)		4	2
4	2x4x82.25 (NS)		4	2
5	.5x3.5x82.25 (NS)Ply		2	1
6	2x4x 95.625 (NS)		8	4
7	.5x3.5x 95.625 (NS) Ply		4	2
8	16ft Top (NS)		2	1
9	44in Top (NS)		2	1
10	2x4x14 (NS)		2	1
11	39in Top (NS)		2	1
12	16ft Sill (NS)		3	2
13	24in Sill (NS)		2	1
14	Wall 8 (1)		1	1
15	123in Top (NS)		2	1
16	2_8 door ext (108.125)		2	-
17	MirrorWall 8 (1)		1	-





DETAIL F
SCALE 1 : 10

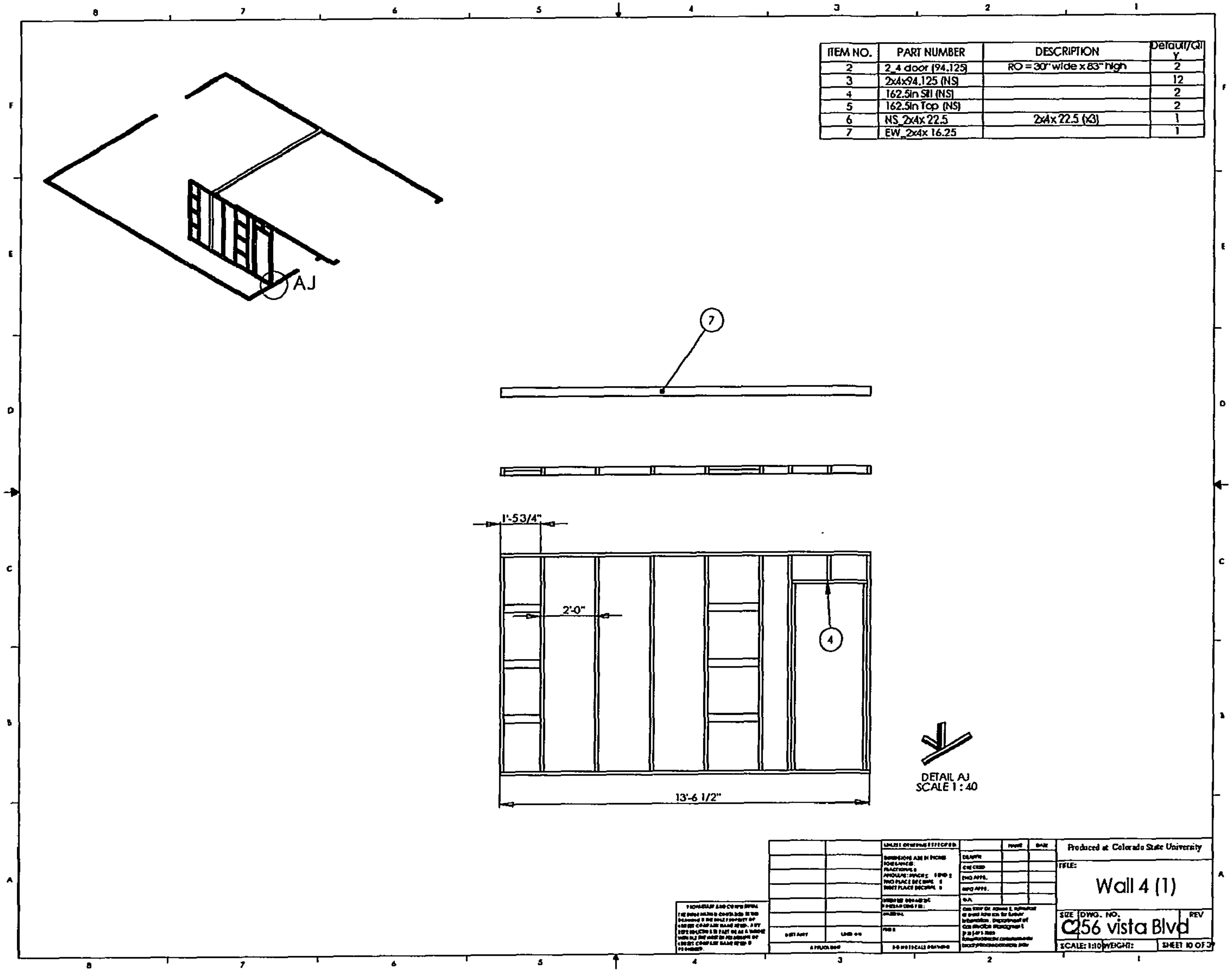
Produced at Colorado State University

TITLE: Wall 3 (1)

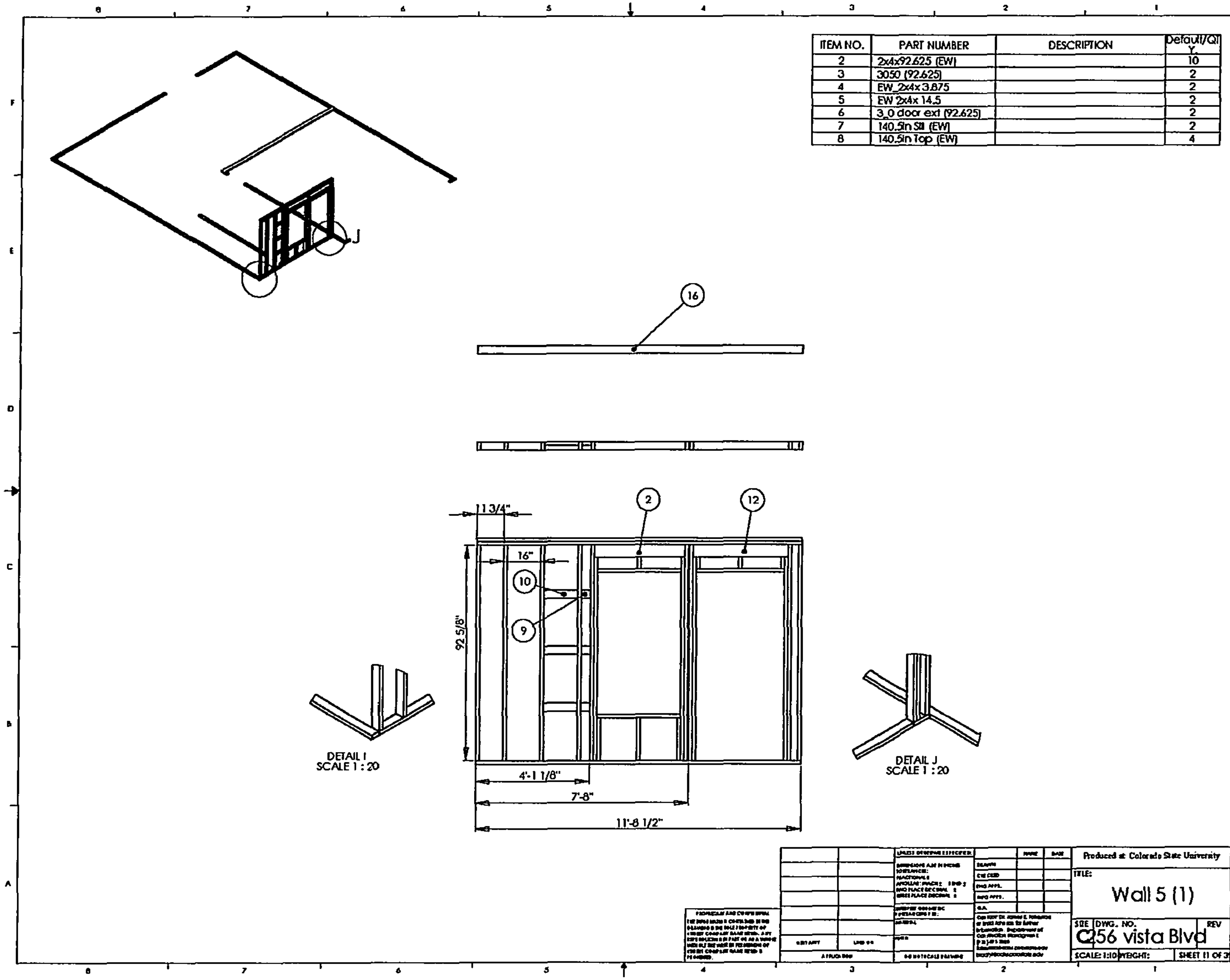
SIZE C | DWG. NO. 256 vista Blvd | REV

SCALE: 1:10 | WEIGHT: | SHEET 9 OF 39

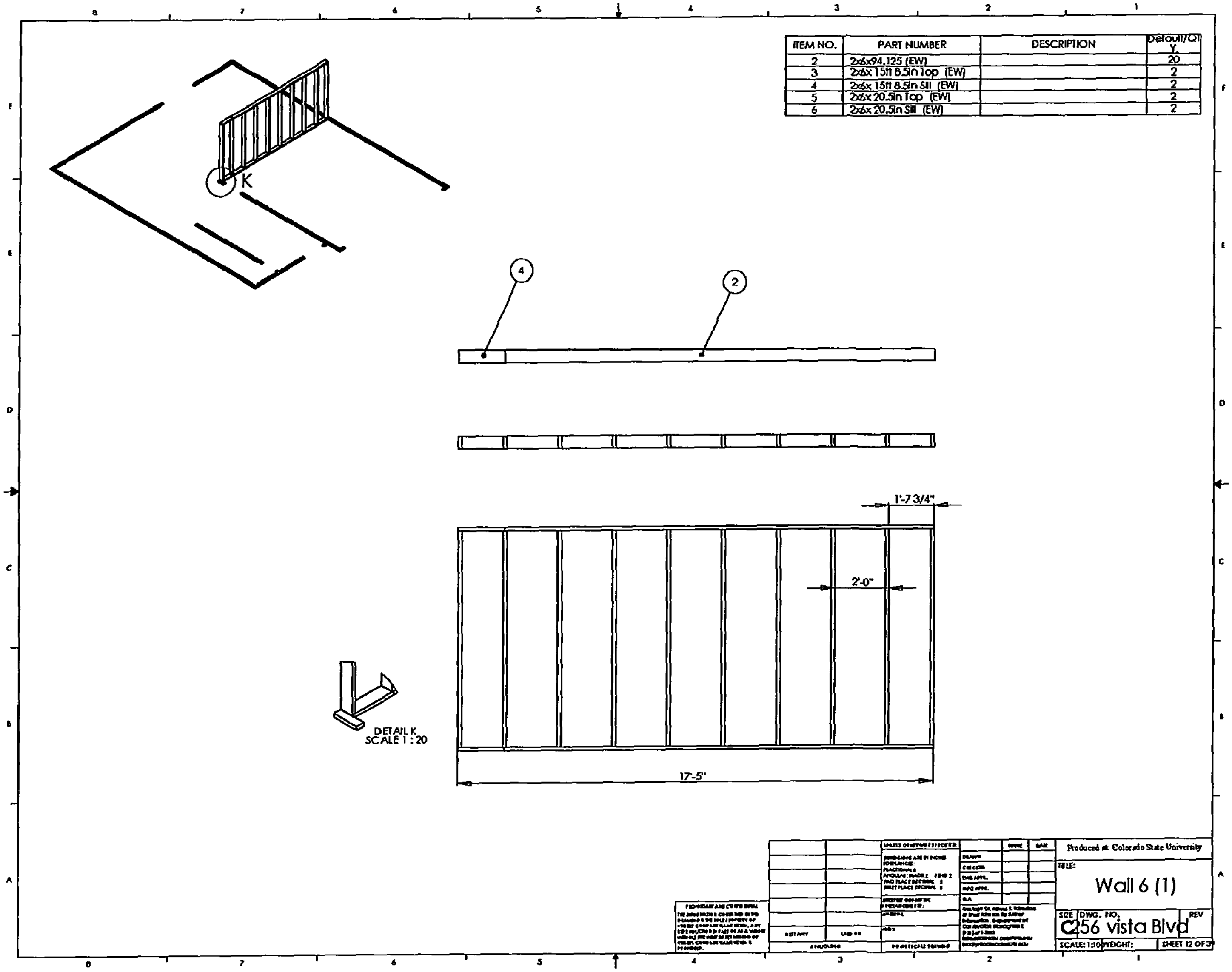
ITEM NO.	PART NUMBER	DESCRIPTION	Default/QTY.
2	2_4 door (94.125)	RO = 30" wide x 83" high	2
3	2x4x94.125 (NS)		12
4	162.5in Sill (NS)		2
5	162.5in Top (NS)		2
6	NS_2x4x 22.5	2x4x 22.5 (x3)	1
7	EW_2x4x 16.25		1

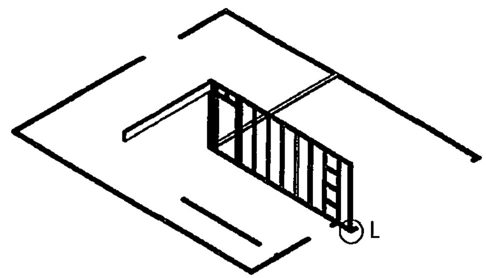


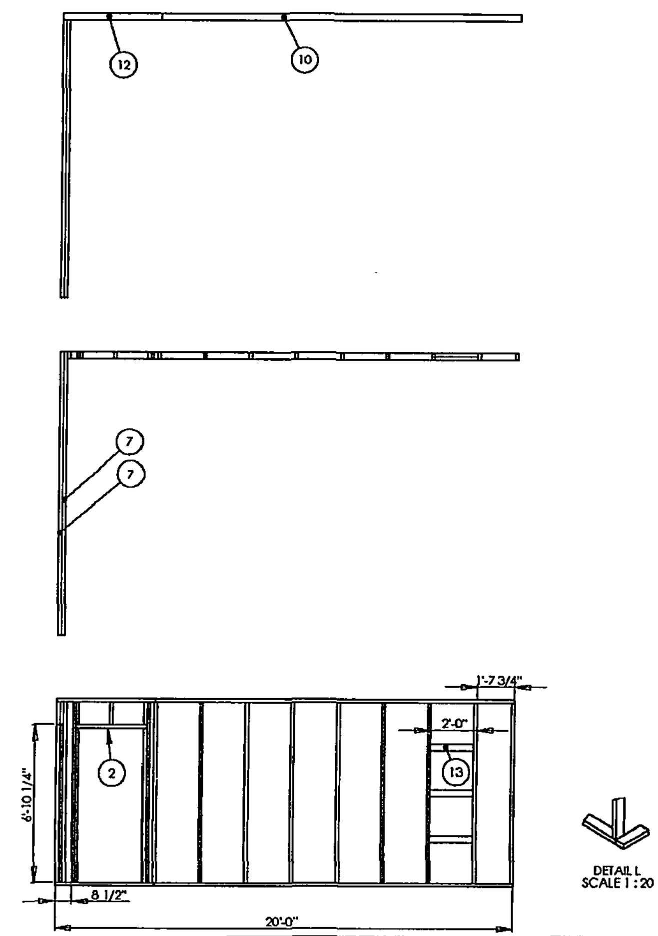
ITEM NO.	PART NUMBER	DESCRIPTION	Default/QTY.
2	2x4x92.625 (EW)		10
3	3050 (92.625)		2
4	EW_2x4x3.875		2
5	EW 2x4x 14.5		2
6	3_0 door ext (92.625)		2
7	140.5in Sill (EW)		2
8	140.5in Top (EW)		4



ITEM NO.	PART NUMBER	DESCRIPTION	Default/QTY.
2	2x6x94.125 (EW)		20
3	2x6x 15ft 8.5in Top (EW)		2
4	2x6x 15ft 8.5in Sill (EW)		2
5	2x6x 20.5in Top (EW)		2
6	2x6x 20.5in Sill (EW)		2







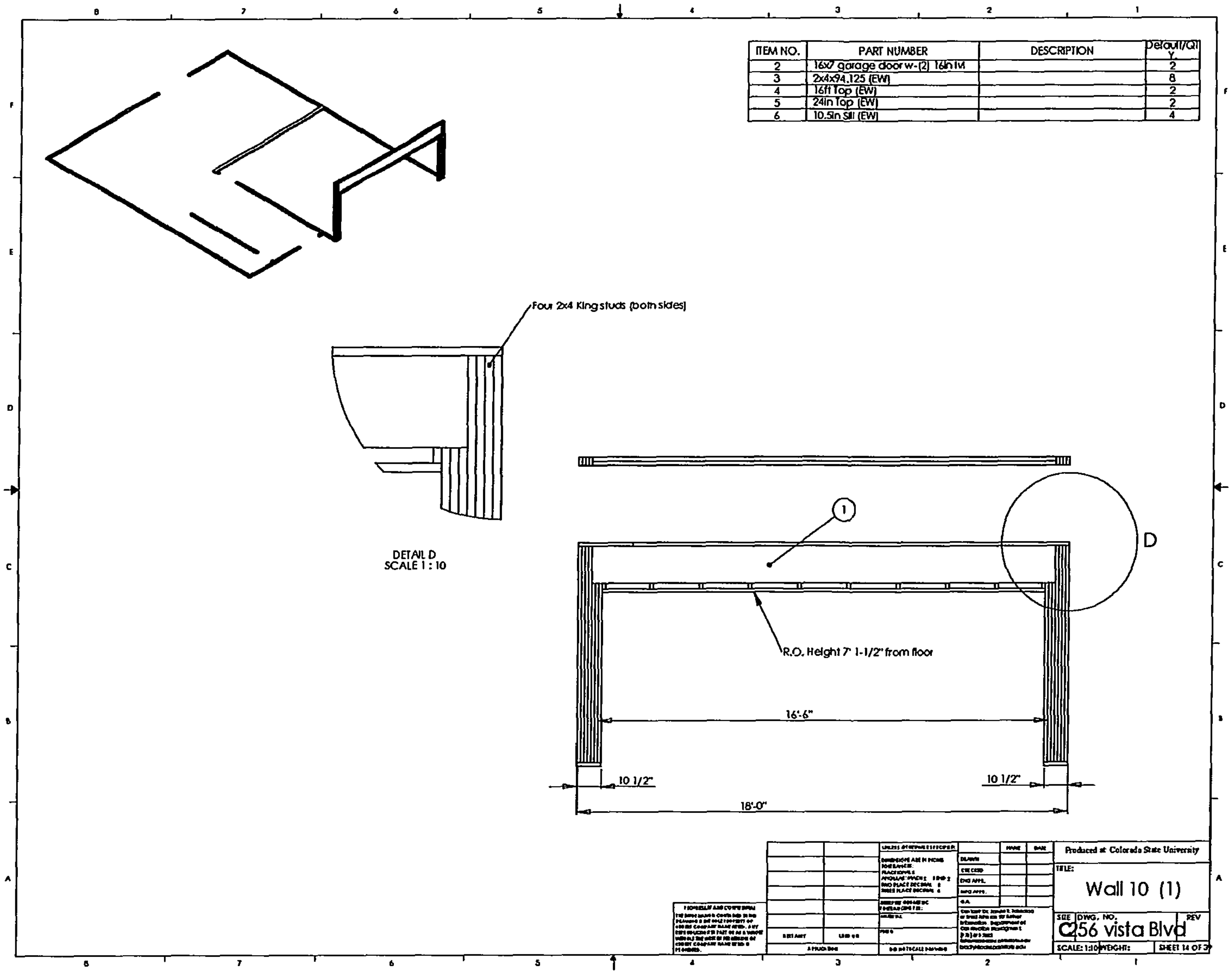
ITEM NO.	PART NUMBER	DESCRIPTION	Default/QTY.
2	2x4x94.125 (NS)		20
3	2_8 door non bearing		2
4	2x4x82.25 (NS)		4
5	11.875x1.75x147.5in lvl		4
6	2x4 x 12.125		2
7	.5x3.5x82.25 (NS)Ply		2
8	15ft 8.5in Sill (NS)		2
9	15ft 8.5in Top (NS)		2
10	51.5in Sill (NS)		2
11	51.5in Top (NS)		2
12	NS_2x4x 22.5	2x4x 22.5 (x3)	2

Produced at Colorado State University

TITLE: Wall 7 (1)

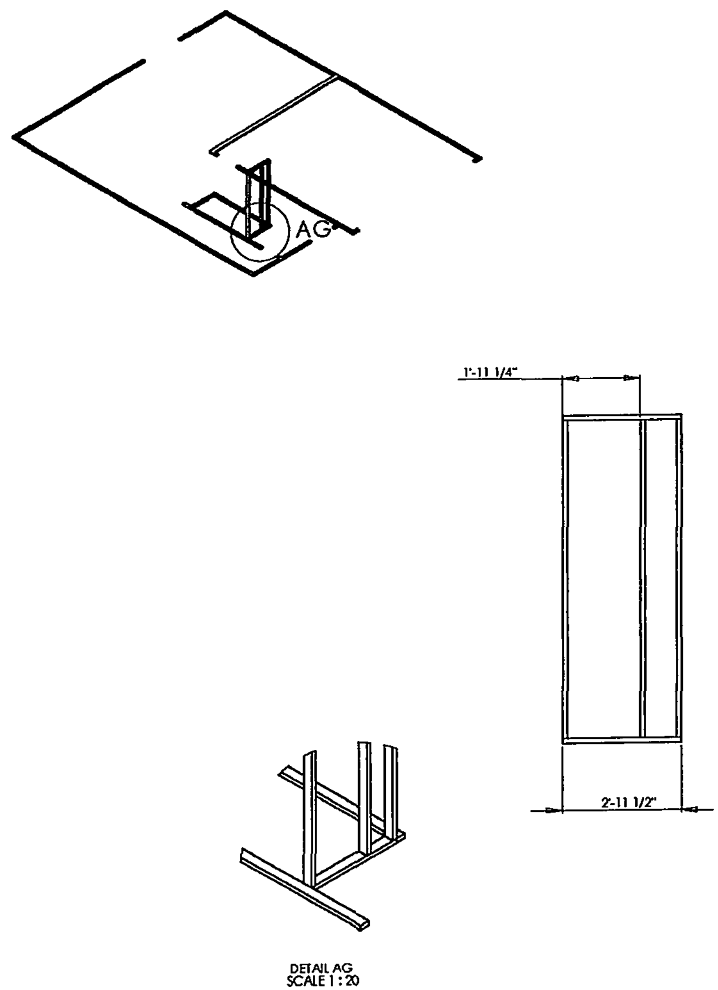
SIZE C | DWG. NO. 256 vista Blvd | REV

SCALE: 1:50 | WEIGHT: | SHEET 13 OF 37



ITEM NO.	PART NUMBER	DESCRIPTION	Default/QTY
2	16x7 garage door w-(2) 16in lvl		2
3	2x4x94.125 (EW)		8
4	16ft Top (EW)		2
5	24in Top (EW)		2
6	10.5in Sill (EW)		4

ITEM NO.	PART NUMBER	DESCRIPTION	Right NP/QTY.
1	35.5 in Sill (EW)		1
2	35.5 in Top (EW)		1
3	2x4x94.125 (EW)		3



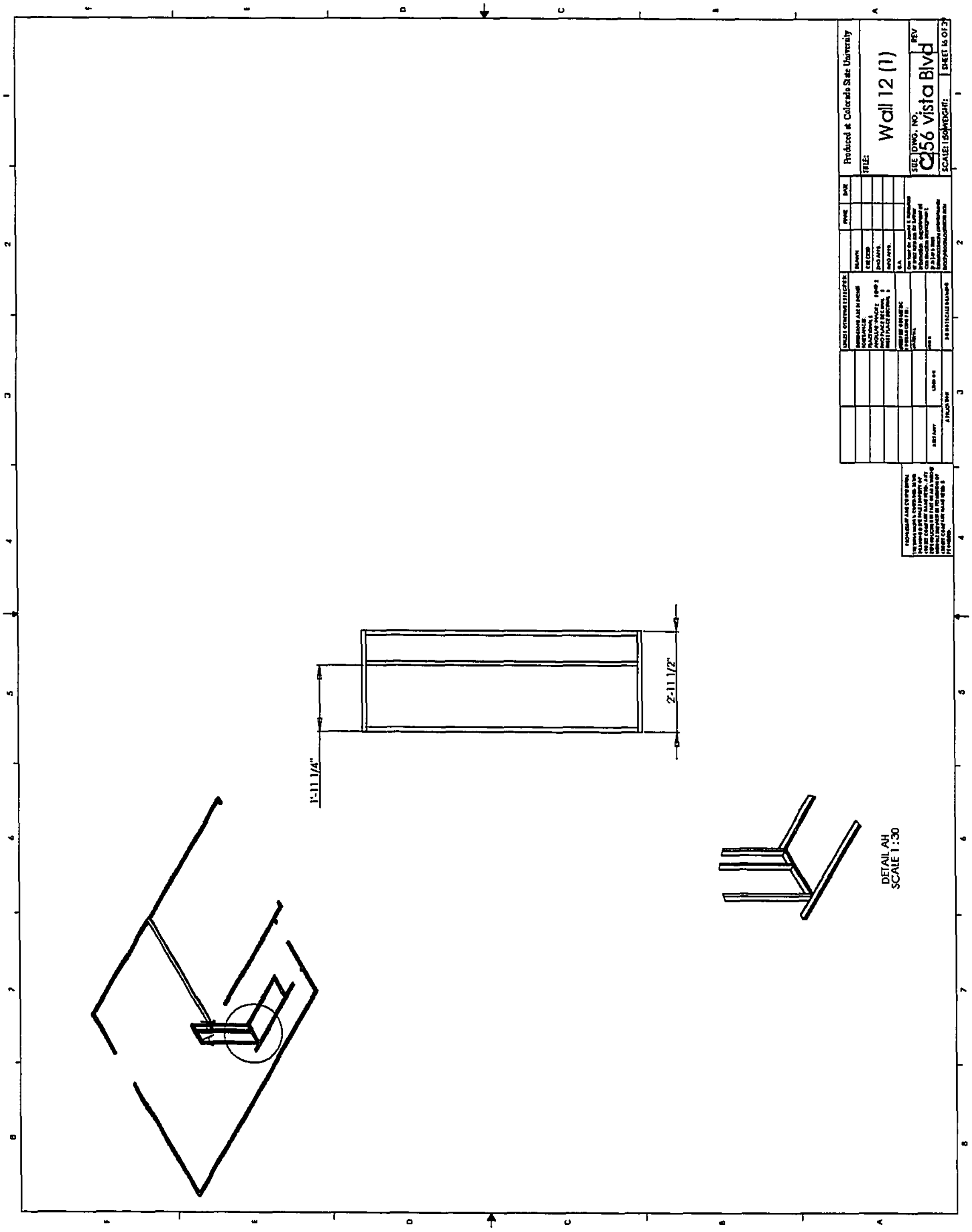
DETAIL AG
SCALE 1 : 20

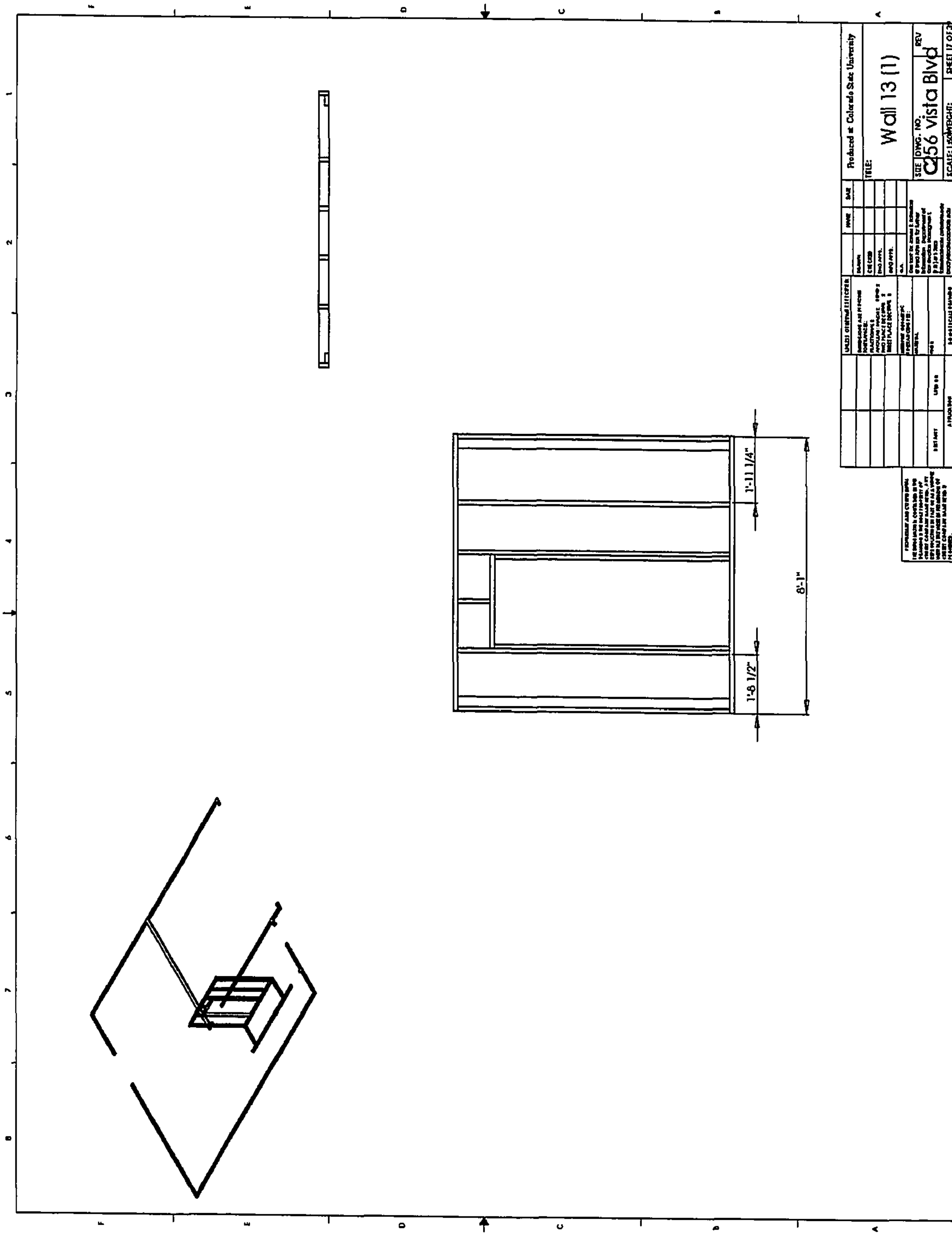
Produced at Colorado State University

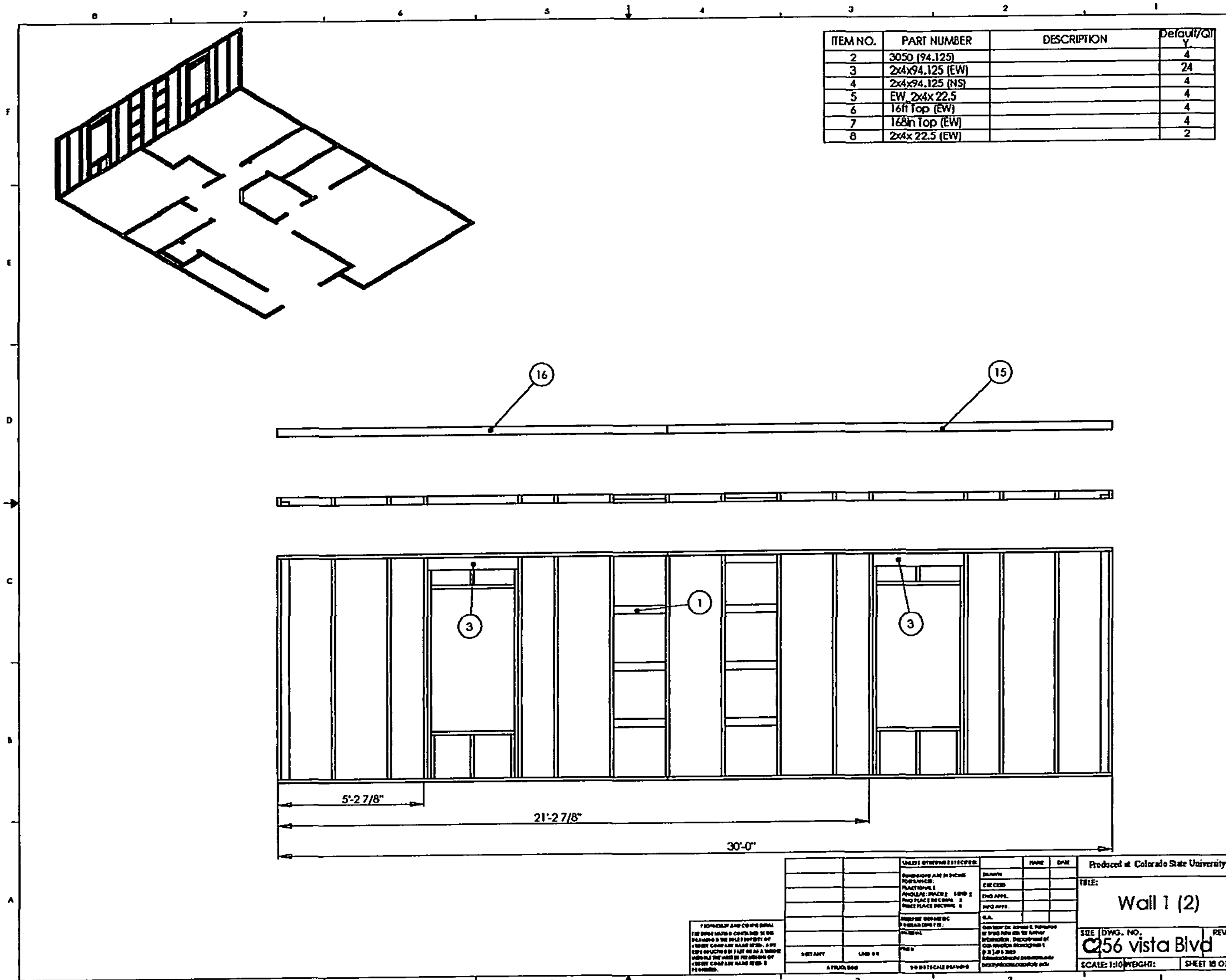
TITLE: Wall 11 (1)

SIZE C DWG. NO. 256 vista Blvd REV

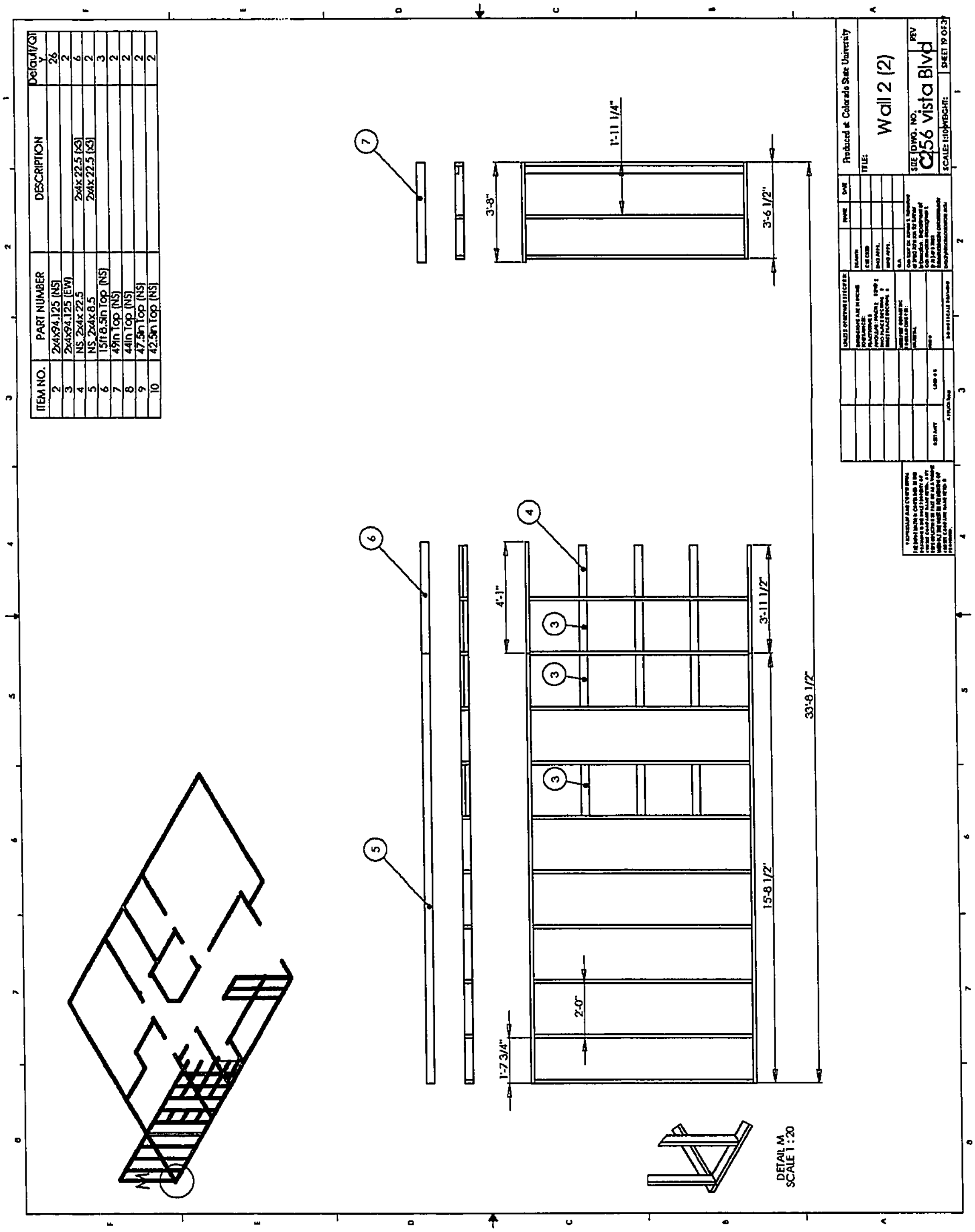
SCALE: 1:50 WEIGHT: SHEET 15 OF 27


Produced at Colorado State University
TITLE:
Wall 12 (1)
SIZE
DWG. NO.
REV
C56 Vista Blvd
1'-11 1/4"
2'-11 1/2"
DETAIL AH
SCALE 1:30

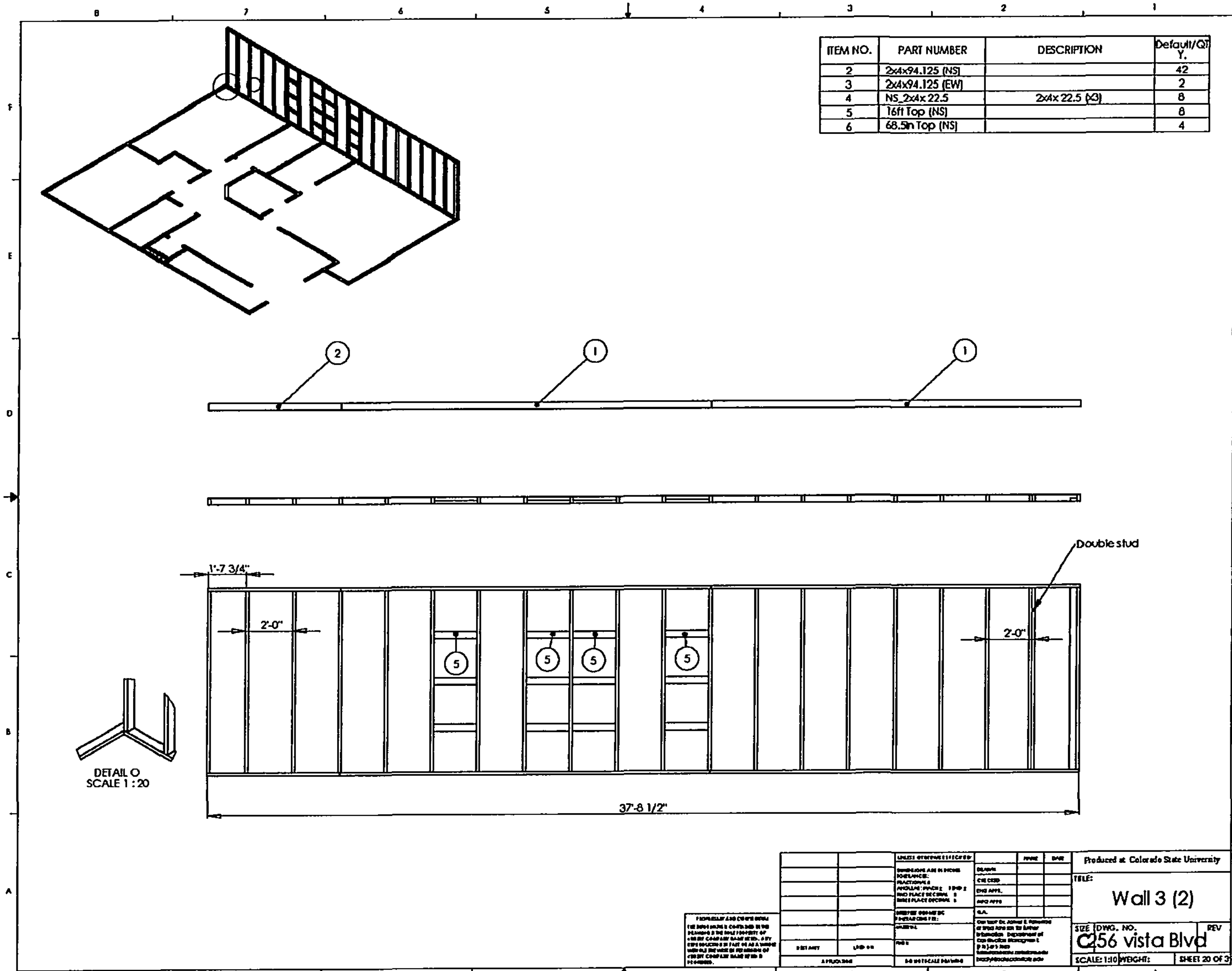

Produced at Colorado State University
Wall 13 (1)
256 Vista Blvd
1'-11 1/4"
8'-1"
1'-8 1/2"



ITEM NO.	PART NUMBER	DESCRIPTION	Default/QTY.
2	3050 (94.125)		4
3	2x4x94.125 (EW)		24
4	2x4x94.125 (NS)		4
5	EW_2x4x 22.5		4
6	16ft Top (EW)		4
7	168in Top (EW)		4
8	2x4x 22.5 (EW)		2

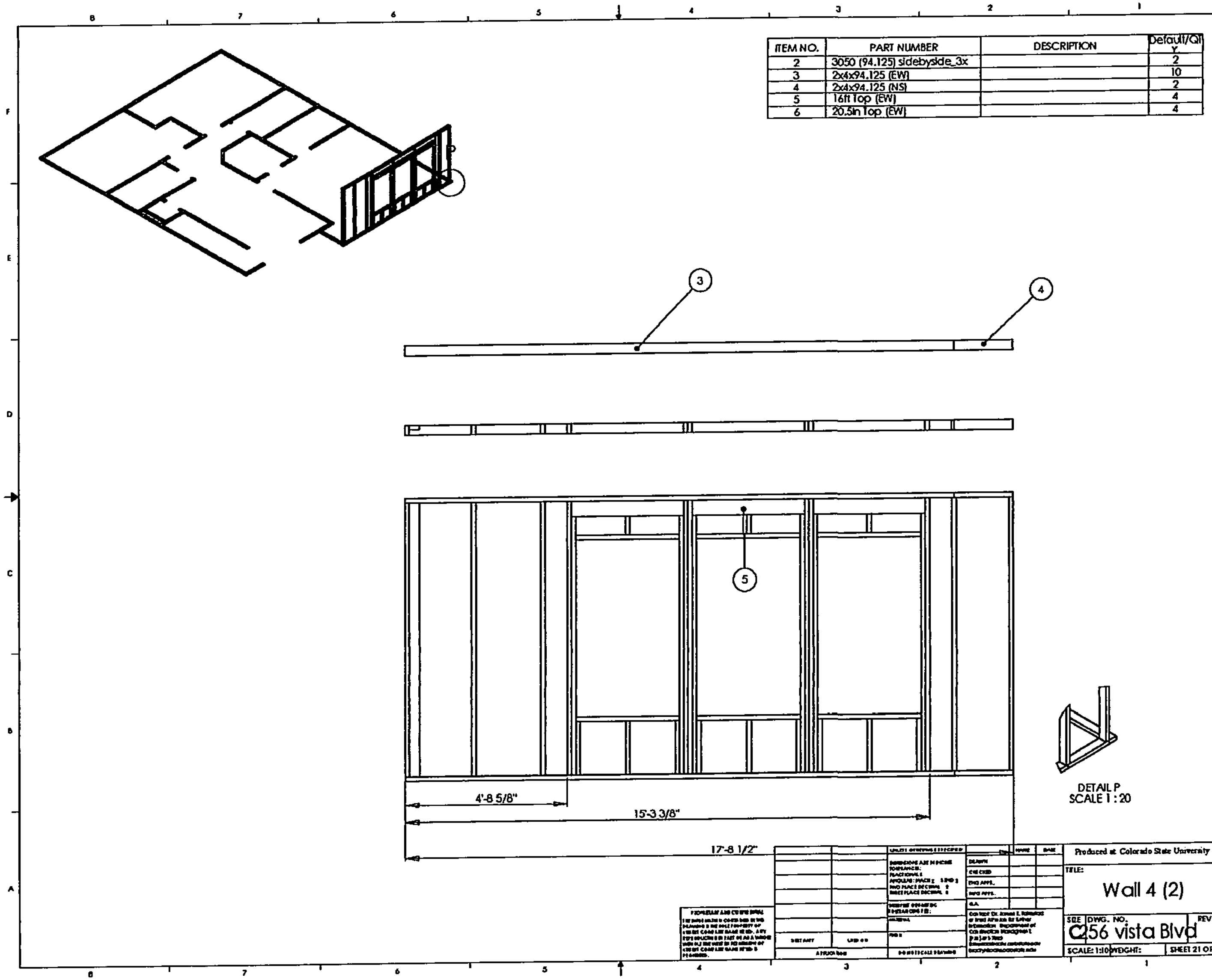


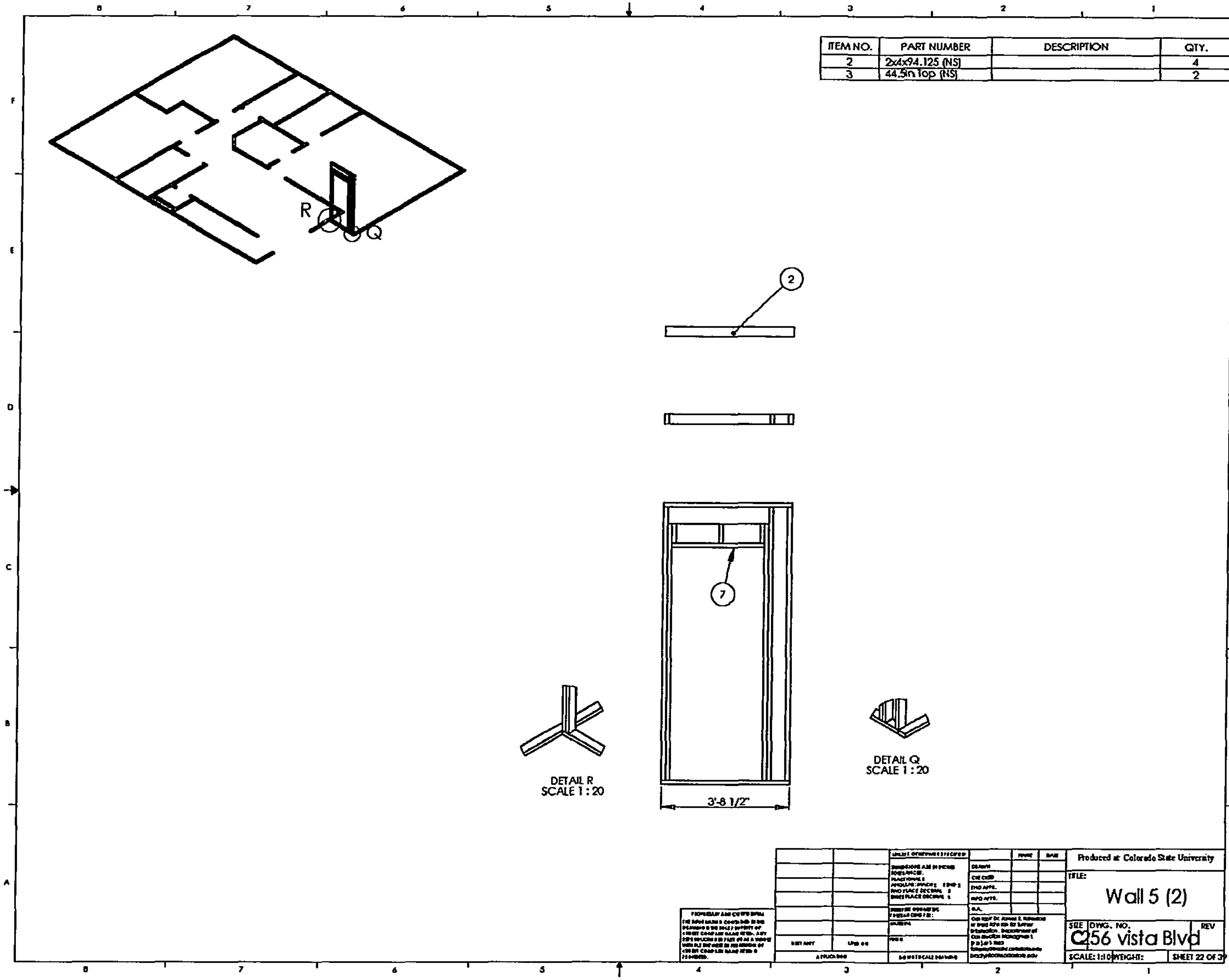
ITEM NO.	PART NUMBER	DESCRIPTION	Default/QTY
2	2x4x94.125 (NS)		26
3	2x4x94.125 (EW)		2
4	NS_2x4x 22.5	2x4x 22.5 (x3)	6
5	NS_2x4x8.5	2x4x 22.5 (x3)	2
6	15ft 8.5in Top (NS)		3
7	49in Top (NS)		2
8	44in Top (NS)		2
9	47.5in Top (NS)		2
10	42.5in Top (NS)		2



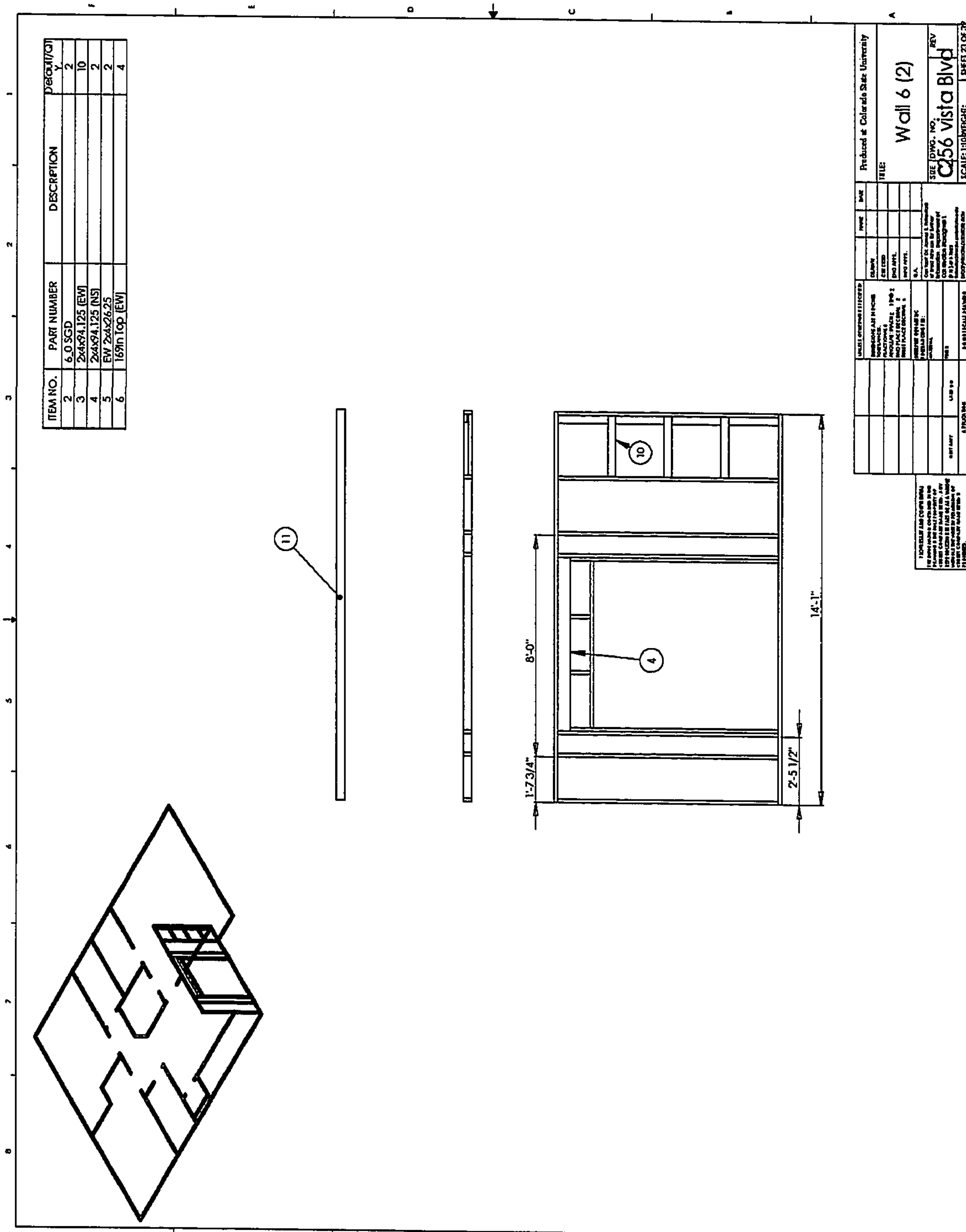
ITEM NO.	PART NUMBER	DESCRIPTION	Default/QTY.
2	2x4x94.125 (NS)		42
3	2x4x94.125 (EW)		2
4	NS_2x4x 22.5	2x4x 22.5 (x3)	8
5	16ft Top (NS)		8
6	68.5in Top (NS)		4

ITEM NO.	PART NUMBER	DESCRIPTION	Default/QTY
2	3050 (94.125) sidebyside_3x		2
3	2x4x94.125 (EW)		10
4	2x4x94.125 (NS)		2
5	16ft Top (EW)		4
6	20.5in Top (EW)		4

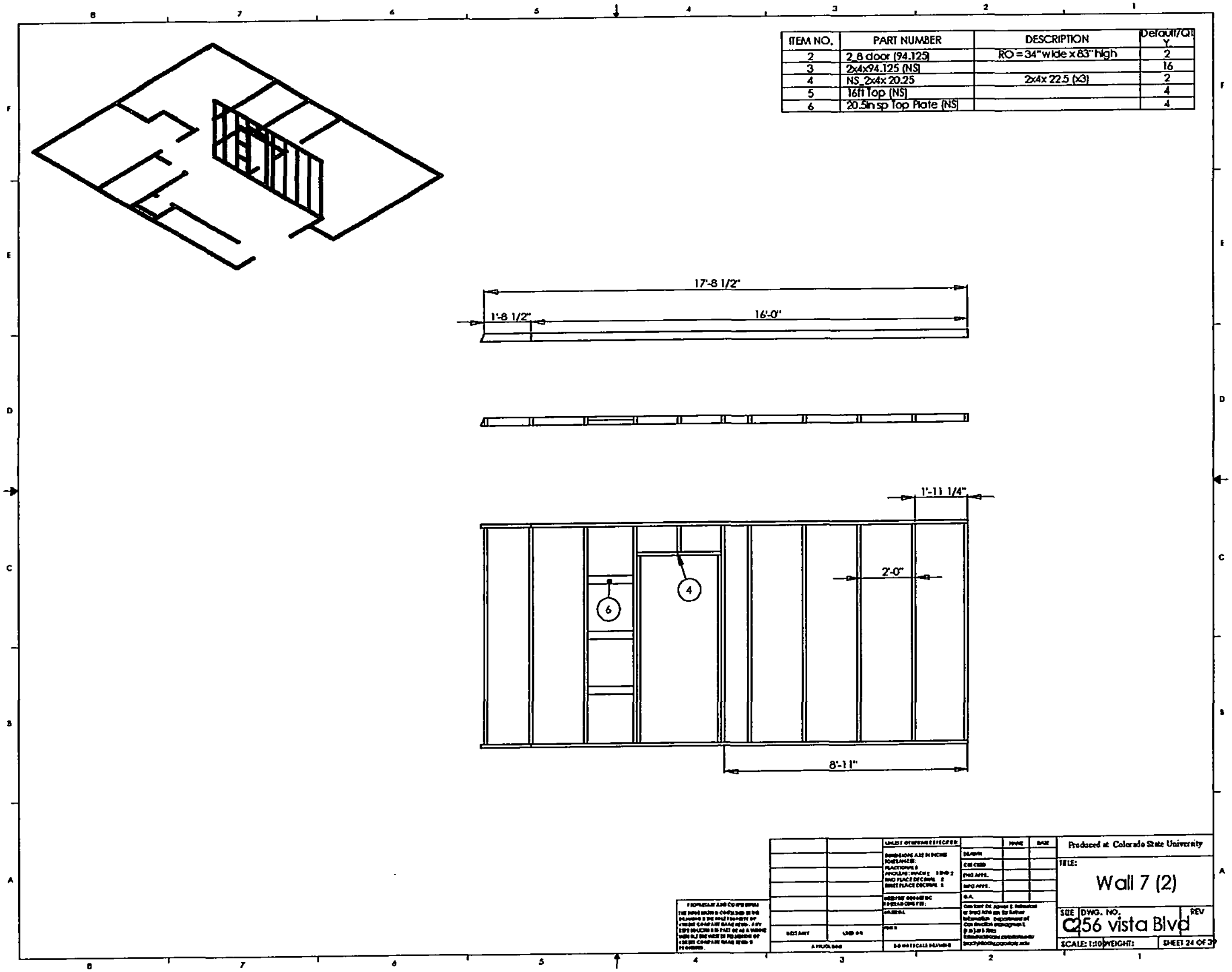




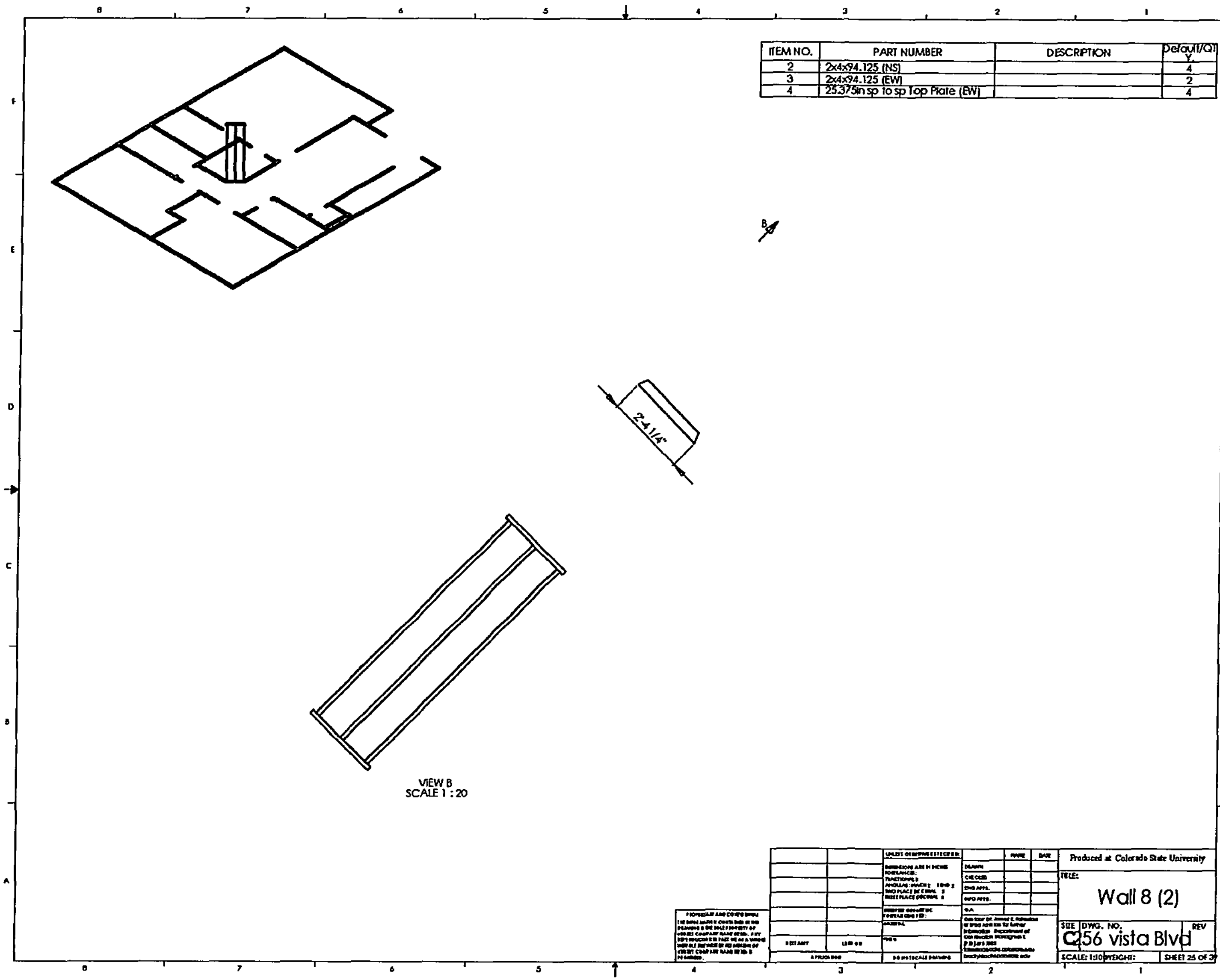
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
2	2x4x94.125 (NS)		4
3	44.5in Top (NS)		2



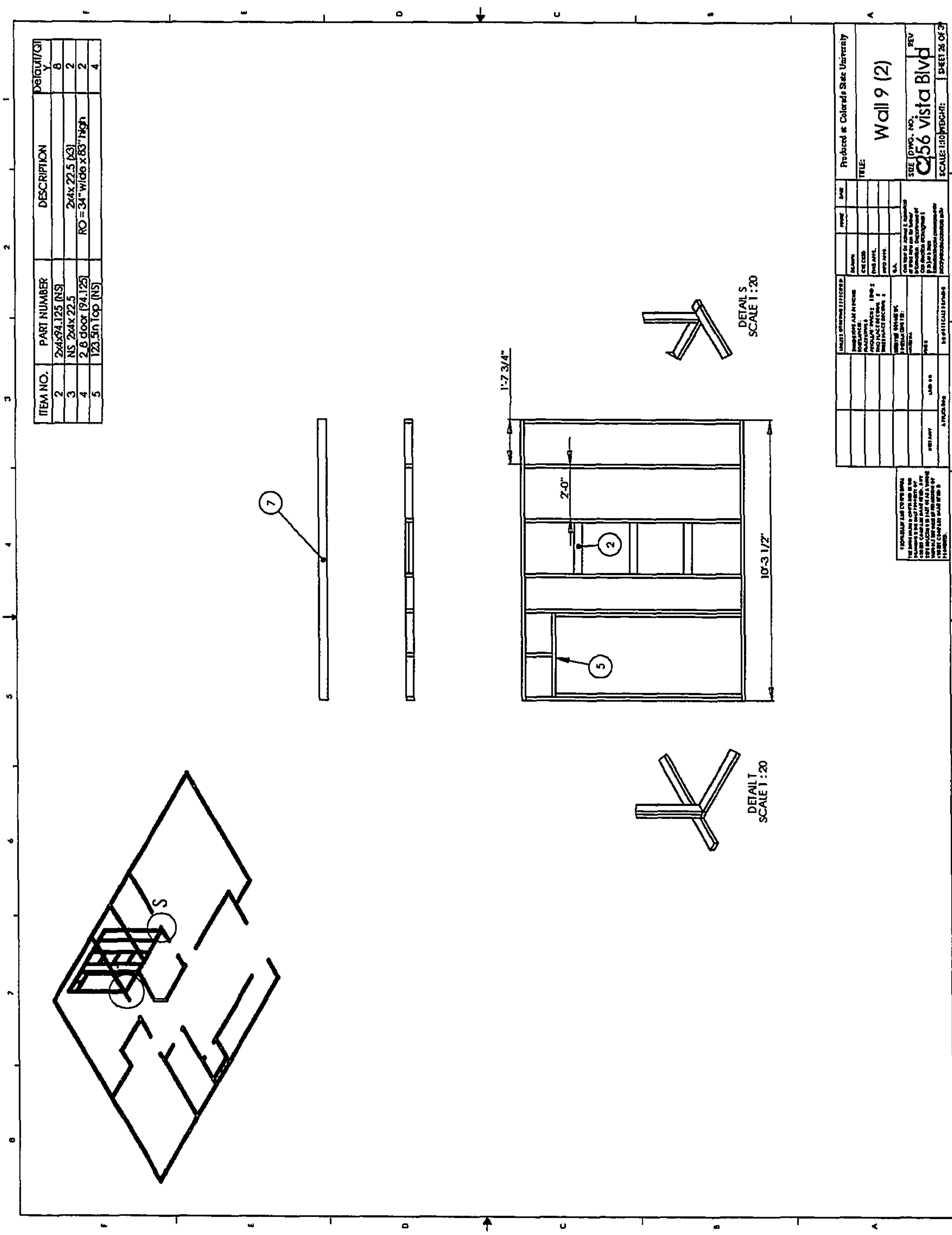
ITEM NO.	PART NUMBER	DESCRIPTION	Default/QTY
2	6_0 SGD		2
3	2x4x94.125 (EW)		10
4	2x4x94.125 (NS)		2
5	EW 2x4x26.25		2
6	169in Top (EW)		4



ITEM NO.	PART NUMBER	DESCRIPTION	Default/QTY.
2	2_8 door (94.125)	RO = 34" wide x 83" high	2
3	2x4x94.125 (NS)		16
4	NS_2x4x 20.25	2x4x 22.5 (x3)	2
5	16ft Top (NS)		4
6	20.5in sp Top Plate (NS)		4

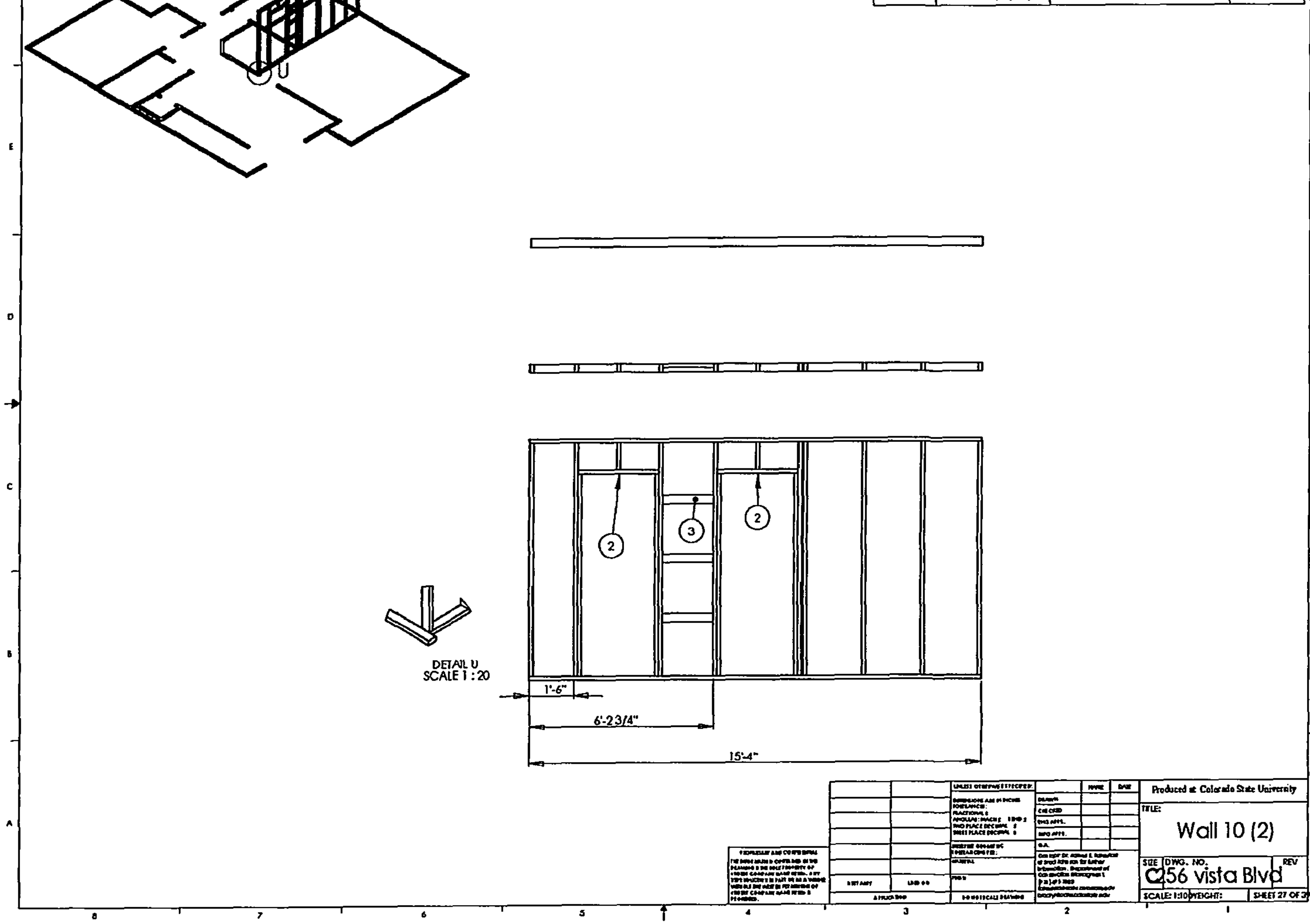


ITEM NO.	PART NUMBER	DESCRIPTION	Default/QTY.
2	2x4x94.125 (NS)		4
3	2x4x94.125 (EW)		2
4	25.375in sp to sp Top Plate (EW)		4

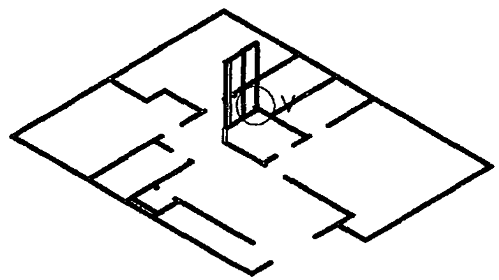


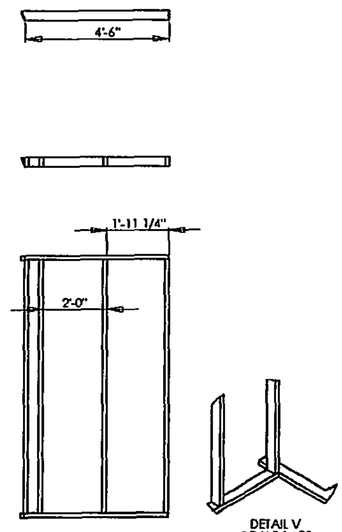
ITEM NO.	PART NUMBER	DESCRIPTION	Default/QTY
2	2x4x94.125 (NS)		8
3	NS 2x4x 22.5	2x4x 22.5 (X3)	2
4	2_8 door (94.125)	RO = 34" wide x 83" high	2
5	123.5in Top (NS)		4

ITEM NO.	PART NUMBER	DESCRIPTION	Right NP/QTY.
1	2x4x94.125 (EW)		5
2	2_4 door (94.125)	RO = 30" wide x 83" high	2
3	EW_2x4x 20.75		1
4	184in Top (EW)		2



ITEM NO.	PART NUMBER	DESCRIPTION	Default/QTY.
2	2x4x94.125 (EW)		8
3	54in sp Top Plate (EW)		4





DETAIL V
SCALE 1 : 20

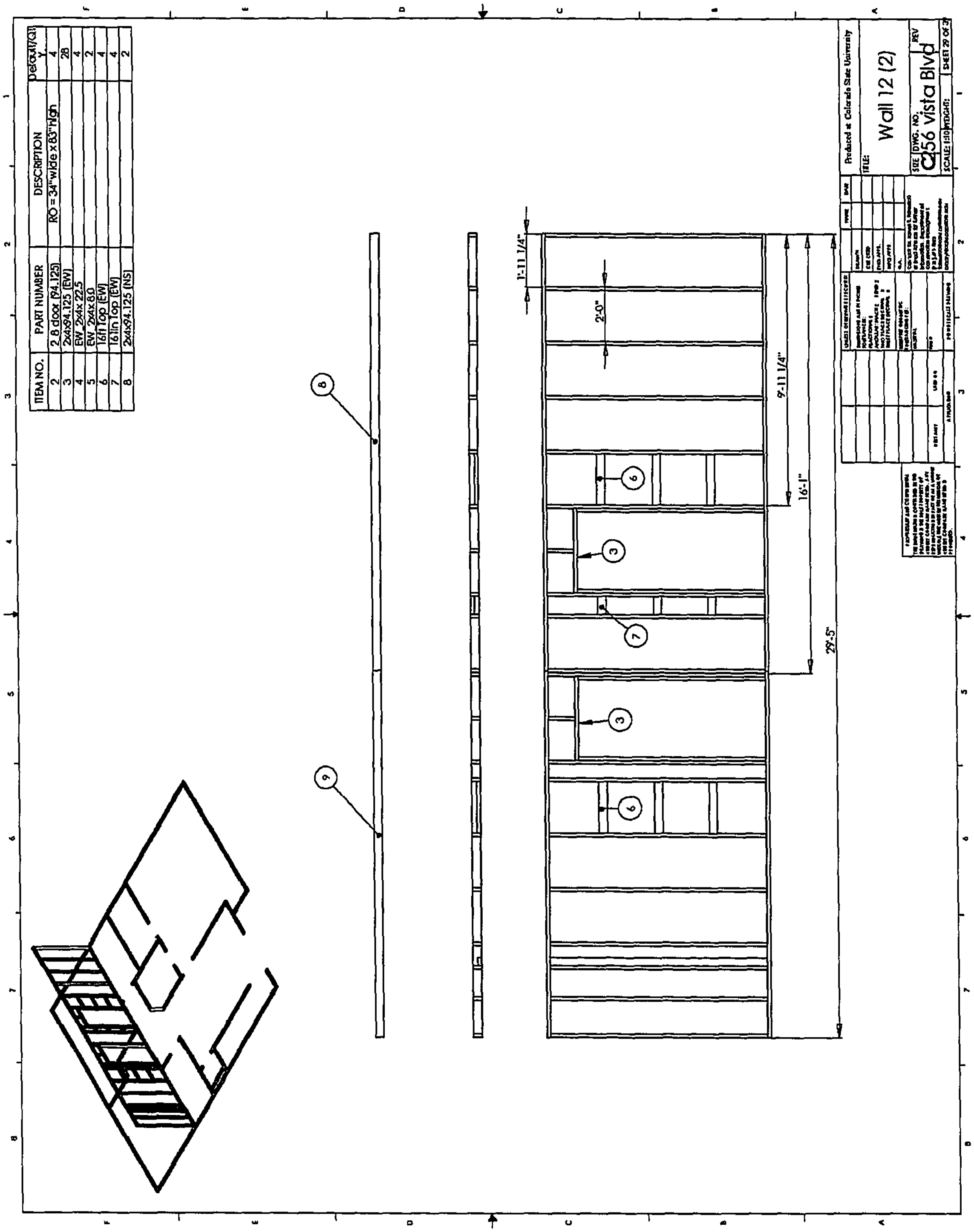
Produced at Colorado State University

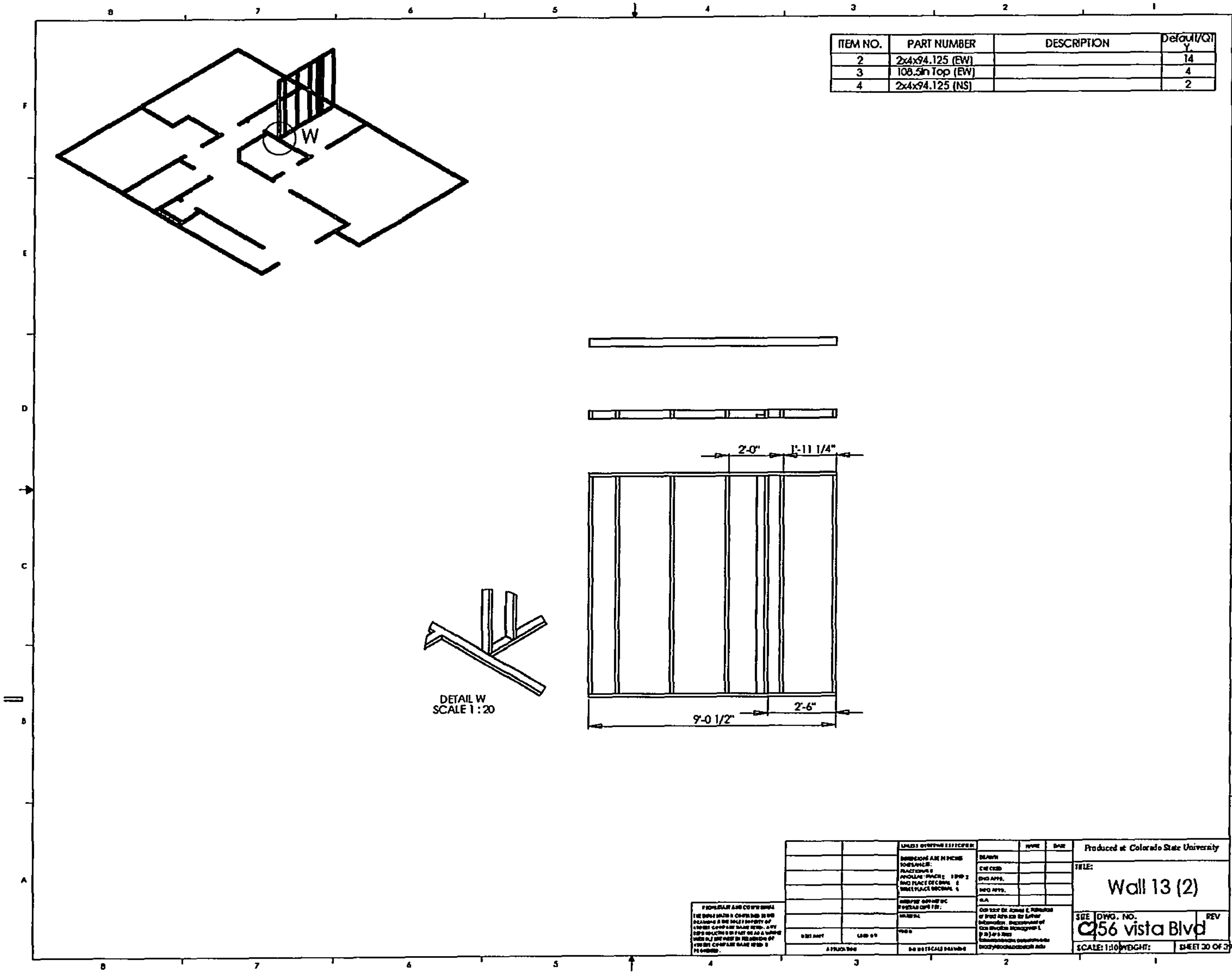
TITLE: Wall 11 (2)

SIZE C DWG. NO. 256 vista Blvd REV

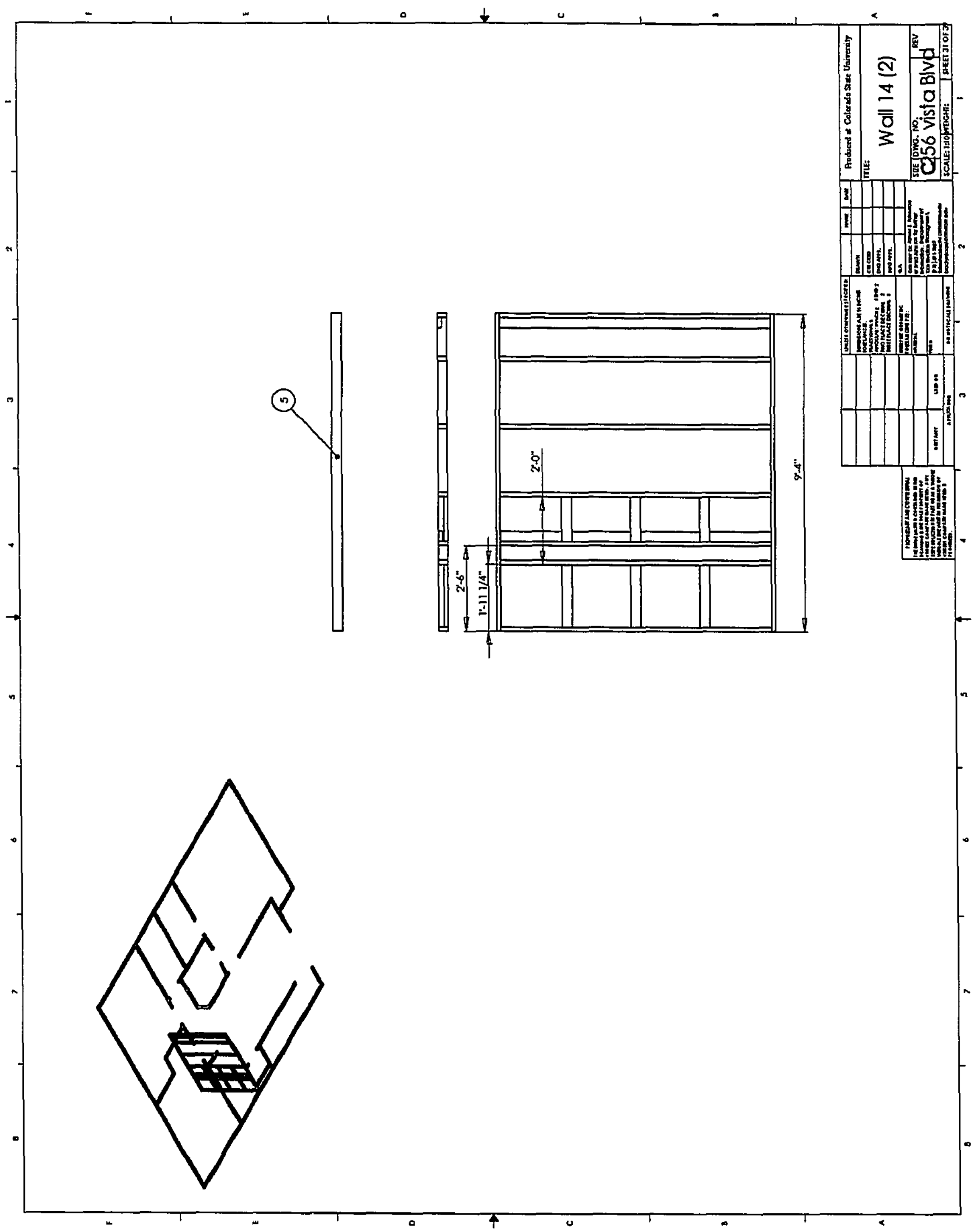
SCALE: 1:10 WEIGHT: SHEET 28 OF 3

174

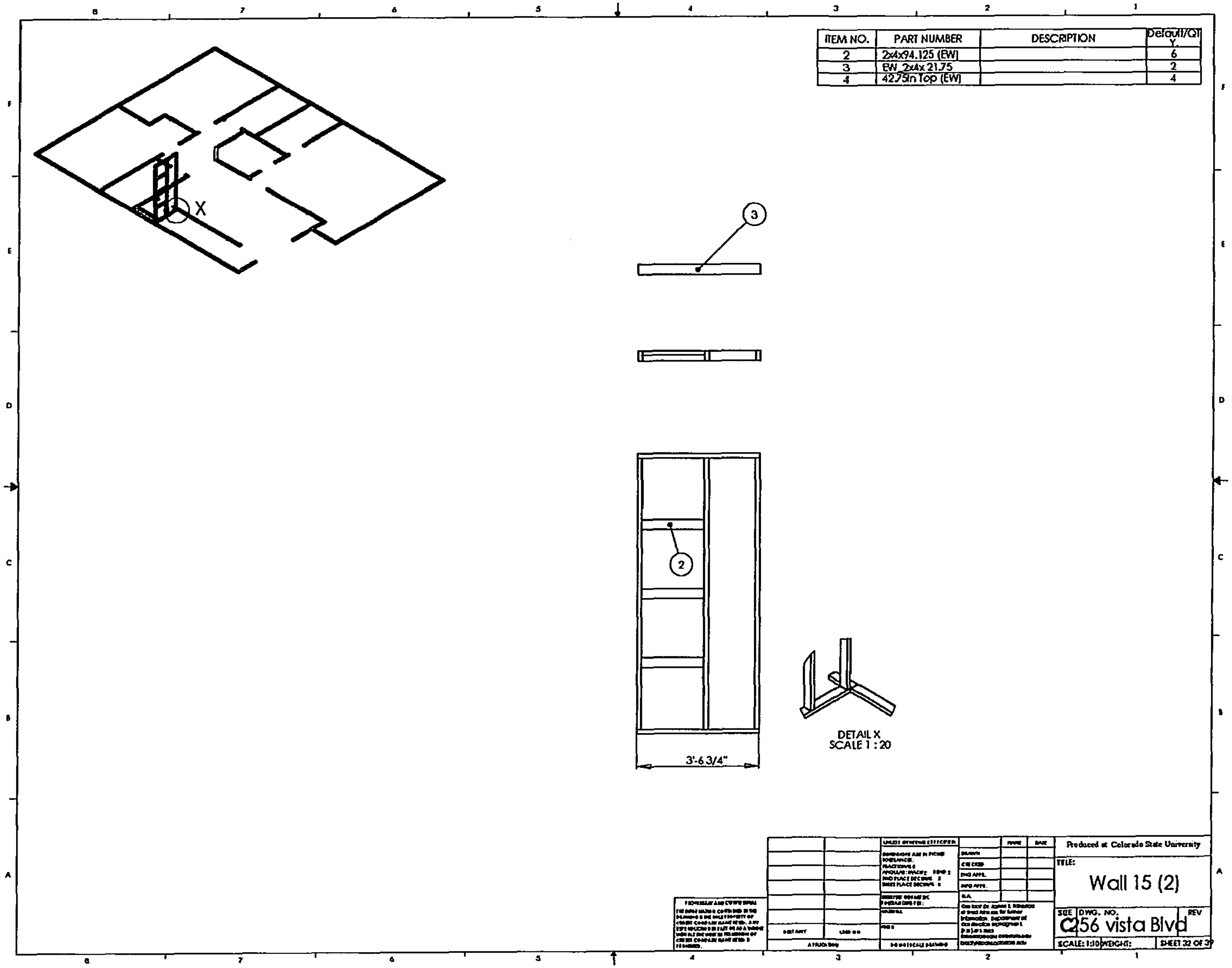

ITEM NO. | PART NUMBER | DESCRIPTION | Default/QTY.
2 | 2_8 door (94.125) | RO = 34"wide x 83"high | 4
3 | 2x4x94.125 (EW) | | 28
4 | EW_2x4x 22.5 | | 4
5 | EW_2x4x 8.0 | | 2
6 | 16ft Top (EW) | | 4
7 | 16 1in Top (EW) | | 4
8 | 2x4x94.125 (NS) | | 2
1'-11 1/4"
2'-0"
9'-11 1/4"
16'-1"
29'-5"
Produced at Colorado State University
TITLE:
Wall 12 (2)
SIZE
C
DWG. NO.
256 Vista Blvd
REV
SCALE: 1:10
WEIGHT:
SHEET 29 OF 3

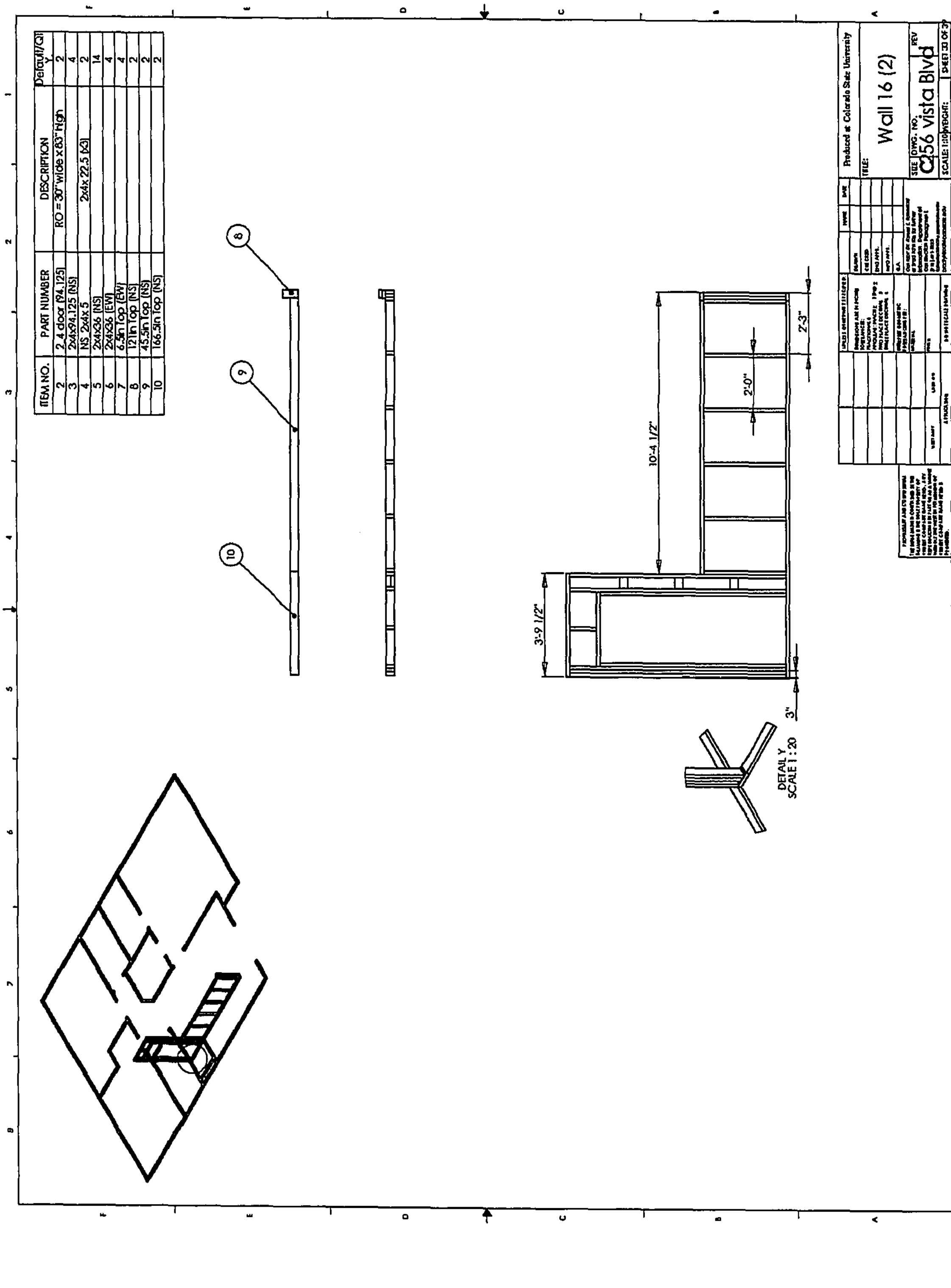


ITEM NO.	PART NUMBER	DESCRIPTION	Default/QTY.
2	2x4x94.125 (EW)		14
3	108.5in Top (EW)		4
4	2x4x94.125 (NS)		2

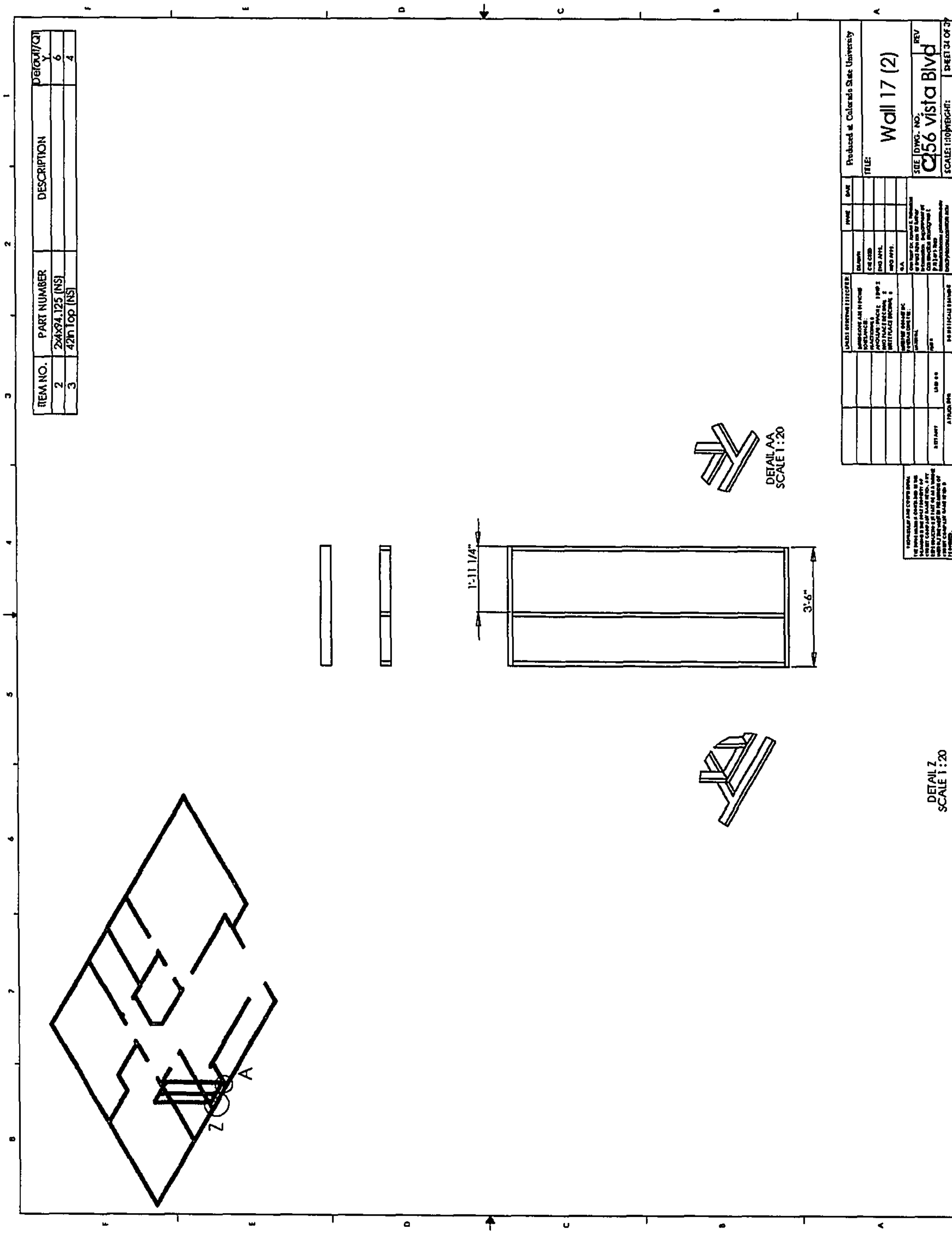


Produced at Colorado State University
TITLE:
Wall 14 (2)
SIZE
DWG. NO.
C
256 Vista Blvd
REV
SCALE: 1:100
WEIGHT:
5
2'-0"
9'-4"
2'-6"
1'-11 1/4"

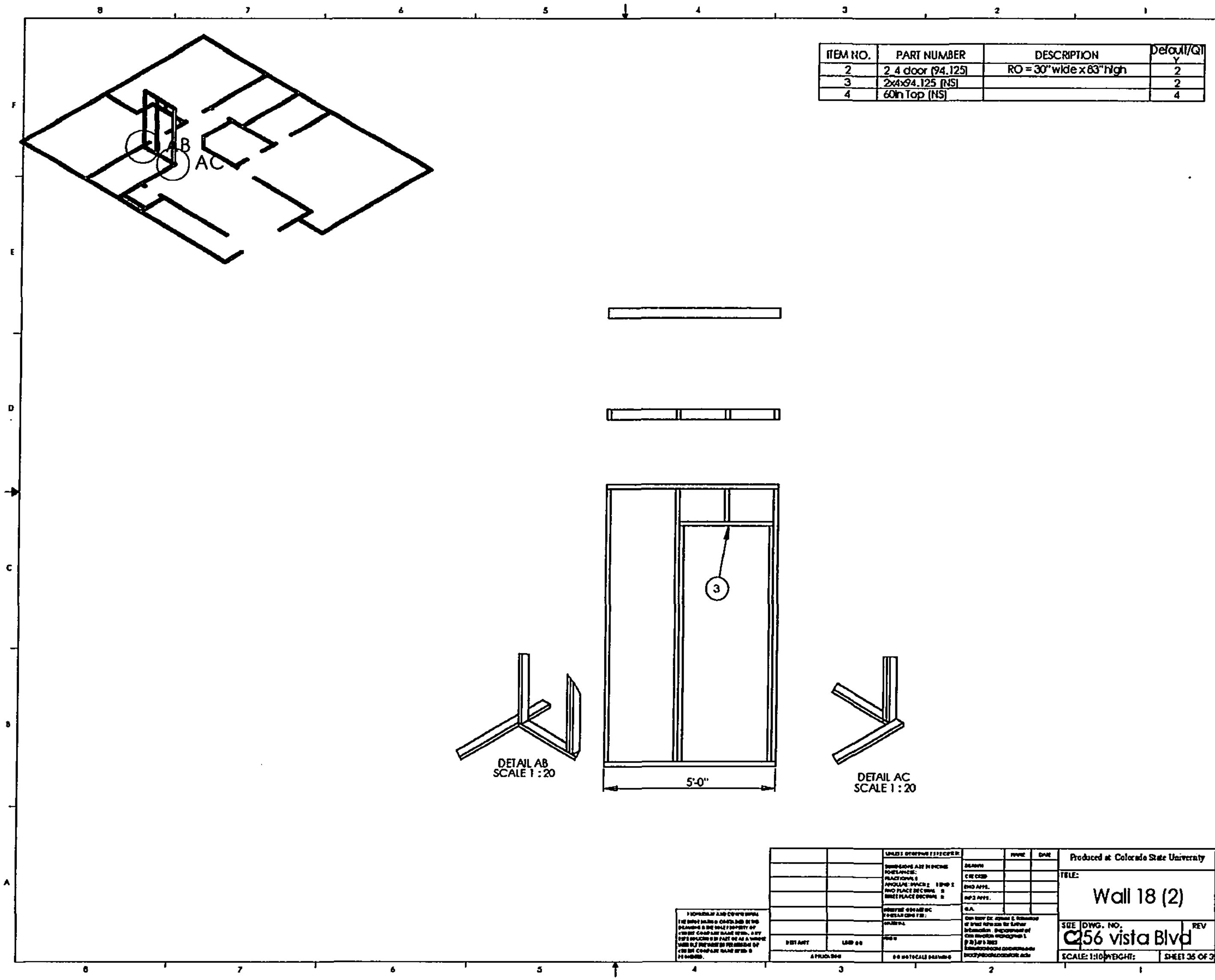

ITEM NO. | PART NUMBER | DESCRIPTION | Default/QTY.
2 | 2x4x94.125 (EW) | | 6
3 | EW_2x4x 21.75 | | 2
4 | 42.75in Top (EW) | | 4
X
3
2
3'-6 3/4"
DETAIL X
SCALE 1 : 20
Produced at Colorado State University
TITLE:
Wall 15 (2)
SIZE
DWG. NO.
C
256 vista Blvd
REV
SCALE: 1:10
WEIGHT:
SHEET 32 OF 37

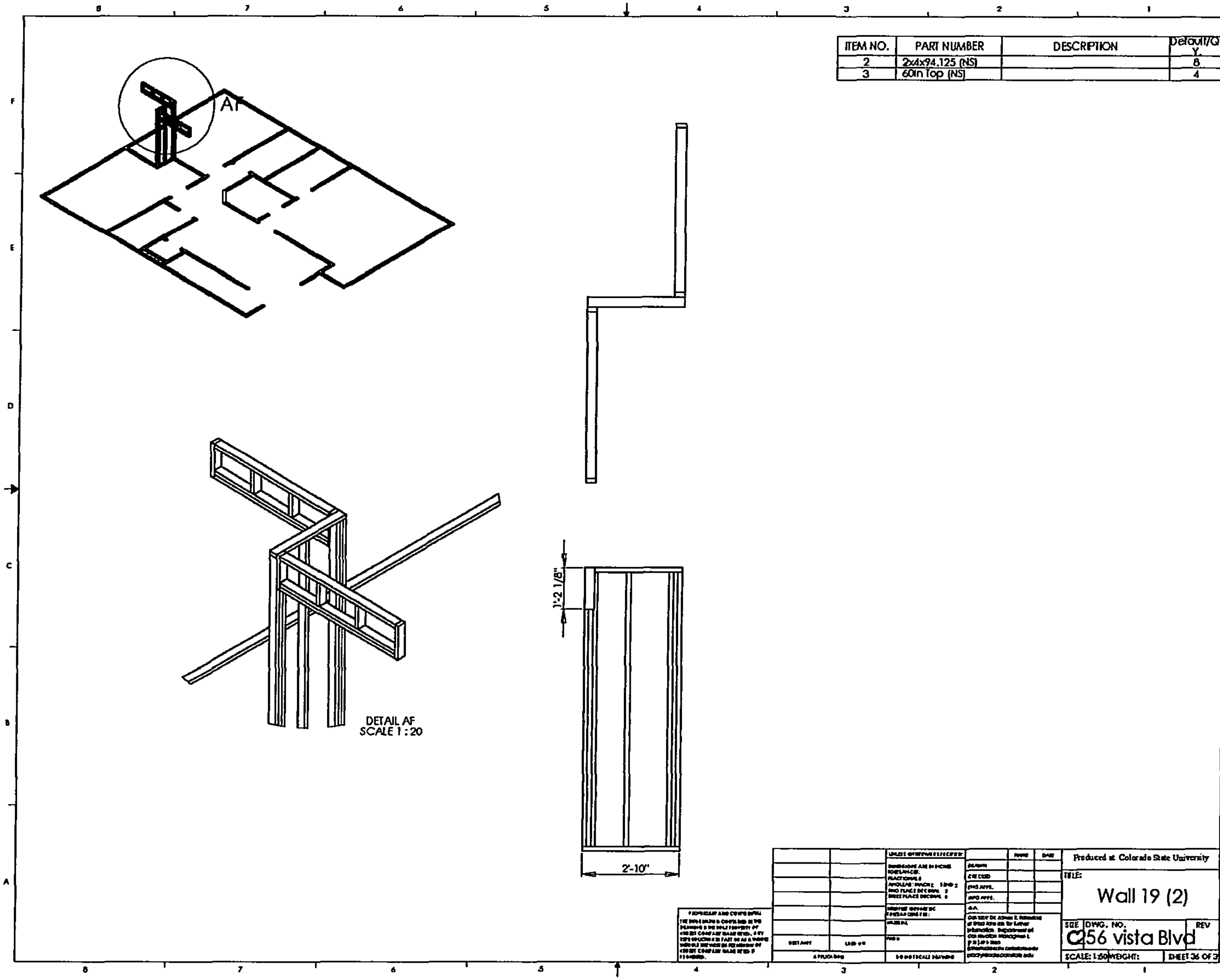


ITEM NO.	PART NUMBER	DESCRIPTION	Default/QTY
2	2_4 door (94.125)	RO = 30" wide x 83" high	2
3	2x4x94.125 (NS)		4
4	NS_2x4x 5	2x4x 22.5 (x3)	2
5	2x4x36 (NS)		14
6	2x4x36 (EW)		4
7	6.5in Top (EW)		4
8	121in Top (NS)		2
9	45.5in Top (NS)		2
10	166.5in Top (NS)		2

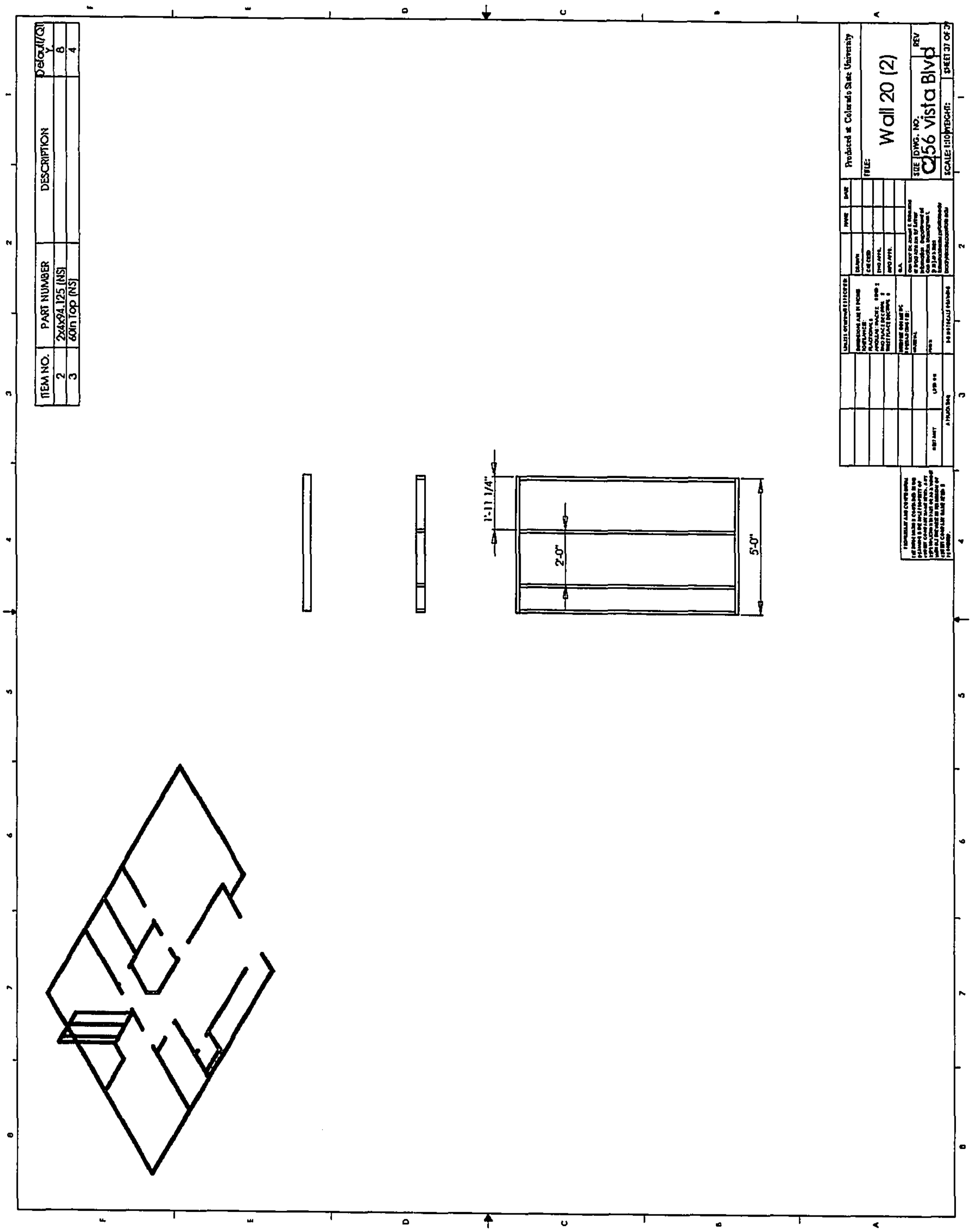


ITEM NO.	PART NUMBER	DESCRIPTION	Default/QTY.
2	2x4x94.125 (NS)		6
3	42in Top (NS)		4

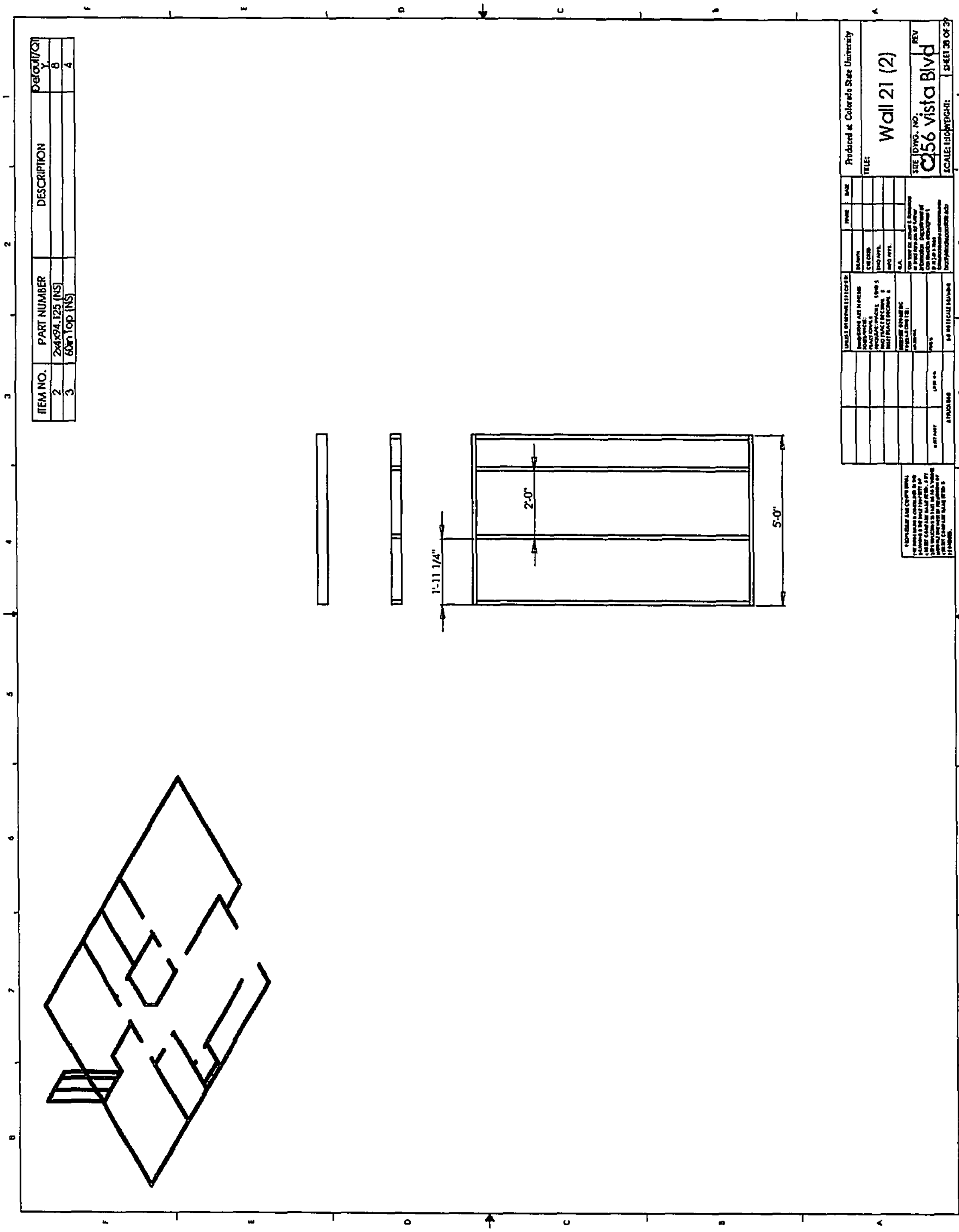

ITEM NO. | PART NUMBER | DESCRIPTION | Default/QTY
2 | 2 4 door (94.125) | RO = 30" wide x 83" high | 2
3 | 2x4x94.125 (NS) | | 2
4 | 60in Top (NS) | | 4
AB
AC
3
5'-0"
DETAIL AB
SCALE 1 : 20
DETAIL AC
SCALE 1 : 20
Produced at Colorado State University
TITLE:
Wall 18 (2)
SIZE
DWG. NO.
C 256 vista Blvd
REV
SCALE: 1:10
WEIGHT:
SHEET 35 OF 3?

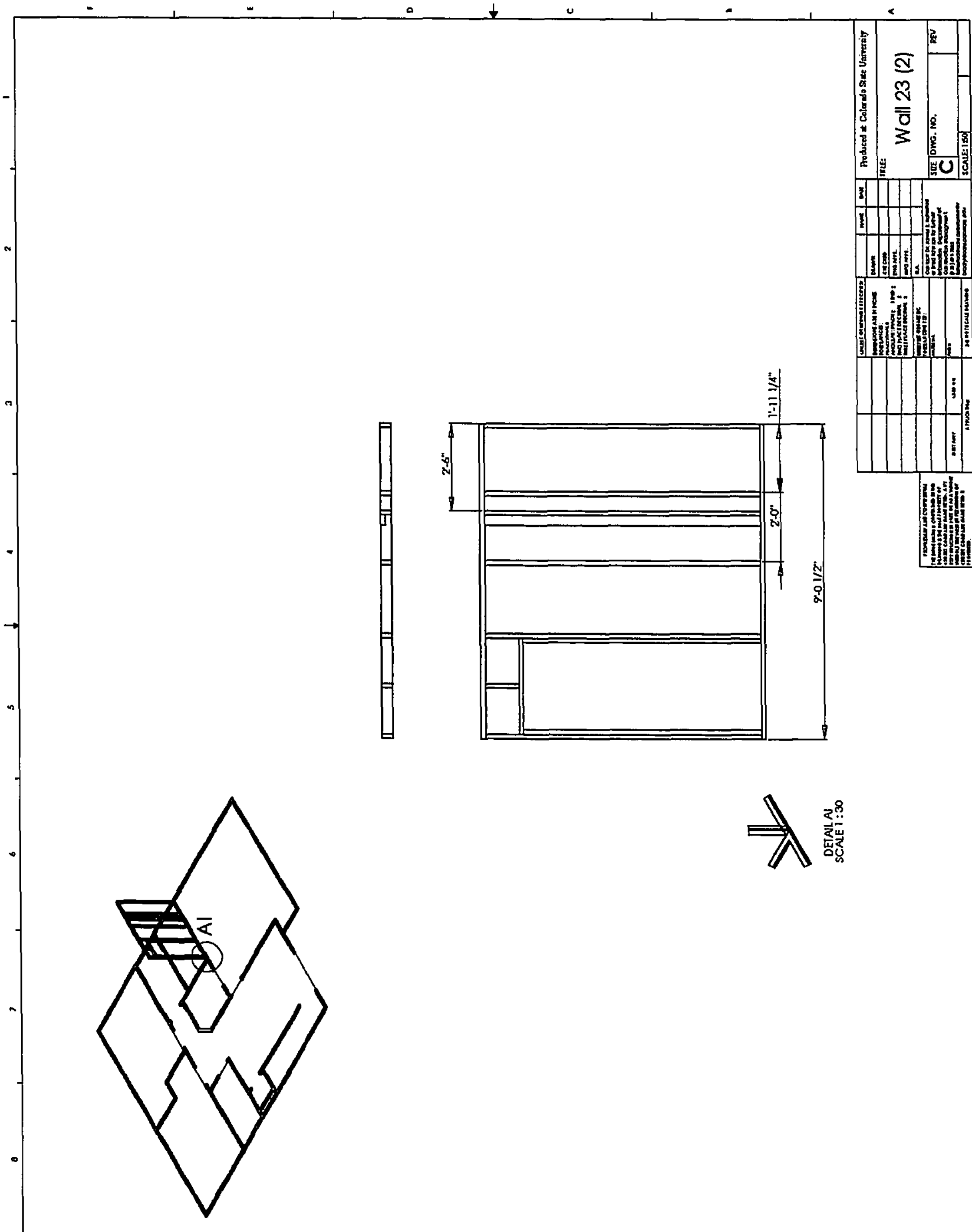


ITEM NO.	PART NUMBER	DESCRIPTION	Default/QTY.
2	2x4x94.125 (NS)		8
3	60in Top (NS)		4



ITEM NO.	PART NUMBER	DESCRIPTION	Default/QTY
2	2x4x94.125 (NS)		8
3	60in Top (NS)		4


ITEM NO.
PART NUMBER
DESCRIPTION
Default/QTY.
2
2x4x94.125 (NS)
8
3
60in Top (NS)
4
1'-11 1/4"
2'-0"
5'-0"
Produced at Colorado State University
TITLE:
Wall 21 (2)
SIZE
DWG. NO.
C
256 vista Blvd
REV
SCALE: 1:10
WEIGHT:
SHEET 38 OF 39


Produced at Colorado State University
TITLE:
Wall 23 (2)
SIZE
C
DWG. NO.
REV
SCALE: 1:50
2'-6"
2'-0"
9'-0 1/2"
1'-11 1/4"
AI
DETAIL AI
SCALE 1 : 30

Appendix E

Error Evaluation Rubric

Error Evaluation Rubric

Total Wall Error	0

Crew/Build/Doc. Set : Crew Build docs

Wall

Build Date:

Total A 0
Total B 0
Total C 0

<u>Quality subjective</u>

Connections 0
Cuts 0
Appearance 0

Description of Error 1

Error Impact Score (select and score all that apply)

Score		Classification
___	A	**Level of error** 1=slight deviance probably not noticed or would not be fixed 2=deviance affects aesthetics 3=deviance requires a fix or effects another system Explanation:
___	B	**Time required to fix error or alter another system** 0 No time required, 2 points for every five minutes required to fix the error (e.g. 2=One to five minute fix 4=Five to ten minute fix 6=Ten to fifteen minute fix) *Time estimation is for one carpenter Explanation:
___	C	**Cost of material wasted** 0=no material wasted or, 1 points for every dollar of material wasted (e.g. 1=$0.01 to $1.00 2=$1.01 to $2.00) Cost calculated at $.35 per lf Of 2x4 and $.55 per lf of 2x6 Explanation:
Total Error 0		

Description of Error 2

Error Impact Score (select and score all that apply)

Score		Classification
___	A	**Level of error** See above Explanation:
___	B	**Time required to fix error or alter another system** See above Explanation:
___	C	**Cost of material wasted** See above Explanation:
Total Error 0		

Description of Error 3

Error Impact Score (select and score all that apply)

Score		Classification
___	A	**Level of error** See above Explanation:
___	B	**Time required to fix error or alter another system** See above Explanation:
___	C	**Cost of material wasted** See above Explanation:
Total Error 0		

Description of Error 4

Error Impact Score (select and score all that apply)

Score		Classification
___	A	**Level of error** See above Explanation:
___	B	**Time required to fix error or alter another system** See above Explanation:
___	C	**Cost of material wasted** See above Explanation:
Total Error 0		

Description of Error 5

Error Impact Score (select and score all that apply)

Score		Classification
___	A	**Level of error** See above Explanation:
___	B	**Time required to fix error or alter another system** See above Explanation:
___	C	**Cost of material wasted** See above Explanation:
Total Error 0		

TRAIL RIDGE PLAN T05 SPECIFICATIONS AND BUILDING CODES

DIVISION 2 – SITE WORK

1. BACKFILL: BACKFILL OF FOUNDATION AND UTILITY TRENCH EXCAVATIONS WILL BE MECHANICALLY COMPACTED TO A DENSITY OF 95%, OR PER ENGINEER'S RECOMMENDATION.

DIVISION 3 – CONCRETE

1. FOUNDATIONS: SLAB ON GRADE CONSTRUCTION STANDARD

2. CONCRETE FLAT WORK: ALL EXTERIOR DRIVEWAYS SHALL BE 4" THICK (NOMINAL) 4000 P.S.I. MIX CONCRETE> TO BE POURED W/ #4 REBAR WITH A 30" O.C. GRID ON CHAIRS. THE REBAR GRID WILL START 4" TO 8" FROM THE EDGES OF ALL EXTERIOR FLAT WORK. GARAGE FLOOR TO BE 4" CONCRETE WITH A MINIMUM SLOPE OF 2" (1/8" PER FT.) MINIMUM TOWARD THE GARAGE DOOR.

DIVISION 4 – MASONRY

1. ALL MASONRY AREAS RETURN 2'-0" AT SIDE ELEVATIONS
BRICK AND STONE SHALL BE APPLIED PER I.R.C.
MASONRY AREAS ARE PREPLANNED AND ADDITIONAL CUSTOMER REQUESTED AREAS WILL NOT BE ENTERTAINED.

2) WITH BRICK VENEER, PROVIDE METAL TIES SPACED SO AS NOT TO SUPPORT MORE THAN 2 S.F. OF VENEER/TILE & NOT MORE THAN 24" O.C. HORIZ. PER I.R.C.

3) WITH STONE VENEER, APPLY WITH 1" MIN. GROUTED BACKING SPACE REINFORCED BY 2" X 2" No. 16 Ga. GALV. WIRE MESH o/ 1/2" ASPHALT IMPREGNATED SHEATHING o/ 2X STUDS @ 16" O.C. MAX. PER I.R.C.

DIVISION 4 – WOOD AND PLASTICS

LUMBER:

1. FLOOR SYSTEM: FLOOR STRUCTURE (SIZED PER PLAN) WILL USE I-JOIST AS PER THE ENGINEERED DESIGN FOR EACH PLAN. SUB FLOORING WILL BE 3/4" TONGUE AND GROOVE OSB, GLUED AND NAILED WITH RING SHANK 8d NAILS TO FLOOR JOIST.

2. WALL SYSTEM: EXTERIOR AND OTHER LOAD BEARING WALLS TO BE 24" O.C.. INTERIOR NON LOAD BEARING ARE TO BE 24" O.C.. ALL NON-VAULTED, NON LOAD BEARING WALLS WILL USE STUDS MEASURING 104 5/8", WITH A SINGLE BOTTOM PLATE AND A SINGLE TOP PLATE.
ALL MAIN FLOOR LOAD BEARING WALLS WILL US A SINGLE BOTTOM PLATE AND DOUBLE INTERLOCKING TOP PLATES.
NON LOAD BEARING HEADERS ARE TO BE 2 X WITH CRIPPLES. ALL LOAD BEARING HEADERS WILL BE SIZED PER THE PLAN. WALL SYSTEMS AND PLATES SHALL BE HEM FIR. EXTERIOR SHEATHING IS 7/16" O.S.B APPLIED AT CORNERS AND 25' O.C. PROVIDE ASPHALT IMPREGNATED FIBERBOARD CELLOTEX OR SIMILAR, WITH DIAGONAL METAL BRACING PER CODE. NOTE: EXTERIOR WALL PARTITIONS ARE LADDER BACKED (PER LOCAL CODE) FOR MAXIMUM INSULATION AND ENERGY EFFICIENCY.

3. ROOF SYSTEMS: ROOF SYSTEMS SHALL HAVE ENGINEERED ROOF TRUSSES, WITH PITCH PER PLAN, TO BE INSTALLED PER PLAN. OPTIONAL SCISSOR TRUSSES TO BE 2-1/2" UNDER THE OUTSIDE PITCH. ROOF OVERHANGS ON ALL ELEVATIONS WILL BE 6" ON SIDES AND REAR OF THE HOME. FRONT ELEVATIONS SHALL HAVE A 16" OVERHANG AT GABLE ENDS ONLY. FACIA DETAIL TO BE 1 X 8 ALUMINUM FACIA. FRONT GABLE FASCIAS TO BE 1 X 10 ALUMINUM FACIA. 6" SOFFITS TO BE VENTILATED VINYL ON ALL ELEVATIONS. ROOF DECKING OS TO BE OSB (15/32" THICK) PER PLAN AND PER LOCAL CODE, WITH H CLIPS. VERTICAL UPRIGHTS ON GABLE END TRUSSES SHALL BE 16" O.C. WITH SPACING TO ALLOW FOR GABLE END VENTS. ALL HARDWARE AND HANGERS AND PLYED-GIRDERS. SUPPLIED PER MANUFACTURER.

4. EXTERIOR SIDING: ALL SIDING TO BE 12" VINYL LAP W/ 4" REVEAL (OR PATTERN PER PLAN) @ .040 (MILL CREEK – ALCOA), WITH VINYL CORNERS AS PER OUR PLANS. ALL PORCH POST TO BE CERTAINTEED "REAL POST". ALL PORCH RAILS, CAPITALS, SHUTTERS, VENTS AND OTHER ARCHITECTURAL DETAILS ARE TO BE VINYL.

5. STAIRS: INTERIOR STAIRS ARE TO BE PRE-BUILT STAIRS USING CLOSED TREAD WITH FULL EXPOSED STRINGERS. GARAGE TO HOUSE STAIRS ARE TO BE PRE-FAB.

6. GENERAL NOTES:

DESIGN LOADS USED ARE AS FOLLOWS:
- A) ROOF SNOW LOAD: 30/SF
- B) FLOORS 40/SF
- C) SEISMIC ZONE 1
- D) WIND 100 MPH

FRAME LUMBER:
- A) ALL LUMBER TO BE HEM FIR LARCH #2 OR BETTER. Fb= 850/978 P.S.I., Fv= 75 P.S.I., Fc= 1,250 P.S.I. E= 1,300,000 P.S.I.
- B) 2 X 4 STUDS TO BE HEM FIR LARCH "STUD" GRADE OR BETTER. Fb= 675/750 P.S.I., Fv= 75 P.S.I., Fc= 800 P.S.I., E= 1,200,000 P.S.I.

HEADERS:
- A) ALL HEADERS TO BE (2) 2 X 10 UNLESS NOTED OTHERWISE ON PLANS
- B) ALL HEADER HEIGHTS OFF OF FLOOR ARE AS FOLLOWS:
  1. INTERIOR SWINGING DOORS: 83"
  2. INTERIOR BYPASS DOORS: 83"
  3. TYPICAL WINDOW OPENINGS: 84"
  4. EXTERIOR GLASS SLIDING DOORS: 80"
  5. EXTERIOR SWING DOOR: 83"
  6. INTERIOR BYFOLD DOORS: 82.5" (ON CARPETED AND TILE SURFACES)
  7. INTERIOR BYFOLD DOORS: 82.5" (NO VINYL W/NO UNDERLAYMENT SURFACES)

POSTS AND BEAMS:
- A) A MINIMUM OF (1) 2X4 UNDER EACH END OF ALL BEAMS AND HEADERS UNLESS NOTED OTHERWISE ON PLANS.
- B) STOP TOP PLATES AT BOTH SIDES OF POST SUPPORTING GIRDER TRUSSES TO AVOID COMPRESSION OF TOP PLATES.
- C) PROVIDE SOLID BLOCKING UNDER ALL POSTS (2) 2X AND LARGER.

CONSTRUCTION MINIMUM STANDARDS:
- A) PROVIDE MINIMUM 4'-0" WIDTH OF 3/8" OSB SHEATHING ON ALL EXTERIOR WALLS (EXCLUDING END GABLE). NAILED W 8d RING SHANK NAILS 4" O.C. ON EDGES AND 12" O.C. ON ALL INTERMEDIATE MEMBERS OR PER CODE
- B) PROVIDE "SIMPSON STRONG TIE" OR EQUAL METAL CONNECTORS AS NECESSARY.
- C) GLUE AND NAIL ALL MULTIPLE MEMBER (2) 2 X AND GREATER W/ 16d NAILS 6" O.C.
- D) ROOF SHEATHING TO BE A MINIMUM OF 15/32" OSB. SHEATHING IS TO BE NAILED W/ 8d RING SHANK NAILS 4" O.C. ON EDGES AND 6" O.C. IN THE FIELD.
- E) FLOOR SHEATHING TO BE A MINIMUM 3/4" T&G OSB. FLOORING IS TO BE GLUED AND NAILED W/ 8d RING SHANK NAILS 4" O.C. ON EDGES AND 6" O.C. IN FIELD.
- F) ALL FLOOR AND WALL SPACE AND STACK PROVIDING SPACE FOR PLUMBING AND MECHANICAL INSTALLATION.
- G) PROVIDE SIMPSON H2.5 OR EQUAL AT ALL TRUSSES AND ROOF RAFTERS BEARING LOCATIONS PER CODE
- H) ALL FRAMING TO MEET OR EXCEED LOCAL CODE REQUIREMENTS.
- I) ALL OVERFRAMES AT ROOF ARE TO CONSIST OF 2X8 RAFTER MEMBERS 24" O.C. THEY ARE TO BE SUPPORTED W/ 2X4 POST MEMBERS NO MORE THAN 48" O.C. BEARING ON TOP TRUSS CHORDS OR SOLID 2X6 BLOCKING BETWEEN TRUSSES. OVERFRAME RAFTERS AND TRUSSES ARE TO BE ATTACHED AT EACH END W/ SIMPSON H2.5 OR EQUAL. ALL POST OVER 36" IN HEIGHT MUST BE LATERAL BRACED @ MID HEIGHT IN INTERVALS OF 36". ALL RIDGE RAFTERS MUST BE WIDE ENOUGH TO BRACE EACH RAFTER FROM TOE TO HEEL.
- J) ALL DIMENSIONS ARE FROM ROUGH STUD FACE TO ROUGH STUD FACE, (3 1/2") FOR 2 X 4 WALLS, (5-1/2") FOR 2 X 6 WALLS, UNLESS NOTED OTHERWISE.
- K) PROVIDE MINIMUM DRYWALL PER CODE ON ALL GARAGE WALLS & CEILINGS THAT ARE ADJACENT TO OR UNDER LIVING AREAS & ON ALL BEARING WALLS, BEAMS & POSTS PER 2003 I.R.C. DRYWALL IN WET AREAS IS TO BE WATER RESISTIVE AS PER 2003 I.R.C.
- L) MINIMUM HEADROOM CLEARANCE IN EACH STAIRWAY IS 6'-8". TOP OF HANDRAILS IS TO BE 34" – 38" ABOVE THE NOSING OF THE TREADS. THE HANDGRIP PORTION OF THE HANDRAIL IS TO BE 1 \" – 2" IN CROSS-SECTIONAL DIMENSION. OPEN HANDRAILS & GUARDRAILS ARE TO HAVE INTERMEDIATE RAILS SUCH THAT A 4" ~ SPHERE CANNOT PASS THROUGH.
- M) PROVIDE BLOCKING FOR ALL HANDRAILS, TOWEL BARS, AND SHOWERHEADS. SHOWERHEAD TO BE LOCATED 6'-10" A.F.F., TYPICAL
- N) PROVIDE 14-1/2" X 24" ROUGH OPENING FOR ALL OPTIONAL RECESS MEDICINE CABINETS TOP OF R.O. @ 5'-6" A.F.F.
- O) THERE IS TO BE ONE STANDARD ATTIC ACCESS LOCATED IN THE UTILITY ROOM AND ONE OPTIONAL ATTIC ACCESS W/ PULL DOWN STAIR LOCATED IN THE GARAGE.
NOTE: PROVIDE 3/4" O.S.B. SHEATHING, 1/2" DRYWALL TO CODE AND INSULATION W/ GARAGE ATTIC ACCESS OPTION.

DIVISION 7 – THERMAL MOIS

ROOFING: ALL ROOFS ARE LIFETILE "TRAI
INSTALLED AT VERTICAL WALLS AT THE TI
PROVIDE CONTINUOUS RIDGE AND VINYL S
2. INSULATION: STANDARD PACKAGE (A
- A) WALLS 2X4 = R-13 BLOW IN CELL
- B) WALLS 2X6 = R-19
- C) CEILING = R-30 BLOW IN CELLUL
- D) FOUNDATION = R-5 RIGID FOAM I

BAYS, CANTILEVERS AND OTHER OVER

3. AIR INFILTRATION PACKAGE: CONSIST
4. GUTTERS AND DOWNSPOUTS: GUTTER

DIVISION 8 – DOORS AND W

1. FRONT DOOR: TO BE 6'-8" HIGH X 3
WITH 3 HINGES, WEATHER STRIPPING, ADJ
2. HOUSE: TO BE 6'-8" HIGH (WIDTH V
3. GARAGE: TO BE 6'-8" HIGH AND 2'-
4. INTERIOR DOORS: JAMBS, CASING, AND
5. WINDOWS: STANDARD WINDOWS AND
PER PLAN AND WINDOWS VISIBLE FROM FR
1" X ROUTED EDGE WOOD WINDOW SILL W

NOTES: 1. EXTERIOR DOORS SHALL OPEN
WILL HAVE MINIMUM DIMENSIO
2. ALL ESCAPES OR RESCUE WIN
W/ 20" IN WIDTH AND 24" IN

DIVISION 9 – FINISHES

1. DRYWALL: WATER RESISTANT GREEN
GARAGES DRYWALLED AND TAPED (NO TE
2. INTERIOR TRIM: ALL INTERIOR TRIM T

PART	LO
NEWEL POST	EACH
FULL RAILING	OPTIO
BALUSTERS	EXPO
BASEBOARD	WALL
CASING	DOC
	1/2 WALLS
WALL CAPS	VARI
DOOR JAMBS	ALL SW
CLOSET/LINEN/LAUNDRY SHELVING	

GENERAL: ROUNDED BASE IS TO BE USED

DIVISION 15 – MECHANICAL

1. PLUMBING GENERAL: GAS LINES TO BE
FIREPLACE, GAS DRYER, AND GAS RANGE.
BOXES USED AT ALL LAUNDRY STATIONS.
CONCRETE FLOOR. ALL SUPPLY LINES TO
PORCH OR REAR DECKS, BUT AS SHOWN O
ALL ROOF JACKS TO BE GALVANIZED. AL
TILE ROOF OPTION WILL REQUIRE DOUBLE J
2. HEATING AND VENTILATION: HEATING
MINIMUM OF 80% EFFICIENCY WITH ELECTRO
PROVIDE (2) 6" ~ EXTERNAL COMBUSTION
AREA: ONE @ 1'-0" BELOW THE CEILING &
IS NOT TO EXCEED 14'-0".
GENERAL: OUTSIDE COMBUSTION AIR MUST
EXHAUST SYSTEMS MUST BE CONNECTED D
VENTS REQUIRED FOR LAUNDRY ROOM DRY
3. FIREPLACES ARE TO BE U.L. APPROVED
MANUFACTURERS SPECIFICATIONS & RECOM

DIVISION 16 – ELECTRICAL

WIRING WILL BE DONE PER CODE PER PLAN
LOCATED AS PER THE BLUEPRINTS. METER
EACH OTHER ON A 110V CIRCUIT AND EACH
CENTER AT OPTIONAL GARAGE DOOR OPENE
THE GAS APPLIANCES (THE 110 WILL BE I
CEILING FAN PRE-WIRE OPTIONAL, ONE IN 1
AND ONE REAR. ALL SWITCHES TO BE ROC
LIGHTS ARE STANDARD. PREWIRES FOR 80
UNDER THE DRYWALL. (LOW VOLTAGE) NO
A WINDOW MUST BE OPEN WHILE ATTIC FAN
BE CREATED WITHOUT AN OPEN WINDOW.
BATH, KITCHEN, GARAGE & EXTERIOR OUTLE

CODE COMPLIANCE

THESE PLANS MEET OR EXCEED THE FOLLOWING BUILDING CODES PER LOCHBUIE BUILDING DEPARTMENT SUBMITTAL REQUIREMENTS:
- 2003 I.R.C.
- 2000 I.E.C.C.
- 2002 N.E.C.
- A.S.C.E. 7-02
- T.P.I. 1-2000
- N.D.S. – 01
- ACI 318-02

DIVISION 7 – THERMAL MOISTURE PROTECTION

ROOFING: ALL ROOFS ARE LIFETILE "TRADITIONAL SHAKE TILE" INSTALLED OVER 2 LAYERS OF 30 LB. FELT. ALL STEP FLASHING TO BE INSTALLED AT VERTICAL WALLS AT THE TIME THE ROOF IS INSTALLED. ROOF MUST BE INSTALLED PRIOR TO SIDING BEING APPLIED. PROVIDE CONTINUOUS RIDGE AND VINYL SOFFIT VENTS PER CODE.

2. INSULATION: STANDARD PACKAGE (AS PER SUBMITTED "MODEL ENERGY CODE")
   - A) WALLS 2X4 = R-13 BLOW IN CELLULOSE
   - B) WALLS 2X6 = R-19
   - C) CEILING = R-30 BLOW IN CELLULOSE ON FLAT SURFACES AND BATTED IN VAULTS
   - D) FOUNDATION = R-5 RIGID FOAM INSULATION

   BAYS, CANTILEVERS AND OTHER OVER HANGS = R-19 BATT INSULATION

3. AIR INFILTRATION PACKAGE: CONSISTS OF FOAM SEALANT AT THE SILLS, GAPS IN FRAMING, BEHIND OUTLETS AND PENETRATIONS INTO THE ATTIC.
4. GUTTERS AND DOWNSPOUTS: GUTTERS ARE TO BE GALVANIZED 4" STEEL PAINTED ON SITE. DOWN SPOUTS ARE TO BE PRE-FINISHED ALUMINUM W/ 5'-0" TIP UPS.

DIVISION 8 – DOORS AND WINDOWS

1. FRONT DOOR: TO BE 6'-8" HIGH X 3' WIDE, STEEL INSULATED (6) PANEL FIBERGLASS WITH SIDELIGHTS PER PLAN ON EXTERIOR JAMB WITH 3 HINGES, WEATHER STRIPPING, ADJUSTABLE OAK THRESHOLD PER CODE
2. HOUSE: TO BE 6'-8" HIGH (WIDTH VARIES PER PLAN).
3. GARAGE: TO BE 6'-8" HIGH AND 2'-8" WIDE, TO HAVE A 20 MIN. FIRE RATING, BEING 1 3/8" MIN. PER CODE
4. INTERIOR DOORS: JAMBS, CASING, AND INTERIOR TRIM TO BE PRE-FINISHED PER LOCAL CODE.
5. WINDOWS: STANDARD WINDOWS AND SLIDING DOORS TO BE DOUBLE GLAZED, WHITE VINYL; GRIDS ON FRONT ELEVATION PER PLAN AND WINDOWS VISIBLE FROM FRONT ENTRY. WINDOW CONFIGURATION SHALL BE PER PLAN, SINGLE HUNG, SLIDER, OR FIXED. ALL WINDOWS TO HAVE 1" X ROUTED EDGE WOOD WINDOW SILL WITH CASING UNDER, (UNLESS CLERESTORY WINDOW OR SIDELIGHT). ALL MASTER BATH WINDOWS ABOVE TUBS ARE REQUIRED TO BE TEMPERED

NOTES:
1. EXTERIOR DOORS SHALL OPEN ON TO A LANDING NOT LESS THAN 6" AND MORE THAN 7.5" BELOW THE HIGHEST POINT OF THE DOOR'S THRESHOLD. THE LANDING WILL HAVE MINIMUM DIMENSIONS OF 36" X 36". THE HIGHEST POINT OF ANY THRESHOLDS WILL NOT BE MORE THAN 1" ABOVE THE INTERIOR FINISHED FLOOR SURFACE.
2. ALL ESCAPES OR RESCUE WINDOWS SHALL HAVE A MINIMUM NET CLEAR OPENING AREA OF 5.7 SQ. FT. AND A MINIMUM CLEAR OPENING OF NOT LESS THAN 5.7 SQ. FT. W/ 20" IN WIDTH AND 24" IN HEIGHT. MAXIMUM SILL HEIGHT OF EGRESS WINDOWS SHALL BE NO HIGHER THAN 44" ABOVE THE INTERIOR FLOOR PER CODE.

DIVISION 9 – FINISHES

1. DRYWALL: WATER RESISTANT GREEN BOARD USED ON ALL WALLS IN BATHS WITH TUBS AND/OR SHOWERS. TEXTURE TO BE KNOCK DOWN ON WALLS AND CEILINGS GARAGES DRYWALLED AND TAPED (NO TEXTURE) TO CODE AND ROCKED ONLY IN AREAS REQUIRED BY BUILDING CODE
2. INTERIOR TRIM: ALL INTERIOR TRIM TO BE PRE-FINISHED WHITE.

PART	LOCATION/SIZE	MATERIAL	MANUF.
NEWEL POST	EACH TERMINATION OF FREE RAIL	FIR	PNP-448
FULL RAILING	OPTIONAL ON ALL EXPOSED STAIRS		
BALUSTERS	EXPOSED STAIRS, STRAIGHT	FIR	TURNED
BASEBOARD	WALL AT FLOOR – 3-1/4"	FJ PINE	ANDERSON-WM346
CASING	DOOR JAMBS, WINDOW SILLS, 1/2 WALLS – 2-1/4"	FJ PINE WM346	ANDERSON
WALL CAPS	VARIOUS – 1" X OR 3/4" PLY	FJ PINE	
DOOR JAMBS	ALL SWING DOORS	FJ PINE	
CLOSET/LINEN/LAUNDRY SHELVING		VENTILATED	CLOSETMAID

GENERAL: ROUNDED BASE IS TO BE USED AT ALL ROUNDED BEAD LOCATIONS.

DIVISION 15 – MECHANICAL

1. PLUMBING GENERAL: GAS LINES TO BE RIGID AND ARE TO BE RUN STANDARD TO THE FURNACE, WATER HEATER AND INCLUDED W/ OPTIONAL FIREPLACE, GAS DRYER, AND GAS RANGE. WATER LINE TO THE REFRIGERATOR IS INCLUDED WITH THE REFRIGERATOR OPTIONS. "CATCH-A-DRIP" BOXES USED AT ALL LAUNDRY STATIONS. PLASTIC USED FOR ALL WASTE LINES WITH EXPANSION JOINTS USED WHERE LINE PASSES THROUGH CONCRETE FLOOR. ALL SUPPLY LINES TO BE COPPER. TWO NO-FREEZE SILL COCKS, (ELKHART #885-AS-8), ARE NOT TO BE PLACED OVER FRONT PORCH OR REAR DECKS, BUT AS SHOWN ON PLANS. THE WATER HEATER IS A RANNAI 2520 -FFU DIRECT VENT, FORCED COMBUSTION PER PLAN ALL ROOF JACKS TO BE GALVANIZED. ALL WASTE STACKS ARE TO BE RUN THROUGH THE ROOF BEHIND THE RIDGE. TILE ROOF OPTION WILL REQUIRE DOUBLE JACKS AT ALL LOCATIONS.
2. HEATING AND VENTILATION: HEATING IS BY A GAS FORCED AIR FURNACE. THIS FURNACE IS TO BE RATED AT A MINIMUM OF 80% EFFICIENCY WITH ELECTRONIC IGNITION AND HIGH VOLUME FAN. PROVIDE (2) 6" ~ EXTERNAL COMBUSTION AIR DUCTS TO THE FURNACE AREA: ONE @ 1'-0" BELOW THE CEILING & ONE @ 1'-0" ABOVE THE FLOOR. DRYER VENT LENGTH IS NOT TO EXCEED 14'-0".

   GENERAL: OUTSIDE COMBUSTION AIR MUST COMPLY WITH UMC SEC.701.1 EXHAUST SYSTEMS MUST BE CONNECTED DIRECTLY OUT SIDE AND SHALL BE 3' INSIDE PROPERTY LINES. VENTS REQUIRED FOR LAUNDRY ROOM DRYER & BATHS WILL CONFORM TO I.R.C.
3. FIREPLACES ARE TO BE U.L. APPROVED AND ARE BE INSTALLED IN STRICT CONFORMANCE WITH MANUFACTURERS SPECIFICATIONS & RECOMMENDATIONS.

DIVISION 16 – ELECTRICAL

WIRING WILL BE DONE PER CODE PER PLAN WITH LIGHTING AND SWITCH LOCATIONS AS SHOWN ON PLANS. PANEL SHALL BE SQUARE D 150 AMP, LOCATED AS PER THE BLUEPRINTS. METER HOUSING AND SERVICE PANEL TO BE ONE PIECE. ALL SMOKE DETECTORS MUST BE INTERCONNECTED WITH EACH OTHER ON A 110V CIRCUIT AND EACH HAVE A 9V BATTERY BACKUP. PLEASE NOTE THAT THERE IS ONE OUTLET IN THE GARAGE CEILING AT THE CENTER AT OPTIONAL GARAGE DOOR OPENER LOCATION. PLEASE NOTE THAT ONE 110V OUTLET WILL ACCOMPANY ALL GAS LINE OPTIONS TO ACCOMMODATE THE GAS APPLIANCES (THE 110 WILL BE IN ADDITION TO THE 220). SECONDARY BEDROOMS INCLUDE TV AND PHONE AS OPTIONAL. THERE ARE TWO CEILING FAN PRE-WIRE OPTIONAL, ONE IN THE MASTER BEDROOM AND ONE IN THE FAMILY ROOM. THERE ARE TWO EXTERIOR OUTLETS – ONE FRONT AND ONE REAR. ALL SWITCHES TO BE ROCKER (VS. TOGGLE), AND ALL OUTLETS / SWITCHES / PLATES TO BE WHITE PLASTIC. TWO EXTERIOR GARAGE LIGHTS ARE STANDARD. PREWIRES FOR BOTH GARAGE DOORS ARE STANDARD UNDER THE DRYWALL (LOW VOLTAGE) NOTE: THE ATTIC FAN IS DESIGNED AS AN AID TO VENTILATION ONLY AND IS NOT A COMPLETE COOLING SYSTEM. A WINDOW MUST BE OPEN WHILE ATTIC FAN IS OPERATING TO PREVENT PILOT FLAMES FROM BEING EXTINGUISHED BY THE VACUUM THAT COULD BE CREATED WITHOUT AN OPEN WINDOW. GROUND FAULT CIRCUIT INTERRUPTER, (GFCI), PROTECTION IS TO BE PROVIDED TO ALL BATH, KITCHEN, GARAGE & EXTERIOR OUTLETS.

CODE COMPLIANCE

THESE PLANS MEET OR EXCEED THE FOLLOWING BUILDING CODES PER LOCHBUIE BUILDING DEPARTMENT SUBMITTAL REQUIREMENTS:
- 2003 I.R.C.
- 2000 I.E.C.C.
- 2002 N.E.C.
- A.S.C.E. 7-02
- T.P.I. 1-2000
- N.D.S. – 01
- ACI 318-02

BUILDING AREA CALCULATIONS

MAIN LEVEL	702 S.F.
UPPER LEVEL	1,093 S.F.
TOTAL STANDARD FINISHED	1,756 S.F.
TOTAL FINISHED W/ OPTION	N.A.

PLAN T05 DRAWING INDEX:

A1	FOUNDATION PLAN
A2	MAIN FLOOR PLAN
A3	UPPER FLOOR PLAN
A4	STANDARD ELEVATIONS
A4.1	ELEVATION OPTION "A"
A4.2	ELEVATION OPTION "B"
A5	CROSS SECTIONS
A6	CABINET ELEVATIONS
A6.1	CABINET ELEVATIONS
A7	FIREPLACE ELEVATIONS
E1	MAIN / UPPER FLOOR ELECTRICAL PLAN
S1	FOUNDATION FOOTING PLAN & DETAILS
S2	FOUNDATION PLAN & DETAILS
S3	SECOND FLOOR FRAMING PLAN & DETAILS
S4	ROOF FRAMING PLAN & DETAILS

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COVER PAGE

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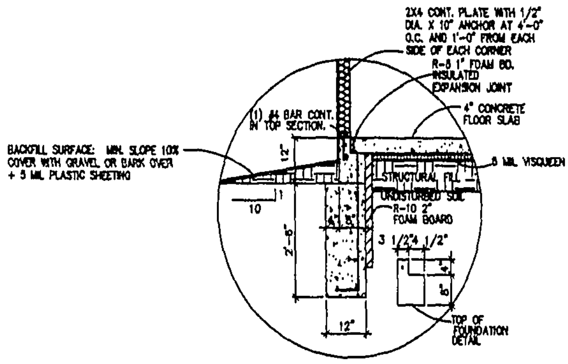
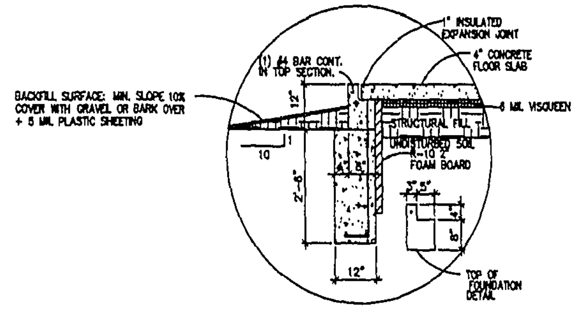
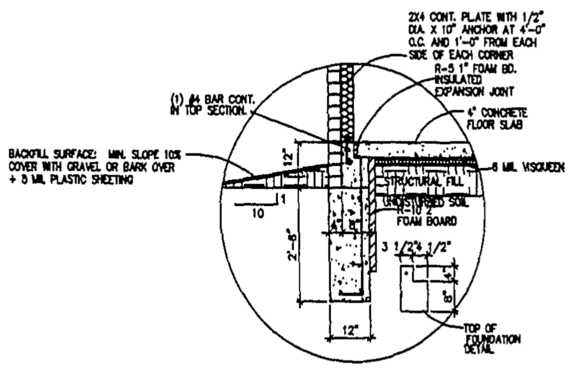


1 / A1 **FOUNDATION WALL SECTION**
1/2" = 1'-0"

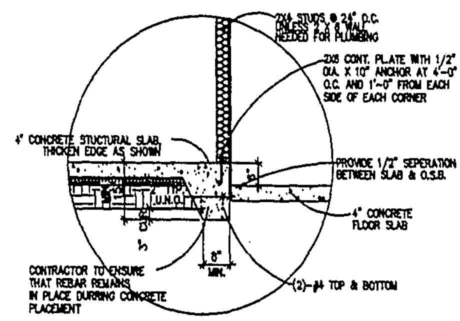


3 / A1 **FOUNDATION WALL SECTION AT DOOR OPENINGS**
1/2" = 1'-0"

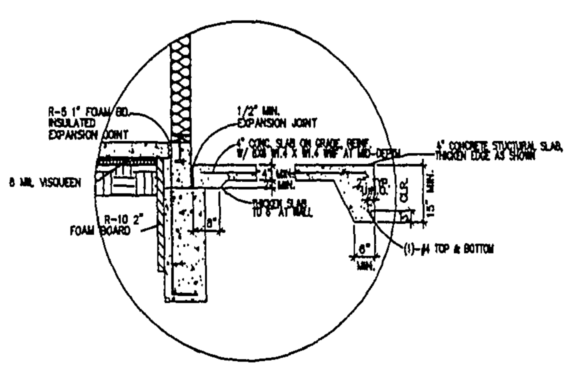
A / A5



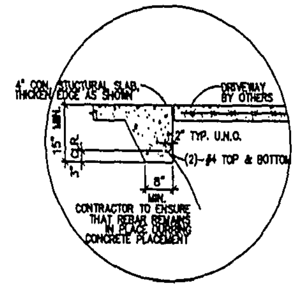
2 / A1 **FOUNDATION WALL SECTION W/ BRICK (STD. + 'A' ELEV. ONLY)**
1/2" = 1'-0"



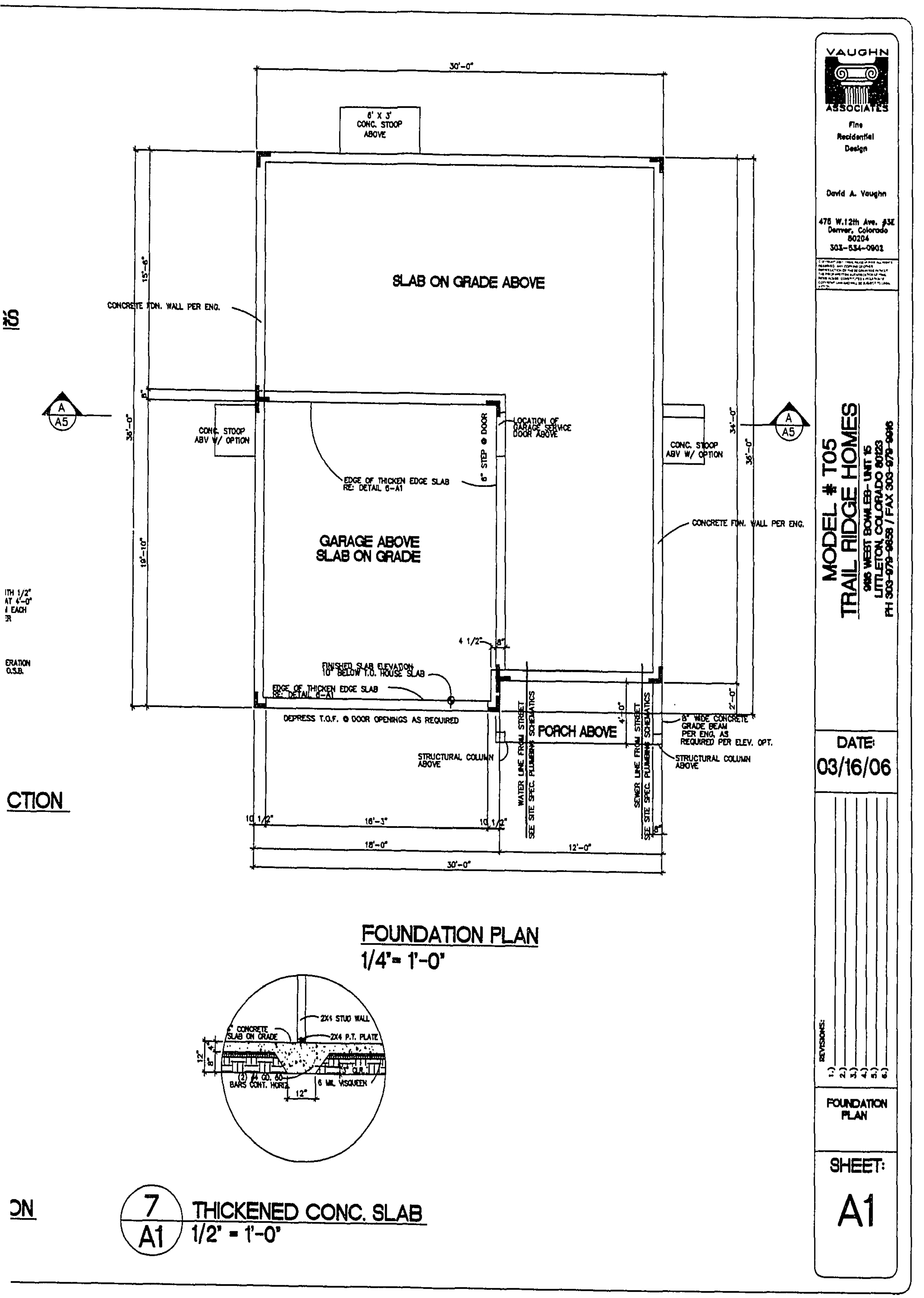
4 / A1 **GARAGE/HOUSE FOUNDATION SECTION**
1/2" = 1'-0"



5 / A1 **CONCRETE PORCH SECTION**
1/2" = 1'-0"



6 / A1 **GARAGE DOOR FOUNDATION SECTION**
1/2" = 1'-0"



30'-0"
6' X 3' CONC. STOOP ABOVE
SLAB ON GRADE ABOVE
CONCRETE FDN. WALL PER ENG.
15'-8"
36'-0"
19'-10"
CONC. STOOP ABV W/ OPTION
LOCATION OF GARAGE SERVICE DOOR ABOVE
6" STEP @ DOOR
EDGE OF THICKEN EDGE SLAB RE: DETAIL 6-A1
GARAGE ABOVE SLAB ON GRADE
CONC. STOOP ABV W/ OPTION
34'-0"
36'-0"
CONCRETE FDN. WALL PER ENG.
4 1/2"
FINISHED SLAB ELEVATION 10" BELOW T.O. HOUSE SLAB
EDGE OF THICKEN EDGE SLAB RE: DETAIL 6-A1
DEPRESS T.O.F. @ DOOR OPENINGS AS REQUIRED
STRUCTURAL COLUMN ABOVE
WATER LINE FROM STREET
SEE SITE SPEC. PLUMBING SCHEMATICS
PORCH ABOVE
4'-0"
SEWER LINE FROM STREET
SEE SITE SPEC. PLUMBING SCHEMATICS
2'-0"
8" WIDE CONCRETE GRADE BEAM PER ENG. AS REQUIRED PER ELEV. OPT.
STRUCTURAL COLUMN ABOVE
10 1/2"
16'-3"
10 1/2"
18'-0"
12'-0"
30'-0"
FOUNDATION PLAN
1/4" = 1'-0"
2X4 STUD WALL
CONCRETE SLAB ON GRADE
2X4 P.T. PLATE
(2) #4 GD. 60 BARS CONT. HORIZ.
6 MIL VISQUEEN
12"
7
A1
THICKENED CONC. SLAB
1/2" = 1'-0"
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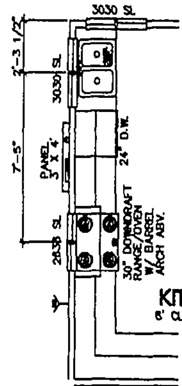
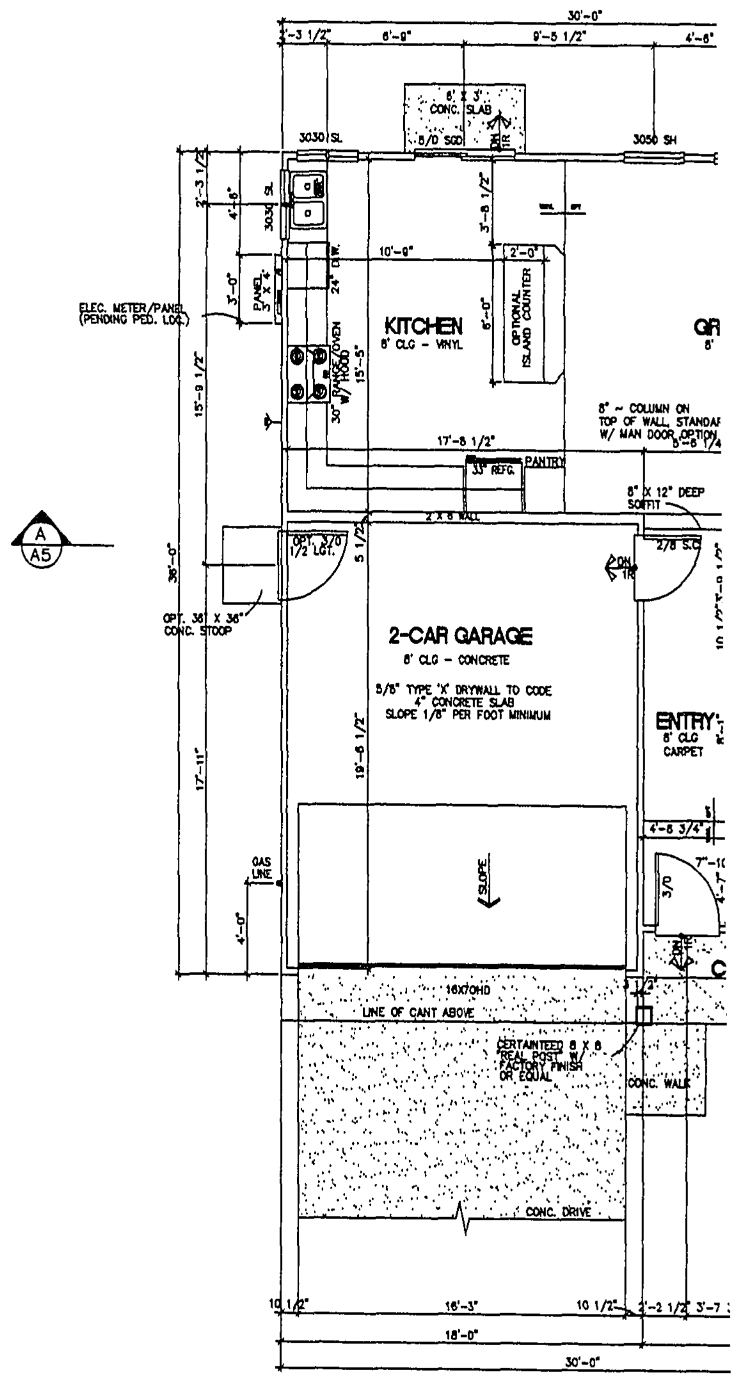
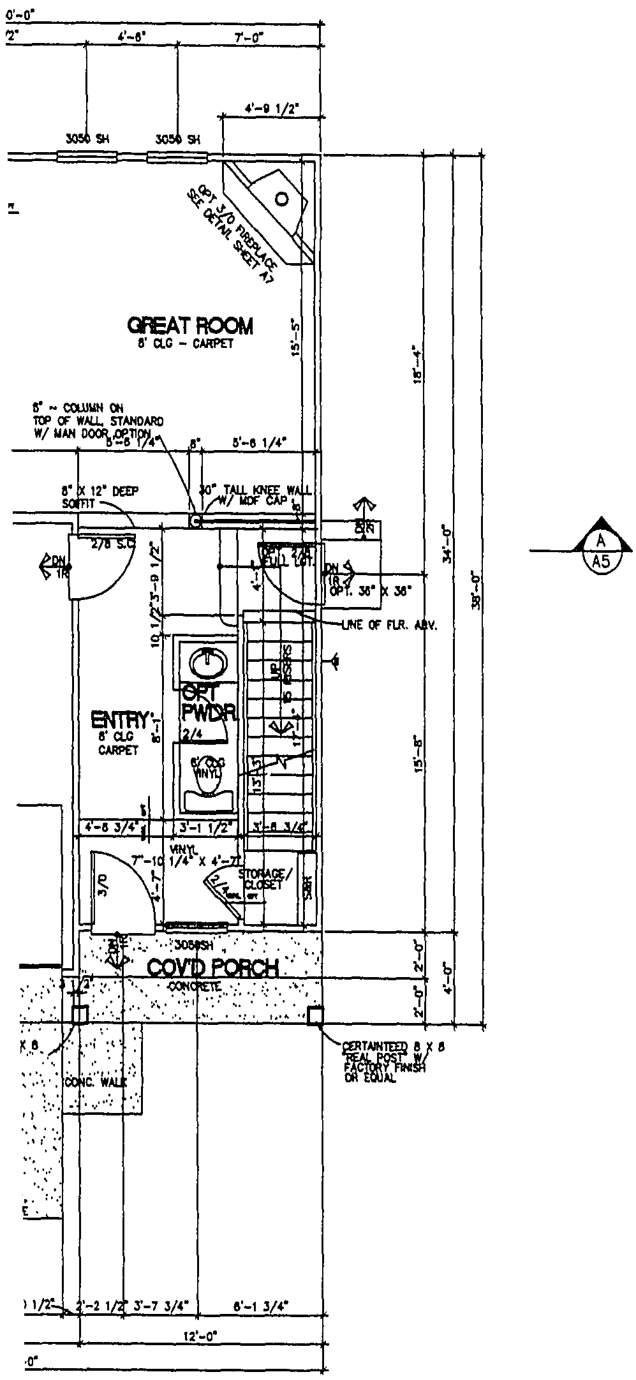
FOUNDATION PLAN
SHEET:
A1



KITCHEN OPT.
1/4"= 1'-0"

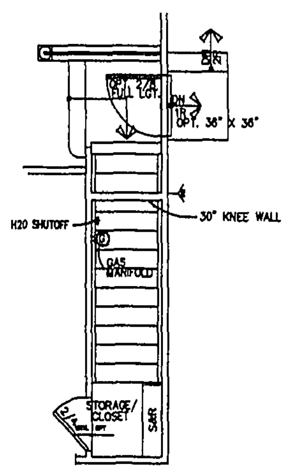


MAIN FLOOR PLAN
1/4"= 1'-0" 702 S.F.
355 S.F.



PLAN

702 S.F.
355 S.F. GARAGE



STOR. CLOSET DETAIL
1/4"= 1'-0"

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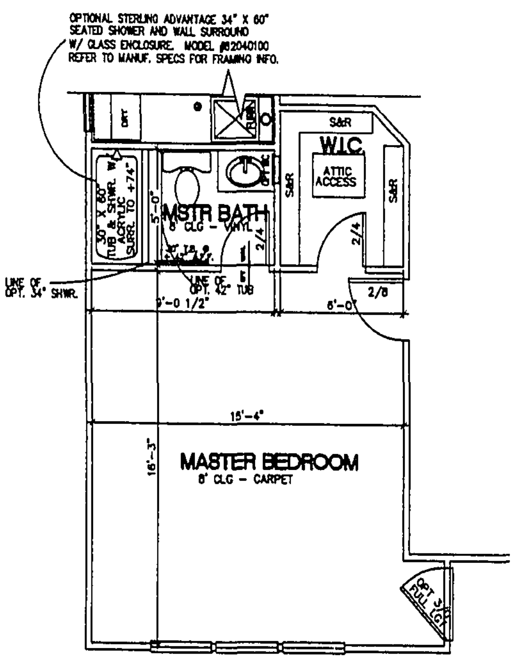
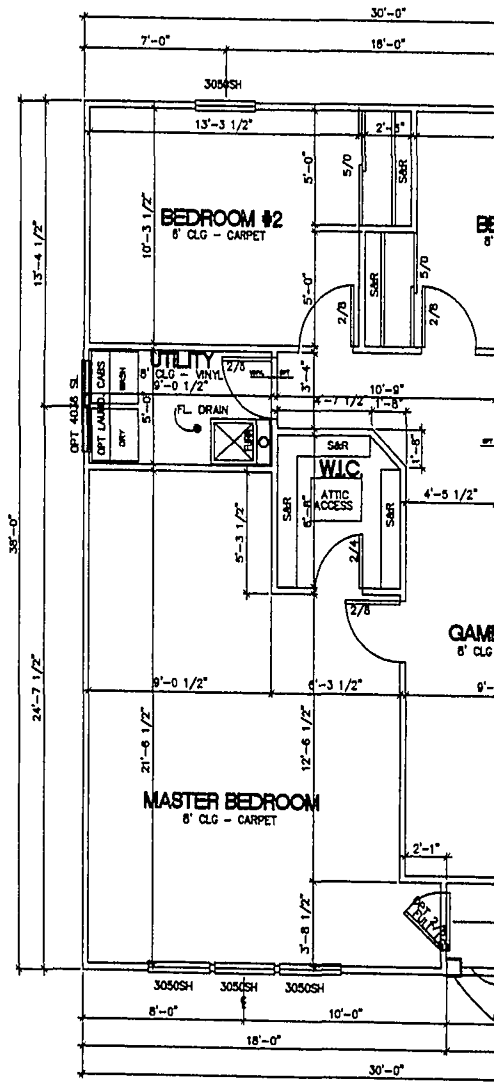
MAIN FLOOR PLAN

SHEET:
A2



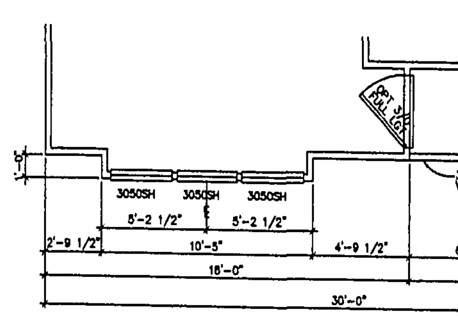
OPT MASTER BATH PLAN

1/4"= 1'-0"



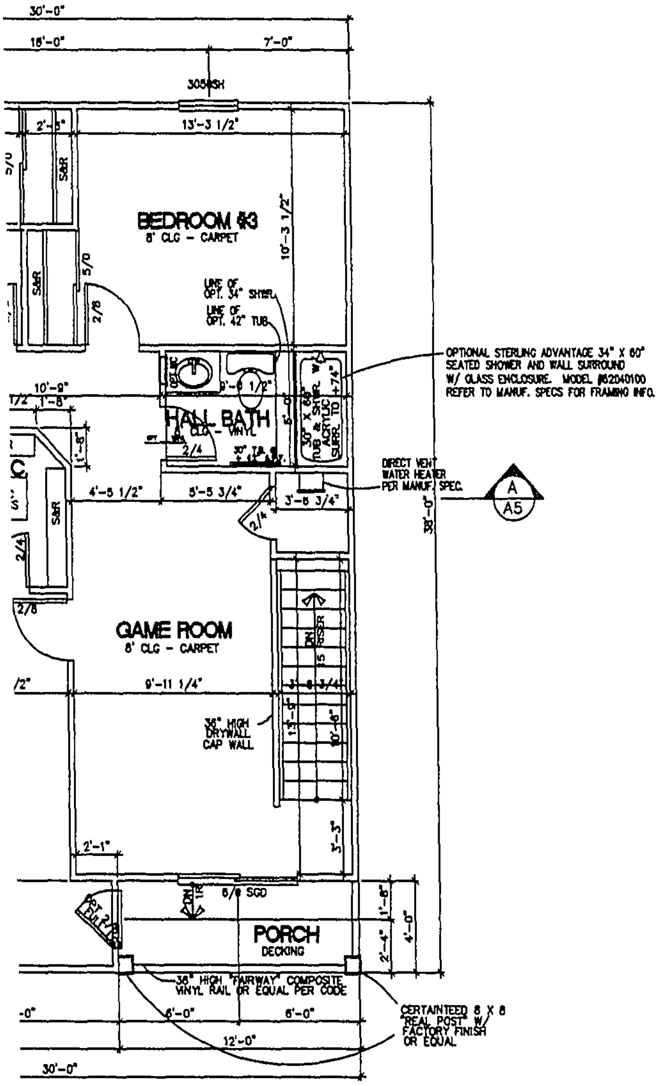
UPPER FLOOR PLAN- STA

1/4"= 1'-0"



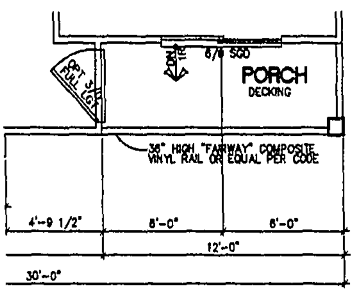
ELEV 'A' PARTIAL SECOND F

1/4" = 1'-0"

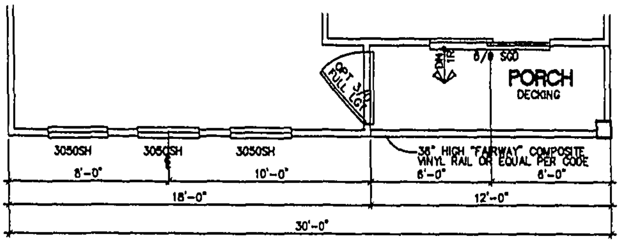


R PLAN- STANDARD

1,054 S.F.



. SECOND FLOOR PLAN



ELEV "B" PARTIAL SECOND FLOOR PLAN

1/4" = 1'-0"

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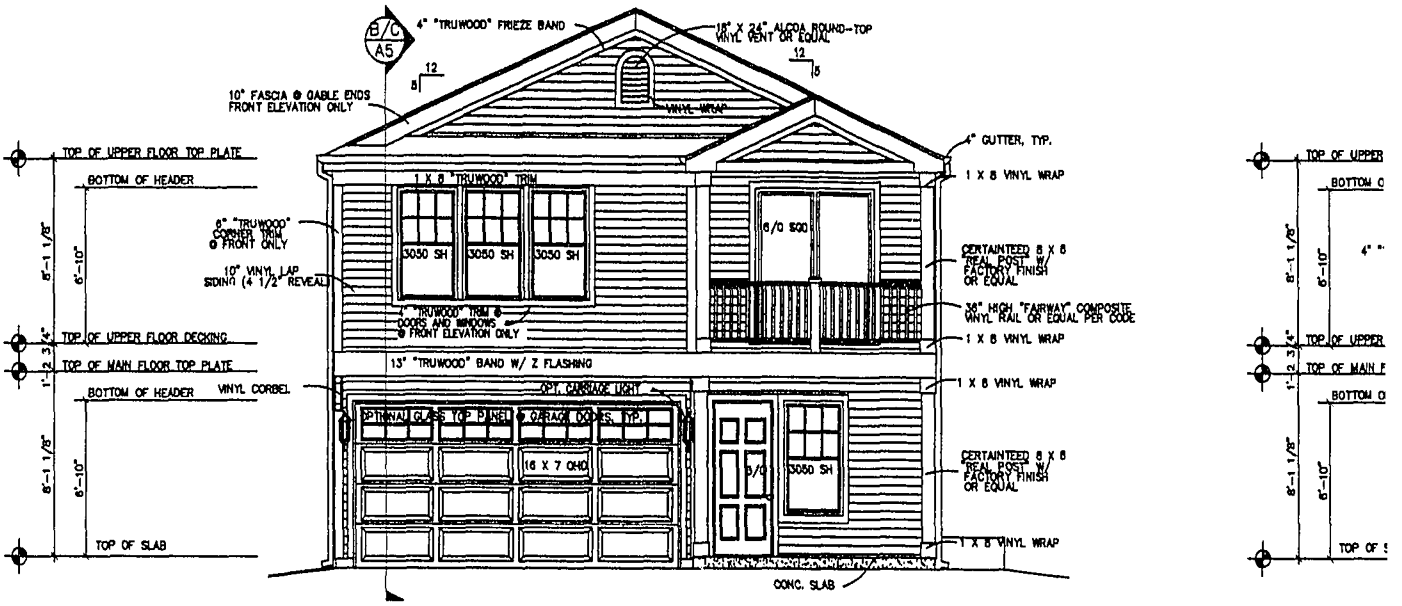
UPPER FLOOR PLAN

SHEET:
A3

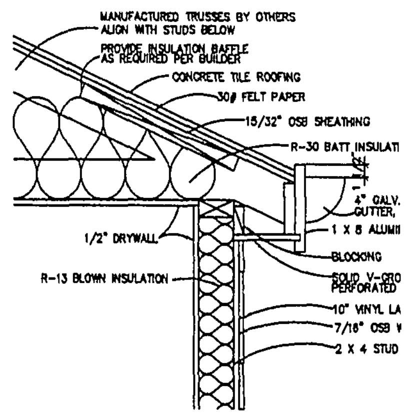


STANDARD FRONT ELEVATION

1/4"= 1'-0"

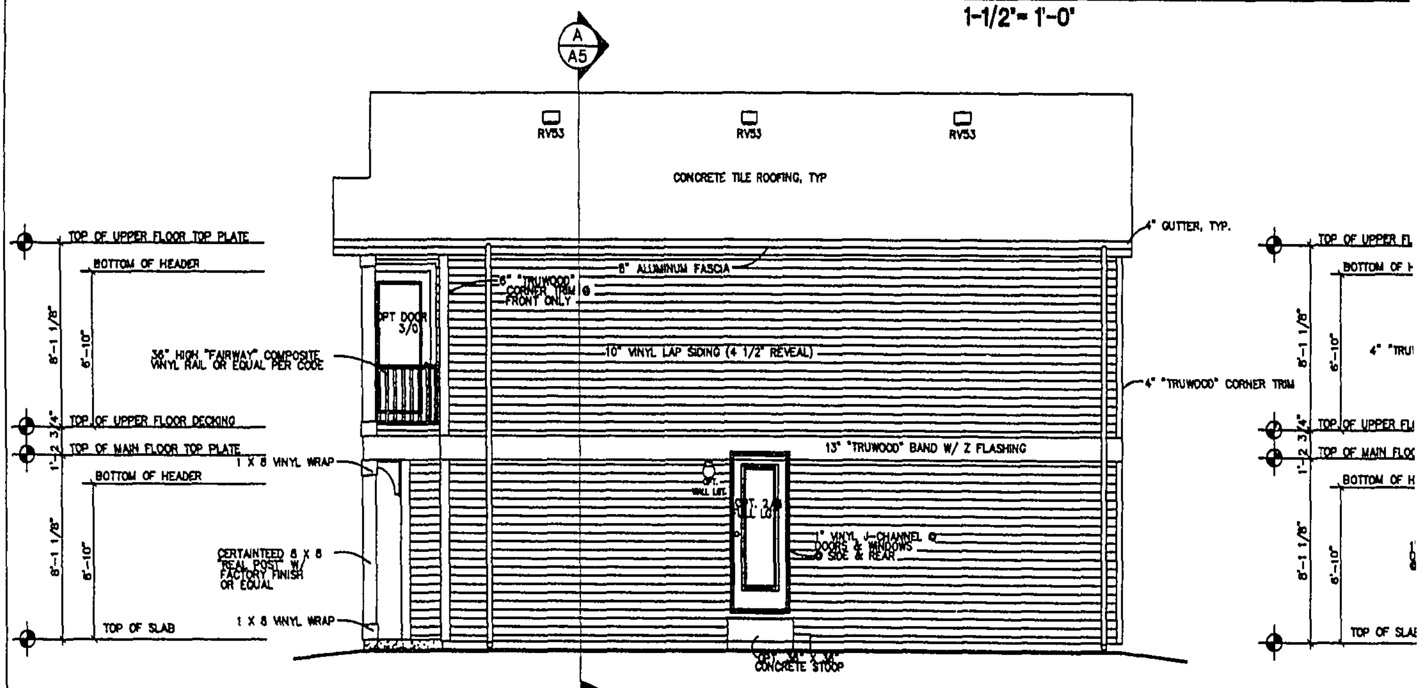
ROOF VENTILATION CALCULATION

1. CEILING AREA = 1,092 SQ. FT.
2. VENT AREA REQUIRED
   1 S.F. VENT PER 300 S.F. CEILING AREA
   1,092 S.F. CEILING AREA / 300 = 3.64 S.F. TOTAL VENT AREA REQUIRED
3. DISTRIBUTE VENTS
   50% (1.82 SQ. FT.) AT RIDGE
   50% (1.82 SQ. FT.) AT EAVE
4. NUMBER OF VENTS
   EAVE VENTS: 1.82 S.F. REQUIRED AREA / 0.9 S.F. NET FREE AREA PER VENT = 2-3 VENTS
   RIDGE VENTS: 1.82 S.F. REQUIRED AREA / 0.6 S.F. NET FREE AREA PER VENT = 3-4 VENTS



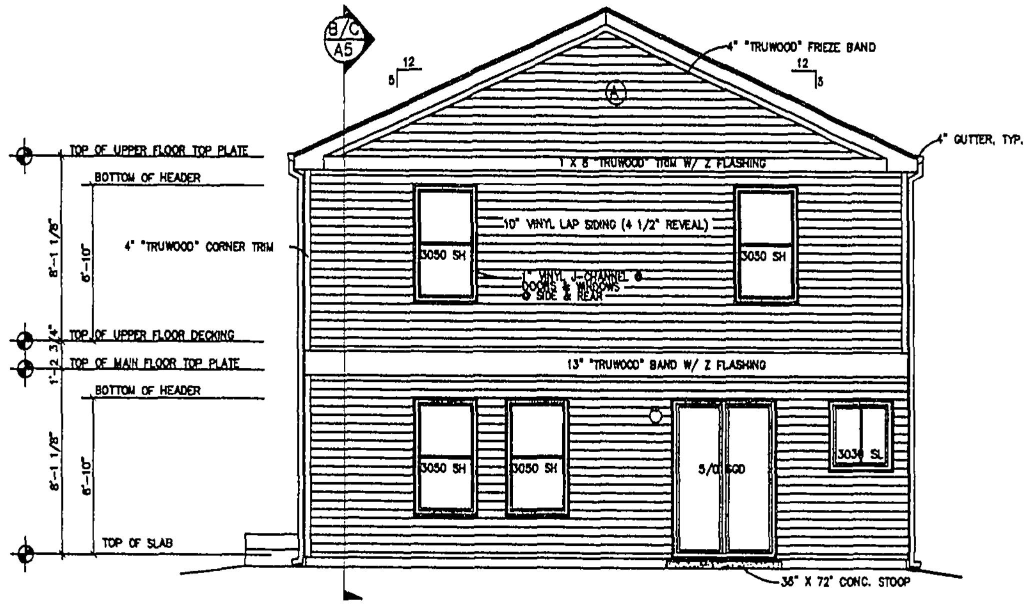
TYPICAL SOFFIT AND EAVE DET

1-1/2"= 1'-0"



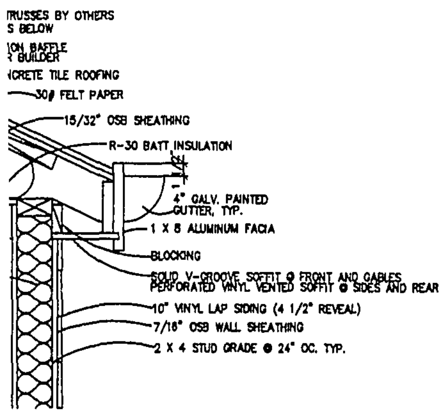
STANDARD RIGHT ELEVATION

1/4"= 1'-0"

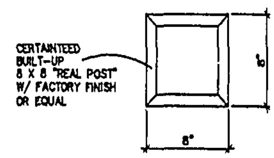


STANDARD REAR ELEVATION

1/4"= 1'-0"



AND EAVE DETAIL

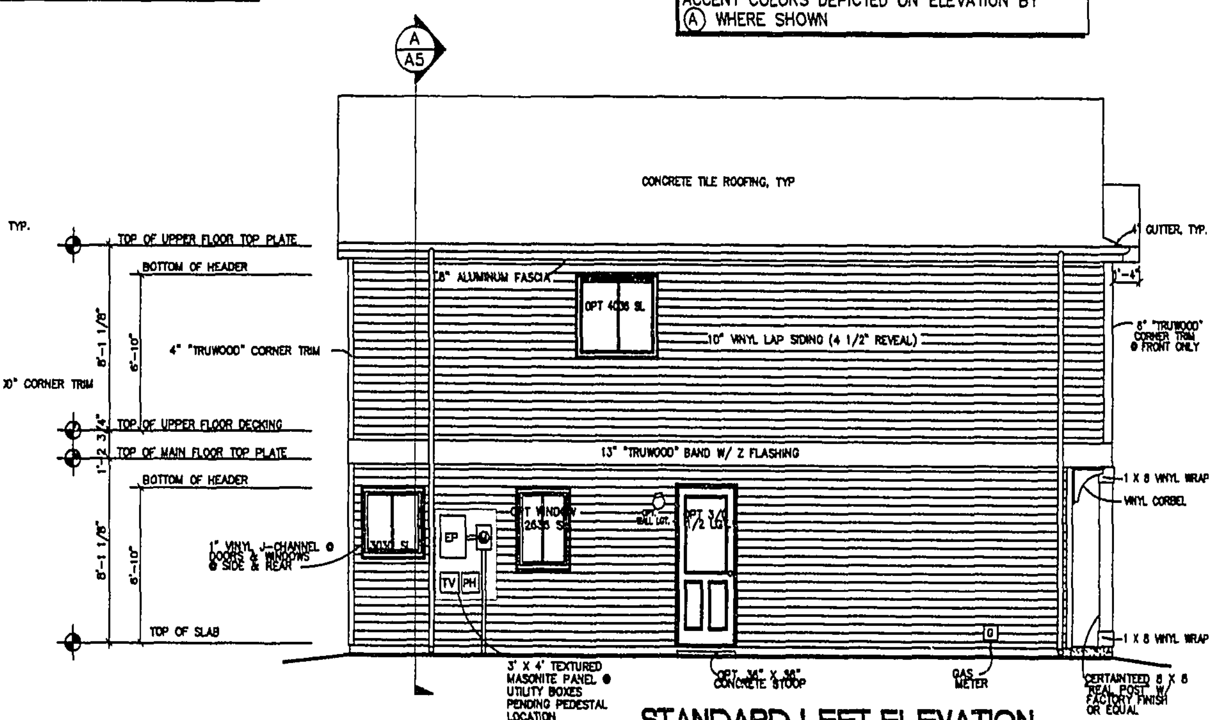


POST SECTION

1-1/2"= 1'-0"

NOTE:

STANDARD BODY COLOR ON ELEVATIONS IS SIDING, BRICK, OR STONE PER ELEVATION OPT. ACCENT COLORS DEPICTED ON ELEVATION BY (A) WHERE SHOWN



STANDARD LEFT ELEVATION

1/4"= 1'-0"

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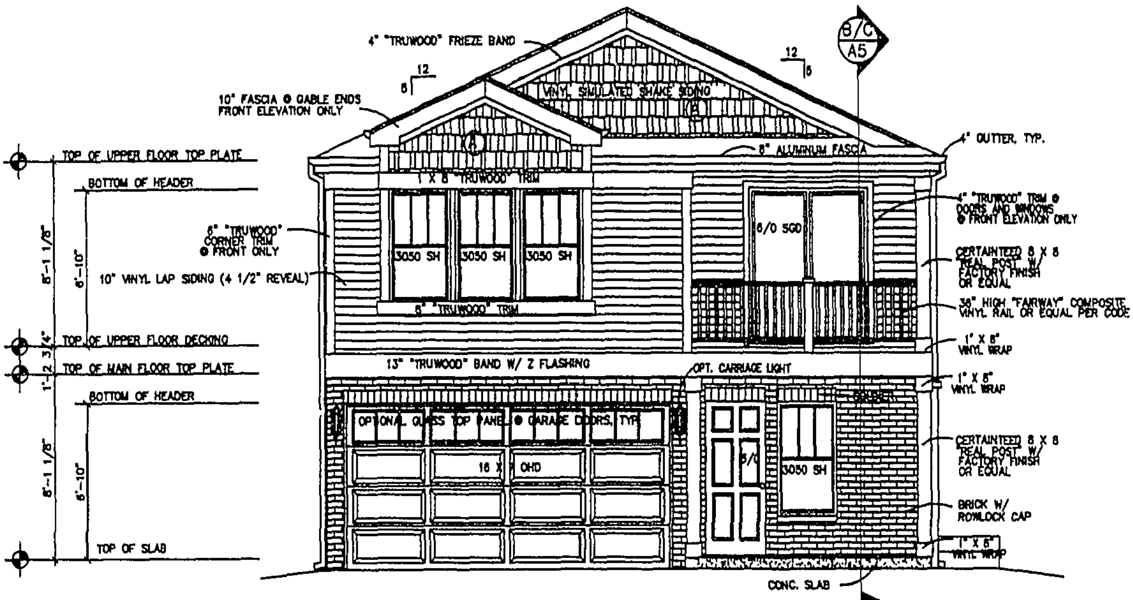
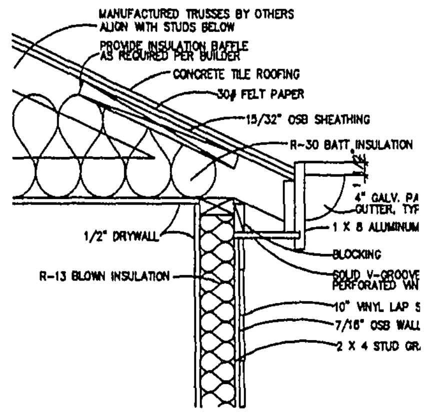
STANDARD ELEVATION

SHEET:
A4



FRONT ELEVATION 'A'

1/4" = 1'-0"



TYPICAL SOFFIT AND EAVE DETAI

1-1/2" = 1'-0"

ROOF VENTILATION CALCULATION

1. CEILING AREA = 1,092 SQ. FT.

2. VENT AREA REQUIRED
   1 S.F. VENT PER 300 S.F. CEILING AREA
   1,092 S.F. CEILING AREA / 300 = 3.64 S.F. TOTAL VENT AREA REQUIRED

3. DISTRIBUTE VENTS
   50% (1.82 SQ. FT.) AT RIDGE
   50% (1.82 SQ. FT.) AT EAVE

4. NUMBER OF VENTS
   EAVE VENTS: 1.82 S.F. REQUIRED AREA / 0.9 S.F. NET FREE AREA PER VENT = 2-3 VENTS
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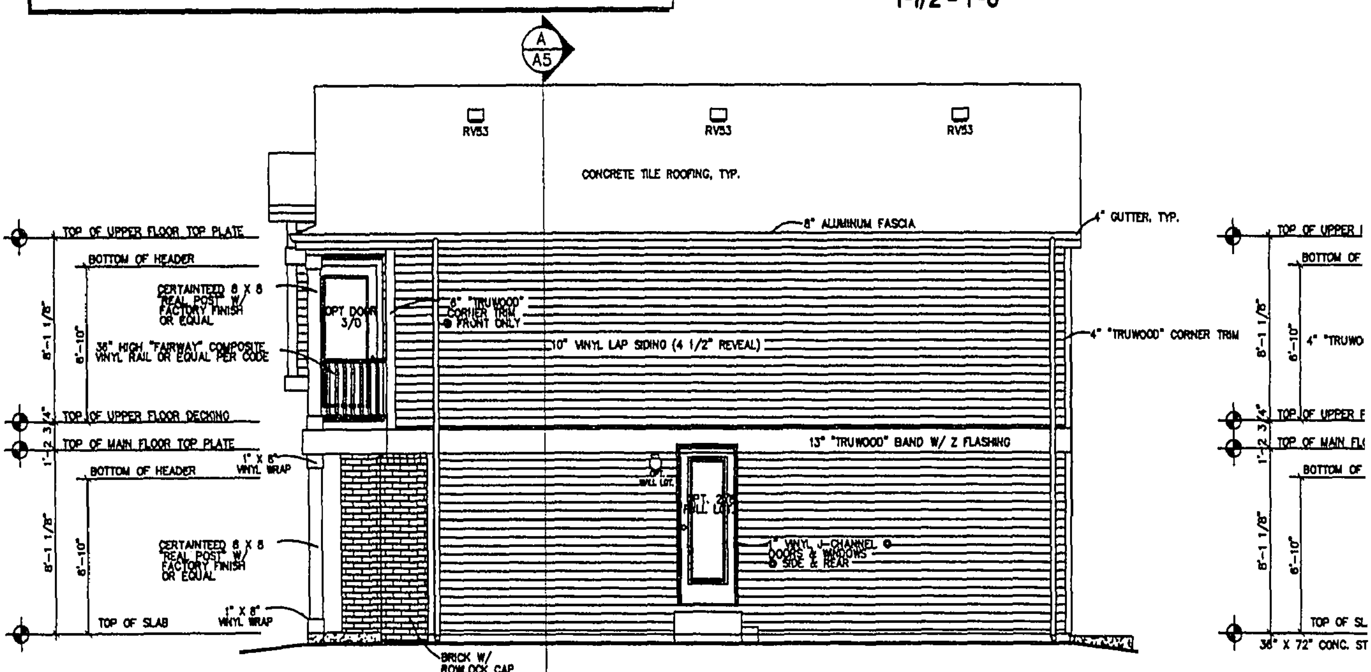
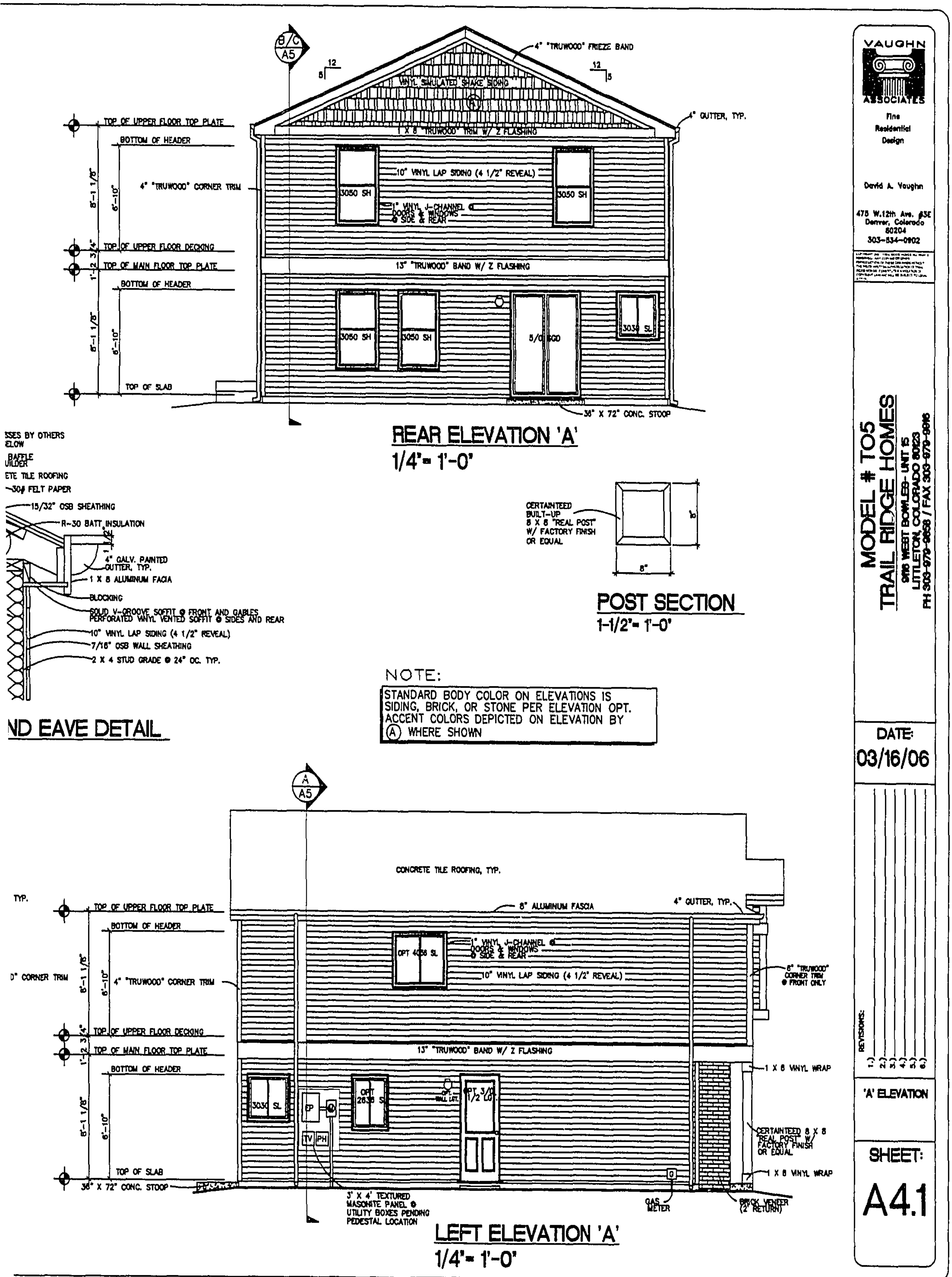
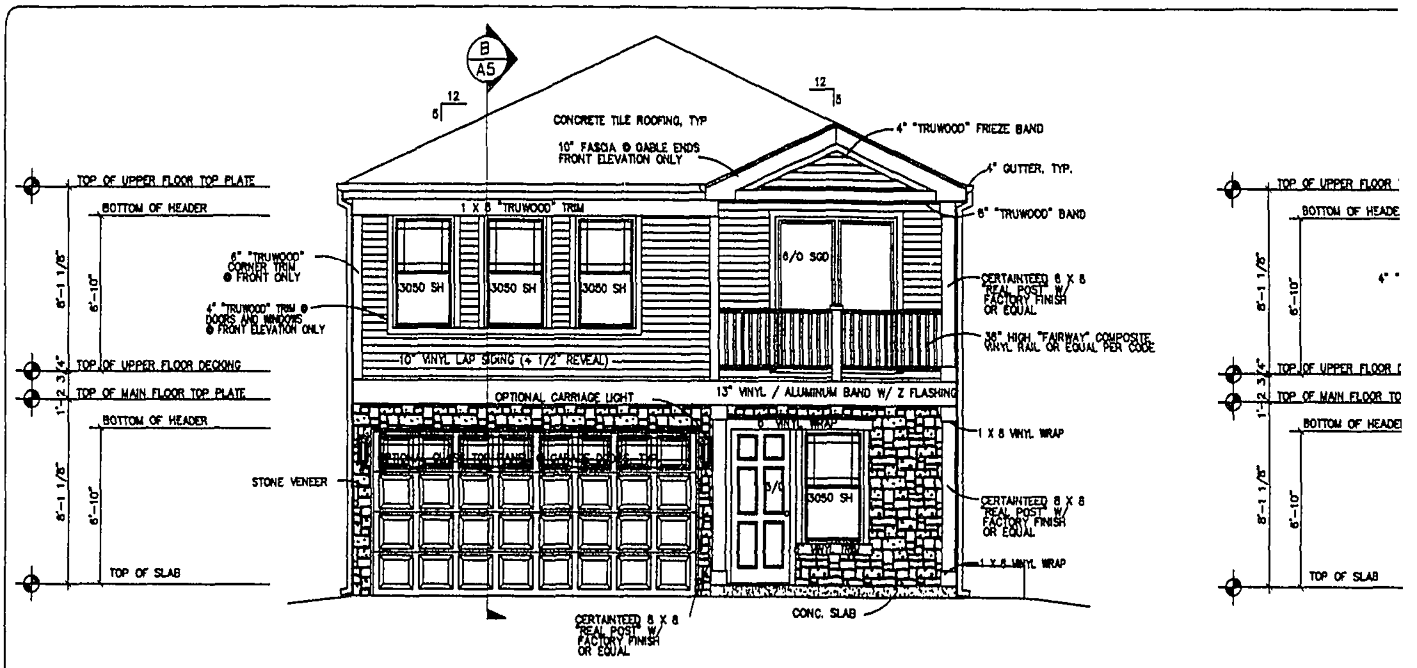


RIGHT ELEVATION 'A'

1/4" = 1'-0"



4" "TRUWOOD" FRIEZE BAND
VINYL SIMULATED SHAKE SIDING
4" GUTTER, TYP.
TOP OF UPPER FLOOR TOP PLATE
BOTTOM OF HEADER
1 X 8 "TRUWOOD" TRIM W/ Z FLASHING
10" VINYL LAP SIDING (4 1/2" REVEAL)
4" "TRUWOOD" CORNER TRIM
3050 SH
1" VINYL J-CHANNEL @ DOORS & WINDOWS @ SIDE & REAR
TOP OF UPPER FLOOR DECKING
TOP OF MAIN FLOOR TOP PLATE
13" "TRUWOOD" BAND W/ Z FLASHING
3030 SL
TOP OF SLAB
36" X 72" CONC. STOOP
REAR ELEVATION 'A'
1/4"= 1'-0"
15/32" OSB SHEATHING
R-30 BATT INSULATION
4" GALV. PAINTED GUTTER, TYP.
1 X 8 ALUMINUM FACIA
BLOCKING
SOLID V-GROOVE SOFFIT @ FRONT AND GABLES PERFORATED VINYL VENTED SOFFIT @ SIDES AND REAR
10" VINYL LAP SIDING (4 1/2" REVEAL)
7/16" OSB WALL SHEATHING
2 X 4 STUD GRADE @ 24" OC. TYP.
ND EAVE DETAIL
CERTAINTEED BUILT-UP 8 X 8 "REAL POST" W/ FACTORY FINISH OR EQUAL
POST SECTION
1-1/2"= 1'-0"
NOTE:
STANDARD BODY COLOR ON ELEVATIONS IS SIDING, BRICK, OR STONE PER ELEVATION OPT. ACCENT COLORS DEPICTED ON ELEVATION BY (A) WHERE SHOWN
CONCRETE TILE ROOFING, TYP.
8" ALUMINUM FASCIA
OPT 4036 SL
6" "TRUWOOD" CORNER TRIM @ FRONT ONLY
1 X 8 VINYL WRAP
OPT 2636 SL
CERTAINTEED 8 X 8 "REAL POST" W/ FACTORY FINISH OR EQUAL
3' X 4' TEXTURED MASONITE PANEL @ UTILITY BOXES PENDING PEDESTAL LOCATION
GAS METER
BRICK VENEER (2" RETURN)
LEFT ELEVATION 'A'
1/4"= 1'-0"
VAUGHN ASSOCIATES
Fine Residential Design
David A. Vaughn
475 W.12th Ave. #3E Denver, Colorado 80204 303-534-0902
MODEL # TO5
TRAIL RIDGE HOMES
LITTLETON, COLORADO 80123
DATE:
03/16/06
REVISIONS:
'A' ELEVATION
SHEET:
A4.1



FRONT ELEVATION 'B'

1/4"= 1'-0"

ROOF VENTILATION CALCULATION

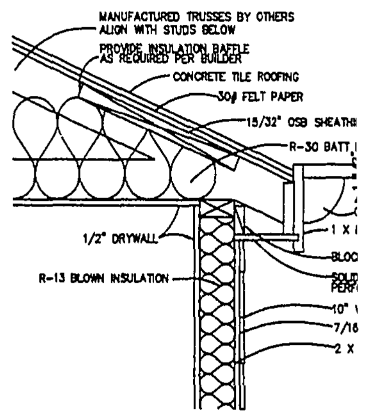
1. CEILING AREA = 1,092 SQ. FT.

2. VENT AREA REQUIRED
   1 S.F. VENT PER 300 S.F. CEILING AREA
   1,092 S.F. CEILING AREA / 300 = 3.64 S.F. TOTAL VENT AREA REQUIRED

3. DISTRIBUTE VENTS
   50% (1.82 SQ. FT.) AT RIDGE
   50% (1.82 SQ. FT.) AT EAVE

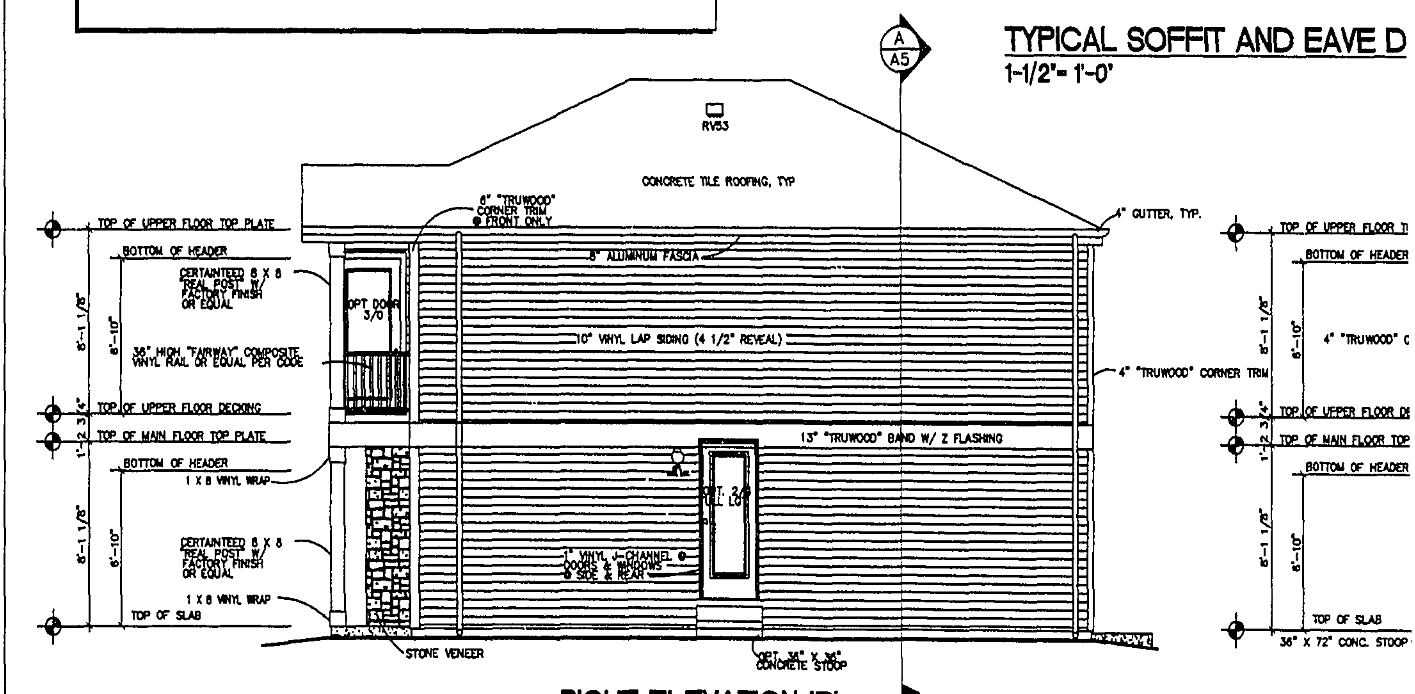
4. NUMBER OF VENTS
   EAVE VENTS: 1.82 S.F. REQUIRED AREA / 0.9 S.F. NET FREE AREA PER VENT = 2-3 VENTS

   RIDGE VENTS: 1.82 S.F. REQUIRED AREA / 0.6 S.F. NET FREE AREA PER VENT = 3-4 VENTS



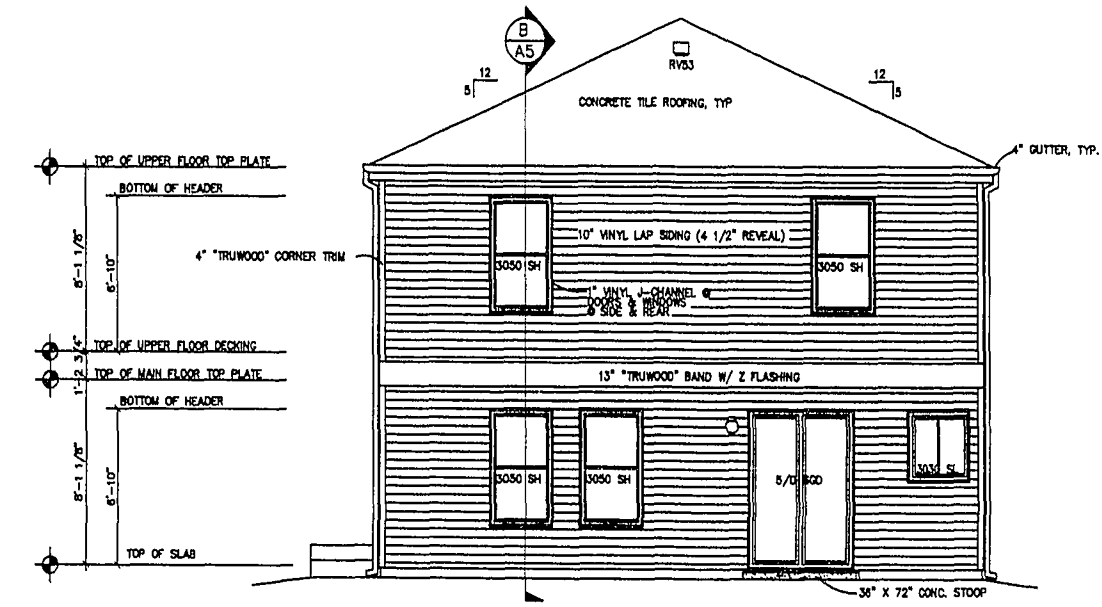
TYPICAL SOFFIT AND EAVE D

1-1/2"= 1'-0"



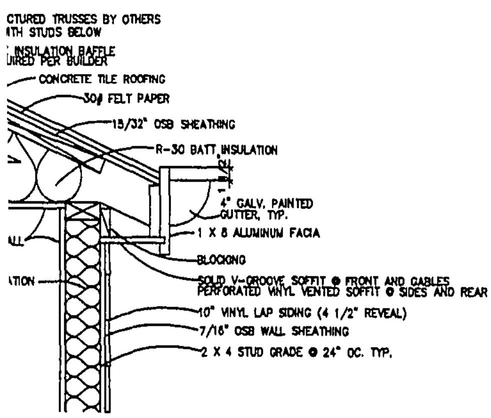
RIGHT ELEVATION 'B'

1/4"= 1'-0"

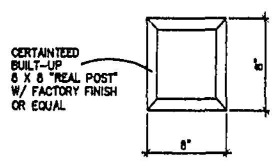


REAR ELEVATION 'B'

1/4"= 1'-0"

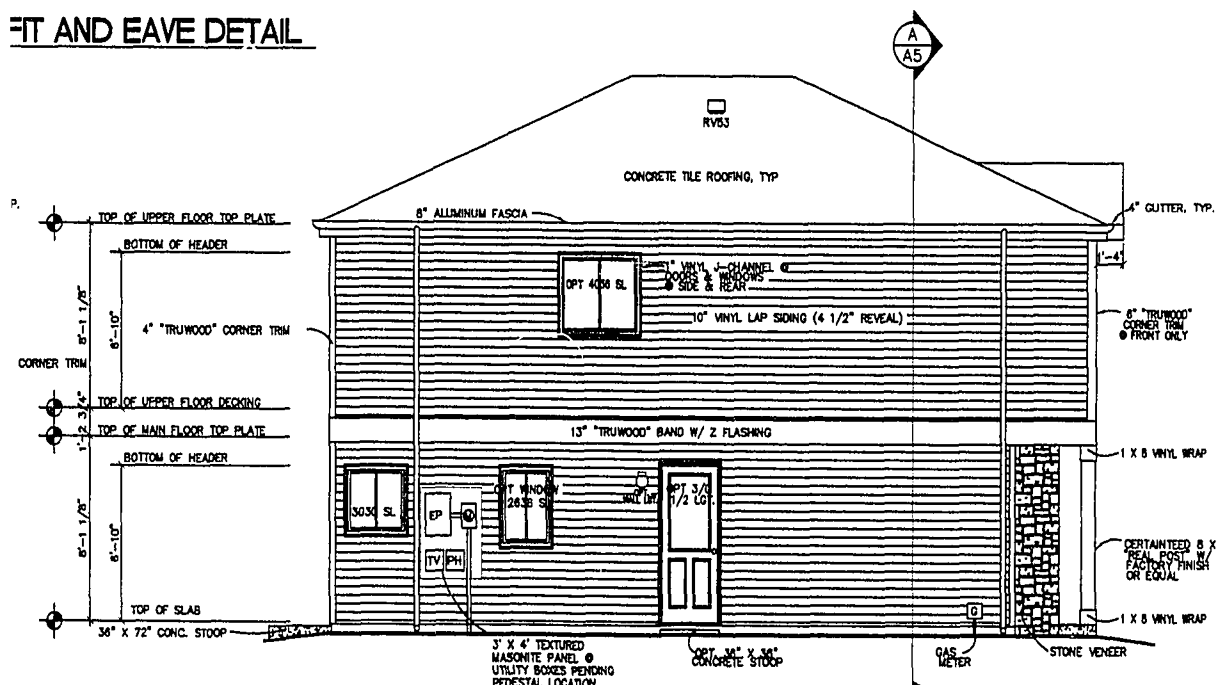


FIT AND EAVE DETAIL



POST SECTION

1-1/2"= 1'-0"



LEFT ELEVATION 'B'

1/4"= 1'-0"

VAUGHN ASSOCIATES
Fine Residential Design
David A. Vaughn
475 W.12th Ave. #3E
Denver, Colorado 80204
303-534-0902

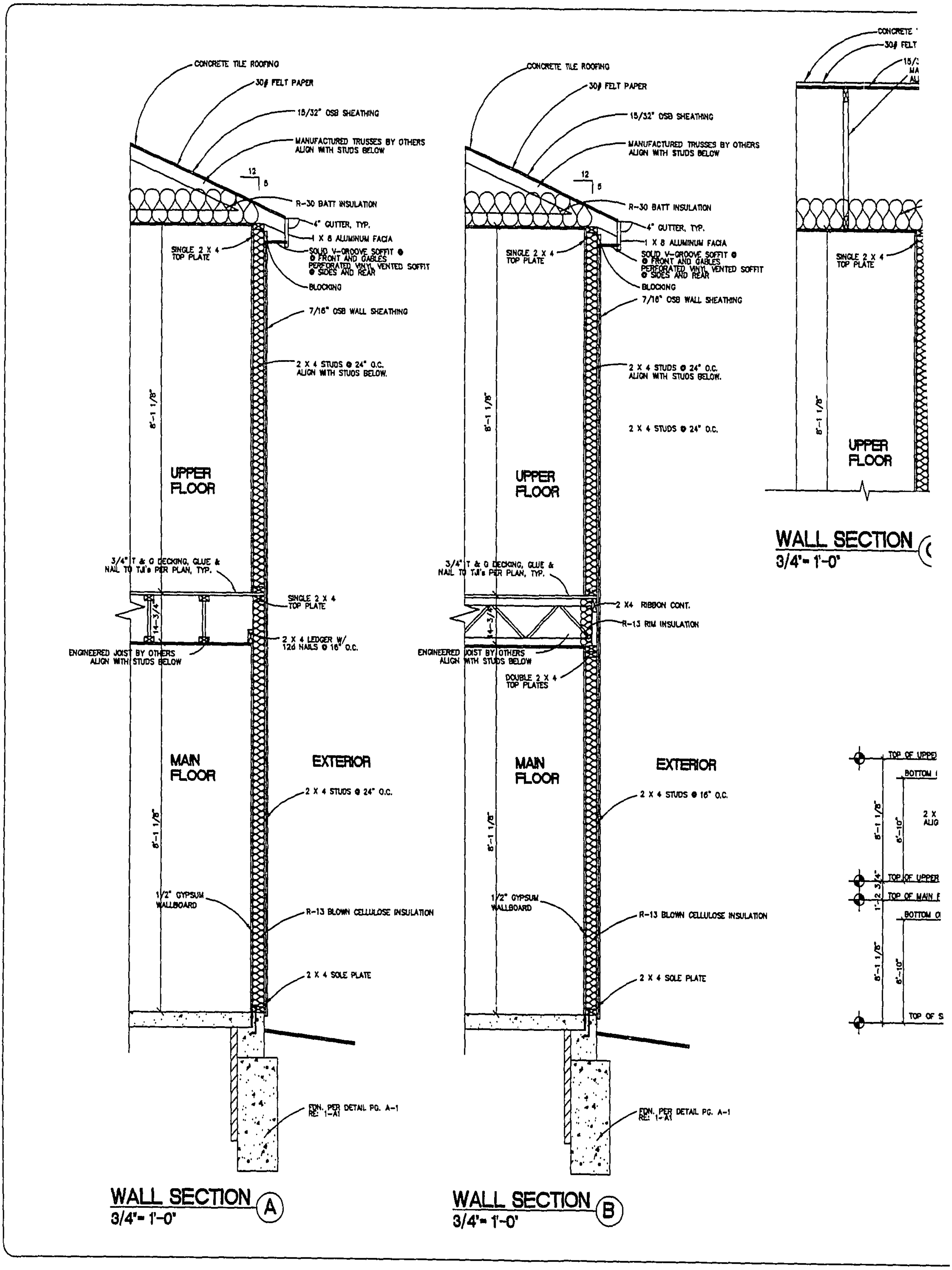
MODEL # TO5
TRAIL RIDGE HOMES
9116 WEST BOWLES- UNIT 15
LITTLETON, COLORADO 80123
PH 303-979-9858 / FAX 303-979-9616

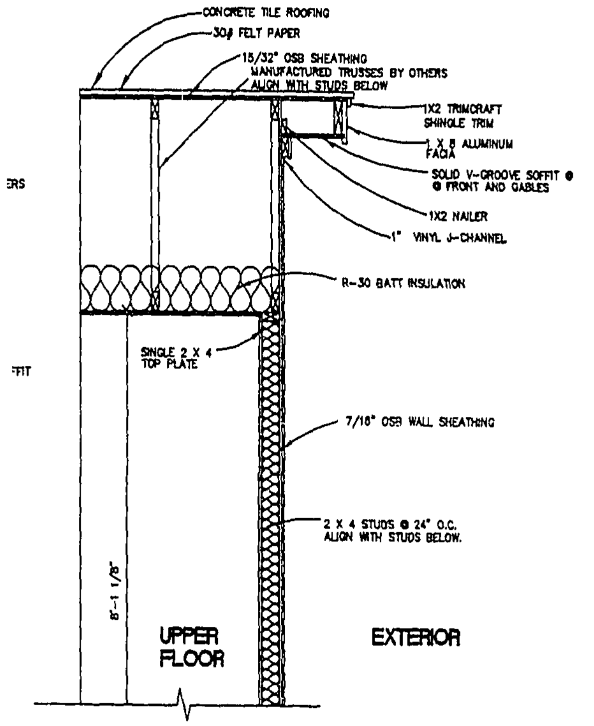
DATE:
03/16/06

REVISIONS:
1.)
2.)
3.)
4.)
5.)
6.)

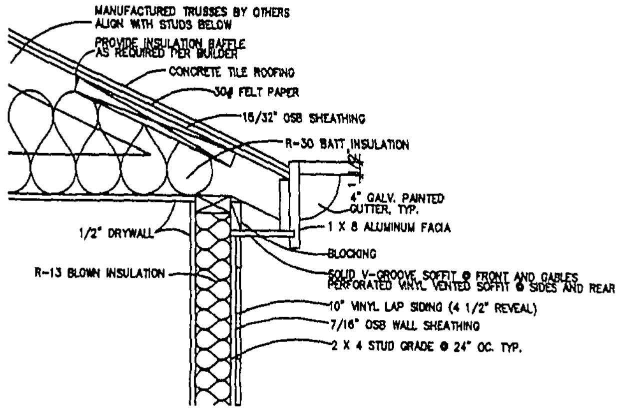
'B' ELEVATION

SHEET:
A4.2

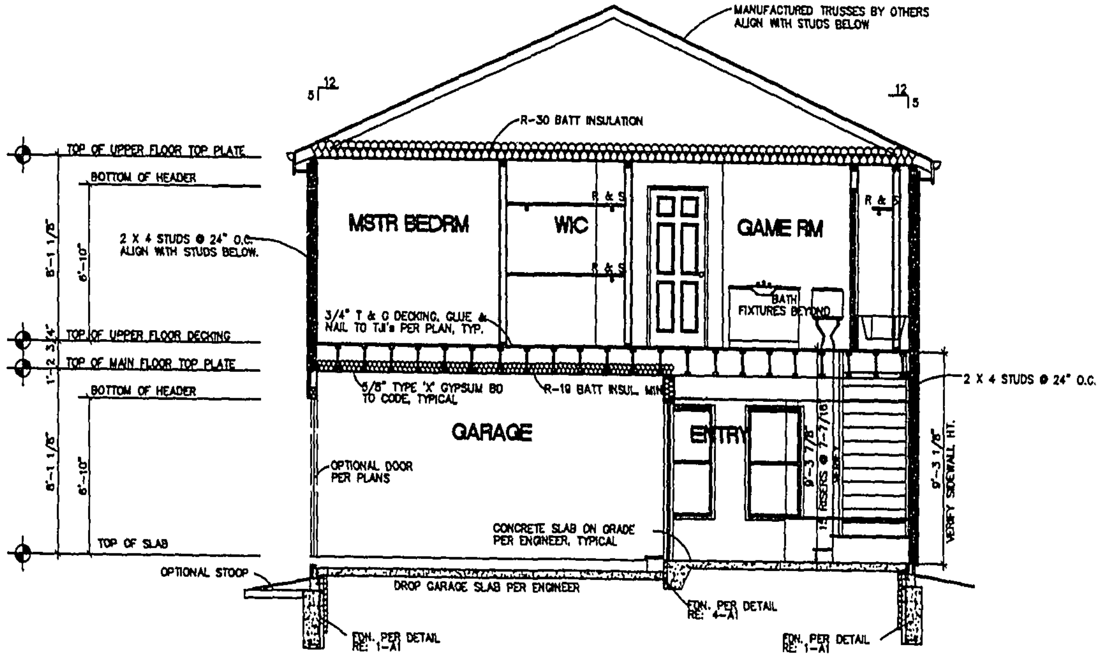

CONCRETE TILE ROOFING
30# FELT PAPER
15/32" OSB SHEATHING
MANUFACTURED TRUSSES BY OTHERS ALIGN WITH STUDS BELOW
12
5
R-30 BATT INSULATION
4" GUTTER, TYP.
1 X 8 ALUMINUM FACIA
SINGLE 2 X 4 TOP PLATE
SOLID V-GROOVE SOFFIT @ FRONT AND GABLES PERFORATED VINYL VENTED SOFFIT @ SIDES AND REAR
BLOCKING
7/16" OSB WALL SHEATHING
2 X 4 STUDS @ 24" O.C. ALIGN WITH STUDS BELOW.
8'-1 1/8"
UPPER FLOOR
3/4" T & G DECKING, GLUE & NAIL TO TJI's PER PLAN, TYP.
SINGLE 2 X 4 TOP PLATE
14-3/4"
2 X 4 LEDGER W/ 12d NAILS @ 16" O.C.
ENGINEERED JOIST BY OTHERS ALIGN WITH STUDS BELOW
MAIN FLOOR
EXTERIOR
2 X 4 STUDS @ 24" O.C.
1/2" GYPSUM WALLBOARD
R-13 BLOWN CELLULOSE INSULATION
2 X 4 SOLE PLATE
FDN. PER DETAIL PG. A-1 RE: 1-A1
WALL SECTION A
3/4"= 1'-0"
2 X 4 STUDS @ 24" O.C.
2 X4 RIBBON CONT.
R-13 RIM INSULATION
DOUBLE 2 X 4 TOP PLATES
2 X 4 STUDS @ 16" O.C.
WALL SECTION B
3/4"= 1'-0"
WALL SECTION
3/4"= 1'-0"
8'-10"
1'-2 3/4"



WALL SECTION (C)
3/4"= 1'-0"



TYPICAL SOFFIT AND EAVE DETAIL
1-1/2"= 1'-0"



SECTION 'A'
1/4"= 1'-0"

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303-534-0902

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PH 303-979-9858 / FAX 303-979-9816

DATE:
03/16/06

REVISIONS:
1.)
2.)
3.)
4.)
5.)
6.)

SECTION

SHEET:
A5

STRUCTURAL DESIGN

LOCATION: PLAN T05, BELLAVISTA SUBDIVISIC

APPLICABLE CODES AND STANDARDS:
INTERNATIONAL RESIDENTIAL CODE, 2003 E
LOCHBUIE BUILDING CODE
AISC MANUAL OF STEEL CONSTRUCTION,
ACI-318-94 "BUILDING CODE REQUIREMEN
TIMBER CONSTRUCTION MANUAL, AITC

FOUNDATION:
CONTINUOUS SPREAD FOOTINGS.
REFER TO SOIL REPORT, PROJECT NO. 534
DATED FEBRUARY 17, 1998, FOR PRELIMIN
ENGINEER TO INSPECT EXCAVATION PRIOR
OF SOILS REPORT.

DESIGN CRITERIA:
MAXIMUM CONTACT PRESSURE = 2,500 PS
MINIMUM CONTACT PRESSURE (DEAD LOAD)
ALL FOOTINGS TO BEAR ON UNDISTURBED

REINFORCED CONCRETE:
3000 PSI COMPRESSIVE STRENGTH, TYPE I
REINFORCING: USE NO. 5 GRADE 60 UNLES

MINIMUM REINFORCING COVER:
CONCRETE CAST AGAINST EARTH: 3"
CONCRETE IN FORMS EXPOSED TO EAR
SLABS AND WALLS NOT EXPOSED TO

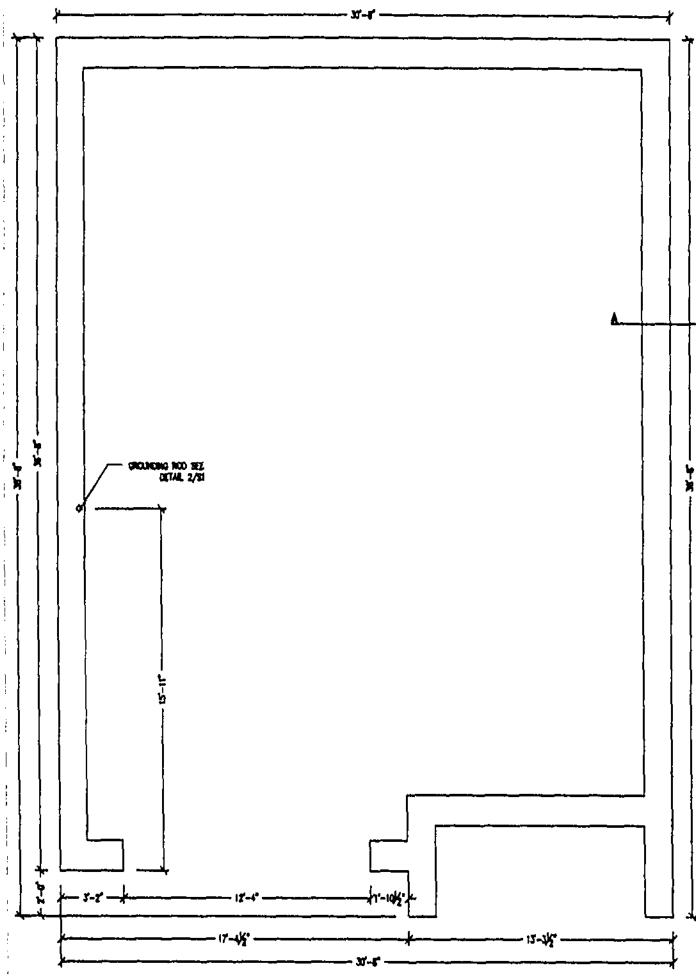
EXPANSION ANCHORS:
HILTI KWIK BOLT II OR EQUAL

DESIGN CRITERIA:
ROOF SNOW LOAD = 35 PSF
ROOF DEAD LOAD = 15 PSF
FLOOR LIVE LOAD = 40 PSF
FLOOR DEAD LOAD = 15 PSF

LATERAL DESIGN CRITERIA:
WIND = 100 MPH, EXPOSURE C
SEISMIC = ZONE "I"

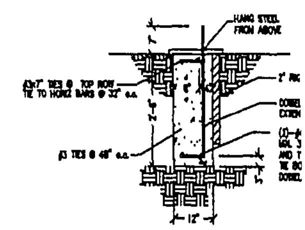
STRUCTURAL STEEL:
STRUCTURAL STEEL TO BE ASTM A36 U.N.O.

CONTRACTOR TO VERIFY ALL DIMENSIONS
BEGINNING CONSTRUCTION.

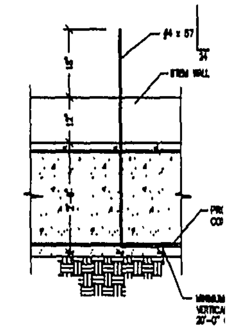


FOUNDATION FOOTING PLAN

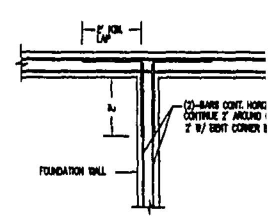
SCALE: 1/4" = 1'-0"



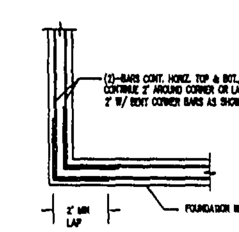
1 S1 FOOTING SECTION



2 S1 GROUNDING ROD DET



JUNCTION REINFORCIN



CORNER REINFORCING

STRUCTURAL DESIGN CRITERIA

LOCATION: PLAN T05, BELLAVISTA SUBDIVISION, LOCHBUIE, COLORADO

APPLICABLE CODES AND STANDARDS:
- INTERNATIONAL RESIDENTIAL CODE, 2003 EDITION
- LOCHBUIE BUILDING CODE
- AISC MANUAL OF STEEL CONSTRUCTION, 9TH EDITION
- ACI-318-99 "BUILDING CODE REQUIREMENTS FOR REINFORCED CONCRETE"
- TIMBER CONSTRUCTION MANUAL, AMER INST OF TIMBER CONST, 3RD ED.

FOUNDATION:
- CONTINUOUS SPREAD FOOTINGS.
- REFER TO SOIL REPORT, PROJECT NO. 53423, KLEINFELDER, INC., DATED FEBRUARY 17, 1999, FOR PRELIMINARY FOUNDATION RECOMMENDATIONS.
- ENGINEER TO INSPECT EXCAVATION PRIOR TO CONSTRUCTION TO VERIFY RESULTS OF SOILS REPORT.

DESIGN CRITERIA:
- MAXIMUM CONTACT PRESSURE = 2,000 PSF
- MINIMUM CONTACT PRESSURE (DEAD LOAD) = N/A
- ALL FOOTINGS TO BEAR ON UNDISTURBED BEDROCK OR COMPACTED FILL

REINFORCED CONCRETE:
- 3000 PSI COMPRESSIVE STRENGTH, TYPE I PORTLAND CEMENT.
- REINFORCING: USE NO. 5 GRADE 60 UNLESS NOTED OTHERWISE.

MINIMUM REINFORCING COVER:
- CONCRETE CAST AGAINST EARTH: 3"
- CONCRETE IN FORMS EXPOSED TO EARTH: 1-1/2"
- SLABS AND WALLS NOT EXPOSED TO WEATHER: 1"

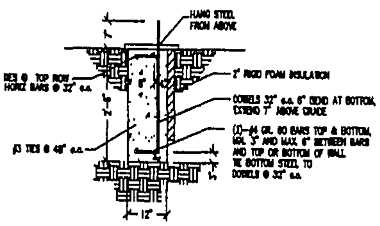
EXPANSION ANCHORS:
- HILTI KWIK BOLT II OR EQUAL

DESIGN CRITERIA:
- ROOF SNOW LOAD = 35 PSF
- ROOF DEAD LOAD = 15 PSF
- FLOOR LIVE LOAD = 40 PSF
- FLOOR DEAD LOAD = 15 PSF

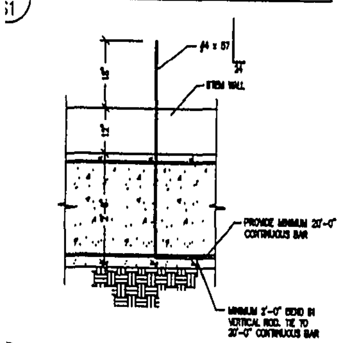
LATERAL DESIGN CRITERIA:
- WIND = 100 MPH, EXPOSURE C
- SEISMIC = ZONE "I"

STRUCTURAL STEEL:
- STRUCTURAL STEEL TO BE ASTM A36 U.N.O.

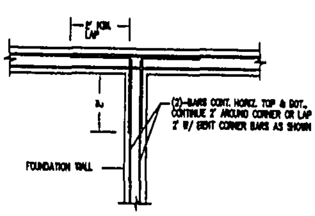
CONTRACTOR TO VERIFY ALL DIMENSIONS SHOWN BEFORE BEGINNING CONSTRUCTION.



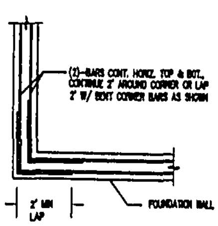
1/S1 FOOTING SECTION



2/S1 GROUNDING ROD DETAIL



JUNCTION REINFORCING



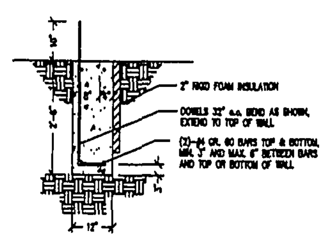
CORNER REINFORCING

REVISIONS	
DATE	REMARKS

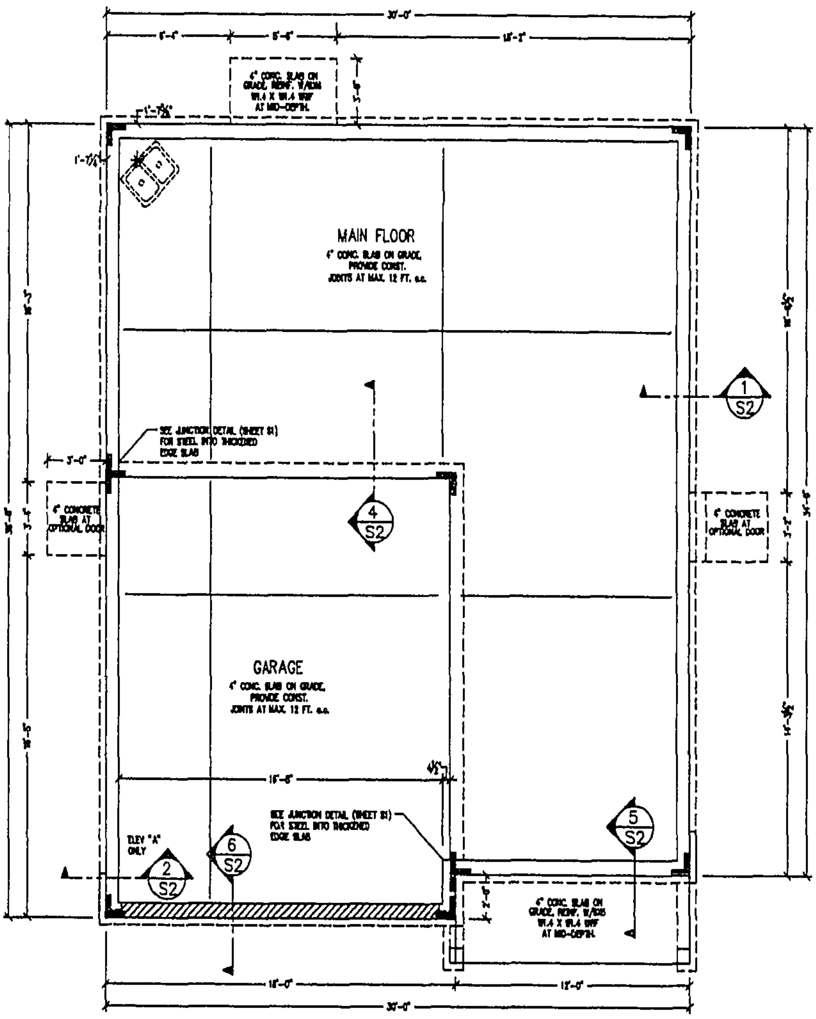
7657FOOTING.DWG

FOUNDATION FOOTING PLAN & DETAILS
SINGLE FAMILY RESIDENCE
PLAN T05
BELAVISTA SUBDIVISION
LOCHBUIE, COLORADO
PROJECT NO. 05-7657 JUNE 29, 2005

COMPLETE ENGINEERING SERVICES
912 TWELFTH STREET
GOLDEN, COLORADO 80401
(303) 279-6418



1/S1 FOOTING TRENCH SECTION

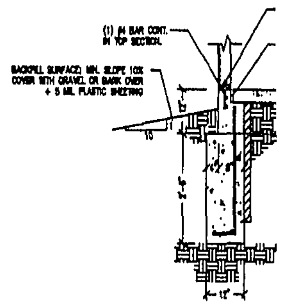


FOUNDATION PLAN

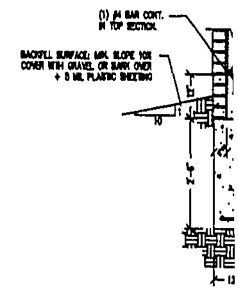
SCALE: 1/4" = 1'-0"

NOTES:

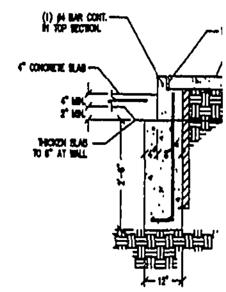
1. T.O.W. INDICATES TOP OF FOUNDATION WALL
2. B.O.W. INDICATES BOTTOM OF FOUNDATION WALL
3. ▪ INDICATES SIMPSON STHD10 HOLDOWN



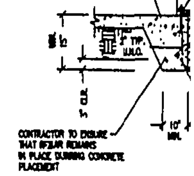
1/S2 FOUNDATION WAI



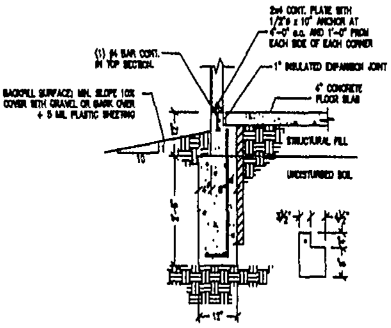
2/S2 FOUNDATION WALL WITH BRICK ("A" E



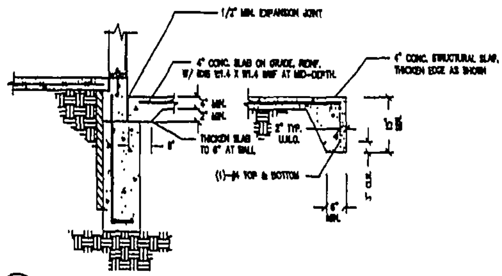
3/S2 FOUNDATION WALL AT DOOR OPENINGS



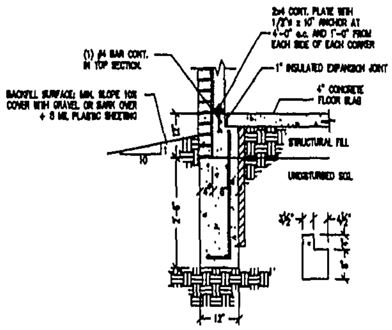
4/S2 GARAGE/HOUSE F



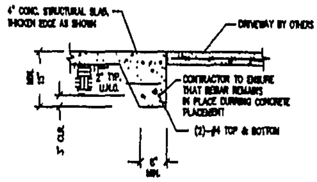
1 S2 FOUNDATION WALL SECTION



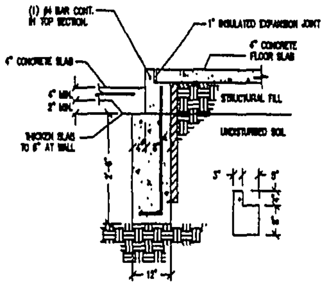
5 S2 CONCRETE PORCH SECTION



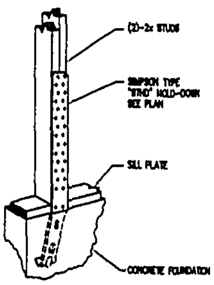
2 S2 FOUNDATION WALL SECTION WITH BRICK ("A" ELEV. ONLY)



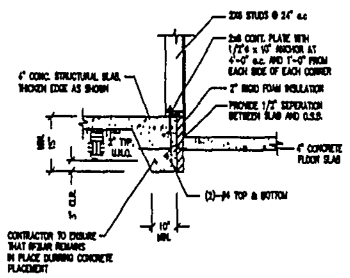
6 S2 GARAGE DOOR FOUNDATION SECTION



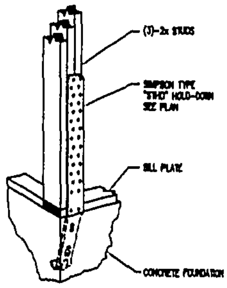
3 S2 FOUNDATION WALL SECTION AT DOOR OPENINGS



TYPICAL HOLD-DOWN DETAIL



4 S2 GARAGE/HOUSE FOUNDATION SECTION



TYPICAL CORNER HOLD-DOWN DETAIL

REVISIONS	
DATE	REMARKS
	7657PLAN.DWG

FOUNDATION
PLAN & DETAILS
SINGLE FAMILY RESIDENCE
PLAN T05
BELLAVISTA SUBDIVISION
LOCHBUIE, COLORADO
PROJECT NO. 05-7657 JUNE 29, 2005

COMPLETE ENGINEERING SERVICES
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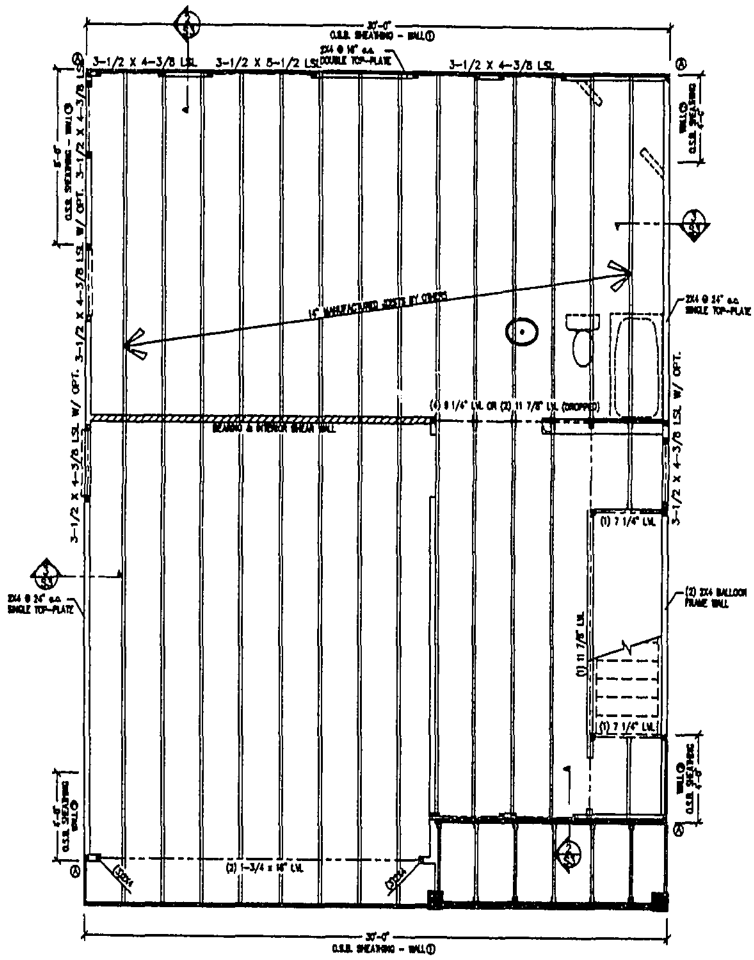
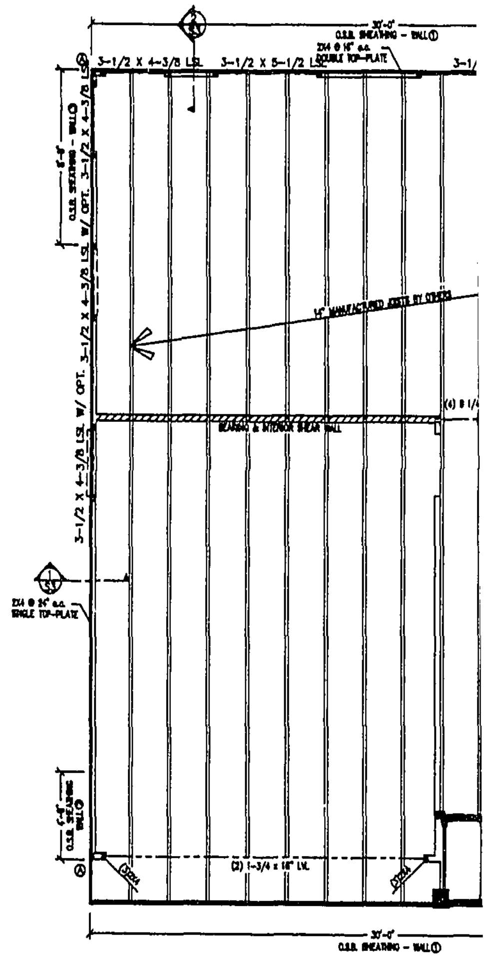
GOLDEN, COLORADO 80401
(303) 279-6418



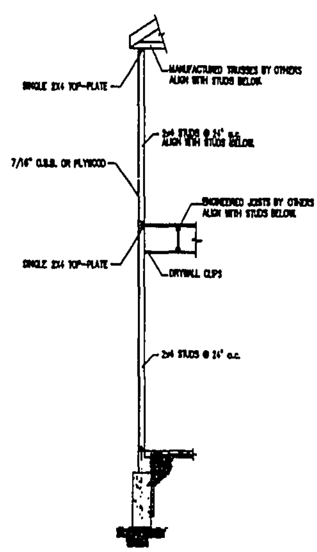
SECOND FLOOR FRAMING PLAN -STANDARD & "A" ELEVATION

SCALE: 1/4" = 1'-0"

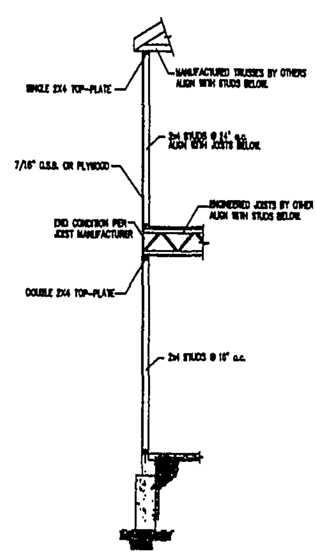


SECOND FLOOR FRAMING PLAN -

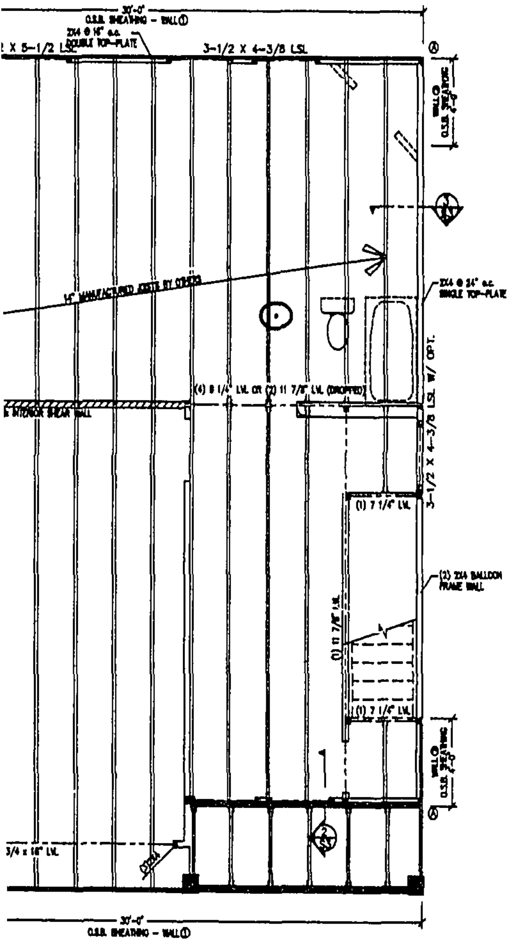
SCALE: 1/4" = 1'-0"



1 S3 WALL FRAMING SECTION

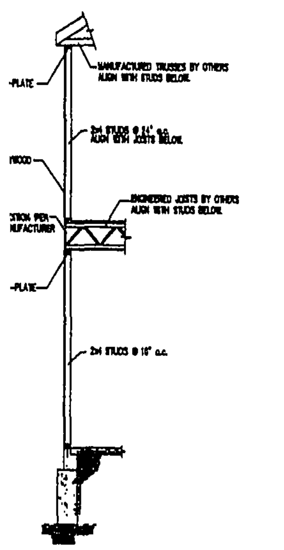


2 S3 WALL FRAMING SECTION

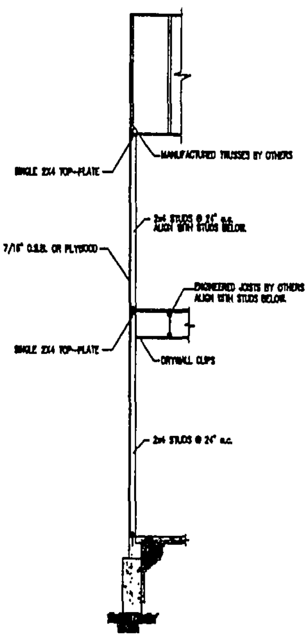


FLOOR FRAMING PLAN - ELEVATION "B"

SCALE: 1/4" = 1'-0"



WALL FRAMING SECTION



3 / S3 WALL FRAMING SECTION

TIMBER:
NON STRUCTURAL SAWN TIMBER TO BE HEM FIR NO. 2 OR BETTER
(Fb = 850, Fv = 180, Fc = 1300, E = 1,300,000)
STRUCTURAL SAWN TIMBER (FLOORS OR RAFTERS) TO BE DOUG FIR NO. 2 OR BETTER.
(Fb = 850, Fv = 180, Fc = 1300, E = 1,300,000)
JOISTS AND RAFTERS MAY BE HEM-FIR #2 WHEN SPANS ARE CHECKED FOR THIS SPECIES.
WALL STUDS TO BE HEM-FIR STUD GRADE UP TO 8'-0" & HEM-FIR #2 GREATER THAN 8'-0".
ALL LAMINATED VENEER LUMBER (LVL) MEMBERS TO BE IN COMPLIANCE WITH LATEST SPECIFICATIONS SET FORTH BY THE MANUFACTURER.
(Fb = 2600, Fv = 285, E = 1,900,000)

STRUCTURAL FRAMING NOTES:

1. MINIMUM SHEATHING REQUIREMENTS:
   ROOF SHEATHING SHALL BE 1/2" APA RATED SHEATHING, 32/16, EXPOSURE 1, PLYWOOD OR OSB.

   FLOOR SHEATHING SHALL BE 3/4" APA RATED STURD-I-FLOOR, 40/20, EXPOSURE 1, PLYWOOD OR OSB.

   WALL SHEATHING SHALL BE 3/8" APA RATED SHEATHING, 24/0, EXPOSURE 1, PLYWOOD OR OSB.

   ALL PANELS OF ALL EXTERIOR WALLS SHALL BE SHEATHED. A SHEATHED WALL ELEMENT OF MIN. 4 FEET WIDE SHALL BE INSTALLED AT EACH CORNER OR AS CLOSE THERETO AS POSSIBLE. (SHEATHING OF ANY MATERIAL THAT HAS BEEN TESTED AND APPROVED BY AN INDEPENDENT TESTING AGENCY MAY BE SUBSTITUTED FOR APA RATED SHEATHING. THE SUBSTITUTE SHEATHING SHALL PROVIDE RACKING SUPPORT EQUIVALENT TO THE SPECIFIED APA RATED SHEATHING.) BRACED WALL LINES SHALL NOT EXCEED 25'-0" ON CENTER AS PER 2003 IRC TABLE R602.10.1.

   PANEL INSTALLATION AND SUPPORT:
   NAIL ALL PANELS WITH 8d COMMON @ 6"oc AT PANEL EDGES AND 12"oc FIELD OR PER LATERAL SHEATHING SCHEDULE ON PLAN. PANELS SHALL BE INSTALLED WITH LONG DIMENSION OR STRENGTH AXIS ACROSS SUPPORTS, (NOT REQUIRED WITH WALL PANELS). APPROVED STAPLES MAY BE SUBSTITUTED FOR NAILS. PROVIDE 1/8" SPACING AT ALL PANEL EDGES. PROVIDE FULL DEPTH BLOCKING FOR WALL PANEL EDGES AT MAX. 8 FEET ON CENTER.

2. BEARING HEADERS SHALL BE SUPPORTED ON MINIMUM (1)-2X TRIM STUD AND (1)-2X KING STUD U.N.O.

3. BEARING POSTS MUST STACK TO BEAM OR FOUNDATION BELOW. PROVIDE FULL DEPTH SOLID BLOCKING AT ALL FLOORS BELOW POSTS.

4. ALL ROOF RAFTERS AND TRUSSES SHALL BE FASTENED TO DOUBLE TOP PLATES WITH USP R7 OR EQUIVALENT TIES. ALL GIRDER TRUSSES SHALL BE FASTENDED TO DOUBLE TOP PLATES WITH (2) USP R7 OR EQUIVALENT TIES.

5. ROOF OVERHANG AT GABLE WALL SHALL BE FLAT 2X6 @ 24"oc WITH MAXIMUM OVERHANG = 2'-0", U.N.O. ON PLAN.

6. MINIMUM NAILING OF ALL FRAMING MEMBERS AND JOINTS SHALL BE PER 2003 INTERNATIONAL RESIDENTIAL CODE TABLE NO. R602.3(1).

7. FLOOR JOISTS SHALL HAVE FULL DEPTH BLOCKING OR BRIDGING AT MIDSPAN, AT BEARING WALLS ABOVE, AND AT CANTILEVER BEARING POINTS.

8. BEAM SPLICES SHALL BE LOCATED PER PLANS. CONTACT ENGINEER FOR ALTERNATE OR ADDITIONAL BEAM SPLICE LOCATIONS

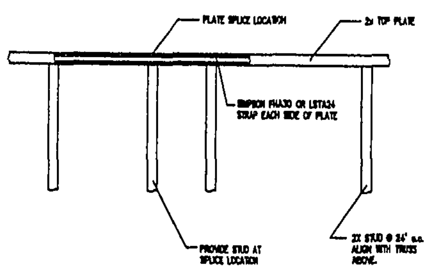
9. FOUNDATION SILL PLATES AND ALL WOOD IN DIRECT CONTACT WITH CONCRETE SHALL BE PRESSURE TREATED WITH PRESERVATIVE OR BE OF WOOD SPECIES WITH NATURAL RESISTANCE TO DECAY. SUCH SPECIES INCLUDE CALIFORNIA REDWOOD AND WESTERN CEDAR.

10. EXTERIOR WALL SHEATHING SHALL BE FASTENED ACROSS FLOOR FRAMING IN ORDER TO TRANSFER WIND LATERAL LOADS TO FOUNDATION WALLS. PROPRIETARY WALL SHEATHING PRODUCTS SHALL BE REVIEWED BY ENGINEER PRIOR TO CONSTRUCTION AND SHALL BE INSTALLED IN ACCORDANCE WITH MANUFACTURER'S SPECIFICATIONS.

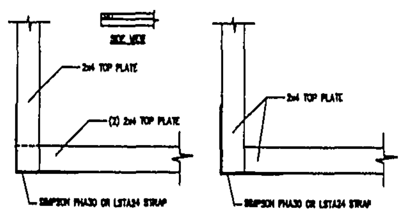
WALL SHEATHING SCHEDULE

WALL NUMBER	SHEATHING	NAIL	EDGE NAIL SPACING
WALL ①	7/16" O.S.B.	8d	6" o.c.
WALL ②	7/16" O.S.B.	8d	4" o.c.
WALL ③	7/16" O.S.B.	8d	3" o.c.

1. FIELD NAIL SPACING TO BE 12" o.c., TYP.
2. ■ Ⓐ INDICATES SIMPSON MSTA36 STRAP ACROSS FLOOR FRAMING. ATTACH TO DOUBLE STUD OR BEAM TOP AND BOTTOM.



TOP PLATE SPLICE DETAIL



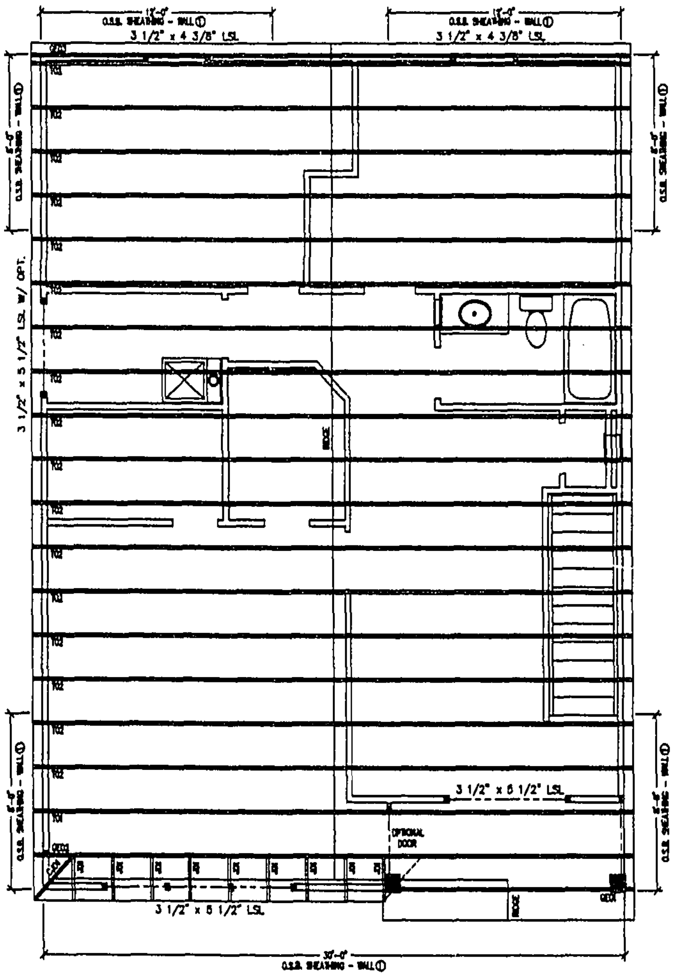
TOP PLATE CORNER DETAIL

REVISIONS	
DATE	REMARKS

765YENOFLOOR.DWG

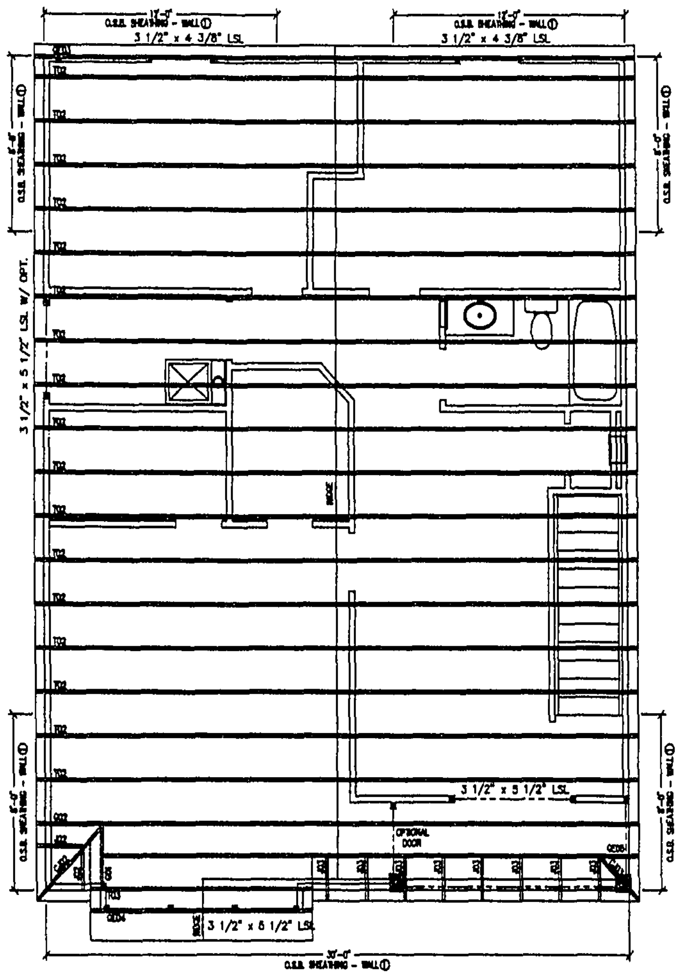
SECOND FLOOR FRAMING
PLAN & DETAILS
SINGLE FAMILY RESIDENCE
PLAN T05
BELAVISTA SUBDIVISION
LOCHBUIE, COLORADO
PROJECT NO. 05-7657 JUNE 29, 2005

COMPLETE ENGINEERING SERVICES
912 TWELFTH STREET
GOLDEN, COLORADO 80401
(303) 279-6418



ROOF FRAMING PLAN – STANDARD ELEVATION

SCALE 1/4" = 1'-0"



ROOF FRAMING PLAN – "A" ELEVATION

SCALE 1/4" = 1'-0"

TIMBER:

NON STRUCTURAL SAWN TIMBER TO BE HEM FIR NO. 2 OR BETTER
(Fb = 850, Fv = 150, Fc = 1300, E = 1,300,000)
STRUCTURAL SAWN TIMBER (FLOORS OR RAFTERS) TO BE DOUG FIR NO. 2 OR BETTER
(Fb = 850, Fv = 180, Fc = 1300, E = 1,300,000)
JOISTS AND RAFTERS MAY BE HEM-FIR #2 WHEN SPANS ARE CHECKED FOR THIS SPECIES.
WALL STUDS TO BE HEM-FIR STUD GRADE UP TO 8'-0" & HEM-FIR #2 GREATER THAN 8'-0".
ALL LAMINATED VENEER LUMBER (LVL) MEMBERS TO BE IN COMPLIANCE WITH LATEST SPECIFICATIONS SET FORTH BY THE MANUFACTURER.
(Fb = 2600, Fv = 285, E = 1,800,000)

STRUCTURAL FRAMING NOTES:

1. MINIMUM SHEATHING REQUIREMENTS:
   ROOF SHEATHING SHALL BE 1/2" APA RATED SHEATHING, 32/16, EXPOSURE 1, PLYWOOD OR OSB.

   FLOOR SHEATHING SHALL BE 3/4" APA RATED STURD-I-FLOOR, 40/20, EXPOSURE 1, PLYWOOD OR OSB.

   WALL SHEATHING SHALL BE 3/8" APA RATED SHEATHING, 24/0, EXPOSURE 1, PLYWOOD OR OSB.

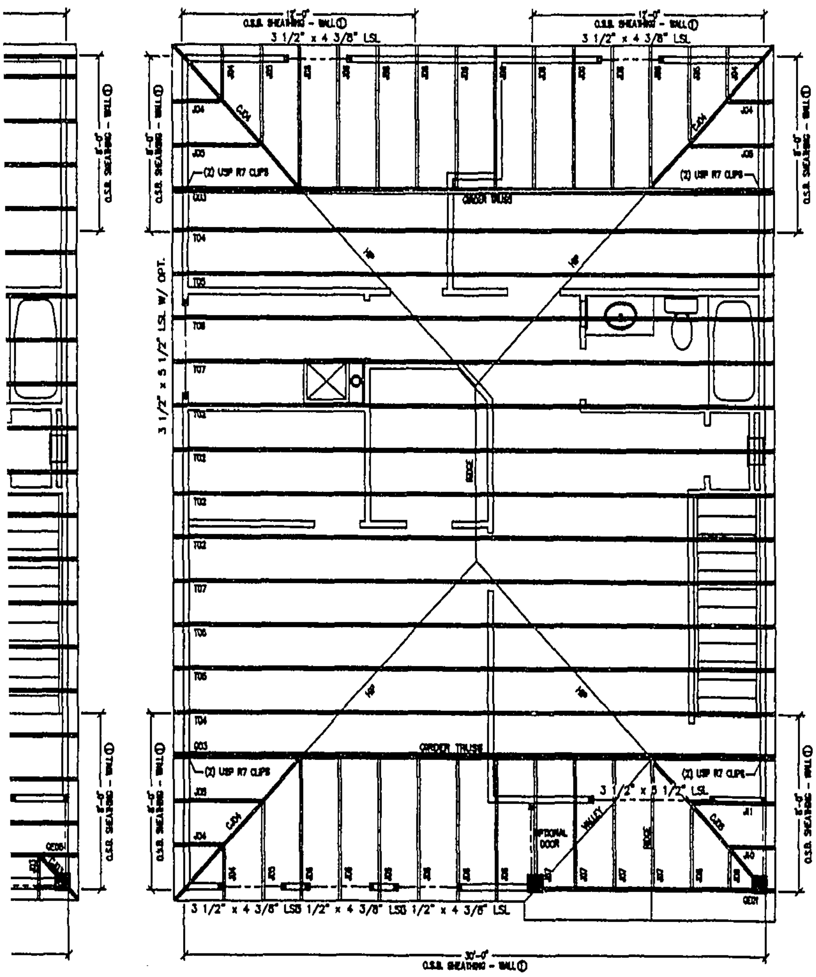
   ALL PANELS OF ALL EXTERIOR WALLS SHALL BE SHEATHED. A SHEATHED WALL ELEMENT OF MIN. 4 FEET WIDE SHALL BE INSTALLED AT EACH CORNER OR AS CLOSE THERETO AS POSSIBLE. (SHEATHING OF ANY MATERIAL THAT HAS BEEN TESTED AND APPROVED BY AN INDEPENDENT TESTING AGENCY MAY BE SUBSTITUTED FOR APA RATED SHEATHING. THE SUBSTITUTE SHEATHING SHALL PROVIDE RACKING SUPPORT EQUIVALENT TO THE SPECIFIED APA RATED SHEATHING.) BRACED WALL LINES SHALL NOT EXCEED 25'-0" ON CENTER AS PER 2003 IRC TABLE R602.10.1.

   PANEL INSTALLATION AND SUPPORT:
   NAIL ALL PANELS WITH 8d COMMON @ 6"oc AT PANEL EDGES AND 12"oc FIELD OR PER LATERAL SHEATHING SCHEDULE ON PLAN. PANELS SHALL BE INSTALLED WITH LONG DIMENSION OR STRENGTH AXIS ACROSS SUPPORTS. (NOT REQUIRED WITH WALL PANELS). APPROVED STAPLES MAY BE SUBSTITUTED FOR NAILS. PROVIDE 1/8" SPACING AT ALL PANEL EDGES. PROVIDE FULL DEPTH BLOCKING FOR WALL PANEL EDGES AT MAX. 8 FEET ON CENTER.
2. BEARING HEADERS SHALL BE SUPPORTED ON MINIMUM (1)-2X TRIM STUD AND (1)-2X KING STUD U.N.O.
3. BEARING POSTS MUST STACK TO BEAM OR FOUNDATION BELOW. PROVIDE FULL DEPTH SOLID BLOCKING AT ALL FLOORS BELOW POSTS.
4. ALL ROOF RAFTERS AND TRUSSES SHALL BE FASTENED TO DOUBLE TOP PLATES WITH SIMPSON H2.5 OR EQUIVALENT TIES.
5. ROOF OVERHANG AT GABLE WALL SHALL BE FLAT 2X6 @ 24"oc WITH MAXIMUM OVERHANG = 2'-0", U.N.O. ON PLAN.
6. MINIMUM NAILING OF ALL FRAMING MEMBERS AND JOINTS SHALL BE PER 2003 INTERNATIONAL RESIDENTIAL CODE TABLE NO. R602.3(1).
7. FLOOR JOISTS SHALL HAVE FULL DEPTH BLOCKING OR BRIDGING AT MIDSPAN, AT BEARING WALLS ABOVE, AND AT CANTILEVER BEARING POINTS.
8. BEAM SPLICES SHALL BE LOCATED PER PLANS. CONTACT ENGINEER FOR ALTERNATE OR ADDITIONAL BEAM SPLICE LOCATIONS
9. FOUNDATION SILL PLATES AND ALL WOOD IN DIRECT CONTACT WITH CONCRETE SHALL BE PRESSURE TREATED WITH PRESERVATIVE OR BE OF WOOD SPECIES WITH NATURAL RESISTANCE TO DECAY. SUCH SPECIES INCLUDE CALIFORNIA REDWOOD AND WESTERN CEDAR.
10. EXTERIOR WALL SHEATHING SHALL BE FASTENED ACROSS FLOOR FRAMING IN ORDER TO TRANSFER WIND LATERAL LOADS TO FOUNDATION WALLS. PROPRIETARY WALL SHEATHING PRODUCTS SHALL BE REVIEWED BY ENGINEER PRIOR TO CONSTRUCTION AND SHALL BE INSTALLED IN ACCORDANCE WITH MANUFACTURER'S SPECIFICATIONS.

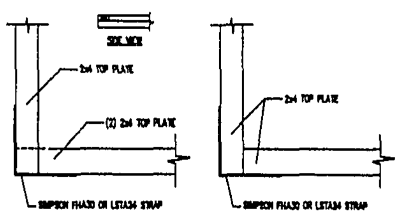
WALL SHEATHING SCHEDULE

WALL NUMBER	SHEATHING	NAIL	EDGE NAIL SPACING
WALL (1)	7/16" O.S.B.	8d	6" o.c.

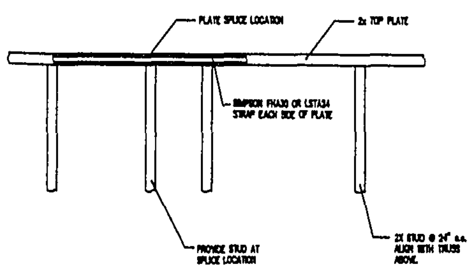
1. FIELD NAIL SPACING TO BE 12" o.c., TYP.



ROOF FRAMING PLAN - "B" ELEVATION
SCALE: 1/4" = 1'-0"



TOP PLATE CORNER DETAIL



TOP PLATE SPLICE DETAIL

REVISIONS	
DATE	REMARKS
7657ROOF.DWG	

ROOF FRAMING PLAN & DETAILS
SINGLE FAMILY RESIDENCE
PLAN T05
BELAVISTA SUBDIVISION
LOCHBUIE, COLORADO
PROJECT NO. 05-7657 JUNE 29, 2005

COMPLETE ENGINEERING SERVICES
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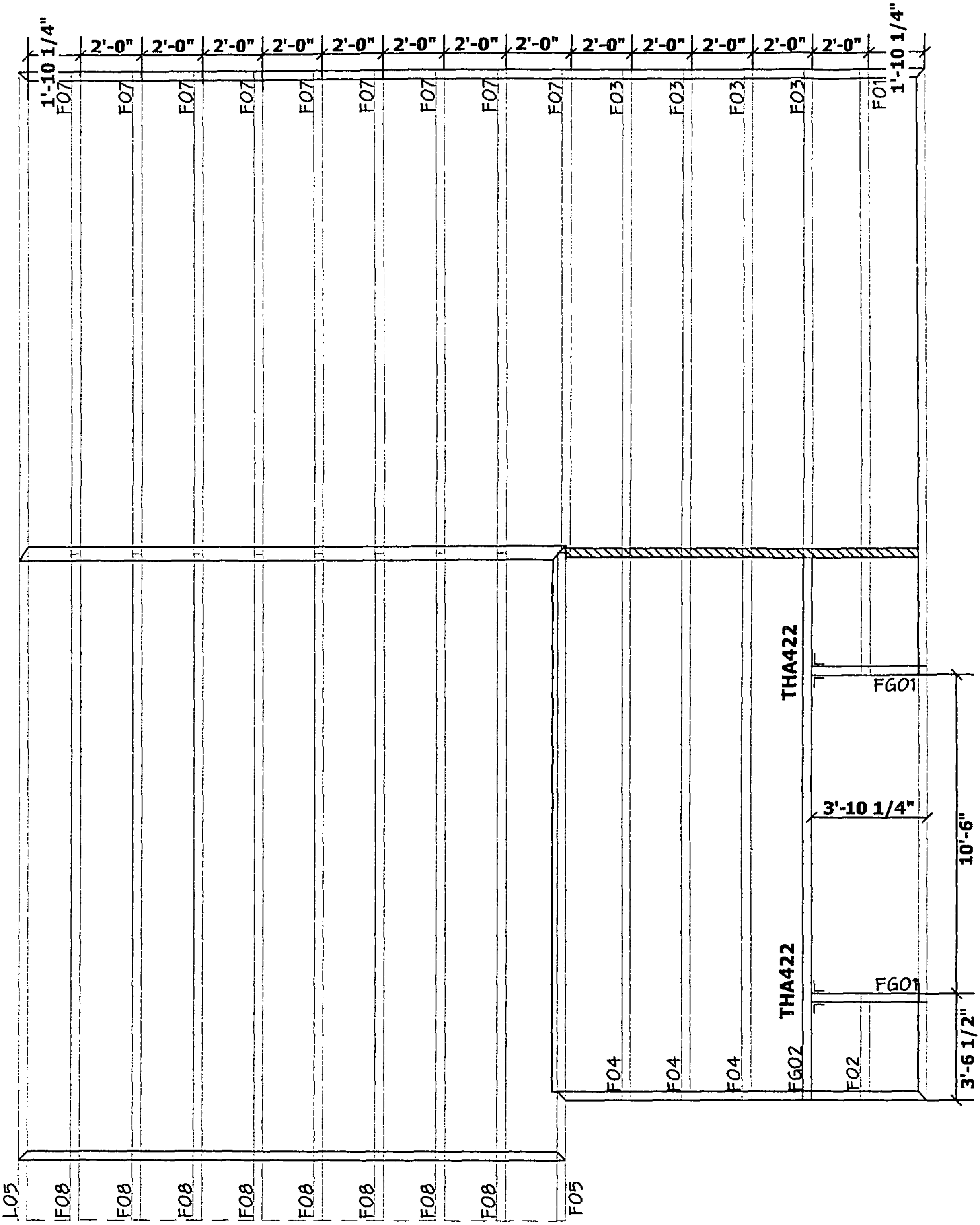
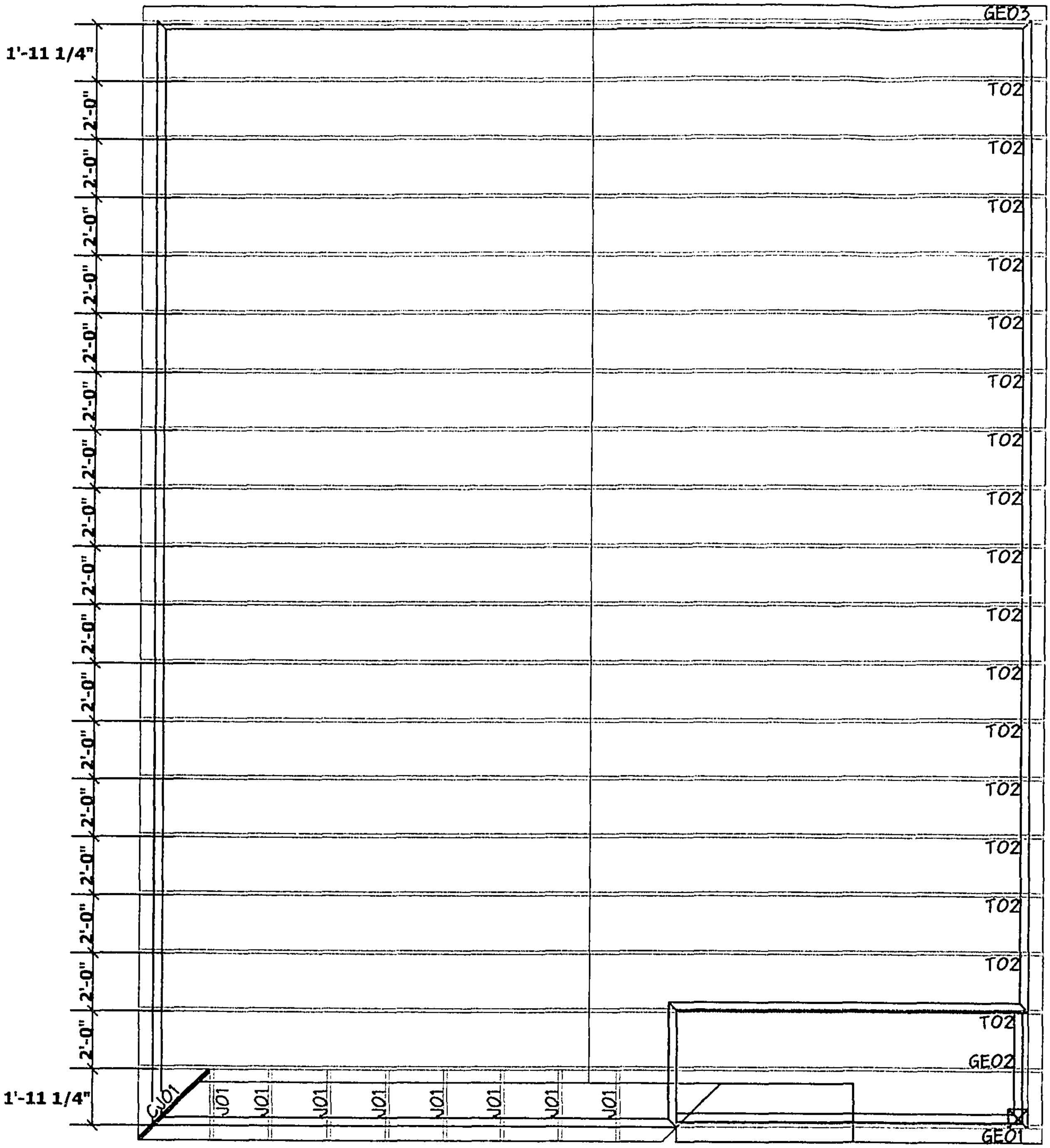


STOCK Building Supply

Denver Truss
1247 E. 68th. Ave
Denver, Colorado 80226
303) 289-5461 / Fax: (303) 289-7998

Plan "T05"	**9/16/2005**
2nd Floor	**Designer: Kirk ext 401**
Trail Ridge Homes	**Page: 1 of 1**



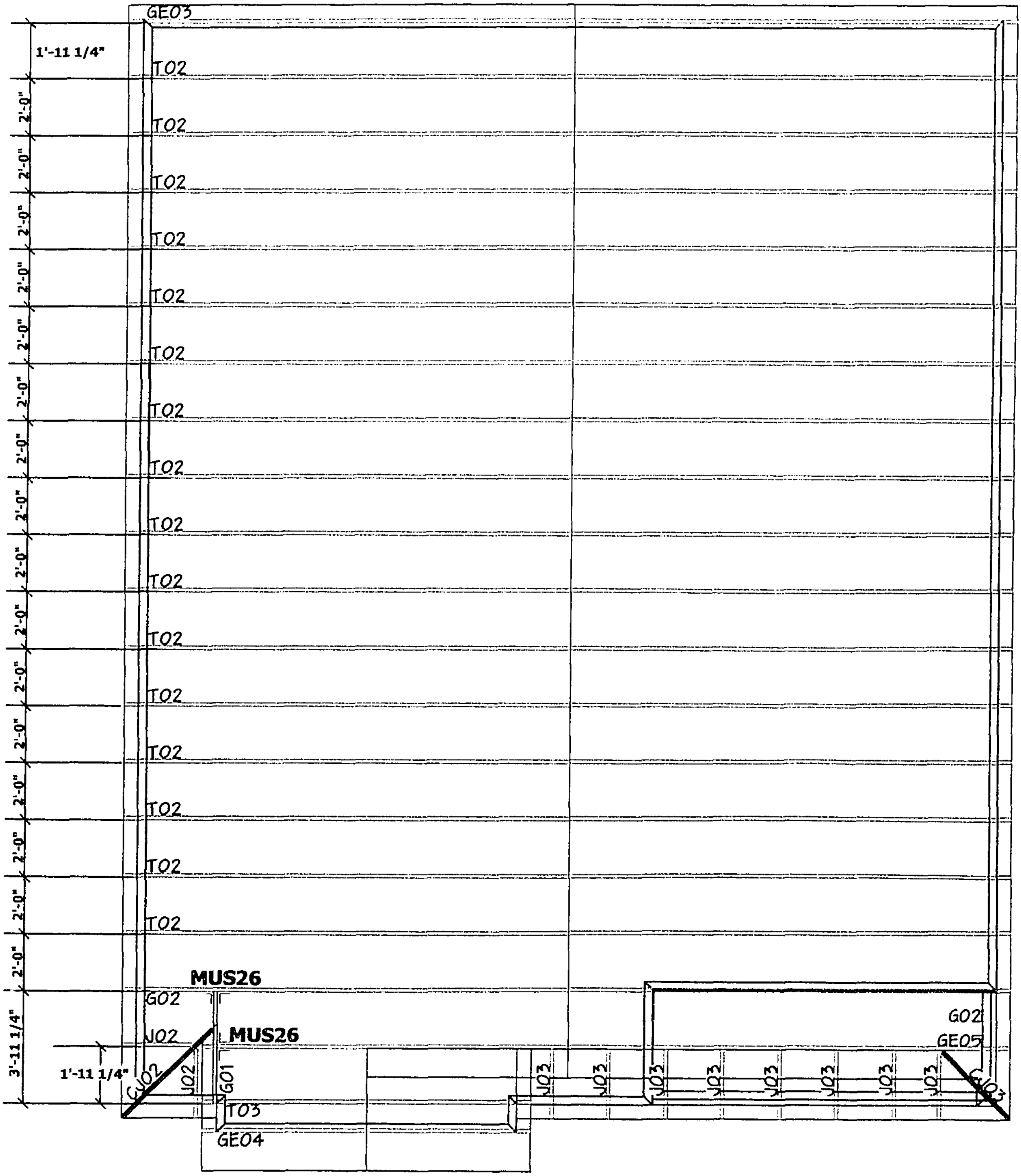
STOCK Building Supply

Denver Truss
1247 E. 68th. Ave
Denver, Colorado 80226
303) 289-5461 / Fax: (303) 289-7998

Plan T05 **5/31/2005**

Standard Elevation **Designer: Kirk ext 401**

Trail Ridge Homes **Revised: 9/21/2005**



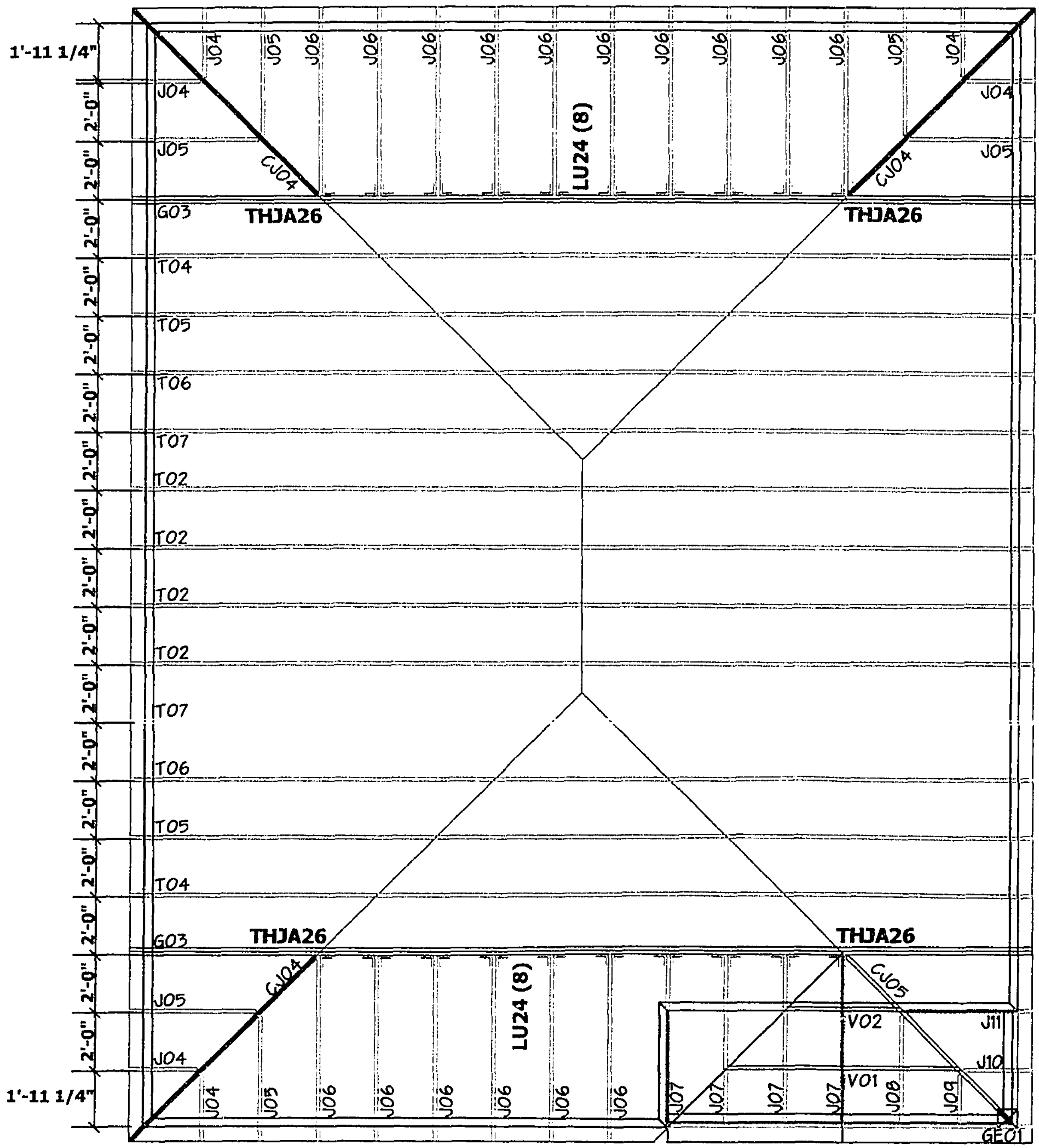
STOCK Building Supply

Denver Truss
1247 E. 68th. Ave
Denver, Colorado 80226
(303) 289-5461 / Fax: (303) 289-7998

Plan "T05" | **5/31/2005**

Elevation "A" | **Designer: Kirk ext 401**

Trail Ridge Homes | **Revised: 9/16/2005**



STOCK Building Supply

Denver Truss
1247 E. 68th. Ave
Denver, Colorado 80226
(303) 289-5461 / Fax: (303) 289-7998

Plan T05 **5/31/2005**

Elevation "B" **Designer: Kirk ext 401**

Trail Ridge Homes **Revised: 9/22/2005**