Identifying the Economic Barriers to CLT Cost Estimation Among Building Construction Professionals

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Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science
In
The Department of Sustainable Biomaterials

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May 3, 2019
Blacksburg, VA

Keywords: Cross-Laminated Timber, Mass Timber, Cost Estimation,

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ACADEMIC ABSTRACT

Cross-laminated timbers (CLTs) are strong and lightweight structural building materials. CLTs are made from renewable wood resources and have significant economic potential as a new value-added product for the United States. However, market penetration has been obstructed by product affordability and lack of availability for use. Previous studies and projects have surveyed opinions of designers and contractors about the adoption of CLTs. No previous study was found that surveyed cost estimators, who serve the essential function of creating economic comparisons of alternative materials in commercial construction. CLTs are not included in these current cost estimation tools and software packages which may be limiting the potential use of CLT in construction.

The purpose of this study was to discover if cost estimation is being used to make structural decisions potentially affecting the marketability of CLT use in construction and building design because of the ability to estimate CLTs adequately. Through the use of a survey, the re-designing of a building, and discussions with subject matter experts, this study examined the knowledge level of cross-laminated timbers of under-surveyed building construction professions and the relationship between cost estimation and structural material choices. Their responses are demonstrating the need for better cost estimation tools for cross-laminated timbers such as inclusion in the Construction Specifications Institute's classification systems in order for CLTs to become a more competitive product. The study concluded that cost estimation is important for CLT market development, because it is being used extensively in the construction industry.

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General Abstract

Cross-laminated timbers (CLTs) are strong and lightweight structural building materials that also serve as a method of sequestering carbon rather than emitting carbon like more traditional construction materials. CLT construction is straightforward and quick to assemble, requiring minimal time and labor. CLTs are made from abundant and renewable wood resources and have significant economic potential as a job creator and as a new value-added product for the United States. However, market penetration has been obstructed by product affordability and lack of availability for use. Previous studies and projects have surveyed opinions of designers and contractors about CLT use. However, no previous study has been found that examined the opinions of cost estimators, who serve an essential function in providing economic comparisons of different construction systems for designers and building owners to select in the commercial construction area. CLTs are currently not included in these cost estimates, and this lack of information may be limiting the potential of this construction system.

The purpose of this study was to discover if cost estimation is being used to make structural decisions potentially affecting the marketability of CLT use in construction and building design because of the ability to estimate CLTs adequately. Through the use of a survey and discussions with subject matter experts, this study examined the knowledge level of cross-laminated timbers of under-surveyed building construction professions and the relationship between cost estimation and structural material choices. They are demonstrating the need for better cost estimation tools for cross-laminated timbers such as inclusion in the Construction Specifications Institute's classification systems in order for CLTs to become a more competitive product. Cost estimation is performed early in the design process before the structural material has been chosen. However, making cost estimates of CLT materials early in the design process is not a practical solution at this point due to the lack of cost data available. As an alternative solution, this project developed a design tool that is meant to accelerate the design process and allow companies to approach suppliers for quotes, which require mostly complete designs. While this is not a complete solution, if designs are made faster and more effortless, they should also be a more affordable investment for clients.

Building construction professionals perceived CLT construction as too expensive, unavailable to the consumer, or unwanted by the client. It was found that the lack of data, due primarily to the material being new to the US construction industry, was a significant barrier to CLT cost estimation. The custom design of many previous CLT projects, due to the lack of CLT construction in the current building codes, limits the collection of standard CLT construction data. There is also an issue with the discrete sizes of CLT panels limiting their competitiveness. These barriers were identified in this study, and further research is needed to develop complete solutions.

Introduction

Wood has been used as a primary construction material since at least the Neolithic age. It was one of the first strong, easily accessible and shapeable materials in history. The close relationship between society and forests meant that wood has been available from antiquity and more advanced tools and production processes have only increased the use of wood in construction. The renewability of wood has sustained use despite increasing demand and exploitation over the centuries. These advantages are still relevant to the modern construction industry. Wood remains the only renewable structural material. With the development of mass timber construction and engineered wood products, like cross-laminated timber (CLT), the possibilities and opportunities for wood as a construction material have expanded.

A Brief History of Wood Construction

In Scotland, excavations of timber buildings such as the Balbridie Hall have been carbon-dated to between 3100 and 2700 BCE [1]. There are even older wood buildings found in Turkey dated to around 6000 BCE. These buildings were limited to using primarily smaller diameter trees. However, when copper, bronze, and iron tools were developed, this limitation was removed. New technology for cutting and shaping trees allowed for even more widespread and massive wood constructions such as the stave churches in Scandinavia, the early forms of Greek temple construction, and the houses and timber bridges of the Romans. These structures began the tradition of timber construction in Europe, which would be brought over with the colonists to the Americas [2].

The first homes in the United States at Jamestown were hastily constructed of wood and the fortifications the settlers built to defend themselves were primarily wood stave constructions, chosen due to the balance of availability, strength, and speed of construction [3]. In New England, settlers adopted the Native American method of building huts of bent saplings, which were replaced quickly by wood-framed houses with clapboard siding, known as the New England saltboxes. Traditional US timber framing and log cabin construction, which became the icon of the pioneer homesteads, were brought over by English and Northern European immigrants during the seventeenth and eighteenth centuries and became the choice of pioneers because the buildings were warm, durable, and could be quickly built and repaired using the materials at hand [4]. Wood construction continued to be an essential construction material throughout the 18th and 19th centuries, joined by brick, stone, and stucco construction, in the Georgian and Federalist styles of architecture of these periods [4,5].

It was during the 19th century that modern heavy timber construction developed using the traditional European timber framing techniques and from the need for a less combustible method of construction for the building of industrial buildings, i.e. factories and warehousing. Heavy timber construction started in New England in the 1820s and spread with the industrial revolution. It was slowly replaced as the choice material for fire protection by steel and concrete after the 1870s when the same industrial development that made heavy timber famous made iron, steel, and concrete more affordable. Since these developments were before the advent of power tools, the construction of heavy timber buildings required a great deal of preparation and skill in the crafting of timber-framed joints. The complexity and skill required for heavy timber combined with the competition of steel and concrete building materials, as well as the need for timber in rail construction and other infrastructure led to the end of heavy timber construction by the 1920s [6].

Housing, however, continued to be dominated by wood construction during the 19th century, and into the 20th century, when the population boom after the second world war dictated the development of a large scale housing boom. Wood light-frame construction met the needs of the country in terms of cost, speed, simplicity, and scale. Light frame construction, including the modern platform framing and its precursor balloon framing, was developed during the 1830s when water-driven sawmills were invented and the processing of large timbers into standard sizes and lengths allowed for faster, cheaper, and structurally efficient constructions. These advantages have remained into the present, making light-frame construction one the most competitive construction methods for single-story and low-rise buildings [4].

The Importance of Wood Buildings in the United States

As wood construction has been indispensable in the past, so it is essential now and in the future of the United States. Light-frame construction is still the primary method chosen for home building in America. Forestry and wood industries employ a significant number of Americans. The wood products manufacturing industry, including lumber and engineered wood products production, alone employed 406,500 people in the US in May 2018 [7]. The primarily wood-based residential construction industry employed 778,530 people in May 2018 [8]. The forestry industry, which supports construction and wood product manufacturing by the growing and harvesting of timber, employed 35,770 people in 2018 [9]. All told, at least 1,220,800 people are employed because of wood construction, before taking into account the developing field of mass timber construction used in commercial, municipal, and multi-family residential construction.

A growing percentage of mid-rise construction is being built out of wood through the products and methods of mass timber construction. It is predicted that cross-laminated timbers and mass timber will be significant sources of economic prosperity for the US. The number of mass timber construction projects that have been initiated has increased from 20 in 2014 to over 200 in 2018 [10,11]. There are currently three manufacturers of CLT panels for construction use in the United States, Smartlam in Montana, DR Johnson in Oregon, and International Beams in Alabama. The last facility opened in 2018, and there are at least three more manufacturing facilities planned: Katerra and Vaagen Timber in Washington, and Smartlam in Maine [11]. The increase in facilities demonstrates a trend of investment and expectation for the future importance of mass timber construction in the US. However, it can be seen in Figure 1, most of the United States without a CLT manufacturer within a couple of hundred miles, this includes the major Canadian manufacturers Structurlam and Nordic, which also supply the US market.

Figure 1: Map of graded CLT Manufacturer planned or constructed in North America [11].

Mass Timber Construction

The American Wood Council defines mass timber construction as a category of framing styles typically characterized by the use of large solid wood panels for wall, floor and roof construction [12]. Mass timber construction has its origins in heavy timber construction, which in turn developed out of the traditional timber framing practices brought to America in the 17th and 18th centuries by European immigrants. Heavy timber construction is construction using wood structural elements that are at least 6 inches nominal in either depth or breadth, as opposed to light-frame construction or post and beam construction that uses 2x and 4x material. The main difference between mass timber and heavy timber construction is that mass timber is commonly used to describe the increased scale of newer buildings allowed by the development of large dimension engineered wood products like glulam and CLTs. Heavy timber has been used for timber-framed housing, but was developed for use in industrial warehousing and factories in the 19th century because large timber beams would not burn through or collapse due to fire as light-frame and brick construction would. This method of construction restricted the size of the buildings by the maximum size of the timbers that could be acquired and could not be expanded without the development of engineered wood products (EWP) in the 20th century [6].

The first engineered wood product developed was plywood, sheets of veneer with alternating grain directions between plies, first created as a building material in the 1920s. This first EWP's revolutionized the light frame construction industry and led the way for more massive and robust products [13].

The first engineered wood product for structural beams was laminated veneer lumber (LVL), which is a series of peeled veneer strips adhered with grain in the machine direction. LVL is not restricted by the size of the trees the veneers are generated from, since the veneer dimensions could be increased by distributing the gaps between veneers in the same layer so that the overall product remained strong and intact. However, the cost of using veneers meant that the economics of this product still restricted its practical use. This restriction, in turn, led to the development of glue-laminated lumber (glulam), which follows the same principle as LVLs but used dimensional lumber. Glue-laminated timbers do not have the same physical constraints of conventional timber beams yet also are far more affordable for large dimensions than LVL. After the development of wood composite products, heavy timber construction became competitive again with other materials for projects at the modern scale of commercial, industrial, and municipal buildings [14].

Glulam

An example of mass timber construction is the Richmond Oval built for the 2010 Vancouver Olympics. It was designed using large glulam arches to create large open spaces combined with the aesthetic appeal of exposed wood ceilings [15]. These buildings are possible because the techniques for manufacturing allow for any length or depth of the beams as well as curved beams for arches. The most significant limitation for the dimensions of a single glulam is the capacity of the transportation method. The relatively lightweight and the softness of wood beams make construction very simple with glue-laminated timbers because customized metal fasteners can connect virtually any shape, size, or number of timbers.

There are some challenges to glulam beams. For one, because glulam beams are made by laminating dimensional lumber upon one another, the width of a beam is maximized by the width of lumber produced, which leads to still being limited by the size of the trees harvested. Glulam, being a laminated material, also has discrete thicknesses that translate to discrete spans and load capacities when being used in construction. Discrete sizing can lead to a design excluding glulam beams as an option. For example, when a 30-foot span beam is needed a 30-foot glulam beam might not be available because of economic factors in manufacturing. A glulam beam with a 28-foot span would be too short, but a glulam beam with a 32-foot span may be too expensive to compete with other more continuously sized materials, like steel and poured concrete. Additionally, glulams are still one-dimensional materials, just like most previous structural wood products. Glulam can act as girders and joists but still requires cladding to create floors and roofs. Cross-laminated timbers do not share this requirement.

CLT

Cross-laminated timbers (CLTs) are the next big step for wood construction and mass timber. Cross-laminated timber is defined by the APA as a prefabricated engineered wood product made of at least three orthogonal layers of graded sawn lumber or structural composite lumber that are laminated by gluing with structural adhesives. Cross-lamination makes a strong, solid wood, two-dimensional panel that can be used as full floors and walls rather than a one-dimensional beam or column. The advantage of this two-dimensional behavior is that CLTs can act as a structural member that does not require cladding between spans or structural supports. A two-dimensional structural element allows for entire walls, floors, and roofs to be constructed out of CLTs. CLT panels can be up to an approximately 10-foot by 40-foot panel limited by the size of presses and the economy of shipping. A full building can be assembled with dozens of panels [16]. The CLT panels are connected by metal fasteners; generally, metal plates using lag screws or self-tapping wood screws[17]. Therefore, a relatively unskilled construction crew assemble a full superstructure of a building in a short time compared to other methods of construction, like concrete [18].

Figure 2: Example photo of CLTs taken at Sauter Timber (A.L. Hammett, 2019).

The Stadthaus project is a good example that demonstrates the speed of construction possible using CLT construction methods. The project was a nine-story residential building in Hackney, London, of which eight stories were built entirely out of CLT, was assembled in 27 days by four carpenters. The entire project was completed in 49 weeks and was estimated to have saved five months of construction over the concrete frame alternative [19]. Brock Commons, another CLT project, in Vancouver, British Columbia is another excellent example of the speed at which CLT structures can be constructed. This 18 story building was assembled using glulam and Parallel Strand Lumber (PSL), a laminated strand lumber product, columns and CLT floors with two concrete building cores to house elevators. The wood structure was built in 70 days, while in comparison, the concrete cores required 12 weeks to complete [20]. Because of this new utility, cross-laminated timbers are currently being used regularly in Europe, North America, and Australia with interest shown in Asia [21]. There will be even more CLT utilization in the United States when the 2021 International Building Code becomes effective in 2024, as it has approved CLT construction up to 21 stories [22].

There have been many previous studies on the performance of CLTs. The structural capacity and behavior of CLTs have been thoroughly explored to establish the safe limits and guidelines for the use of CLTs [23,24,25,26,27,28,29,30,31,32]. Structural research includes studies on the various methods of connecting CLTs [33,34,35,36]. The environmental impacts of using CLTs as a substitute for steel and concrete have also been evaluated [37,38,39,40], as well as the impact of the moisture and climate on CLTs [41,42]. Research on the fire-performance and safety of CLT buildings demonstrating that mid-rise buildings can be safely built from CLTS, which was a fundamental concern in the changing of the International Building Code (IBC) [43,44,45]. From these studies, CLTs have been proven structurally safe and within required safety limits for fire resistance when used according to the guidelines of the IBC.

There have also been several studies [46, 47, 48] examining the knowledge of CLTs and the barriers to its adoption in the wider construction community. A 2013 study [46] asked a group of architects, engineers, contractors, and developers about their awareness and perceptions of CLTs. While there was adequate awareness of CLTs, an understanding of the capabilities of CLT buildings was severely lacking. The three most significant concerns found in their study were concerns over high costs, building codes, and seismic performance. A 2015 survey [47] of architectural firms examining the industry awareness of CLT concluded that architects had a low awareness of CLTs. Architects perceived CLTs as being aesthetically desirable with excellent structural and environmental benefits, but having a high cost and poor fire performance. A similar study in 2016 [48] focused on designers and contractors, attempting to discover barriers to the commercial adoption of CLTs. Study participants were highly concerned about the high cost of CLTs, as well as the uncertainty of performance, concerns over warranty and insurance with CLTS, and lack of client demand. From these studies, the two highest resistances to the adoption of CLTs were the perceived risk to costs and unfamiliarity with the product.

These three studies all agreed that the construction industry had limited awareness of CLTs as an option, but more importantly have consistently held concerns over its use, particularly a repeated concern of its perceived high cost. Perceived is the operative word in that phrase. Costs for CLTs vary by regional market, how it is being used, and the experience and efficiency of the businesses involved, i.e., the CLT processors, manufacturers, and installers [49]. So whether CLT construction is expensive or not is dependent on the circumstances. As such, the ability to assess the cost of a CLT building at an early stage could be vital to the adoption of this product. Assessing the cost could be done by using cost estimation.

CLT Cost Estimation

Cost estimation is an attempt to predict the cost of a building during the various stages of construction from concept to final product using historical data. There are many forms of cost estimation, but they all use historical building information and costs. Cost estimates can be created simply by averaging the previous buildings with similar designs and square footage, such as giving an average price for a 500,000 square foot hospital. Alternatively, a cost estimate could be based on the expected fees and materials list. Cost estimates can also include allowances for specialty items, overages, scheduling issues as well as the net present value of money. Each method of cost estimation has its level of accuracy and required building definition, i.e., how complete the design must be before the cost estimate.

An industry standard for cost estimation, made during the preconstruction phase of building construction, is called assembly or systems based cost estimation. It uses the concept of building systems and assemblies to predict the majority of a building's cost by assuming that most buildings are similar in their design at the structural level. There are standards for how walls, floors, roofs, and shafts walls are built that are almost universal in design. Standard assemblies mean that by knowing the cost of a square foot of a particular type of wall and knowing how many feet of wall is in the design, a designer can predict, within a reasonable margin, how much the building's walls should cost. Creating a cost estimate with this method can be expensive and time-consuming, which is why assembly based cost estimates generally are made for larger-scale buildings.

Cost estimation is most commonly used with mid-rise and high-rise commercial and multi-family buildings which are the sectors in which CLTs are expected to compete. Cost estimates are used in these projects to compare structurally similar systems of construction against one other on an economic basis. For instance, when comparing the cost of a steel frame building against a concrete masonry unit (CMU) building without altering the exterior or interior layout or appearance. If a cost estimate is not created, the cost of the materials cannot be compared to each other without receiving multiple quotes. However, quotations require near-complete designs in order for companies to accurately guess the price, and designs often change with the material being used. So without a cost estimate, designers would have to create multiple designs to know the potential costs of comparable materials. Because of the cost of generating multiple designs, builders will use other metrics to make decisions, such as aesthetics or embodied energy, which may be less critical to the client. Unfortunately, there is no historical cost data on the use of CLTs with which to create accurate cost estimates, and so they cannot be accurately compared to competing materials by cost.

One example of the lack of CLT data is that the absence of CLT information from MasterFormat and UniFormat. These are classification systems created by the Construction Specifications Institute (CSI). MasterFormat describes materials and is commonly used by contractors and designers to list materials. MasterFormat allows programs such as LEED to gather information about the materials and their content used in a building without having to examine the building plans in detail [50]. UniFormat describes building assemblies such as wall sections and used to generate simple square foot costs for initial building designs and can be an essential part of the contractor bidding process [51]. The lack of CLT entries for these systems means that CLTs are not considered from any construction process that follows this traditional path. Without a cost estimate, CLTs must be specifically chosen as the primary structural material for reasons other than the cost of the building, and this severely limits the marketability of the material.

Estimating the cost of cross-laminated timber buildings is currently challenging, at least at the earlier phases of design. Cost is heavily dependent on the location of the building before considering even the challenges that may exist in the design. As of April 2019, there are only three manufacturers actively producing CLTs for construction in the United States [11]. Smartlam and D.R. Johnson are both located in the Pacific Northwest with high transportation costs for delivering to the East Coast; whereas International Beams, located in Alabama, has only really begun to produce panels. According to Reinhard Sauter (an expert in CLT processing), it is currently cheaper to purchase panels from Austria than buy panels from any North American source [52]. However, the introduction of the ANSI/APA PRG-320-2018: *Standard for Performance-Rate Cross-Laminated Timber* [53], the CLT grading document, and inclusion of CLTs into the International Building Code has led to European panels being at a disadvantage due graded North American CLTs panels can now be used prescriptively, not requiring additional structural analysis and approval by building inspectors [22, 52]. Currently, CLT and mass timber projects are typically bespoke projects that do not necessarily lend themselves to conventional building designs. They often expose wood for aesthetic or biophilic reasons in areas that would generally be covered, so the costs of finishing are not applied to these uses. These economic variabilities mean that it is challenging to generate an estimate without developing a full design and receiving a quote from the manufacturer.

Purpose of the Study

Wood has held advantages throughout history of being strong, lightweight, plentiful, and replenishable material and power tools have made the shaping of wood one of the easiest of construction materials. The development of engineered wood products has removed the barrier to wood use in construction of dimensional limitations. These advantages, when applied in heavy and mass timber construction methods, makes for a fire-resistant and competitive system, particularly with cross-laminated timber applied in prefabricated panels. One significant potential barrier for the marketing of this new material and mass timber construction is the ability of professionals to estimate the costs of CLTs.

The purpose of this research is to examine the importance of cost estimation in the selection of building materials for structural decisions. Through the distribution of a survey, this study explored the need for assembly-based cost estimation, such as UniFormat-based estimation, which includes standard building sections and systems, i.e., wall, floors, roofs, mechanical systems, into cost per square foot for an assembly. The survey also examined whether the professions of architects, contractors, and cost estimators are not just aware of cross-laminated timbers but also have an accurate view of the abilities of this material. The second portion of the study focused on re-designing a steel-frame building and attempting to compare the cost to an equivalent CLT design and gain firsthand insight into the challenges of CLT cost estimation. The survey and building design were complemented by the third approach of the study, speaking with CLT experts in order to answer questions and fill in any missing information.

Methods

Project Overview

The purpose of this study was to examine the role of cost estimation in the choice of structural materials like CLTs. This study was divided into three phases. The first phase was to survey building construction professionals. The survey was in three sections: demographics, CLT knowledge, and cost estimation use. The first two sections were used to understand the experience and position of the professionals participating in the survey.

The second phase was to understand the process of cost estimation with CLTs so that the barriers obstructing the estimation of CLT buildings could be experienced. In order to obtain this better understanding, a case study of a steel-frame building re-designed to use CLTs as its primary structural element was used. Additionally, a design tool was developed during the process of re-designing this building. The design tool was meant to accelerate the design process by allowing simple inputs to automatically check the structural, fire, and lateral soundness of a new element. This phase provided first-hand experience with CLT designing to inform the researchers about the challenges designers face in the CLT design process.

The third phase was to interview CLT experts to corroborate information obtained through a literature review, the survey, and through the experience of design. Two experts were contacted: Reinhard Sauter, owner of Sauter Timber, and Terry Pattillo, an architect and Regional Director for Woodworks, a building support organization for mass timber buildings.

These three methods of research were chosen so to provide a circumspect perspective on CLT cost estimation and whether cost estimation is vital for the developing CLT construction industry. The survey has supplied a source of direct industry opinions on the topics in question. The building re-design provided firsthand experience in the process of CLT building design and cost estimation. Finally, the experts contacted were able to give more elaborate and anecdotal information that could answer questions beyond the survey and design. Together, these approaches gave a more circumspect answer to the research question than any one of them could alone.

Project Objectives	
Phase 1	Survey Distribution and Analysis
Phase 2	Building Re-Design and Development of CLT Design Tool
Phase 3	Discussions with Subject Matter Experts

Figure 3: Project Objectives Chart.

Phase 1: Survey Distribution and Analysis

The survey was distributed in October 2018 through January 2019. The survey included questions to judge the recipients' understanding and awareness of CLTs, usage of UniFormat, 3D modeling, and cost estimates and the potential impact of a building economic standard for CLT walls and floors. The survey was approved by the Virginia Tech Institutional Review Board (VTIRB), through the Western Institutional Review Board (WIRB), as being minimal risk to the participants of the survey [Appendix A]. The target demographics for the first survey was construction cost estimators, contractors, construction specifiers, and architects. The intention was also to distribute this survey to construction engineers. However, no organization of construction, structural, civil, or architectural engineers agreed to release the survey to their members or alumni. The Association for the Advancement of Cost Engineering (AACE), an international professional organization for cost estimators, released the survey to their approximately 4,162 members [54] and the Virginia Tech School of Architecture and Design released the survey to 1,133 architectural and building construction alumni who consist of primarily contractors and architects. Both groups were also sent a reminder to participate a month after the initial contact. Of the 5,295 individuals to which the survey was available, 45 responded for an approximate response rate of 0.85%. The size and national scope of these organizations should help prevent any bias from being placed into the sampling of these populations.

The survey results from Phase 1 were analyzed by dividing the survey into three categories: demographics, CLT knowledge, and use of cost estimation. The first and third sections were analyzed simply by tallying the information collected and comparing the results for individual questions.

The second category was more involved in its analysis. The data regarding CLT knowledge was gathered by asking eight questions covering general CLT topics, including fire and structural safety. Responses were given point values based on whether the answer to a particular question was reflective of accurate information, based on research that has been performed on CLTs by others, or if they have experience with the material.

The possible profiles ranged ratings of participant knowledge of 7 to -4. One point was given for an answer corresponding to the actual performance of CLTs based on research. A negative point was assigned to an answer contrary to CLT research. No value was assigned to uncertain answers or answers not supported by preexisting research. An additional point per answer was given if they responder had previously heard of CLTs, worked on a CLT project, or was aware of one or more manufacturers of CLTs. An example question was, “Do you think CLTs are fire-resistant?”, and had possible answers of “Yes”, “Maybe”, “No”, or “Not sure”. “Yes” answers were given a value of positive one. “No” answers were given values of negative one. “Maybe” and “Not sure” answers were given a zero value. This method is partially subjective in that the interpretation of the questions and the accuracy of the point associated with a given answer are arguable. This CLT profiling was meant to gauge a general understanding of a responder’s awareness level regarding CLTs. Specific values associated with each answer for each question can be found in the survey, Appendix B. Survey graphs can be found in Appendix C.

Phase 2: Building Re-Design and CLT Design Tool Development

The second phase was the re-design of VTCRC 1311, which is a building in the Corporate Research Center at Virginia Tech (VTCRC). It was designed by SMBW, an architecture firm located in Richmond, Virginia and constructed by EDC, the general contracting and construction management company also headquartered in Richmond, Virginia. Raymond Hunt from EDC, the construction manager for the project, provided the structural drawings, architectural drawings, and a project budget dated December 21, 2017. The building is scheduled for completion in 2019.

The building a two-story 42,816 square foot steel frame building with steel hollow structural sections (HSS) for columns and steel wide flange beam girders and joists with a five-inch concrete slab for floors and roof. Metal framing was used between supports to mount a brick and stone veneer and gypsum board interior. The roof was enveloped by a two-and-a-half-foot parapet and with an enclosure housing the mechanical systems. Figure 2 and 3 are photos of the building, on April 28, 2019. Figure 4 is the ground floor layout the shows the general floor plan for the building.

Figure 2: Photo of VTCRC 1311: Northwest Corner View (Stutesman, 2019)

Figure 3: Photo of VTCRC 1311: Southeast Corner View (Stutesman, 2019)

The re-design was intentionally limited to the structural framing elements for simplicity in comparison and design. Most of the original design was left intact including the interior layout, exterior appearance, and any structural members necessary to accomplish these goals, such as metal framing between structural supports. It was also decided not to alter the design of the foundation so that a direct comparison of the framing elements could be made. The design process was facilitated by the development of a CLT design tool. The tool was created in Microsoft Excel. It followed the design process illustrated in the CLT Handbook [17].

Originally a cost estimate was intended to be created for materials and labor of CLTs, present in the new building design. However, information from literature and the conversation with Terry Pattillo made it clear that creating a cost estimate at this time would be inaccurate and without adequate supporting data. To support the future creation of CLT costing tools, a CLT design tool, which would produce material estimates suitable for an assembly based costing estimation, was created.

Phase 3: Discussions with Subject Matter Experts

In February 2019, two industry experts were contacted to discuss CLT processing, design, and cost estimation. Reinhard Sauter of Sauter Timber in Tennessee was contacted regarding his experience with processing CLTs and how he manages costs and pricing in his business. Terry Pattillo from Woodworks, a building support organization for mass timber construction, was contacted regarding his work advising building construction professionals with constructing mass timber buildings, more accurately how they estimate the cost of buildings. The goal of these two conversations was to fill in any gaps in knowledge about what constituted a reasonable baseline for costing the CLT assemblies in Phase 2.

Results

This section presents the results of the three phases of research in this study and discusses their implications on the research question and the CLT industry as a whole.

Phase 1: Survey Distribution and Analysis

The following section describes the results of the survey including the demographics, CLT knowledge, and cost estimation use. In each section, the responses to each question are presented and discussed.

Demographics of Survey Participants

The survey received a total of 45 responses, though the exact number of responses per question varies, in large part due to some questions being dependent on whether the responder used cost estimation or not. The small number of responses was expected due to the method of distribution as the survey was sent out through email without financial compensation.

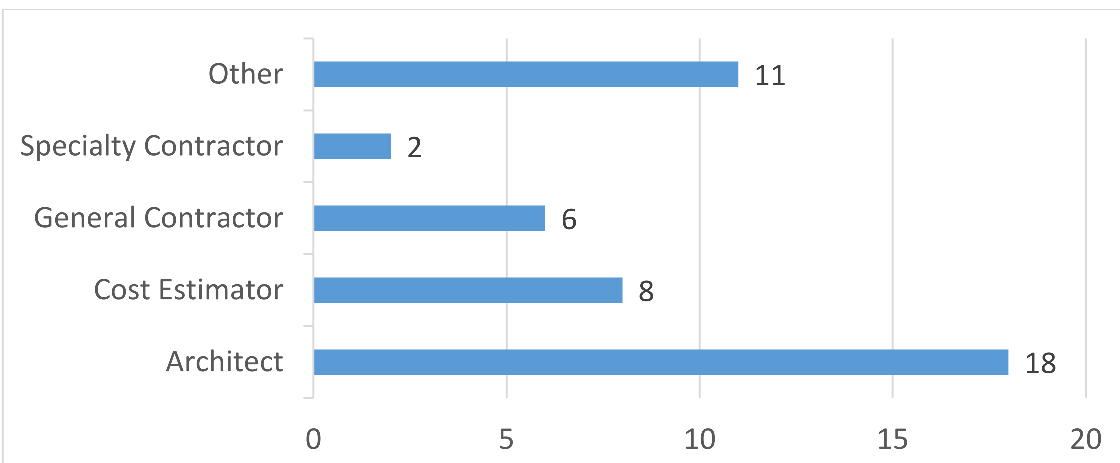


Figure 5: (Q1) Survey Participants by Profession; Total Responses = 45

The responses to Question 1 are shown in Figure 5. Professions varied with responses from architects at 40% of responders, cost estimators at 17.8% of responders, and contractors, both general and specialty contractors, at 17.8% of responders and other professions at 24.4% of responders, as shown in Figure 5. The responses “Design Consultant” and “Construction Engineer” were options in the survey, but received no responses. It is unknown to which profession the “Other” participants belong, as these respondents answered questions similar to the other categories of the construction industry.

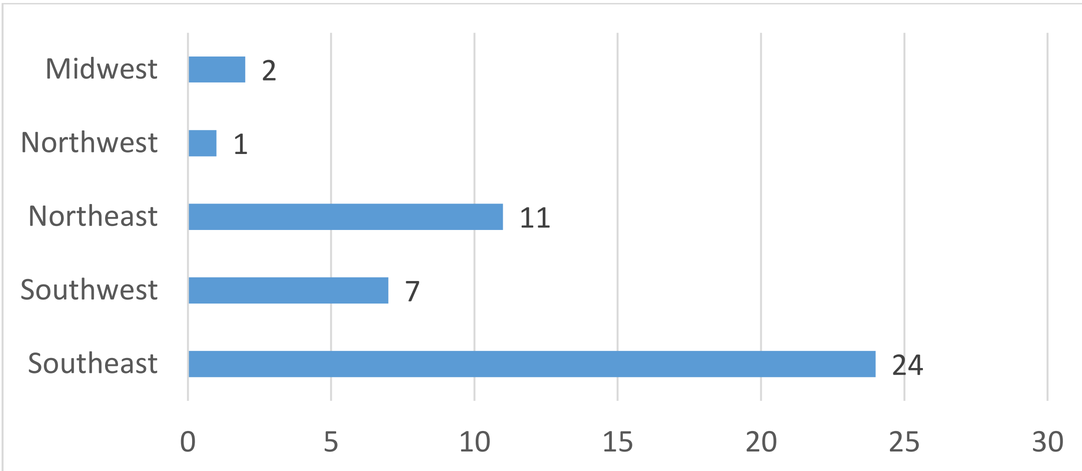


Figure 6: (Q2) Regional Distribution of Participants; Total Responses = 45

The responses to Question 2 are shown in Figure 6. The majority of the participants, 53%, were located in the Southeastern region of the United States. The next highest regions represented were the Northeast, 24%, and Southwest, 16%. Participation was skewed to the eastern United States (Figure 6). This result was to be expected due to one of the two distribution channels being the alumni of the Virginia Tech School of Architecture and Design. Because of the disproportionate response from across the country, the under-represented regions may not represent the perspective of all building construction professionals in these regions. This skewing of the data towards the eastern United States could affect the results of the CLT awareness questions, since the Pacific Northwest has three of the current North American CLT manufactories, two new manufactories planned, and one hundred and nine CLT projects of the five hundred and forty-five projects in the nation [10, 11].

In question 3, the participants were asked in which construction markets they typically worked (Figure 7). Since architecture, engineering, and construction firms often operate in multiple construction markets, multiple answers were allowed for participants, and therefore, the number of answers exceeds the number of responses. The most represented construction market was “Public/Government” followed by “Low-Rise Commercial”, then “Industrial”, “Other”, and “Single-Family Residential”. Unfortunately, the least represented sectors were “Multi-Family Residential” and “Mid/High-Rise Commercial” as these two of the three sectors that are the most likely to utilize CLTs, based on the previous projects reported by Woodworks [10]. The third sector that is likely to use CLTs being "Public/Government", was the most represented. The low representation for two of the three most significant sectors may limit the relevance of this survey to CLTs in the "Multi-Family Residential" and "Mid/High-Rise Commercial" sectors, but should be representative of the knowledge and use of CLTs and cost estimation in the "Public/Government" sector.

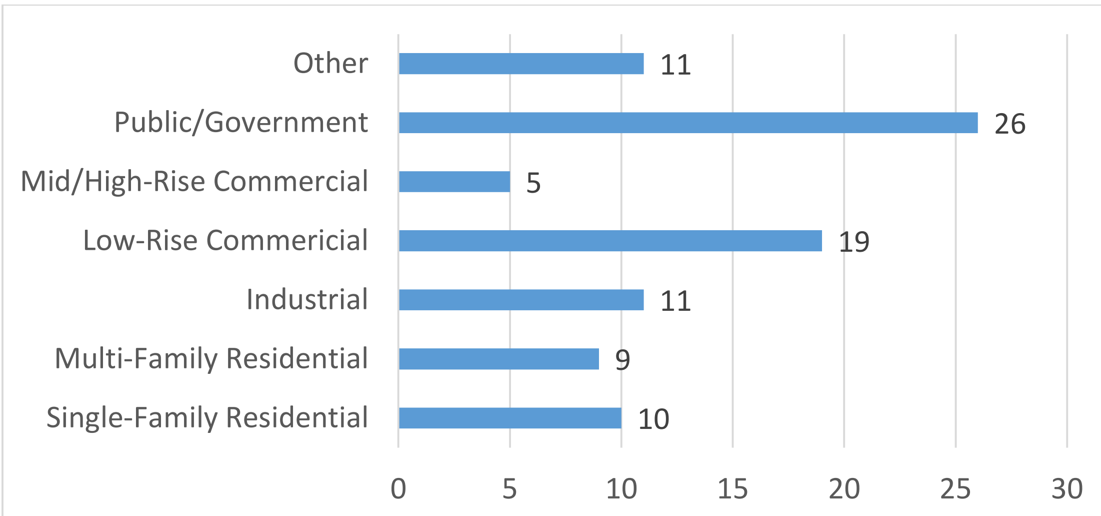


Figure 7: (Q3) Construction Markets in which Participants Work; Total Responses = 45

In Question 4, the participants identified the phases of construction in which they work, allowing multiple answers because professionals often work in multiple phases. Of the forty-five responders, thirty-eight said that they work in the "Construction" phase, thirty-four in the "Design" phase, and thirty-three in the "Preconstruction" phase. These are the most relevant phases as they are the most affected by cost estimates. Twenty participants also replied that the work in "Finishing", nineteen in the "Renovation/Restoration" phase, and thirteen "Operation/Maintenance" phase. This question revealed that the majority of participants operate in the phases most relevant to cost estimation and this study.

Participants were permitted multiple answers for the project sizes they typically work on because professionals often work on multiple project scales. Since the survey had at least 10 participants with experience in every scale of project from below $50,000 to $100 million, with the largest group having worked on buildings with budgets between $1 million and $5 million, as shown in Figure 8.

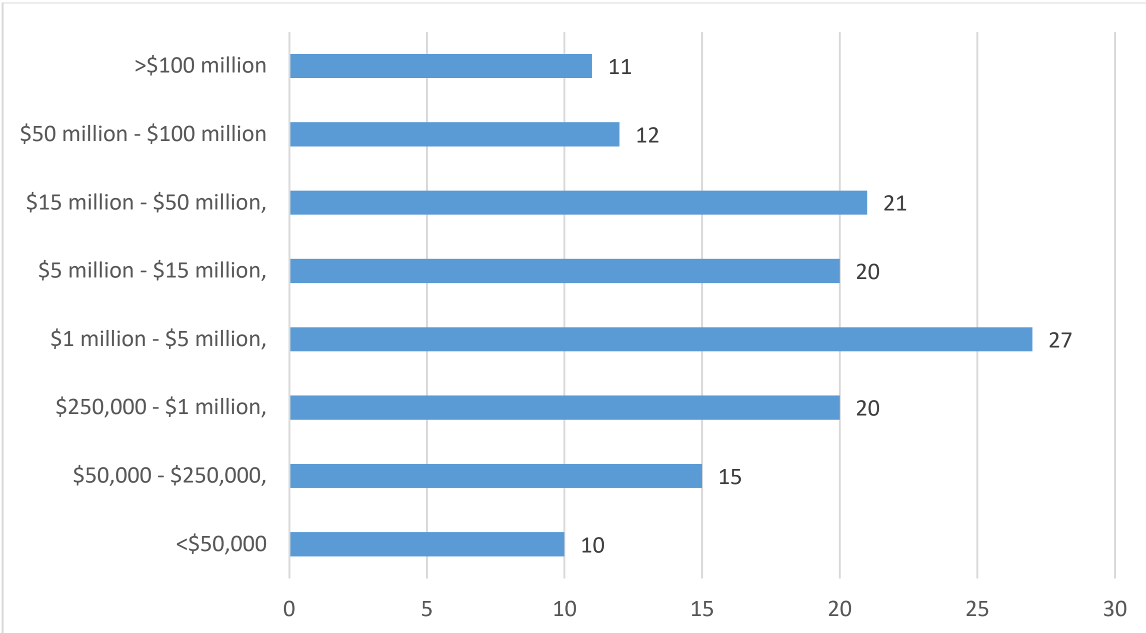


Figure 8: (Q5) Scale of Projects for Participants; Total Responses = 44

Question 6 focused on the size of the construction firm of the respondents. From examining the responses to question 6, the sample was split relatively evenly between 15 participants from large-sized firms of over 500 employees, 13 participants from medium-sized firms of more than 50 employees, and 17 participants from small firms of less than 50 employees.

Question 7 asked the respondant how many years of experience they had in the industry. From the responses to question 7 in the survey asking the years of experience of the participant, the majority of participants had at least ten years of experience in the construction industry, with almost all participants having more than five years.

Question 23 asked the respondants about the type of structural systems typically used in the buildings in their projects. The responses to question 23 revealed that roughly half the participants work with steel framing systems for their structural systems. About a third of the participants used light-frame construction. Another third of the participants used either reinforced concrete or CMU block systems. Therefore, the survey was felt to contain a variety of construction methods. With a diverse collection of construction methods represented, a bias towards any specific construction methods or industry was avoided.

The participants surveyed seemed to have a good range of experience in regards to the size of their firms, the scale of their projects, the construction markets in which they operate, and the phases of construction they work. However, these responses may be skewed towards the architecture profession and individuals from the southeastern region of the US. While the survey did not receive enough responses to be representative of the industry as a whole, there is value in the dozens of responses from veteran construction professionals in directing further surveying and exploration of this topic.

<u>Awareness of CLT</u>

This section of the survey questions the CLT knowledge of the responder and establishes their awareness and education level.

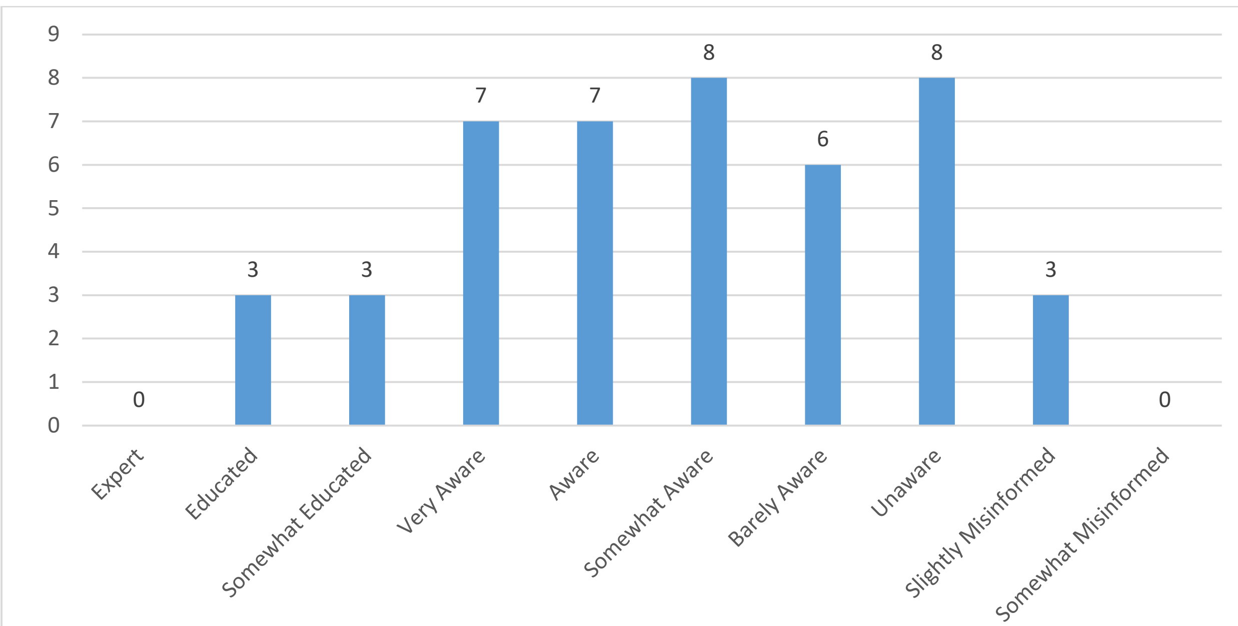


Figure 9: CLT Knowledge Profile Distribution; Total Responses = 45

The distribution of the knowledge profiles generated by the eight questions in this section provide a glimpse into the general understanding of CLTs by the participant is shown in Figure 9. No participants were considered experts, meaning they answered all questions correctly and had previous CLT project experience. Those who were considered educated had previous experience with CLT projects but did not answer all questions correctly. Three participants were profiled as being slightly misinformed, meaning they answered enough questions incorrectly to receive a negative value for their profile. The majority were in between educated and slightly misinformed.

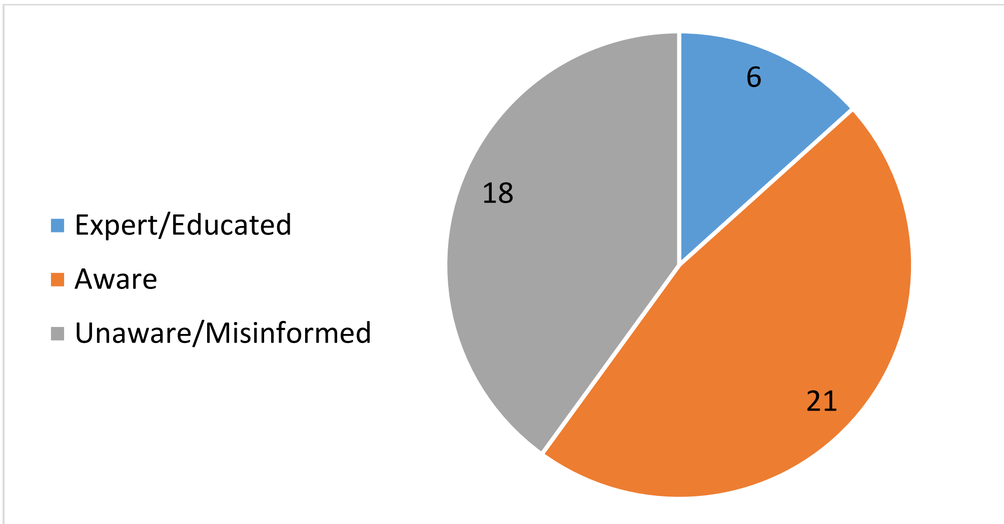


Figure 10: Total CLT Awareness; Total Responses = 45

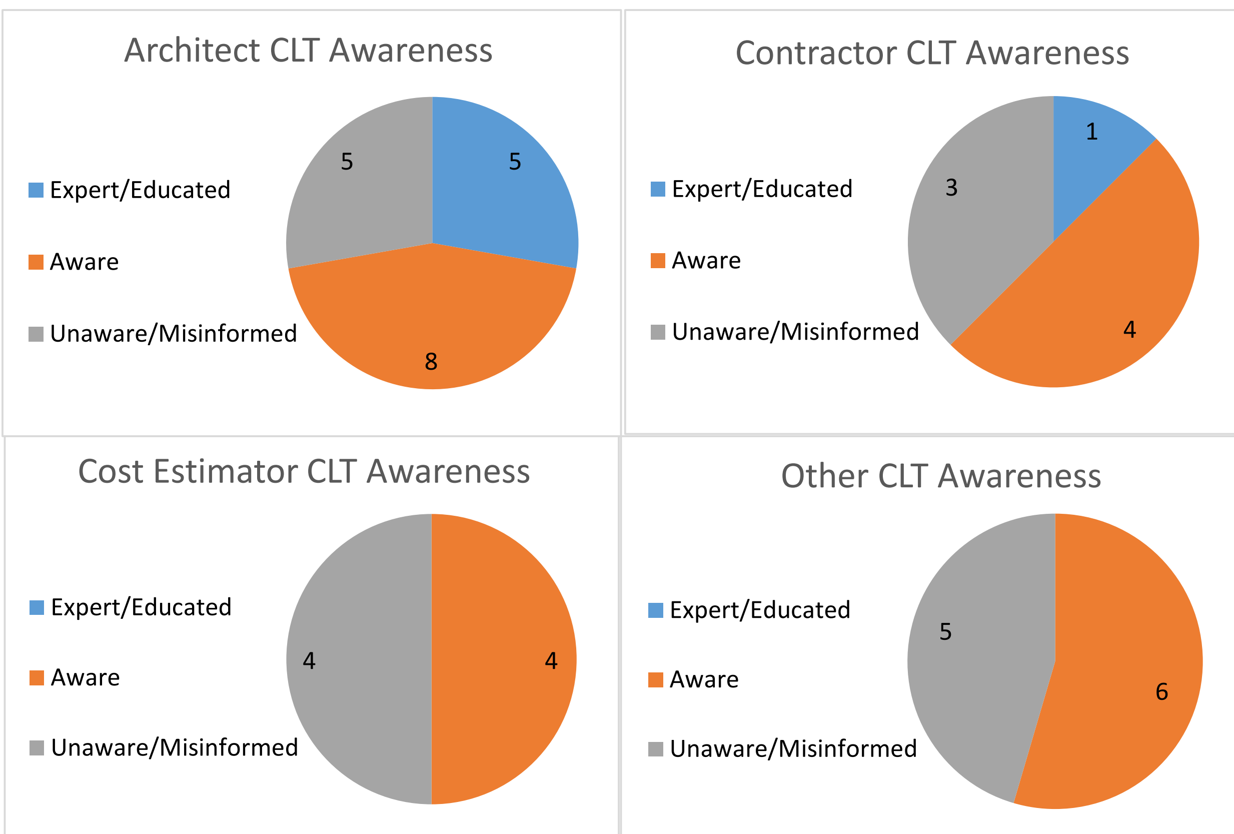


Figure 11: CLT Awareness by Profession; Total Responses = 45

Twenty-seven out of the 45 total responders or 60% were profiled as being "Aware" of CLTs, i.e. between "Very Aware" and "Somewhat Aware', but only six participants could be considered "Experts/Educated", i.e., "Educated" or better, with the material (Figure 10). Each of the professions surveyed had a relatively large portion of individuals who could be considered unaware or misinformed, having received a knowledge profile of 0 or below (Figure 11). Only six architects and contractors were considered educated about CLTs, that is people with both some experience using CLT and a good understanding of the material performance. This information demonstrates that there has been some success in raising awareness of CLTs with architects and contractors, but there is still room for improvement. However, only four out of the eight cost estimators and five out of the eleven of the "Other" professions were aware of CLT and their capabilities. More work is necessary to educate the construction industry about the performance of CLTs fully and that cost estimators especially need to more education about CLT.

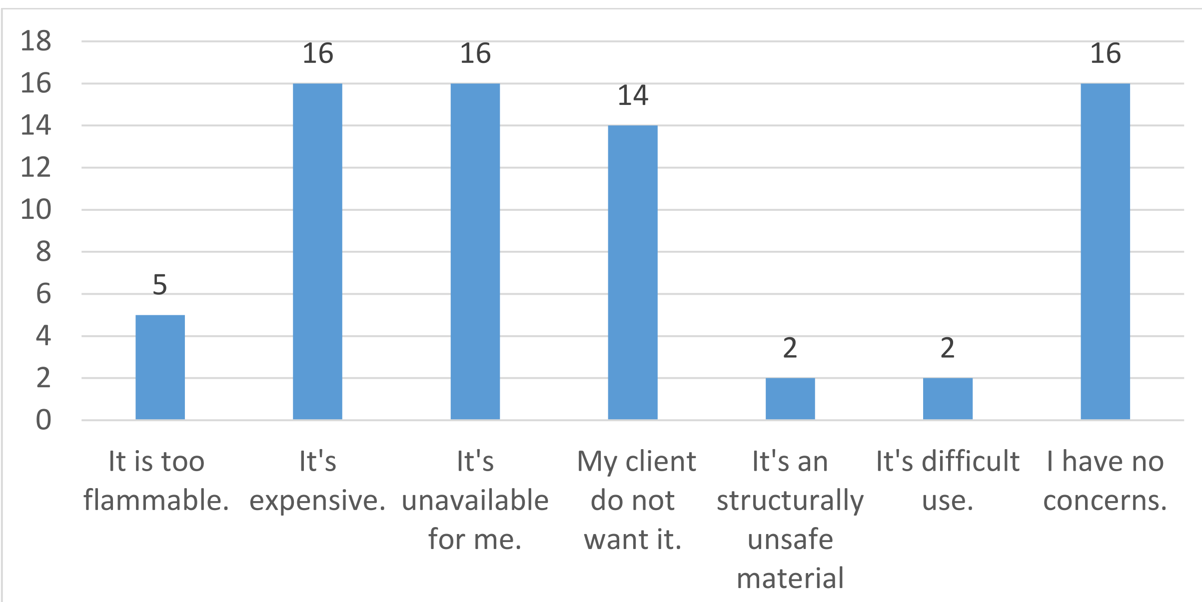


Figure 12: Top Concerns for CLTs, Total Responses = 45

Every responder was asked their top two concerns with CLT. Only sixteen responders out of the forty-five total, 35.6%, had no concerns about CLTs (Figure 12). The three greatest concerns were the material is too expensive, too unavailable, or undesirable to the client. These concerns support the argument that cost estimation is important because cost estimate can provide information about the expense of CLTs and potentially make the material more desirable if it is shown to be more affordable for an individual project. Nine responders had concerns about technical aspects of the material, including fire safety, structural safety, and difficulty of use. Of the three responders that had previously worked on a CLT project, only one had a concern, and that was about the expense of CLTs.

As expected from the previous studies, architects had the most extensive understanding of cross-laminated timbers, followed by contractors. These results also demonstrate that there is still room to continue to educate these professions and to expand the knowledge of cost estimators and similar professions. The top concerns found were promising as the most significant concerns regarding the utilization of CLTs regarded its marketability rather than its functionality. These concerns are evidence that cost estimation is an essential area of exploration for CLT construction since cost estimation assesses the expense of a material, takes into account the availability of the material, and presents an economic argument to the client regarding its use on a project. These functions match the three highest concerns identified in this survey.

<u>Use of Cost Estimation</u>

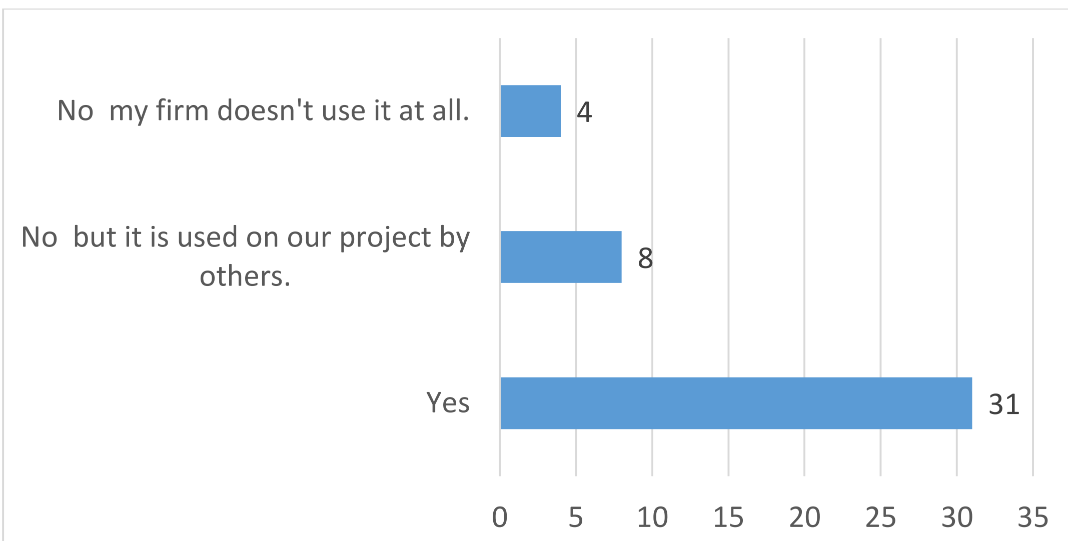


Figure 13: (Q17) Do you use cost estimation in your business?; Total Responses = 43

Question 17 asked if cost estimation is used in your business and the results are shown in Figure 13. The first question asked in the cost estimation section was whether the participant used cost estimations or not. Thirty-one out of the forty-three people who responded to this question answered that they directly use cost estimation in their business, illustrated in Figure 13.

91% of the responders, thirty-nine of forty-third, answered that cost estimation is used by someone in their projects. Of the thirty-nine professionals who responded to Question 18 indicated that they use cost estimation, 90% or thirty-four of thirty-nine said that they use cost estimates on at least 60% of their projects, as shown in Figure 14.

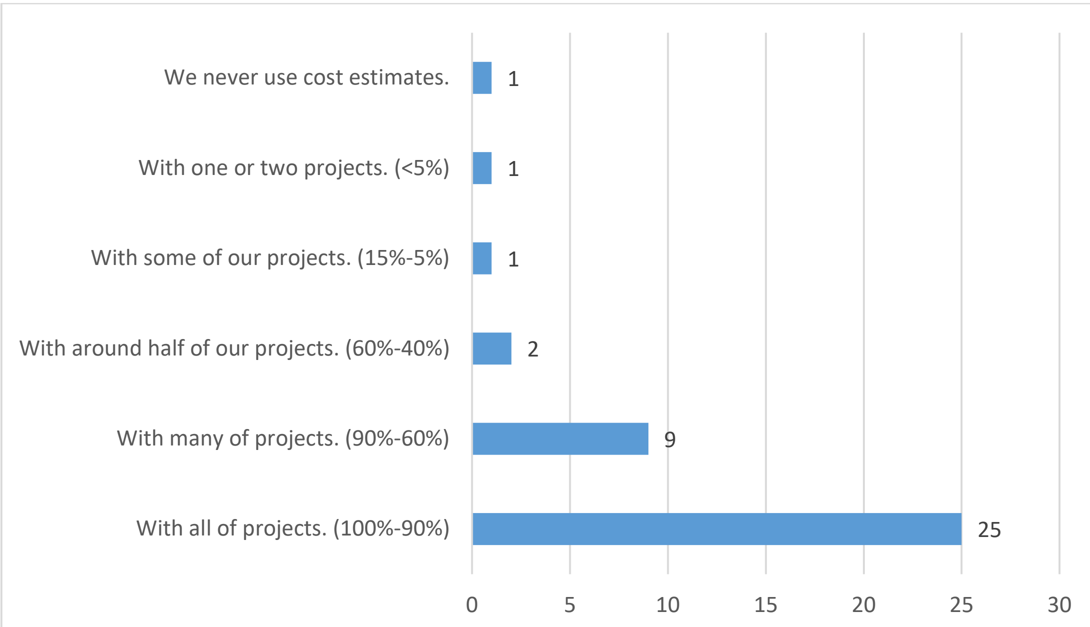


Figure 14: (Q18) How often do you use cost estimation?; Total Responses =

Figure 15: Cost Estimation Use by Profession; Total Responses = 32

In Figure 15, cost estimation was found to be used on the majority of projects by both architects and contractors. This figure excludes the responses from “Other” professions because, without information about the participants’ professions, it does not add any valuable information to compare their responses to the other participants when analyzing by profession. A vast majority of both these professions also answered that they use cost estimates on over 60% of their projects in question 18, shown in Figure 14.

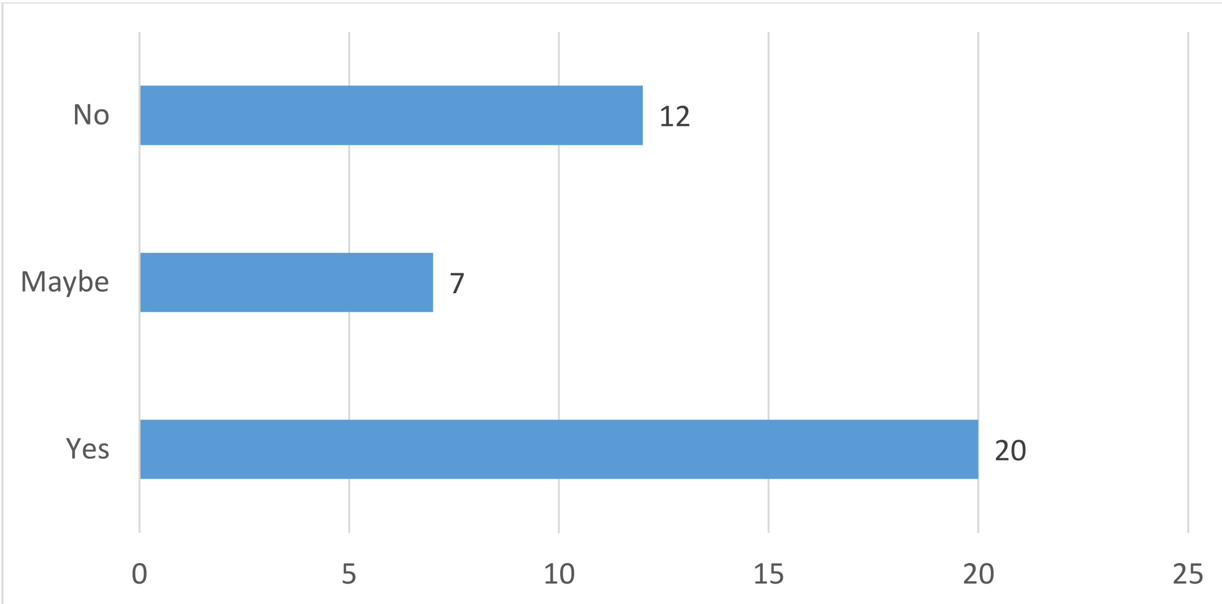


Figure 16: (Q19) Do you use an assembly or systems based cost estimates?;
Total Responses = 39

However, even though all of these professionals said that they use cost estimation for a majority of their projects only half said that they use assembly or system based cost estimation systems like UniFormat, as can be seen in Figure 16. Assembly based cost estimation requires the use of building assemblies or systems, such as wall sections, combined with historical cost data. Assembly based cost estimation is opposed to the many other cost estimation methods possible in question 18, such as costing by the quantity of predicted material needed or using formulas or statistics to predict the cost.

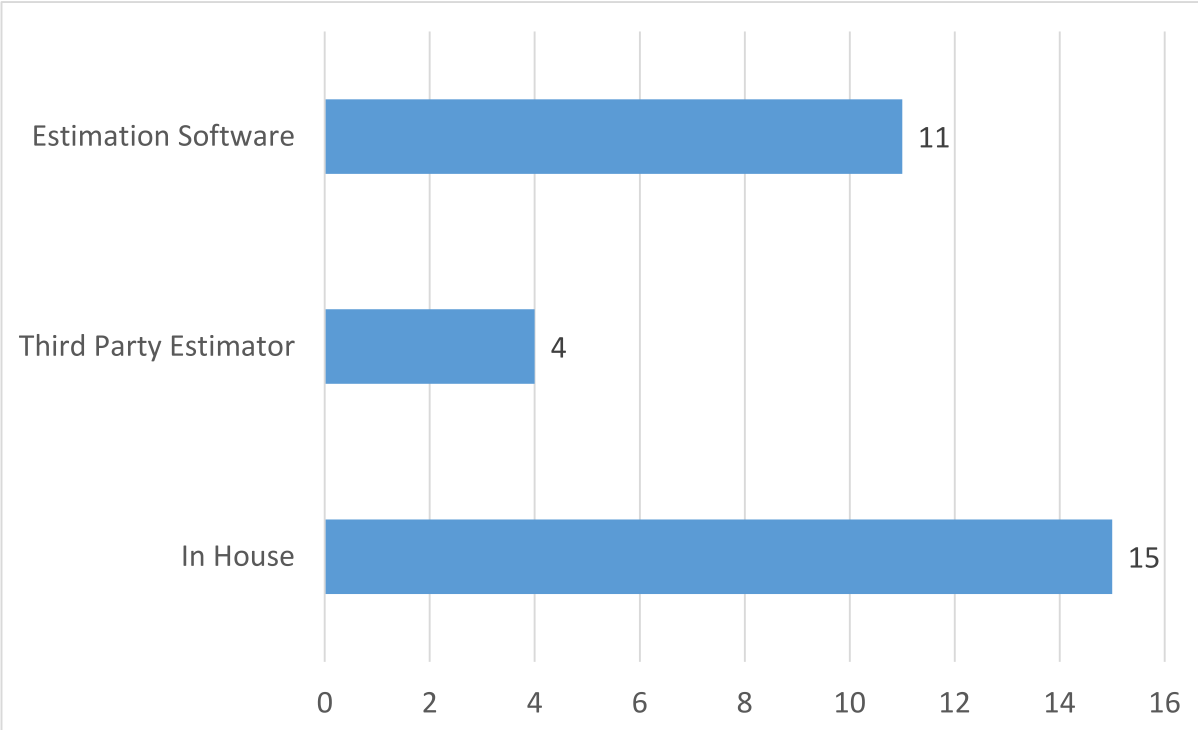


Figure 17: (Q21) Method of Cost Estimation?; Total Responses = 30

Question 20 addressed whether firms create their cost estimates or not. Twenty-three of the thirty-eight participants who responded to this question answered that their firms create their cost estimates. Seven responded that they might create their estimates, and eight answered that they do not create cost estimates.

The thirty participants who answer "Yes" or "Maybe" to question 20 about creation of their cost estimates all answered question 21. Half the responders answered that they use their in-house cost estimation system, which are estimation methods that generally begin by using outside sources of data like UniFormat and RSMeans construction cost data (Figure 17). These in-house systems then collect their project costs and build their own firm-specific historical cost database for estimating future projects. Eleven participants answered that they use a cost estimation software, such as CostWorks, which is an estimation software sold by RSMeans. This software also uses outside historical cost data generally provided by the creator of the software. The concern is if using only a purchased software instead of using company-specific data constitutes a firm performing its own cost estimate. This confusion could account for the answers of “Maybe” in the previous question. The remaining four responders, of the thirty total responders, answered that they use a third-party estimator, i.e., a sub-contractor or consultant, who create cost estimates from their previous experiences and cost data. The information gathered from this question reiterates the importance of historical cost data because both cost estimation software and in-house estimation systems are based on historical cost data.

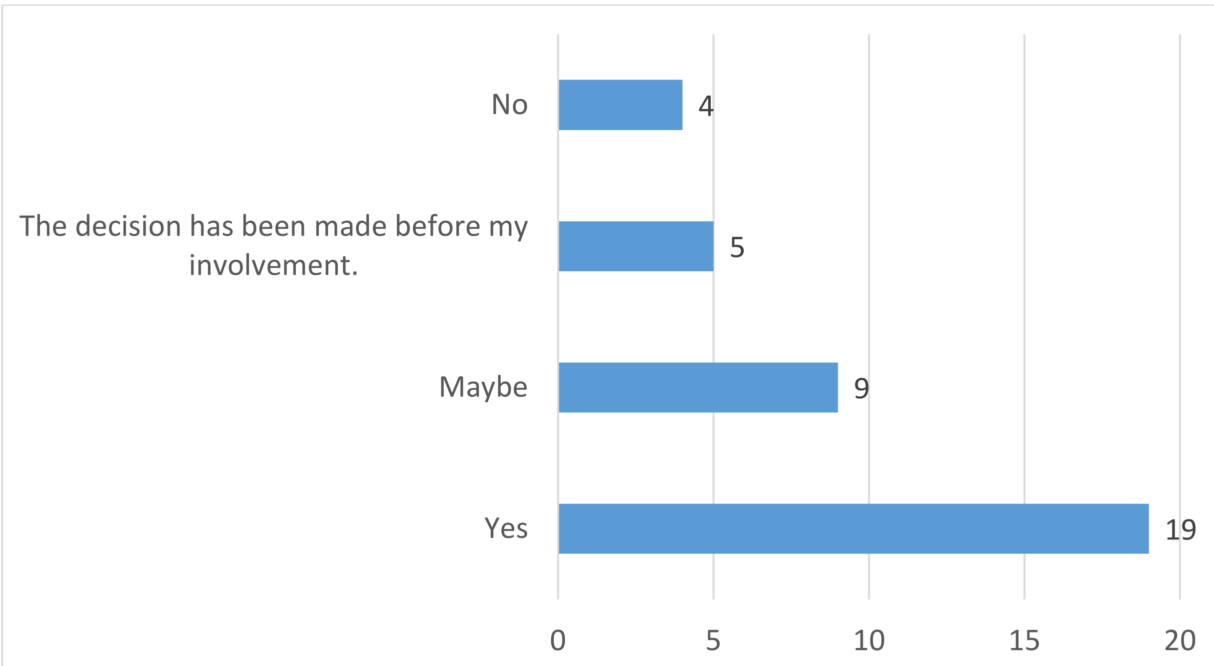
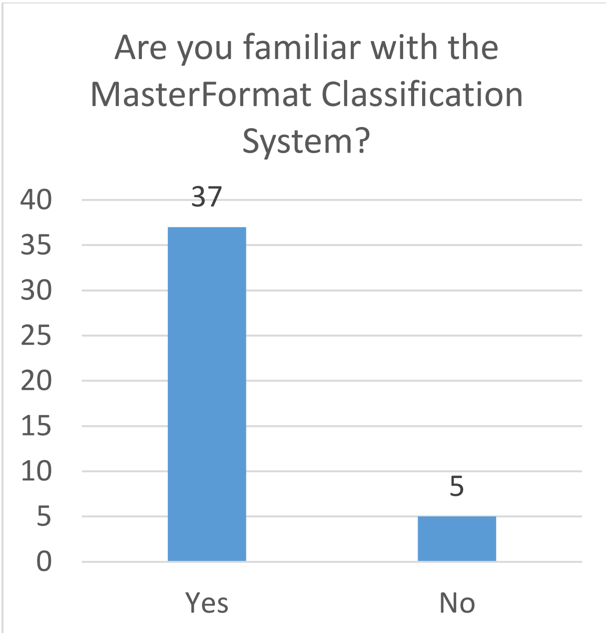


Figure 18: (Q22) Do cost estimates get used in the decision process for choosing the structural material?; Total Responses = 37

Nineteen of the thirty-seven participants answered that cost estimates are used to make decisions about selecting structural material, and nine answered they might use cost estimates to make decisions (Figure 18). The responses saying that the decision of material choice was made before the professional’s involvement was split between the architects, the contractors and cost estimators with a plurality of all their professions answer that cost estimates were being used in the selection of structural materials. This question demonstrates the importance of the use of cost estimates since the majority replied that they use estimates in selecting structural material or might use estimates.



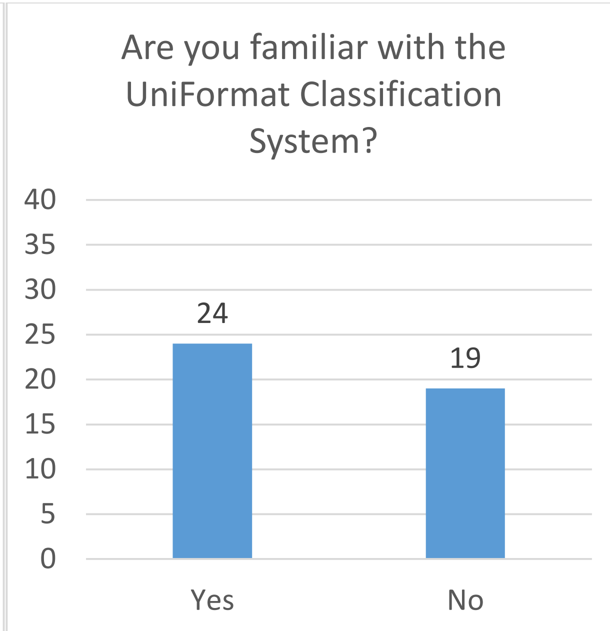


Figure 19a: (Q24) Familiar with MasterFormat; Total Responses = 42	Figure 19b: (Q25) Familiar with UniFormat; Total Responses = 43

From questions 24 and 25, there is a higher proportion of construction professionals familiar with MasterFormat than UniFormat, which is the primary classification system used for cost estimation (Figure 19a and 19b). The number of responders who previously answered that they use assembly or system based cost estimation (51%) is similar to those who answered that they are familiar with UniFormat (54%). The greater familiarity with MasterFormat suggests that it could be more impactful to focus on including CLTs in MasterFormat rather than UniFormat.

This section showed that cost estimation is being used by architects and contractors on their projects for one reason or another. They are also often creating this estimate themselves either through an in-house system or an estimation software. However, assembly or system-based methods are only definitely being used half of the time, though this may be affected by the lack of comprehension of UniFormat. The survey also showed that a majority of professionals were using cost estimates to affect their selection of structural materials.

Phase 2: Building Re-Design and CLT Design Tool Development

The building, VTCRC 1311, was a two-story, steel frame building that was redesigned using CLTs and glulam beams and columns. The second floor and roof, constructed with steel girders with a five-inch concrete slab, were replaced by eighty-five E1 grade CLT panels. The CLTs were 7-ply panels for the second floor and 5-ply panels for the roof, because of the higher load requirement for the second floor. These panels were reinforced in their weaker direction by 8.75-inch by 16.5-inch glulam girders beneath the panels and running between the columns. The original six-inch steel columns were replaced by 5.5-inch by 6.875-inch glulam columns. The CLT Design Tool developed in this project was used to design the elements in the VTCRC 1311 building redesign.

Figure 20 illustrates the basic layout of the new design using Excel. The numbers in the individual cells describe the dimensions of the CLT panels, before any necessary cutting to shape such as in the case of the trapezoidal stairwells which cannot be easily using Microsoft Excel. The glulam girders are represented by the light blue lines and would also follow the perimeter of the building. The columns are represented by the blue diamonds in the figure. A more detailed illustration was not generated because of the time constraint of the project and the lack of a need for detailed structural drawings for this research.

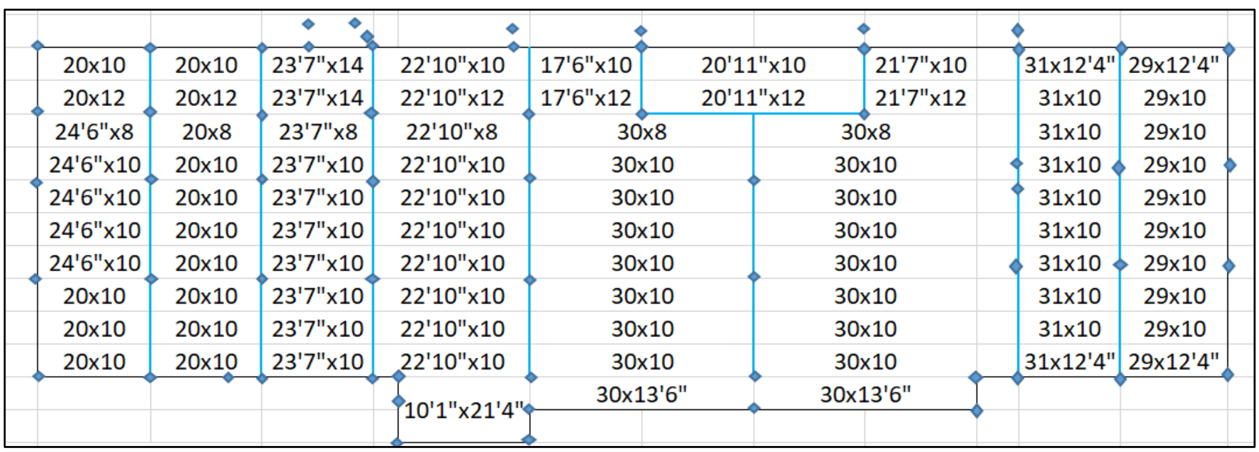


Figure 20: Building CLT Panel, Glulam Girder, and Column Grid

<u>CLT Design Tool</u>

The design tool for CLTs is based on the *CLT Handbook*, PRG-320, and the National Design Specifications for Wood Construction 2015 Edition [17, 52, 55] and made in Microsoft Excel. The methods of design used in the *CLT Handbook*, modified when necessary to meet the NDS 2015. The design tool allows for the input of the dimensions, PRG-320 grade, and loads to return the allowable strength design (ASD) adjusted resistance and compare it to the applied loads. The design tool includes a section for calculating floor spans, walls and columns, connections, and glulam columns and beams. It also has sections for checks for lateral and fire designs.

The tool is still under development, though mostly functional. The lateral design and the connection design with adjusted bearing length are still being developed. Additionally, instruction for the operation of this tool and how to add new data, such as new CLT grades, will be included. It is intended that once this tool has been completed and checked, it will be made available to building professionals to facilitate their work with CLTs. An example page of the CLT Design Tool is shown in Figure 21 with further images of the CLT Design Tool in Appendix D.

Column/Wall Design

Load	10000	plf	=	10000 plf
Load Type	Snow			
Grade	V3			
# of Plies	5-ply			
Ply Thickness	1.375			
Strength Direction	Major			
Column Breadth	10.000 feet			
Column Height	20.00 feet			
Loading	Uniformly distributed			
End Fixity	Pinned			

Resistances				Loads	
Compression	(Fc')A	28176 lbs	>=	Compression	10000 lbs

Factors	
Cd	1.15
Cp	0.3960

Variables	
(EI app-min)'	175 x10^6 lb*in^2
Pc	71156.25
Pce	30023.65748
A	49.5 in^2
EI app	338.00
EI eff	363
Ks	11.5
GA eff	0.98

Figure 21: CLT Column/Wall Design Example

Phase 3: Discussions with Subject Matter Experts

This section details the information gathered in discussions with experts in the field of CLT and its production. Specific questions are not included in the summary because of the conversational nature of the interviews did not necessarily provide direct answers to direct questions.

Reinhard Sauter, Sauter Timber, CLT Processor

Mr. Sauter was interviewed at his place of business, Sauter Timber, in Tennessee on February 14th, 2019. He processes cross-laminated timbers which he buys from Binderholz in Austria and sells to clients in the US, though half of his processing is on panels purchased by his client from another source. He was asked questions regarding the cost associated with his business and how he priced his panels.

His quotation process begins with receiving CAD and Revit drawings from his client or their designer. Then he confirms the size and thickness of the panels needed and whether he will be purchasing them from his supplier or will be given them by his client. Then he applies a roughly 10-11% markup of the panel cost for the work, fasteners, and connecting boards. He purchased his panels from Binderholz because he claimed that their product was half the cost of the North American producers, despite having been shipped from Europe.

Terry Pattillo, Woodworks, Architect/Mass Timber Building Support

Terry Pattillo is a regional director for the Woodworks, which is a non-profit builder's support organization for mass timber construction. He is an architect and works primarily as a consultant and support person for designers and contractors building with mass timber. He was interviewed by phone on March 4th, 2019 regarding estimating the cost of a CLT building.

Mr. Pattillo alleged that mass timber and tall wood buildings are typically competitive with steel and concrete construction systems, within 10% of each other, the rankings are dependent on the regional markets. Outside of cost, mass timber has an advantage in aesthetics, biophilia, sustainability, labor requirements, and time of construction. Mass timber does not typically require more than a few experienced supervisors for construction. Most labor can be performed rapidly and effectively by unskilled workers who are trained onsite and learn very quickly, due to the simplicity of the process of wood construction, namely craning elements into place and drilling and screwing in fasteners. A significant advantage is that buildings are often finished faster than competitive systems and often sooner than expected because of the speed of assembly. Finishing earlier means that sometimes tenants can move in earlier or operations can begin sooner, resulting in extra revenue for the building owner. The low labor requirements are also an advantage for the construction industry, which is experiencing a labor shortage, particularly for skilled labor.

There are currently too many pieces to consider for CLT and mass timber construction for anyone to accurately estimate what the cost for a building might be. Factors might include regional markets prices, distance from CLT supplier, savings from labor and time and many other considerations. The decision to build with CLTs or mass timber depends on which factors are the primary drivers for selecting the building system and how significant they are to each client. For instance, if the cost is the main driver for selection of the building's structural system, and the cost of a mass timber building is 2% higher than the alternative, does the advantage of the aesthetic value of exposed wood or the increased revenue from the building being available to tenants earlier offset the 2% additional cost. Altogether, Mr. Pattillo concluded that it is not yet possible to make an accurate cost estimate for a CLT building, but that his experience has been that the cost of a mass timber building usually is within 10% more or less than the possible substitutes depending on the region in which it is built and it is other factors like aesthetics that are driver material choices.

Mr. Pattillo did identify an issue in the mass timber industry that he had personally come across. He explained that many designers eliminate mass timber construction as a reasonable option before the decision of structural material comes into question. The problem comes about in that mass timber materials, like glulam and CLT, have discrete sizes, meaning there might be a 28-foot glulam beam and a 32-foot beam but no available size in-between. So the use of glulam often gets eliminated from the material options when a designer decides on a 30'x30' room, because the 32-foot glulam beam would be more expensive than a 30-foot steel alternative, even if the glulam beam is cheaper than a steel beam of the same size. So because mass timber design uses materials that have limited size options, designers currently need to start out with mass timber in mind in order to create a compatible design. While this observation by Mr. Pattillo is not directly related to the importance of cost estimation, the issue of discrete sizing of CLTs and other engineered wood products does significantly affect the ability of professionals to create comparable and accurate cost estimate comparisons for building projects.

Conclusions

The purpose of this thesis was to explore the need for cost estimation for CLT buildings. The study used three phases of research in order to achieve this purpose. The first phase surveyed construction professionals intending to discover how often they use cost estimation in their work and if it was central for the selection of structural materials, like CLTs. The second phase was the re-designing of a steel frame building to use CLT and other wood composite materials as the structural elements. The goal of this phase was to gain firsthand knowledge of the complications in estimating CLT building costs. The third phase was to speak with CLT experts to fill in any gaps in information resulting from the other sources of information so that a more comprehensive understanding of the issues could be obtained. The goals of each method were achieved, and the conclusions were that cost estimation is important for the future use of CLTs.

The survey, despite its limitations, demonstrated that cost estimation is essential in making decisions between structural materials. It is being used frequently in many sectors of the construction industry and by multiple professions. The top areas of concern with CLTs also lend weight to the argument that cost estimation is vital for the development of the CLT industry. As these top concerns for the industry were the expense of the material, the availability of the material, and that clients do not want the material. Each could be affected by providing accurate cost estimates to clients. If a designer can show that CLT is an affordable option regardless of the distance, via an accurate cost estimate, the opinion of their clients may change. The more knowledge made available to a client or designer, the better decisions they can make regarding materials.

The lack of available tools for designers was made apparent during the re-designing of the VTCRC 1311 building. There is only one complete design document, the *CLT Handbook* published by the American Wood Council and FPInnovations. The *CLT Handbook* contains numerous unanswered questions and the occasional error requiring external support from professionals experienced with CLTs. The problems with the document create a barrier for designers new to the material or wood building design. The design tool was developed to incorporate the design method detailed in the *CLT Handbook* and the answers to the questions that appeared during the process. However, the design tool can only facilitate the design not provide any cost estimate assistance since the historical data is not available.

In the discussions with CLT experts, it was explained that the cost for an individual CLT building project is not possible to predict, at least before suppliers, processors, and contractors have been selected and their quotations obtained. Companies like Sauter Timber have directly attributable costs and can give simple estimates of what their prices will be, but at this point in the industry there are not any standard practices for CLT manufacturing or processing, so costs and prices can vary between companies, according to Terry Pattillo. Pattillo made it very clear that any estimate of the cost of a CLT building would either be unjustified or very specific to circumstances. So despite the survey supporting the hypothesis that cost estimation is essential for CLT construction, both the building re-design and the conversations with professionals demonstrate that CLT cost estimation is not yet practical. These three methods of exploring the difficulties led to the identification of several barriers that make CLT cost estimation impractical.

Identified Barriers

Lack of Data

This project was hampered by the fact that there is not enough historical cost data for CLTs, and the cost of building re-design could not be reliably estimated. Terry Pattillo agreed that this is an issue with CLTs and mass timber construction. He said that while his experience is that mass timber construction is within plus or minus 10% of its competitors depending on the regional market, an accurate cost estimate is not possible, as of March 2019. Mass timber buildings are being selected because of other reasons than cost such as aesthetics, which leads to non-traditional building design that exposes the structural wood members. Without traditional building designs, standard costs will be challenging to learn, and cost estimation will remain inaccurate.

Regional Markets

There is a significant issue in the reasonable access for builders to manufacturers of CLTs. The map of CLT manufacturers generated showed how poorly distributed the manufacturers are in North America, with the majority of panels being produced in either the Northwest or Northeast of the continent. Only one producer operates outside of these two regions. For the cost estimate, the closest manufacturer for the E1 grade panels was Nordic in northern Canada, about 1280 miles away from Blacksburg, Virginia. These vast distances are a barrier to CLTs being cost-effective since the transportation cost could potentially raise the price above what is competitive in the region. The only solution for this issue is the continued development of CLT production around the country. CLT production could be potentially aided by improving the marketability and therefore, the demand for CLTs, increasing the incentive for investment in these facilities. One method of increasing the marketability of CLTs identified through the survey would be to develop cost estimation for CLTs.

Custom Design

Conversations with Terry Pattillo confirmed that most, if not all, projects constructed of mass timber are currently custom design. Custom designs are a problem because custom buildings do not reflect standard costs and do not provide the most relevant information for predicting the cost of CLT buildings. This problem will probably be mitigated by the fact that the International Building Code will include buildings up to 21 stories with the release of the 2021 IBC. An increase in available, graded CLT panels, which do not require additional structural analysis by a structural engineer to be used in buildings following the IBC prescriptive code, could make more traditional buildings more likely to be built using CLTs.

Discrete Sizes

It was suggested by Terry Pattillo that there is a significant issue with mass timber and CLT construction in that laminated materials, like glulam and CLTs, are produced in discrete sizes. Discrete sizing is a barrier for CLT construction and cost estimation because it leads to over-engineering of structural elements, which can out-price mass timber materials. In reality, this is an issue of discrete structural capacities with too few options for these materials. It could be solved by increasing the number of capacities available from which designers can choose. Options could be created by increasing the variety of species in graded panels, changing the thicknesses of the layers of existing grades, or creating composite grades with multiple species or structural composites. Each grade created would have a different structural capacity and could bridge the separation between the existing grades of CLT.

Summary

The barriers identified can all be addressed by increasing the marketability and availability of CLT panels, which were also the main concerns of the professionals surveyed. These factors could be increased by the development of cost estimation for CLTs. More data must be collected regarding typical CLT construction to make CLT cost estimation possible. If more standard and traditional designs, both on the building and assembly scales, are constructed, then relevant data could be collected to supply cost estimates with reasonable values. More grades and available structural capacities could also make more building traditional designs economically accessible. Overall, it appears that the CLT industry needs to standardize and focus on traditional construction rather than unique designs in order to increase market acceptance.

Suggestions for Further Research

Further Surveying of Cost Estimation

The survey results provide some evidence to the importance of cost estimation in the process of design and construction of buildings. However, this project was limited due to being unfunded. It was dependent on the willingness of others to distribute and support the electronic survey. It only received 45 responders and could not reach construction engineers due to lack of a willing organization to distribute the survey. A funded survey could improve the distribution methods, with better targeting by using methods such as using mail and phone surveys and compensating participation. With these methods, a more representative sample of building design and construction professions could be generated and the real importance of cost estimation in developing the mass timber and CLT markets.

Creation of Standard CLT Assemblies and Products

The development of more standard CLT grades and assemblies could increase the options available to designers and improve the versatility of the product. Standardizing assemblies could also make predicting the cost of CLT buildings easier. With standard section designs, consistent historical cost data could be gathered through its continued use. Inclusion in the CSI classification systems would achieve this goal. Collecting historical data is a necessary step in developing the ability to estimate the cost of CLT construction. If designs are different on even the wall and floor section level in every building, it will always remain difficult to predict what the next building design will cost.

Developing More CLT Grades

Research should be done into developing more CLT grades to be included in the PRG-320. New grades that include more species, such as Yellow Poplar, could open up more manufacturing possibilities in regions outside of the current areas of CLT production. Increasing the variety of grades could also increase structural options and make CLT construction cheaper by allowing for more efficient design.

Structural Composites in CLTs and Glulam

A potential solution for the issue of discrete sizes would be to develop cross-laminated and glue-laminated timbers with structural composites, like LSL and LVL, in at least one layer. Outside of the likely structural performance advantage of using wood composites in CLTs and glulam, the continuous, as opposed to discrete, sizes of laminated strand and laminated veneer lumber could be transferred to glulam and CLTs. Continuous sizes mean that these products could be designed specifically to applications avoiding over-engineering.

Limitations of the Study:

- Limited time to seek information,
    - Due to being a Master's thesis.
- The survey was skewed to Architects.
- The survey was skewed to East Coast.
- No engineers in the study.
- The small size of the study

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Appendices:

Appendix A: WIRB Determination Letter

November 14, 2018

Daniel Hindman,
PhD Virginia Tech
Brooks Forest Products Center
(0503) 1650 Research Center Drive
Blacksburg, VA 24061

Dear Dr. Hindman:

SUBJECT: REGULATORY OPINION—IRB EXEMPTION
Protocol Title: CLT Cost Estimation Use in Building Design
Investigator: Daniel Hindman, PhD

This letter is in response to your request to Western Institutional Review Board (WIRB) for an exemption determination for the above-referenced research project. WIRB's IRB Affairs Department reviewed the exemption criteria under 45 CFR §46.101(b)(2):

> (2) Research involving the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures or observation of public behavior, unless:
> (i) Information obtained is recorded in such a manner that human subjects can be identified, directly or through identifiers linked to the subjects; and (ii) any disclosure of the human subjects' responses outside the research could reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, or reputation.

We believe that the research fits the above exemption criteria. The data will be collected in a way so that the subjects cannot be identified, directly or through identifiers linked to the participants. You have also confirmed that the results of this study will not be submitted to the Food and Drug Administration (FDA) for marketing approval.

This exemption determination can apply to multiple sites, but it does not apply to any institution that has an institutional policy of requiring an entity other than WIRB (such as an internal IRB) to make exemption determinations. WIRB cannot provide an exemption that overrides the jurisdiction of a local IRB or other institutional mechanism for determining exemptions. You are responsible for ensuring that each site to which this exemption applies can and will accept WIRB's exemption decision.

Please note that any future changes to the project may affect its exempt status, and you may want to contact WIRB about the effect these changes may have on the exemption

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status before implementing them. WIRB does not impose an expiration date on its IRB exemption determinations.

If you have any questions, or if we can be of further assistance, please contact Zach Burr, J.D., at 360-252-2475, or e-mail RegulatoryAffairs@wirb.com.

ZHB:dao
B2-Exemption-Hindman (11-14-2018)
cc: Jonathan Stutesman, Virginia Tech
WIRB VA Tech
WIRB
Accounting
WIRB Work Order #1-1131503-1

Appendix B: Survey

CLT/UniFormat Use Project

Start of Block: Consent Form

RESEARCH SUBJECT CONSENT FORM

Title: CLT Cost Estimation Use in Building Design
Protocol No.: 18-832
Sponsor: Virginia Tech
Investigator: Daniel Hindman
Brooks Forest Products Center
1650 Research Center Drive
Blacksburg, VA, 24061
United States
Daytime Phone Number: (540) 231-8853

You are being invited to take part in a research study. Participation is voluntary. You can choose not to take part, or agree to take part and later change your mind. There will be no penalty or loss of benefits to which you are otherwise entitled.

The purpose of this research is to ask you questions and determine your feedback. Your participation in this research will last until you have completed the questionnaire. The only risk is effort involved in the questionnaire. There are no benefits to you from your taking part in this research. Others may benefit from the information gained during this research. Your alternative is to not take part in the research. We may publish the results of this research. As we are not collecting any identifiable information, your information will be confidential.

If you have questions, concerns, or complaints, or think this research has hurt you, talk to the research team at the phone number listed above. This research is being overseen by an Institutional Review Board ("IRB"). An IRB is a group of people who perform independent review of research studies. You may talk to them at (800) 562-4789, help@wirb.com if you have questions, concerns, or complaints that are not being answered by the research team or you have questions about your rights as a research subject.

You will not be paid for taking part in this research.

By continuing in the survey, you are consenting to continue.

End of Block: Consent Form

Start of Block: Demographics

Q1 What best describes your job title?

- ○ Architect (1)
- ○ Structural Engineer (2)
- ○ Cost Estimator (3)
- ○ General Contractor (4)
- ○ Specialty Contractor (5)
- ○ Design Consultant (6)
- ○ Other (7)

Q2 In what region are you located?

- ○ Southeast (1)
- ○ Northeast (2)
- ○ Midwest (3)
- ○ Northwest (4)
- ○ Southwest (5)

Q3 What type of projects do you typically work on? (Select all that apply)

- ☐ Single-Family Residential (1)
- ☐ Multi-Family Residential (2)
- ☐ Industrial (3)
- ☐ Low-Rise Commercial (4)
- ☐ Mid/High-Rise Commercial (5)
- ☐ Public/Government (6)
- ☐ Other (7)

Q4 In which phases of construction are you typically involved? (Select all that apply)

- ☐ Design (1)
- ☐ Preconstruction (2)
- ☐ Construction (3)
- ☐ Finishing (4)
- ☐ Operation/Maintainance (5)
- ☐ Renovation/Restoration (6)

Q5 Which scale of project are you typically involved? (Select all that apply)

- ▢ <$50,000 (1)
- ▢ $50,000 - $250,000 (2)
- ▢ $250,000 - $1 million (3)
- ▢ $1 million - $5 million (4)
- ▢ $5 million - $15 million (5)
- ▢ $15 million - $50 million (6)
- ▢ $50 million - $100 million (7)
- ▢ >$100 million (8)

Q6 How large is your firm?

- <10 employees (1)
- 10-25 employees (2)
- 26-50 employees (3)
- 51-100 employees (4)
- 101-200 employees (5)
- 201-500 employees (6)
- 501-1000 employees (7)
- >1000 employees (8)

Q7 How many years of experience do you have in the industry?

- <1 year of experience (1)
- 1-2 years of experience (2)
- 2-5 years of experence (3)
- 5-10 years of experience (4)
- 10-20 years of experience (5)
- 20-50+ years of experience (6)

End of Block: Demographics

Start of Block: CLT Knowledge

Q8 Before this survey, had you heard of Cross Laminated Timbers (CLTs)?

- Yes (1) [+1]
- No (2) [0]

Q9 Do you think CLTs are fire-resistant?

- Yes (1) [+1]
- Maybe (2) [0]
- No (3) [-1]
- Not sure (4) [0]

Q10 Do you think CLTs are an expensive material?

- Yes (1) [0]
- Maybe (2) [0]
- No (3) [0]
- Not sure (4) [0]

Q11 Do you think CLT structures are fast and simple to construct?

- Yes (1) [1]
- Maybe (2) [0]
- No (3) [-1]
- Not sure (4) [0]

Q12 Do you think CLT structures require little labor to construct?

- Yes (1) [1]
- Maybe (2) [0]
- No (3) [-1]
- Not sure (4) [0]

Q13 Do you think CLTs are structurally safe to use?

- Yes (1) [1]
- Maybe (2) [0]
- No (3) [-1]
- Not sure (4) [0]

Q14 Do you know where to obtain CLTs?

- Yes, I know of multiple manufacturers of CLTs. (1) [1]
- Yes, I know of one manufacturer of CLTs. (2) [1]
- No, I do not know of any manufacturers of CLTs. (3) [0]

Q15 Have you worked on a CLT building project in the past?

- Yes (1) [1]
- Maybe (2) [0]
- No (3) [0]

Q16 What are your top 2 concerns about using Cross Laminated Timbers?

- It is too flammable. (1)
- It's expensive. (2)
- It's an structurally unsafe material (3)
- It's difficult use. (4)
- It's unavailable for me. (5)
- My client do not want it. (6)
- I have no concerns. (7)

End of Block: CLT Knowledge

Start of Block: Cost Estimation

Q17 Do you use cost estimation in your business? (If you answer #3, please skip to Question 23)

- ○ Yes (1)
- ○ No, but it is used on our project by others. (2)
- ○ No, my firm doesn't use it at all. (3)

Q18 How often do you use cost estimates?

- ○ With all of projects. (100%-90%) (1)
- ○ With many of projects. (90%-60%) (2)
- ○ With around half of our projects. (60%-40%) (3)
- ○ With some of our projects. (15%-5%) (4)
- ○ With one or two projects. ((5)
- ○ We never use cost estimates. (6)

Q19 Do you use an Assembly or Systems based cost estimate?

- ○ Yes (1)
- ○ Maybe (2)
- ○ No (3)

Q20 Does your firm create their own cost estimates?

- ○ Yes (1)
- ○ Maybe (2)
- ○ No (3)
- ○ Not sure (4)

Q21 What is your preferred cost estimation system? (i.e. in-house estimation system, WinEst, etc...)

____

Q22
Do cost estimates get used in the decision process for choosing the structural material?

- Yes (1)
- Maybe (2)
- No (3)
- The decision has been made before my involvement. (4)
- Not sure (5)

Q23 For your projects, which structural systems is most often used?

- Steel Framing (1)
- Concrete Masonry Units (2)
- Reinforced Concrete (3)
- Light Frame Construction (4)
- Mass Timber Construction (5)
- Other (6)

Q24 Are you familiar with the MasterFormat Classification System?

- Yes (1)
- No (2)

Q25 Are you familiar with the UniFormat Classification System?

- Yes (1)
- No (2)

Q26 Do you use Autodesk Revit?

- Yes (1)
- No, I use another Autodesk 3D modelling software. (2)
- No, I use a different 3D modelling software. (3)
- No, I don't use 3D modelling software. (4)

End of Block: Cost Estimation

Appendix C: Survey Graphs

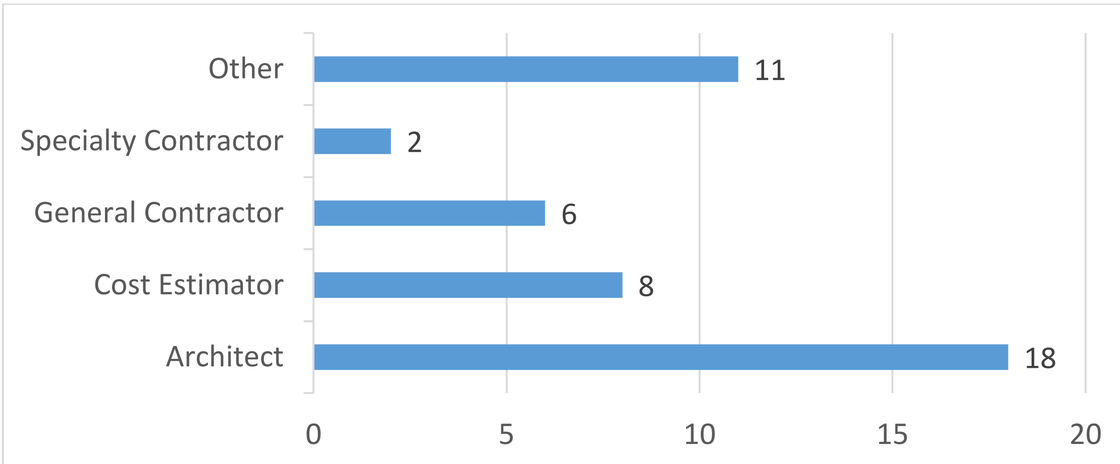


Figure 5: (Q1) Survey Participants by Profession; Total Responses = 45

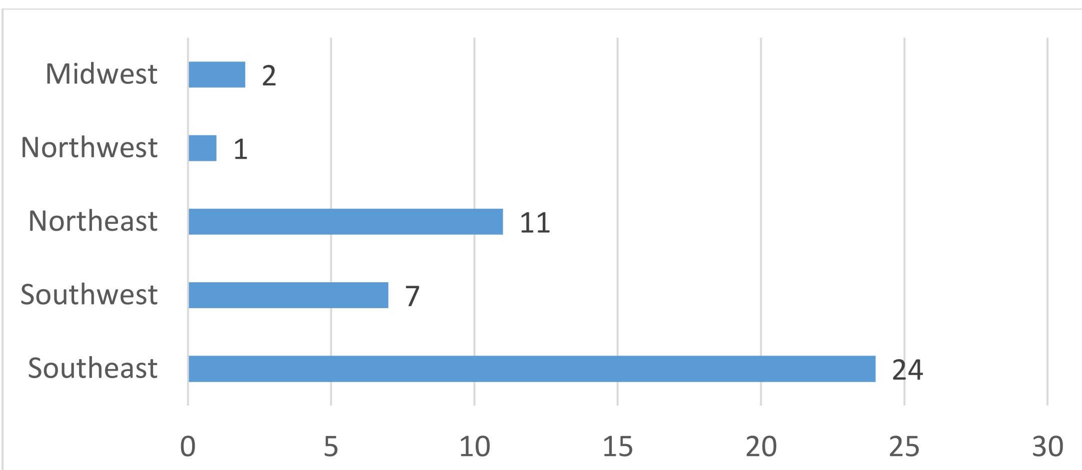


Figure 6: (Q2) Regional Distribution of Participants; Total Responses = 45

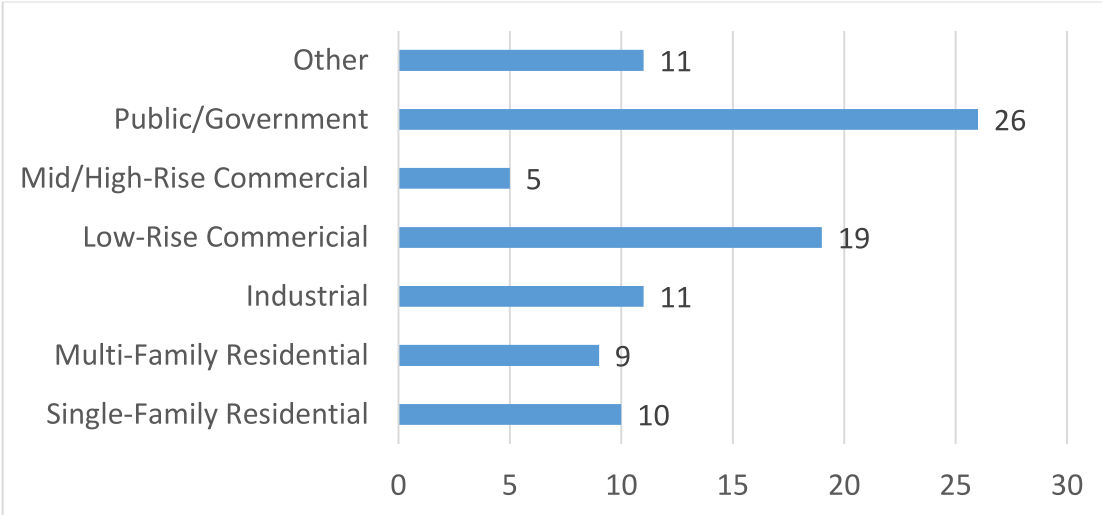


Figure 7: (Q3) Construction Markets in which Participants Work; Total Responses = 45

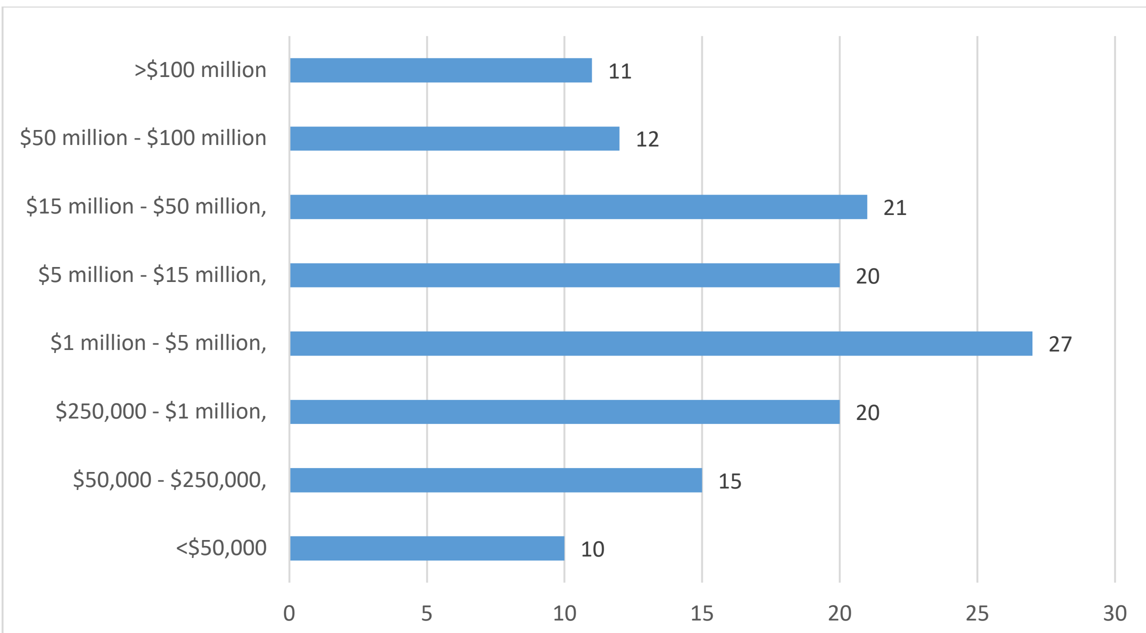


Figure 8: (Q5) Scale of Projects for Participants; Total Responses = 44

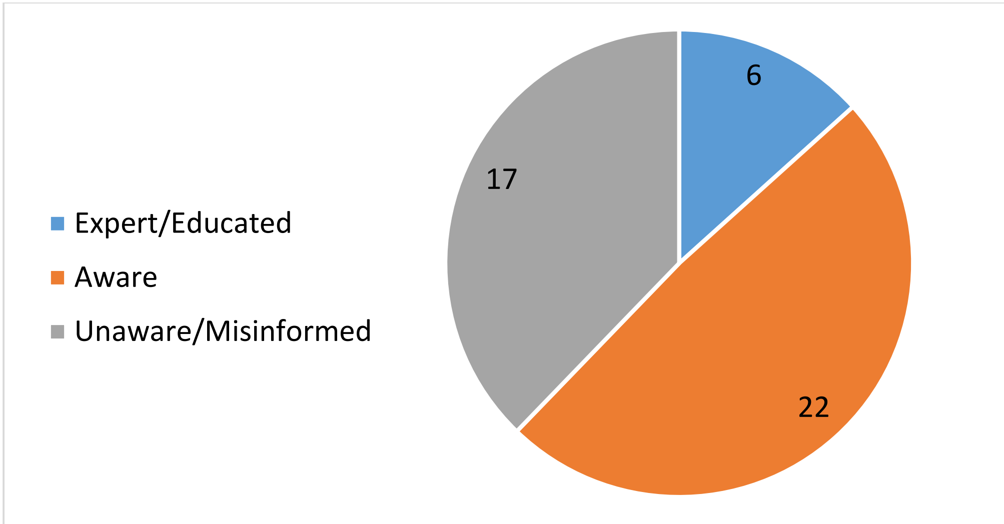


Figure 10: Total CLT Awareness; Total Responses = 45

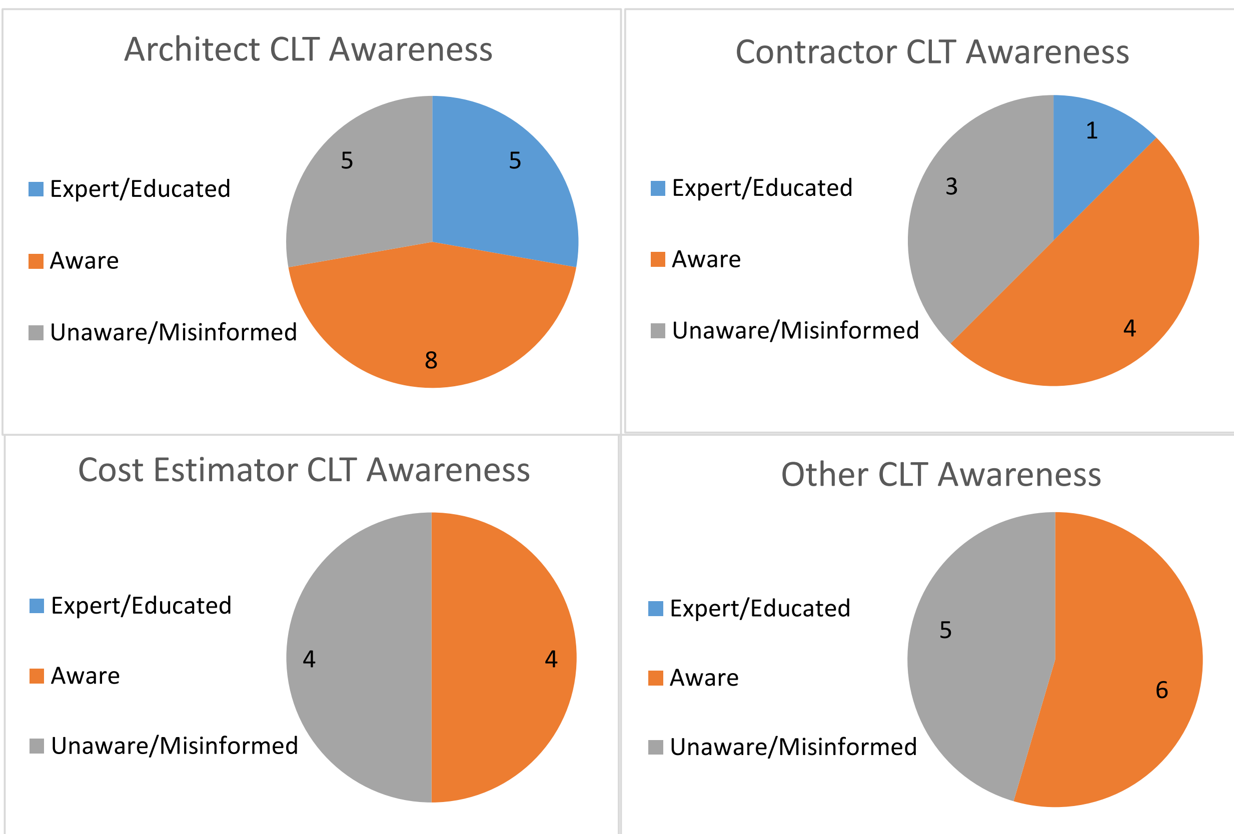


Figure 11: CLT Awareness by Profession; Total Responses = 45

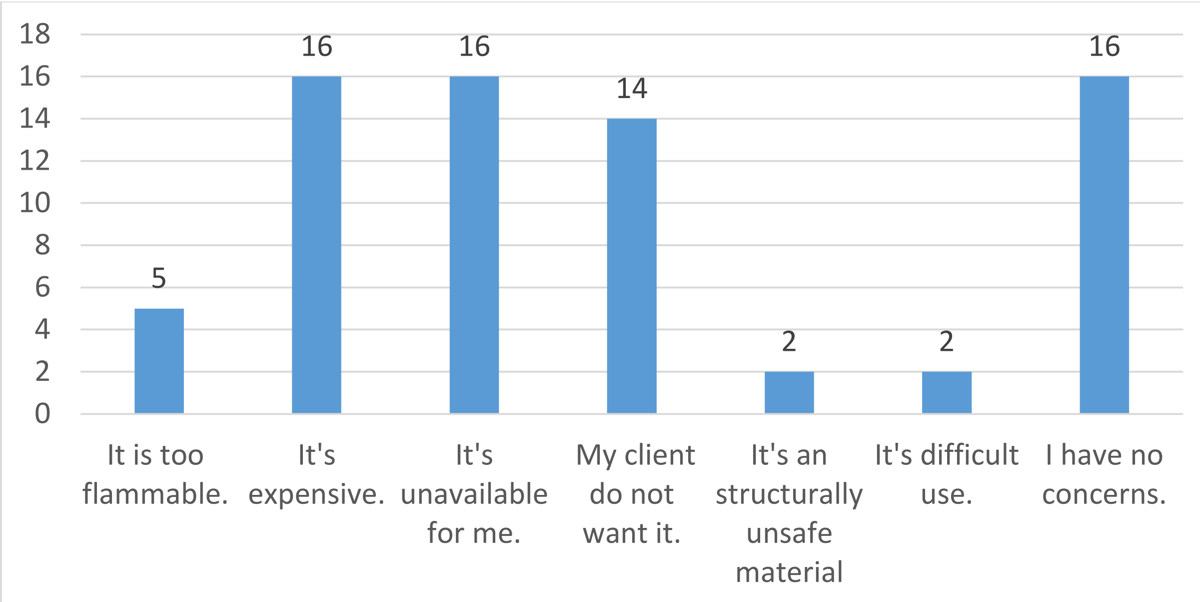


Figure 12: Top Concerns for CLTs, Total Responses = 45

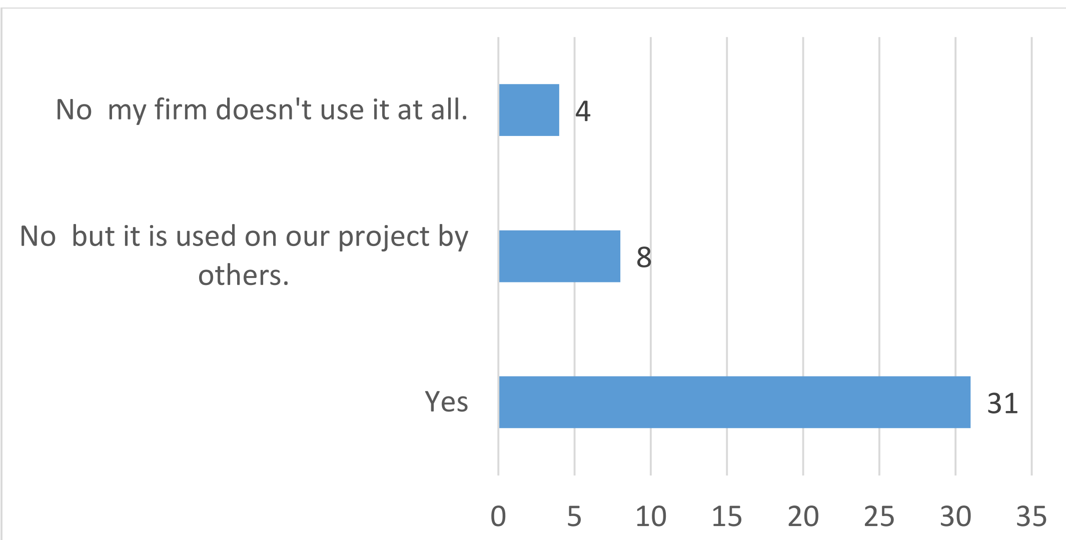


Figure 13: (Q17) Do you use cost estimation in your business?; Total Responses = 43

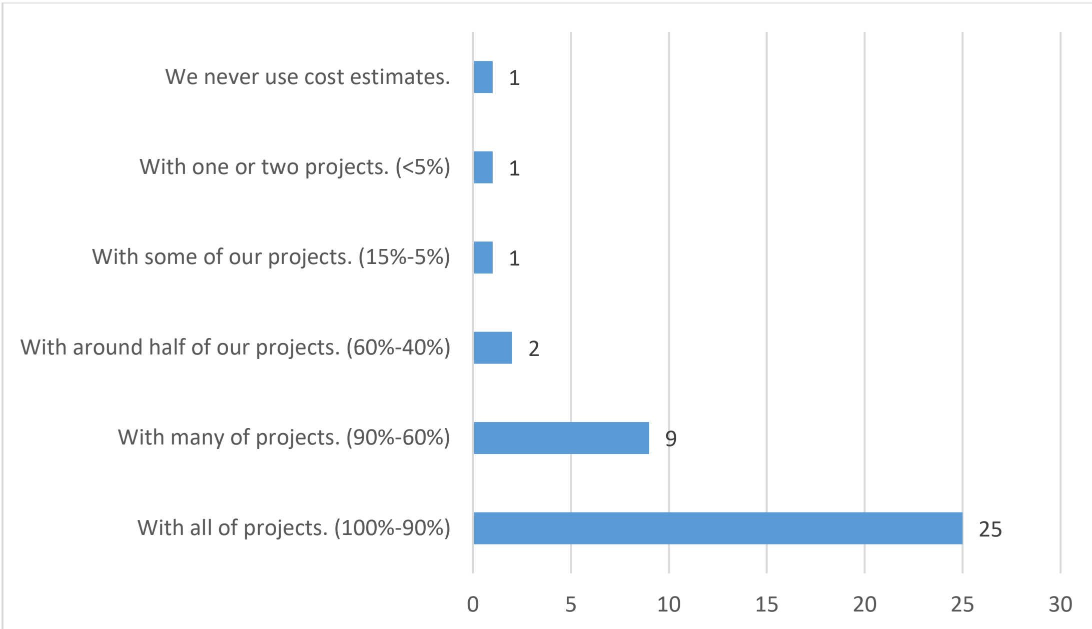


Figure 14: (Q18) How often do you use cost estimation?; Total Responses = 39

Figure 15: Cost Estimation Use by Profession; Total Responses = 32

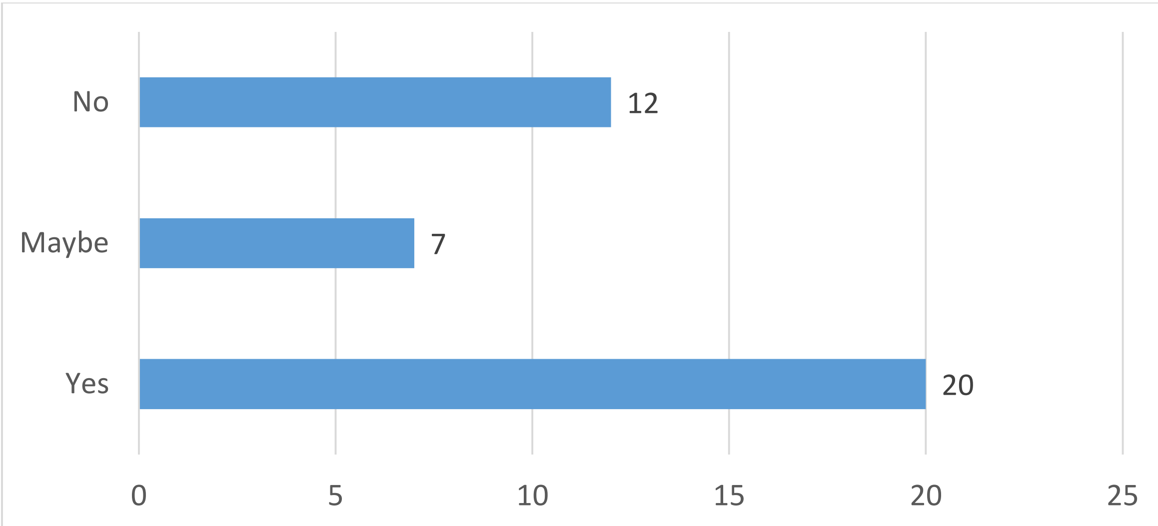


Figure 16: (Q19) Do you use an assembly or systems based cost estimates?; Total Responses = 39

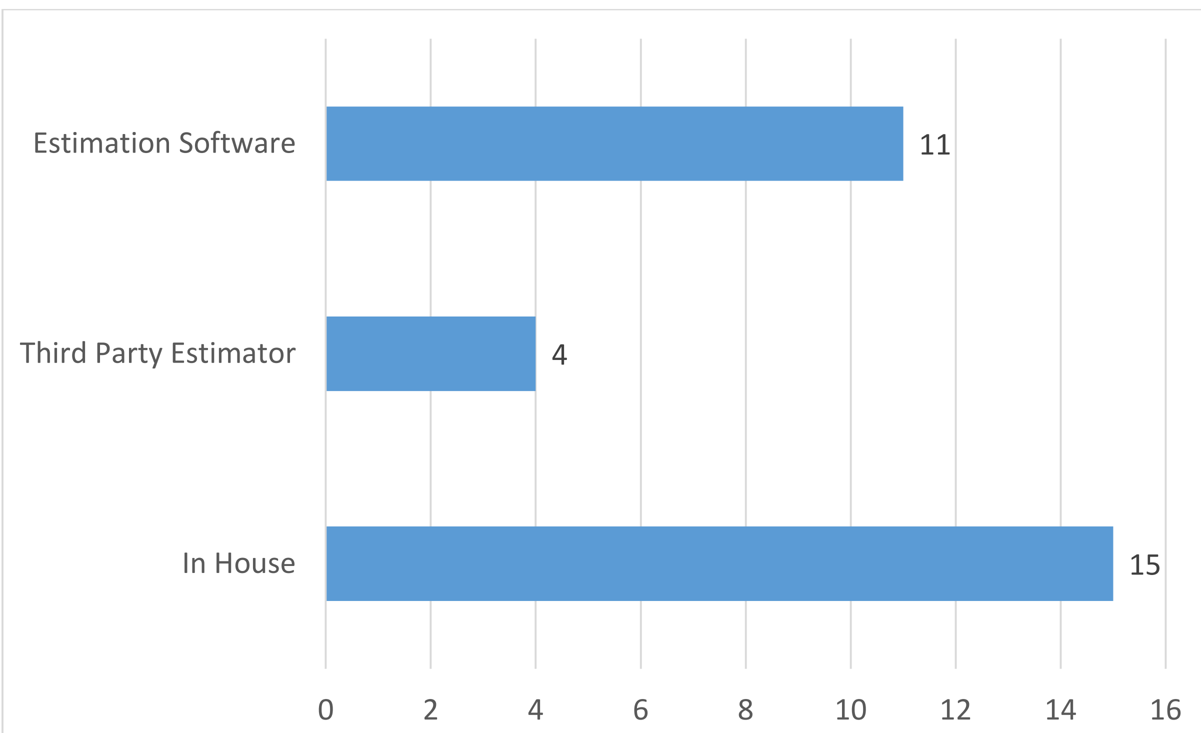
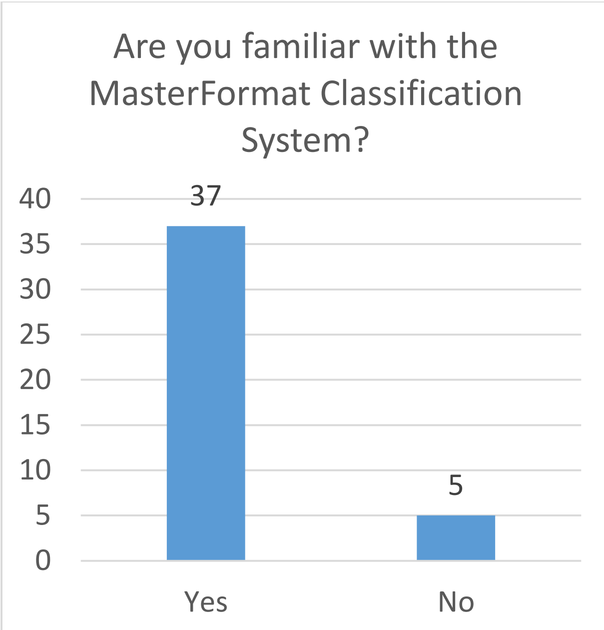


Figure 17: (Q21) Method of Cost Estimation?; Total Responses = 30



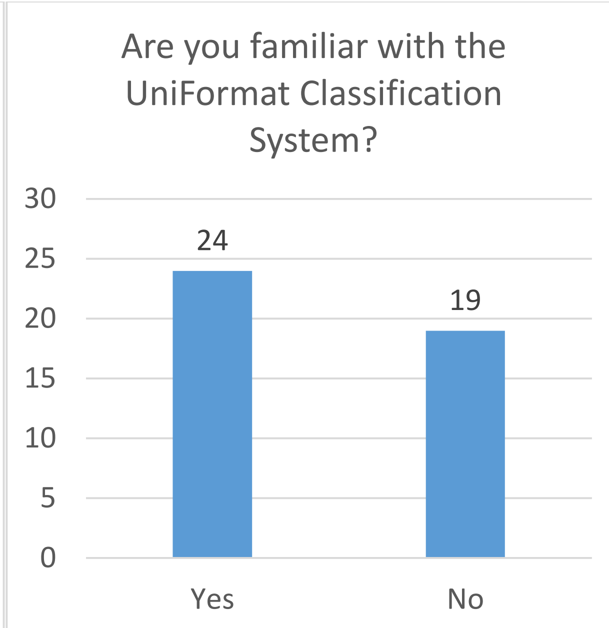


Figure 19a: Familiar with MasterFormat; Total Responses = 42	Figure 19b: Familiar with UniFormat; Total Responses = 43

Appendix D: CLT Design Tool Example

What follows is an example of the state of the CLT Design Tool as of the writing of this document. The tool is still a work-in-progress and any or all details of this tool may be changed over the course of its development.

CLT Design Tool

Instructions

To be written
will include:

Legend of colors
instructions on inputing and reading outputs
maybe - instrucitions on adding CLT grades or other new information

Column/Wall Design

Load	10000	plf	=	10000 plf
Load Type	Snow			
Grade	V3			
# of Plies	5-ply			
Ply Thickness	1.375			
Strength Direction	Major			
Column Breadth	10.000 feet			
Column Height	20.00 feet			
Loading	Uniformly distributed			
End Fixity	Pinned			

Resistances				Loads	
Compression	(Fc')A	28176 lbs	>=	Compression	10000 lbs

Variables	
(EI app-min)'	175 x10^6 lb*in^2
Pc	71156.25
Pce	30023.65748
A	49.5 in^2
EI app	338.00
EI eff	363
Ks	11.5
GA eff	0.98

Factors	
Cd	1.15
Cp	0.3960

Column/Wall Fire Check

Load	10000	plf	=	10000 plf
Element	Column			
Grade	V3			
# of Plies	5-ply			
Column Length	20.0 feet			
Required Rating	1.00 Hours			
CLT Hour Rating	.50 Hours			
+Fire Protection	.50 Hours			

Resistances				Loads	
Major Span				**Major Span**	
Compression	P'	27110 lbs	>=	Compression	10000 lbs
Combined Load Check		1	>=		0.45

Column Variables	
a char	1.02 inches
Thickness After	5.85 inches
Ieff	107.39
Seff	31.8
Neutral Axis	2.47
A	37.21
Slenderness	40.8
Major E	1.4
E'min	1.47
Pce	27110.1
Pc*	119987.2
Fce	1250.00
Fb	750.00
(Fb*S eff)'	4811 lb*ft
EI app	338.00
EI eff	363
e	0.97
Δf	.083 inches
Δ	1.05 inches
Ks	11.5
GA eff	0.98

Cd	1.15
Cp	0.23

5402318636

Floor/Roof Span Design

Load	100	psf	= 100 psf
Load Type	Live		
Grade	E1		
# of Plies	5-ply		
Ply Thickness	1.375		
Bearing Length	6.00 inches		
Bearing Width	6.00 inches		
Tributary Width	10 feet		
Tributary Length	10 feet		
Major Span	20 feet		
Minor Span	12.0 feet		
Loading	Uniformly distributed		
End Fixity	Pinned		

Panel Thickness = 6 7/8 inches

Resistances				Loads	
Major Span				**Major Span**	
Bending Moment	(Fb*S eff)'	10400 lb*ft	>=	Applied Moment	5000 lb*ft
Shear	Fs*Ib/Q eff	2441 lbs	>=	Shear	1000 lbs
Bearing Strength	Fc⊥*Ac	15300 lbs	>=	Bearing Load	10000 lbs
Deflection	Δ	.67 inches	>=	Deflection	.075 inches
Minor Span				**Minor Span**	
Bending Moment	(Fb*S eff)'	1370 lb*ft	>=	Applied Moment	1800 lb*ft
Shear	Fs*Ib/Q eff	2441 lbs	>=	Shear	600 lbs
Bearing Strength	Fc⊥*Ac	15300 lbs	>=	Bearing Load	10000 lbs
Deflection	Δ	.40 inches	>=	Deflection	.050 inches

Major Span Variables	
EI app	402 x10^6 lb*in^2
EI eff	440
Ib/Q eff	54.25
Ac	36
Ks	11.5
GA eff	0.92

Factors		
Cd	=	1
Cb	=	1

Minor Span Variables	
EI app	78 x10^6 lb*in^2
EI eff	81
Ib/Q eff	54.25
Ac	36
Ks	11.5
GA eff	1.2

Floor/Roof Span Fire Check

Load	93.2	psf	=	93 psf
Element	Floor			
# of Plies	5-ply			
Required Rating	1.50 Hours			
CLT Hour Rating	1.50 Hours			
+Fire Protection	.00 Hours			

Floor Major Direction Variables	
a char	2.84 inches
Thickness After	4.03 inches
Ieff	63.01
Seff	30.9
Neutral Axis	1.99
E	1.7
Fb	1950.0

Resistances				**Loads**	
Major Span				**Major Span**	
Bending Moment	(Fb*S eff)'	12156 lb*ft	>=	Applied Moment	4661 lb*ft

CF	1
CV	1
Cfu	1
CL	1

Lateral Design

Under Development

Load Major	27.2	psf	=	27 psf
Load Minor	27.2	psf	=	27 psf
Load Direction	Major			
Major Width	214 feet			
Minor Width	100 feet			
Wall Height	14.0 feet			
Floor Number	2			
Sub Material	Floor			
Sub: Grade	E1			
Sub: Plies	5-ply			
Floor	0.42			
Main Material	Wall			
Main: Grade	V3			
Main: Plies	5-ply			
Main: SG	#N/A			
	100 feet			
Minor Width	100 feet			

Story	1	2	3	4	5	6	7	8
Story Weight	127	75						
Cumulative Weight	202	75	0	0	0	0	0	0
Height From Ground	14.6	29.50						

Variables	
Wind Load Major	81491
Wind Load Minor	38080
Unit Shear Major	1.78
Unit Shear Minor	3.81
Chord Force Major	190.4
Chord Force Minor	190.4
Shear Stiffness	#REF!
E	
pt	1.69

Unadjusted Resistances	
Mode Im	#REF!
Mode Is	#REF!
Mode II	#REF!
Mode IIIm	#REF!
Mode IIIs	#REF!
Mode IV	#REF!
Withdrawal	#N/A

Adjusted Resistances	
Mode Im	#REF!
Mode Is	#REF!
Mode II	#REF!
Mode IIIm	#REF!
Mode IIIs	#REF!
Mode IV	#REF!
Withdrawal	#REF!

Controlling Failure	
#REF!	#REF!
Withdrawal	#N/A

Controlling Failure	
#REF!	#REF!
Withdrawal	#REF!

# Of Fasteners Required	
Lateral	#REF!
Withdrawal	#N/A

# Of Fasteners Required	
Lateral	#REF!
Withdrawal	#REF!

Factors		
Cd	=	0.0
Cm	=	1.0
Ct	=	1.0
Ceg (W)	=	#REF!
Ceg (L)	=	#REF!
Cg	=	#REF!
CΔ	=	1.0

Connection Design

Load	14000	lbs	=	14000 lbs
Load Type	Seismic/Wind			
Direction of Load	Spline			
Fastener	Lag-Screw			
Fastener Type	Dowels			
Diameter	0.500			
Fastener Length	3.5			
Root Diameter	0.371			
Thread Length	2.00			
Tip Length	0.31			
Fyb	45000			
Sub Material	Spline			
Sub: Grade	OSB			
Sub: Plies	1			
Sub: SG	0.5			
Thickness	1.375			
Grain Angle	90			
Narrow Face	No			
Main Material	Floor			
Main: Grade	E1			
Main: Plies	5-ply			
Main: SG	0.42			
Thickness	6.875			
Grain Angle	90			
Narrow Face	Yes			

Unadjusted Resistances	
Mode Im	448 lbs
Mode Is	403 lbs
Mode II	197 lbs
Mode IIIm	254 lbs
Mode IIIs	233 lbs
Mode IV	277 lbs
Withdrawal	291 lbs

Controlling Failure	
Mode II	316 lbs
Withdrawal	590 lbs

# Of Fasteners Required	
Lateral	45 Fasteners
Withdrawal	24 Fasteners

Non-Functioning

Adjusted Resistances	
Mode Im	lbs
Mode Is	4566 lbs
Mode II	2239 lbs
Mode IIIm	#DIV/0!
Mode IIIs	1825 lbs
Mode IV	277 lbs
Withdrawal	#REF!

Controlling Failure	
#DIV/0!	#DIV/0!
Withdrawal	#REF!

# Of Fasteners Required	
Lateral	#DIV/0!
Withdrawal	#REF!

Factors		
Cd	=	1.6
Cm	=	1.0
Ct	=	1.0
Ceg (W)	=	0.75
Ceg (L)	=	0.67
Cg	=	1.0
CΔ	=	1.0

Plate Size	0.00
Plate Strength	0
Spline Material	OSB
Spline SG	0.5

Variables	
Fes	5600
Fem	4704
Fes	3158
Fem	2452.2
W	291.3
C End	1.5 inches
T End	2.0 inches
Spacing	2.5 inches
Edge Spacing	1.5 inches
Unadjusted ls	1.38 inches
Unadjusted lm	1.97 inches
Adjusted ls	15.59
Adjusted lm	0.00
p	2.13
pt	1.69

Glulam Column Design

Load	10000	lbs	=	10000 lbs
Load Type	Seismic/Wind			
Species	SPF			
# of Plies	14			
Width	5.50 inches			
Column Depth	6.88 inches			
Effective Length	14.6 feet			
End Fixity	Pinned			

Resistances				Loads	
Compression	Fc'	3189 psi	>=	Compression	264 psi

Variables	
Fc	2000
Fc	3200
Fce	99154.04
A	37.8 in^2
E min	0.85
Slenderness	31.854545

Factors	
Cd	1.6
Cp	0.9967

Glulam Beam Design

Load	10000	lb/ft	=	#N/A 0
Load Type	Live			
Species	SPF			
# of Plies	12			
Bearing Length	6.00 inches			
Bearing Width	6.00 inches			
Breadth (b)	8.75 inches			
Span Length	20 feet			
Axis Of Loading	y-y			
Loading	Uniformly distributed			
End Fixity	Pinned			
Beam Thickness (d)	= 18 inches			

Resistances				Loads	
Major Span				**Major Span**	
Bending Strength	Fb'	2357 lb*ft	>=	Applied Moment	1058 lb*ft
Shear Strength	Fs'	215 lbs	>=	Shear	635 lb*ft
Bearing Strength	Fc ⊥'	560 lbs	>=	Bearing Load	
Deflection	Δ'	.67 inches	>=	Deflection	#########

Variables	
Fb	2400
Fv	215
Fc⊥	560
S	472.5
I	4252.5
Av	158 inches
E'	1.6 x10^6 lb*in^2
Fb*	2400
Fbe	8775.4
E min	0.85 x10^6 lb*in^2
1/x (Cv)	0.10
Rs	10.78

Factors		
Cd	=	1
Cl	=	0.982
Cfu	=	1
Cv	=	1.00
Cc	=	1
Ci	=	1
Cvr	=	1
Cb	=	1

Tables and Calculators

CLT Grade Values

Major Direction

Outside Lumber Grade	Grade	3-ply (FbS)eff	5-ply (FbS)eff	7-ply (FbS)eff	3-ply Vs	5-ply Vs	7-ply Vs
MSR SPF	E1	4525	10400	18375	1430	1970	2490
MSR DF-L	E2	3825	8825	15600	1910	2625	3325
MSR E S,N S,W W	E3	2800	6400	11325	1110	1530	1940
MSR SYP	E4	4525	10400	18400	1750	2410	3050
No. 2 DF-L	V1	2090	4800	8500	1910	2625	3325
No. 1/2 SPF	V2	2030	4675	8275	1430	1970	2490
No. 2 SYP	V3	1740	4000	7100	1750	2420	3050

Grade	3-ply (EI)eff	5-ply (EI)eff	7-ply (EI)eff	3-ply (GA)eff	5-ply (GA)eff	7-ply (GA)eff
E1	115	440	1089	0.46	0.92	1.4
E2	102	389	963	0.53	1.1	1.6
E3	81	311	769	0.35	0.69	1
E4	115	440	1089	0.5	1	1.5
V1	108	415	1027	0.53	1.1	1.6
V2	95	363	898	0.46	0.91	1.4
V3	95	363	899	0.49	0.98	1.5

Minor Direction

Grade	3-ply (FbS)eff	5-ply (FbS)eff	7-ply (FbS)eff	3-ply Vs	5-ply Vs	7-ply Vs
E1	160	1370	3125	495	1430	1960
E2	165	1430	3275	660	1910	2625
E3	110	955	2180	385	1110	1520
E4	140	1230	2800	605	1750	2400
V1	165	1430	3275	660	1910	2625
V2	160	1370	0.4409	495	1430	1960
V3	140	1230	2800	605	1750	2400

Grade	3-ply (EI)eff	5-ply (EI)eff	7-ply (EI)eff	3-ply (GA)eff	5-ply (GA)eff	7-ply (GA)eff
E1	3.1	81	309	0.61	1.2	1.8
E2	3.6	95	360	0.56	1.1	1.7
E3	2.3	61	232	0.44	0.87	1.3
E4	3.4	88	335	0.62	1.2	1.9
V1	3.6	95	360	0.59	1.2	1.8
V2	3.1	81	309	0.52	1	1.6
V3	3.4	88	335	0.52	1	1.6

Major Direction

Ft	Fc	Fc	Fv	Fs	E major	Fb
1375	1800	425	135	45	1.7	1950
1020	1700	625	180	60	1.5	1650
600	1400	335	110	35	1.2	1200
1375	1800	565	175	55	1.7	1950
575	1350	625	180	60	1.6	900
450	1150	425	135	45	1.4	875
450	1250	565	175	55	1.4	750

Lumber Weight
31 lbs/ft^3
26 lbs/ft^3

Minor Direction

Ft	Fc	Fv	Fs	E minor	Fb
250	650	135	45	1.2	500
325	775	180	60	1.4	525
150	475	110	35	0.9	350
250	725	175	55	1.3	450
325	775	180	60	1.4	525
250	650	135	45	1.2	500
250	725	175	55	1.3	450

Lumber Weight
26 lbs/ft^3
26 lbs/ft^3

Structural Design Values

Ks	Pinned	Fixed	tilevered
Uniformly distributed	115	57.6	4.8
Concentrated at midspan	14.4	14.4	n/a
oncentrated at quarter poin	10.5	n/a	n/a
Constant moment	11.8	n/a	n/a
Concentrated at free-end	n/a	n/a	3.6

Reference Values	
Load	100
Major Span	20
Minor Span	12
EI Major	401.648
EI Minor	78.0772

Moment Major	Pinned	Fixed	tilevered
Uniformly distributed	5000	5000	20000
Concentrated at midspan	500	500	n/a
oncentrated at quarter poin	375	n/a	n/a
Constant moment	100	n/a	n/a
Concentrated at free-end	n/a	n/a	2000

oment Min	Pinned	Fixed d
rmly distri	1800	1200
ntrated at m	300	150'a
ated at quar	225	n/a'a
nstant mom	100	n/a'a
ntrated at fr	n/a	n/a

Shear Major	Pinned	Fixed	tilevered
Uniformly distributed	1000	1000	2000
Concentrated at midspan	50	50	n/a
oncentrated at quarter poin	25	n/a	n/a
Constant moment	0	n/a	n/a
Concentrated at free-end	n/a	n/a	100

hear Mino	Pinned	Fixed d
rmly distri	600	600
ntrated at m	50	50'a
ated at quar	25	n/a'a
nstant mom	0	n/a'a
ntrated at fr	n/a	n/a

Deflection Major	Pinned	Fixed	tilevered
Uniformly distributed	0.075	0.075	0.717
Concentrated at midspan	0.072	0.072	n/a
oncentrated at quarter poin	0.048	n/a	n/a
Constant moment	0.002	n/a	n/a
Concentrated at free-end	n/a	n/a	1.147

flection Mi	Pinned	Fixed d
rmly distri	0.050	0.010
ntrated at m	0.080	0.020'a
ated at quar	0.053	n/a'a
nstant mom	0.003	n/a'a
ntrated at fr	n/a	n/a

	Floor	Wall
Ply Thickness	1.375	1
Floor Panel Thickness	3-ply	5-7-ply
	4 1/8 #	9 5/8
Wall Panel Thickness	3-ply	5-7-ply
	4 1/8 #	9 5/8

Compression A

	3-ply	5-7-ply
Minor	16.5 #	49.5
Major	33 #	82.5

Conversion to lbs or lb*in or psi or plf

lbs	1
kips	1000
lb*in	12.000
lb*ft	1
k*in	12000
k*ft	1000
psf	1
psi	144
ksi	144000
ksf	1000
plf	1

h	Q Calc		
1.375			
	E	z	Ehz
		1.375	3.214
		0.6875	0.038
3-ply			3.252
	E	z	Ehz
		2.75	6.428
		1.375	0.076
		0.6875	1607
5-ply			8.111
	E	z	Ehz
		5.5	12856
		4.125	0.227
		2.75	6.428
		1.375	0.076
		0.6875	1607
7-ply			19.51

Glulam Values

	Fb	$Fc_{\perp}$	Fv	E	Er	Fc
24F-E/SPF SPF	2400	560	215	1.6	1	2000
30F-E2SP SYP	3000	805	300	2.1	1	

Reference Values

Load	10000	
Span	20	#######
E	1.6	
nsformed I	4252.5	

Moment	Pinned	Fixed	tilevered
Uniformly distributed	500000	500000	#REF!
Concentrated at midspan	50000	#REF!	n/a
ncentrated at quarter poir	375	n/a	n/a
Constant moment	0	n/a	n/a
Concentrated at free-end	n/a	n/a	#REF!

Shear	Pinned	Fixed	tilevered
Uniformly distributed	100000	#REF!	#REF!
Concentrated at midspan	0	0	n/a
ncentrated at quarter poir	#REF!	n/a	n/a
Constant moment	0	n/a	n/a
Concentrated at free-end	n/a	n/a	0

Deflection	Pinned	Fixed	tilevered
Uniformly distributed	0.441	#REF!	#REF!
Concentrated at midspan	0.072	0.072	n/a
ncentrated at quarter poir	#REF!	n/a	n/a
Constant moment	0.002	n/a	n/a
Concentrated at free-end	n/a	n/a	1.147

# of Layers	3	4	5	6	7	8	9
SYP							
ern Species							

SYP Possible Glulam Depths
5.5
6.875
8.25
9.25
9.5
9.625
11
11.25
11.875
12.375
12.625
13.75
14
15.125
16
16.5
17.875
18
19.25
20
20.625
22
23.375
24
24.75
26.125
27.5
28.875
30.25
31.625
33
34.375
35.75
37.125
38.5
39.875
41.25
42.63
44.00
45.38
46.75
48.13
49.5
50.875
52.25
53.63
55.00
56.38
57.75
59.125
60.5

Fire Safety: Column/Wall Design

Hour Ratin	.00 Hours	#######	.75 Hours	########	########	#	######
t	0	0.5	0.75	1	1.25	2	2
βeff	#DIV/0!	2.05	1.90	1.80	1.73	#	1.58
a char	0.00	1.02	1.42	1.93	2.42	#	3.79
Layers Bur	0	0	1	1	1	2	2
Visual Char			1.19	1.5		2	2.64
Zero-Strength			0.24	0.3		0	0.53

K	R factor		e		t	0.5
2.85	0.85		3-ply	4.125	tf	0.90
2.85	Wood Burn Rate		5-ply	6.875	th	1.38
2.58	1.5		7-ply	9.625	a l	0
2.03	Reference Values		Weight		a	1.02
2.03	Load	93	Major	0	h f	5.85
	EI Major	150.3	Minor	0		

Dead Load	3-ply	5-ply	7-ply
.00 Hours	0	0	0
.50 Hours	0	0	0
.75 Hours	0	0	0
1.00 Hours	0	0	0
1.25 Hours	0	0	0
1.50 Hours	0	0	0
2.00 Hours	0	0	0

Residual	3 5-ply	7-ply
#######	1.38	1.38
#######	0.35	0.35
#######	1.33	1.33
#######	0.82	0.82
#######	0.33	1.28
#######	1.28	1.28
#######	0.33	0.33

Neutral A	3-	5-ply	7-ply
#######	#	3.44	4.81
#######	#	2.47	3.83
#######	#	2.06	3.44
#######	#	2.06	3.44
#######	#	2.06	3.44
#######	#	1.99	3.36
#######	#	1.12	2.45

Remainin	3 5-ply	7-ply
#######	5	7
#######	5	7
#######	4	6
#######	4	6
#######	4	6
#######	3	5
#######	3	5

b(h^3)/1:	3-	5-ply	7-ply
#######	#	7.80	10.40
#######	#	5.24	7.84
#######	#	5.20	7.80
#######	#	5.20	7.80
#######	#	5.20	7.80
#######	#	4.72	7.32
#######	#	2.64	5.24

A	3 5-ply	7-ply
#######	49.50	66.00
#######	37.21	53.71
#######	33.00	49.50
#######	33.00	49.50
#######	33.00	49.50
#######	31.91	48.41
#######	20.49	36.99

Major I ef	3-	5-ply	7-ply
#######	#	257.36	634.30
#######	#	107.39	542.88
#######	#	67.59	257.36
#######	#	67.59	257.36
#######	#	67.59	257.36
#######	#	63.01	159.89
#######	#	18.60	105.78

Fire Safety: Floor/Span Design

Hour Ratin	.00 Hours	#######	.75 Hours	########	########	#	######
t	0	0.5	0.75	1	1.25	2	2
β eff	#DIV/0!	2.05	1.90	1.80	1.73	#	1.58
α char	0.00	1.02	1.42	1.93	2.42	#	3.79
Layers Bur	0	0	1	1	1	2	2
Visual Char			1.19	1.5		2	2.64
Zero-Strength			0.24	0.3		0	0.53

K	R factor		e		t	1.5
2.85	0.85		3-ply	4.125	tf	0.90
285	Wood Burn Rate		5-ply	6.875	th	1.38
2.58	1.5		7-ply	9.625	n l	1
2.03	Reference Values		Weight		α	2.84
2.03	Load	93	Major	31.1	h l	4.03
	EI Major	0.0	Minor	26.1		

Dead Load	3-ply	5-ply	7-ply
.00 Hours	10.12	16.67	23.23
.50 Hours	7.46	7.46	7.46
.75 Hours	6.45	9.99	9.99
1.00 Hours	5.35	8.68	8.68
1.25 Hours	7.41	7.41	9.88
1.50 Hours	9.88	9.88	9.88
2.00 Hours	7.42	7.42	7.42

Residual ` 3	5-ply	7-ply
#######	1.38	1.38
#######	0.35	0.35
#######	1.33	1.33
#######	0.82	0.82
#######	0.33	1.28
#######	1.28	1.28
#######	0.33	0.33

Neutral A 3		5-ply	7-ply
#######	#	3.44	4.81
#######	#	2.47	3.83
#######	#	2.06	3.44
#######	#	2.06	3.44
#######	#	2.06	3.44
#######	#	1.99	3.36
#######	#	1.12	2.45

Remainin 3	5-ply	7-ply
#######	5	7
#######	5	7
#######	4	6
#######	4	6
#######	4	6
#######	3	5
#######	3	5

b(h^3)/1: 3		5-ply	7-ply
#######	#	7.80	10.40
#######	#	5.24	7.84
#######	#	5.20	7.80
#######	#	5.20	7.80
#######	#	5.20	7.80
#######	#	4.72	7.32
#######	#	2.64	5.24

A 3	5-ply	7-ply
#######	49.50	66.00
#######	37.21	53.71
#######	33.00	49.50
#######	33.00	49.50
#######	33.00	49.50
#######	31.91	48.41
#######	20.49	36.99

Major I ef 3		5-ply	7-ply
#######	#	257.36	634.30
#######	#	107.39	542.88
#######	#	67.59	257.35
#######	#	67.59	257.35
#######	#	67.59	257.35
#######	#	63.01	159.89
#######	#	18.60	105.78

Moment Major	Pinned	Fixed	tilevered	**Ioment Min**	Pinned	Fixed d
Uniformly distributed	4660.54	4660.54	18642.17	Uniformly distribut	1677.8	1118.53
Concentrated at midspan	466.05	466.05	n/a	Concentrated at midsp	279.63	139.816'a
oncentrated at quarter poin	349.54	n/a	n/a	ncentrated at quarter p	209.72	n/a'a
Constant moment	93.21	n/a	n/a	Constant moment	93.211	n/a'a
Concentrated at free-end	n/a	n/a	1864.22	Concentrated at free-e	n/a	n/a

Connection Design

	W
Lag-Screw	291.3224435
Wood Scre	251.37
Smooth-Sh	78.88098348
Ring Shank	158.76
Bolts	N/A

	In-Plane Spacings			of-Plane Spa	
	spacing di	compressi	tension-en	Ec	a2
Dowels	2.5	1.5	2	2	1.5
Bolts	2.5	2	2	2	2

	Min SG
E1	0.42
E2	0.5
E3	0.36
E4	
V1	0.5
V2	0.42
V3	

Plate thick	0.00
Is	1.38
Is Adjusted	15.59
p w/ plate	2.13
P w/o plat	2.13
Threaded l	1.69
Im	1.97
Im Adjuste	0.00
pmin	1.48

		II	IIIm	IIIs	IV
Adjusted Ir Is		2239.07	#DIV/0!	1825.41	#
0.25<=D<	4565.95	2172.68	#DIV/0!	1574.48	#
0.17<D<.	4922.86	3563.92	#DIV/0!	2655.14	#
D<=.17	8301.73				

		II	IIIm	IIIs	IV
Unadjust Ir Is		197.471	254.136	232.985	#
0.25<=D<	402.687	191.616	219.201	200.958	#
0.17<D<.	434.164	323.134	369.653	338.888	#
D<=.17	732.159				

	Adjusted	Unadjusted	
Fes	3157.558018	3157.56	
Fem	2452.202348	2452.2	
Re	0.776613552	0.77661	
Rt	1.431818182	1.43182	
k1	0.441344592	0.44134n	Adjusted
k2	#DIV/0!	1.15927	
k3	1.143482815	1.65486	

	Half-Lap	Spline		M Butt Joint
Is	0.6875	1.375	#	1.38
p	2.8125	2.125	#	2.13
Im	2.65625	1.96875	#	1.97

Rd	D<=17	0.17<D<.2	0.25<=D<=1
Im	2.2	3.71	4
Is	2.2	3.71	4
II	2.2	3.71	4
IIIm	2.2	3.71	3
IIIs	2.2	3.71	3
IV	2.2	3.71	3

		Total # Pl
Ply Thickn	1.375	1
Ply Thickn	1.375	5
	Parallel	Perpendi
# of Plies i	4	3
# of Plies i	3	2

Lag Screw Dimension Table

D	0.25	0.3125	0.375	0.4375	0.5	1	0.75	0.875	1	1.25			
Dr	0.173	0.227	0.265	0.328	0.371	0	0.579	0.683	0.78	1.012			
E	0.156	0.188	0.219	0.281	0.313	#	0.500	0.578	0.672	0.730			
											10	11	12
L	1	1.5	2	2.5	3	4	5	6	7	9	5.5	6	6
T	0.75	1.25	1.5	1.75	2	3	3	3.5	4	5			