

**Critical Factors in the Willingness to Adopt Innovative Wood-  
based Building Materials in the Construction Industry:  
The Case of CLT**

A DISSERTATION

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# Dedication

To my Family

# Abstract

Energy use and carbon emissions from the built environment have been gaining significant attention worldwide. The construction of buildings across the world is currently dominated by concrete, but production of cement, a primary ingredient in concrete, is a major source of pollution, producing a ton of CO<sub>2</sub> for every ton of cement. One approach to reducing the environmental impacts of construction involves increasing the use of materials with lower environmental footprints, such as wood. However, the utilization of wood as a building material is not free from challenges. Because wood is a natural material, its properties are not homogeneous, and it must be protected from biological attack. The development of Engineered Wood Products (EWP) was in part a response to those challenges, while at the same time allowing a more efficient use of raw materials. EWPs are manufactured to targeted structural properties. New EWPs, such as Cross-Laminated Timber (CLT), have increased the possibilities of building with wood. CLT consists of multi-layer panels, manufactured with lumber that are glued together, alternating the direction of their fibers for each layer. Cross-lamination confers CLT rigidity, stability and desirable mechanical properties. CLT is currently being used for a wide range of applications, such as houses, high-rise apartment and office buildings, schools, bridges, and wind turbine towers, among others. This has added visibility to the system, which has been able to compete with steel, brick, and concrete in the European markets since its introduction more than two decades ago. The successful introduction of CLT into the Canadian market indicates that there is potential for further market penetration in North America, and more specifically the United States.

To increase the understanding of the market potential for CLT in the U.S., this dissertation aimed at identifying the critical factors influencing the willingness of U.S. construction professionals to adopt innovative wood-based construction materials. The overall objective was achieved by: (a) investigating the level of awareness, perceptions, and willingness to adopt CLT among structural engineers and construction firms; (b) developing a conceptual model including the most critical factors that influence the adoption of innovative wood-

based construction materials among structural engineers and construction firms; and (c) identifying distinct market segments for CLT adoption in the U.S.

Through a series of surveys and interviews to U.S. engineering and construction firms, this study found that environmental performance was the main perceived advantage of CLT. Another important benefit of CLT over traditional construction systems, as perceived by construction professionals, is the lower labor cost and faster construction associated with building with CLT. U.S. construction professionals also mentioned CLT's aesthetic attributes as an advantage of the system. The most commonly cited disadvantages of CLT were its fire performance, durability, and lack of availability in the U.S. market. Regarding familiarity with CLT among the target audience, results show that the level of awareness about CLT is low. Barriers to CLT's adoption in the U.S. market, as perceived by construction professionals, are lack of availability in the domestic market, high maintenance costs, and lack of experience working with CLT among professionals. Both U.S. engineering and construction firms seem to be interested in adopting CLT for future projects, especially if it is cost-competitive with traditional building systems. Results show that diffusion of knowledge about CLT and the role of early adopters will be essential for the successful introduction of this new building technology into the U.S. market.

The conceptual model developed for U.S. engineering firms includes factors such as firm size, aesthetics, moisture performance, vibration performance, LEED credits, and availability of design tools as the main factors affecting willingness to adopt innovative wood-based construction materials such as CLT. In regards to construction firms, location, innovativeness, level of awareness, maintenance requirements, durability, vibration performance, labor cost, and LEED credits were associated with willingness to adopt CLT. Using cluster analysis, distinct market segments were identified in the two populations of interest (U.S. engineering and construction firms). From this analysis, priorities and demographics of those segments were also identified. This information is useful to develop better marketing strategies to target potential adopters and provide more customized services, products, and better design educational programs.

The outcomes from this research helps fill the gap in the knowledge about the market adoption process for innovative wood-based materials in the construction industry. This

study also advances the development of the CLT industry in the U.S. by increasing the demand of wood-based construction materials and supporting the creation of employment in a sector of critical importance to the U.S. economy. The target audience for this study is comprised of construction professionals, manufacturers, organizations supporting the wood industry, government agencies, and building officials. Findings from this thesis provide useful information that will help these actors accelerate the adoption of CLT through well-designed educational programs, demonstration projects, marketing strategies, and policy incentives.

*Keywords: Cross-laminated timber (CLT), massive timber, engineered wood products, sustainable buildings, wood-based construction, adoption, willingness, perceptions, segmentation.*

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# **Chapter 1**

## **Introduction and Literature Review**

## ***Introduction***

Wood has played a crucial role in the development of civilization, by providing heat, energy, transportation and shelter (Ritter, Skog, & Bergman, 2011). Wood's inherent attributes make it remarkably flexible and versatile, demonstrated by the wide variety of successful applications in which it has been used. As a construction material, wood has been the preferred building material for millennia, due to its affordability, abundance, and outstanding structural and environmental performance (CEI-Bois, 2010).

However, the utilization of wood as a building material is not free from challenges. Wood is a natural material, its properties are not homogeneous, and vary widely depending on species, cellular arrangement, moisture content, and location of the tree and within the same tree (Forest Products Laboratory, 2010). Furthermore, due to the anisotropic nature of wood, its properties change with direction (e.g., longitudinal vs. radial direction) (Hoadley, 2000). To address wood's variability and better utilize the material, Engineered

Wood Products (EWPs) were developed. These products are manufactured to achieve targeted engineering properties, such as high performance, reliability, and consistency. EWPs also allow for a more efficient utilization of forest resources (Forest Products Laboratory, 2010). Manufacturing techniques, mechanical evaluation, special connectors, and adhesives are used to increase EWPs performance under load and harsh conditions. One of the latest innovations in the area of EWPs has been the development of Cross-Laminated Timber (CLT), also known as “Cross-Lam”, “X-Lam” or “Massive Timber” (Podesto, 2011). CLT panels are strong and stiff, which allows them to be used in a wide range of applications (Ceccotti, Sandhaas, & Yasumura, 2010). CLT is a relatively new construction technology developed in the early 1990s in Europe, where it has become an important building material. It has been recently introduced into the Canadian and Australian markets, where it has been used in over 50 buildings (Crespell, 2015). CLT is currently used for a wide range of structures, from houses, barns, power line towers, churches and bridges, to high-rise apartment and office buildings. This has been adding visibility and reputation to the system (Sanders, 2011), which has been able to compete with steel, brick, and concrete in some markets. While CLT is used in many countries, the U.S. market for CLT is still in its embryonic stage. So far, only a handful of projects have CLT as the main structural material, and most of them were built with panels imported from Austria and Canada. Furthermore, the market development in the U.S. has been hindered by the lack of manufacturing facilities in the country. As of October of 2017, there were only three commercial CLT manufacturers in the country certified to produce panels for structural applications. There is, however, great interest in the material among the construction and manufacturing industries. Federal, state, and local governments are also interested in the employment generation potential of CLT and the opportunity to improve timber resource utilization.

However, despite the perceived advantages and benefits of an innovative new construction material, these are typically not readily accepted (Gourville, 2005). The market acceptance of new building materials is a slow process, and widespread adoption of systems such as CLT depends on several factors like: prominent projects being implemented, changes to the building code, and changes in potential adopters’ perceptions; and most importantly in

the early stages, an increase in the product awareness among design and construction professionals. For example, recent research by the author (Appendix 1) about the level of awareness, perceptions, and willingness to adopt CLT by the U.S. architecture community, has shown that the level of awareness about CLT among U.S. architecture firms is low. The same study also found positive perceptions about the environmental, structural, and aesthetic performance of CLT, but low ratings on acoustics, seismic performance, and maintenance costs. Lastly, a positive and significant association was identified between awareness about CLT by U.S. architecture firms and their willingness to adopt it.

*This research builds on previous work by the author, and aims at increasing the understanding of the critical factors associated with the adoption of innovative wood-based building materials by U.S. engineering and construction firms; with a focus on commercial and multifamily buildings. Cross-Laminated Timber was used as case study. This research addresses the lack of information on the adoption of innovative wood-based construction materials by major decision makers in the construction industry. This research also contributes to a better understanding of the adoption process and market potential for CLT and other innovative wood-based construction materials in the U.S.*

## ***Literature review***

Over the centuries, wood has been proven an excellent material for structural applications (Brostow, Datashvili, & Miller, 2010). Wood possesses outstanding structural and environmental performance characteristics in comparison with other materials like concrete or steel (CEI-Bois, 2010). Important attributes of wood as a building material include flexibility of design, and proven thermal, structural, and environmental performance. Moreover, wood is widely available, renewable, and easy to transform.

In part to address wood's inherent variability, and to utilize this material more efficiently and create new high value-added wood-based products, Engineered Wood Products (EWPs) were developed. These products are manufactured by binding together strands, particles, fibers, veneers or boards with adhesives or other methods to achieve targeted mechanical properties, reliability, and consistency (APA, 2015; Forest Products

Laboratory, 2010; LeVan-Green & Livingston, 2003; Wang et al., 2003). EWP are subject to strict standards and rigorous structural qualification testing (Forest Products Laboratory, 2010). These products are manufactured to achieve targeted engineering properties, such as high strength, enhanced durability, and consistency.

The development and improvement of adhesion technologies, mechanical connections, and grading technology have resulted in EWPs that greatly extend the possibilities for wood-based construction (CWC, 2014). Over the past decades, EWPs have become very popular among construction professionals (Anderson, 2008). Thanks to these developments, wood can now be used where once materials like steel or concrete were the only options, such as mid-high rise construction and long-span applications, allowing a great diversity and flexibility in building (Mayo, 2015). EWPs' structural and aesthetic attributes have made possible their use in diverse applications, as an exposed or covered structure, for bridges, stadium roofs, and churches, and many others. Designers and builders are attracted to the consistency, strength, quality, aesthetics and structural reliability of such products. EWPs usually have higher initial costs compared to solid lumber but are competitive with non-wood materials, such as steel, concrete, and plastic; and can be used in applications where solid wood is not an option or with a higher efficiency. EWPs also contribute to a more efficient use of low-value and small-diameter trees (APA, 2015; Forest Products Laboratory, 2010; LeVan-Green & Livingston, 2003; Wang, et al., 2003). EWPs can utilize small diameter trees, and lower grade lumber to manufacture a value-added product. During the manufacture of these products, small pieces of lumber (without knots and inconsistencies that could reduce the strength) or particles are reassembled to create a product that has greater structural performance than each individual part (Mayo, 2015).

The variety of EWPs available in the market provides architects, engineers and builders with virtually limitless design possibilities. Glued-laminated beams (also known as Glulam,) for example, represented an important advance in achieving long spans (CWC, 2014). Glulam beams are manufactured gluing together machine or visually graded pieces of dimension lumber to produce much larger sections. In the manufacture of these elements, wood pieces are finger-jointed and arranged in horizontal layers or lamellas (Slavid, 2005). The development of panel products also established new uses for wood in

building construction (Slavid, 2005). Products such as plywood, Oriented Strand Boards (OSB), Medium Density Fiberboard (MDF), and particleboard have gained considerable market share during the last decades. Another EWP, the I-joist, is made by gluing solid sawn lumber or Laminated Veneer Lumber (LVL) flanges to a plywood or OSB web, to produce a dimensionally stable, lightweight structural element (APA, 2015). The uniform strength of I-joists makes them well suited to perform as long span beams (CWC, 2015). I-joists also show a high strength-to-weight ratio. The moisture content of the elements present in the I-joist is low (around 10% MC), thus the tendency to shrink or warp is greatly reduced, which results in more stable structures (CWC, 2015). The strength, reliability, long span capability and the possibility of using lower quality wood to create value-added products (APA, 2015), resulting in a better utilization of the forest resource, are attributes that make EWPs attractive alternatives to solid wood in most types of buildings.

### ***Cross-Laminated Timber***

Cross-laminated timber (CLT) is one of the latest innovations in EWPs. CLT technology was developed in the early 1990s in Austria, as a cooperative project between industry and academic partners at the Graz University of Technology in Graz, Austria (KLH Massivholz GmbH, 2015; Kramer, Barbosa, & Sinha, 2014). As the market in Europe began demanding more environmentally friendly products, more people turned to CLT for their construction needs and it quickly grew in popularity during the last two decades. CLT has experienced market success in Europe, and there is increasing interest on its adoption in Asia, Oceania, and North America. CLT is not just a material; it is a building system composed of large-format solid timber panels that can be used as walls or slabs (Lattke & Lehmann, 2007). These panels are configured similarly to plywood (some have described it as “Jumbo Plywood” (FPInnovations, 2013; Karacabeyli & Douglas, 2013)), with boards that are glued to another layer of boards placed at right angles with the adjacent layers (Figure 1). This cross-lamination is intended to improve rigidity, stability, and mechanical properties (Evans, 2013), thus increasing the number of applications that use wood as major material (Kuilen, Ceccotti, Xia, & He, 2011).

Typically, a cross section of a CLT element has typically between 3 and 7 layers (odd numbers to achieve a balanced construction) of boards placed orthogonally to each other. The final dimensions of CLT panels are typically between 2 and 9 feet wide, and up to 79 feet long (Crespell & Gaston, 2011). In special applications, unique configurations can be created, for example, consecutive layers may be placed in the same direction to obtain a specific structural performance (Karacabeyli & Douglas, 2013). Lumber in the outer layers of CLT panels that are used as walls are usually oriented parallel, to maximize the wall's vertical loading capacity. Likewise, for floor and roof systems, the outer layers run parallel to the major direction of the span (Karacabeyli & Douglas, 2013). During the manufacturing of CLT panels, lumber is visually graded or machine stress-rated and kiln dried before boards are often finger-jointed and glued together using structural adhesives. After panels have been pressed and machine-surfaced, openings for windows, doors and service channels, connections and ducts are cut using CNC (Computer Numerical Controlled) routers, which allow for high-precision and speed. Finally, elements are packed and sent to the construction site, ready to be put in place with cranes. CLT elements are typically connected using metal connectors such as steel angles, and metal splines. Screws are used to attach these connectors to the panels (Crespell & Gagnon, 2011).



**Figure 1. Example of 3 and 5-layer CLT panels.**

## *CLT's properties*

### *Environmental performance*

Multiple authors have studied the environmental benefits of wood as a building material. There is wide consensus that when forests are sustainably managed, wood is carbon-neutral, and acts as a repository of carbon, either as growing stock or as a value-added product (Oneil & Lippke, 2010). Trees convert carbon dioxide (CO<sub>2</sub>) to biomass as a result of the process of photosynthesis, effectively storing carbon, a process known as carbon sequestration. It is roughly estimated that one cubic meter of wood stores around 1.10 U.S. tons of CO<sub>2</sub> (Puettmann et al., 2010).

The environmental qualities of wood as building material have been contrasted with other materials, such as steel and concrete (Chen, 2012; John, Nebel, Perez, & Buchanan, 2009; A. B. Robertson, 2011). Chen (2012) conducted a Life-Cycle Analysis (LCA) study comparing two five-story office buildings, one built in concrete and another with CLT, and concluded that over the building life-cycle, the wood-based alternative consumed 15% less energy compared to concrete. Chen (2012) calculated the operational energy (defined as the amount of energy that is required by a building to satisfy the demands for HVAC systems (heating, ventilation and air conditioning) of a five-story office building in CLT and another in concrete and concluded that CLT buildings have a 10% lower operational energy demands, adding that further reductions are possible through improved technology and design optimization. The results from a comparative study of two mid-rise office buildings conducted by John, Nebel, Perez and Buchanan (2009) indicated that CLT has a favorable environmental performance, in all impact categories (ozone depletion, global warming potential, eutrophication), compared to a comparable building built with concrete. The same study also concluded that the carbon sequestration potential associated with CLT would allow the building to operate for the first 12 years with no net CO<sub>2</sub> emissions. Research conducted by Darby, Elmualim and Kelly (2013) in the United Kingdom showed that a reinforced concrete six-story building contains more embodied CO<sub>2</sub> than an equivalent CLT building (1661 vs. 655 U.S. tons). More specifically, CLT turns out to have more than a third (39.4%) of the CO<sub>2</sub> embodied in the concrete alternative. However, if carbon sequestration included in the analysis, a CLT building turns out to be carbon-

negative, with a value of approximately -2,314 U.S. tons of embodied CO<sub>2</sub>. For this reason, massive timber construction systems, such as CLT, offer the opportunity to turn buildings into “carbon sinks” (Lehmann, 2012).

More recently, the advantages of CLT in comparison to other wooden structural systems have been studied. The research conducted by Dodoo, Gustavsson and Sathre (2014), evaluated the carbon implications of three timber multi-story building systems: a building made of CLT panels, one using a glulam beam and column system, and the last one composed of light-frame wooden elements. Results of the analysis of the entire lifecycle of the buildings showed that CLT building have the lowest lifecycle carbon emission (because of less insulation required) while the traditional version of the beam-and-column building has the highest (Dodoo, et al., 2014).

CLT is also suited for incorporation of underutilized and low-quality timber. Due to insufficient demand and lack of resources to manage U.S. forests, the prevalence of small-diameter timber is growing (Perkins, 2006). In addition, decades of fire suppression and high-grading led to an over-abundance of small-diameter timber of low quality and value. Studies have suggested that small-diameter logs can yield high quality material, when processed with the proper equipment and methods (LeVan-Green & Livingston, 2003; Lowell & Green, 2001). U.S. forest resources have also been subject to stress due to insect infestation, such as the mountain pine beetle (MPB), the gypsy moth, the southern pine beetle, the spruce budworm, and several others (Alvarez, 2007). However, neither the fungus nor the beetle eats the wood structure, and the resulting stain does not cause decay problems (Forintek, 2003). Tests on properties of timber from MPB-killed trees show that there is no significant reduction in stiffness and breaking strength performance (Uyema, 2012). Consensus exists that traditional markets cannot absorb all the low quality timber in existence. Since CLT is made of small components assembled and glued together, the quality of individual pieces is not as critical as with other timber-based building components. Increased demand from newly developed markets, such as Cross-Laminated Timber (CLT) presents the opportunity to use this lower value, yet mechanically unaffected material at economically attractive prices to pay for increased forest management costs. New high value-added uses, such as CLT, are of critical importance to support proper forest

management and to enhance the economic wellbeing of rural communities that rely on forest products industries.

#### *Installation simplicity and cost competitiveness*

CLT is a system based on large format, lightweight panels that vary in size from manufacturer to manufacturer. Typical widths are two, four, eight, and ten feet; panel length can be up to sixty feet or more, and thickness can be up to 20 inches. Using fewer but larger elements implies greater construction simplicity (Waugh, 2010). According to Bejder (2012), CLT makes possible a new way of building structures, shifting the design from “frames” to “plates”.

Previous research conducted by the author, evaluating the cost of a CLT building and the equivalent building in concrete and steel, showed that CLT would signify a cost reduction of up to 21.7% in the cost of structure, depending on the extent to which CLT is used in the building and the manufacturer selected (Laguarda-Mallo and Espinoza, 2016).

CLT’s installation simplicity depends in great part on the connections used during construction. Panels are assembled using mechanical fastening systems, such as self-drilling threaded screws (Evans, 2013). Gavric, Fragiaco, Popovski and Ceccotti (2014) established that these screws enable the creation of structurally stable constructions with effective response to both vertical and lateral (i.e. horizontal) forces. Concealed metal plates and dowels can also be used as connections. Research conducted in Canada by FPInnovations (2013) concluded that this type of fastening system provides considerable advantages over exposed plates and brackets, especially when it comes to fire resistance, since surrounding wood protects them.

One of the most attractive features of CLT as a building system relates to the speed in which CLT buildings can be erected, in great part due to its prefabricated nature. This allows for high precision (openings in the panels are cut using a CNC machine), faster completion, increased safety, less disruption to the surroundings, and less waste generation (Evans, 2013; FPInnovations, 2013; Karacabeyli & Douglas, 2013). Several case studies highlight construction times, which may be as short as three to four days per story (WoodWorks, 2013), compared to twenty eight days per story for typical concrete

construction<sup>1</sup> (Kosmatka & Wilson, 2011). Construction may take as little as three to four months for buildings of up to nine stories, less than half the time compared to traditional construction methods, such as concrete (Kosmatka & Wilson, 2011; Lehmann, 2012). A report by Mahlum Architects Inc. (2014) compared two ten-story residential buildings, one in CLT and another in concrete, and concluded that significant reductions in cost and construction time are possible if CLT is chosen. Authors also estimate that the reduction of construction time will be greater with further development of the CLT industry (Mahlum Architects Inc., 2014).

### *Structural performance*

CLT panels are built with layers orthogonal to each other, in a way similar to plywood. With this configuration, adjacent layers act as reinforcement of the whole panel, adding to dimensional stability and allowing panels to span and carry load in both directions, similar to a concrete slab (Turner, 2010; Van de Kuilen, Ceccotti, Xia, He, & Li, 2010). Several experimental tests on CLT elements, in particular those conducted by Steiger, Gülzow, and Gsell (2008) concluded that those characteristics allow CLT panels to be used as load-bearing plates and shear panels, in contrast to other wood engineered products. Cross-lamination also enhances dimensional stability, as individual layers constrain the expansion and contraction of the adjacent layers (Evans, 2013).

Several studies have placed attention on the structural performance of CLT, especially in respect to stiffness, bending, shear and compression strength, and deflection (Ashtari, 2012; Hindman & Bouldin, 2014; Hochreiner, Füssl, Serrano, & Eberhardsteiner, 2014; Li & Lam, 2015; Oh & Lee, 2014; Okabe, Yasumura, Kobayashi, & Fujita, 2014).

In-plane stiffness of CLT floors was evaluated by Ashtari (2012). The analysis included the effect of panel to panel connections, shear modulus of panels, stiffness of shear walls and floor panel's configuration. Results showed that stiffness of CLT floor is highly dependent of the stiffness of shear walls (Ashtari, 2012). Stiffness of CLT panels were

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<sup>1</sup> Concrete needs to be cured for at least 28 days before 90% of the material's final strength is reached and the formwork for the next floor can be placed (Kosmatka & Wilson, 2011).

evaluated by testing panels following product standards such as the European Standards EN 13353 (DIN, 2003), EN 13986 (DIN, 2005b), and EN 789 (DIN, 2005a).

In North America, the requirements and test methods for qualification and quality assurance of CLT panels is covered by the American Standard for Performance-Rated Cross-Laminated Timber (ANSI/APA PRG 320) (ANSI, 2012). A recent research published by Hindman and Bouldin (2014) studied the bending, shear properties as well as delamination of southern pine CLT panels, compared to the requirements established in the ANSI/APA PRG 320 Standard. Experimental results show that bending and shear strength, and stiffness exceeded the published values, while resistance to delamination did not meet the required criteria established in the Standard. Authors speculate that glue performance and consequent delamination of the samples could have been affected by the uncontrolled moisture content of the boards used to fabricate the CLT panels (Hindman & Bouldin, 2014).

Bending strength has also been evaluated on CLT panels consisting of wooden boards from different strength classes (Hochreiner, et al., 2014), which helped determine the influence of the quality of the wooden boards on the load carrying capacity of CLT elements. Hochreiner et al. (2014) carried out bending tests on 24 CLT plates, consisting of wooden boards from three different strength classes, and concluded that individual board strength did not influence the elastic limit load of the CLT plates, which is attributed to the cross-laminated nature of the panels.

In regards to the performance of CLT under compressive loads, Oh and Lee (2014) studied the effect of the number and mechanical properties of laminae on the compression strength of panels. Compression resistance of each laminae and the entire panels were modelled. Experimental testing was then performed on short column CLT samples, made from Korean Larch, to verify the theoretical model. After comparing the results, Oh and Lee (2014) concluded that there was a positive correlation between the experimental tests and predicted results. Results also showed that the compressive strength increases with the increase in the number of laminae.

The influence of Duration of Load (DOL) on the strength properties of wood products has been widely documented in the literature (Barrett, 1996; Barrett & Foschi, 1978; Foschi &

Barrett, 1982; Gerhards & Link, 1987; Liu & Schaffer, 1991). Li and Lam (2015) conducted a study to quantify the DOL effect on the shear strength of CLT panels and predict the time to failure under different types of loading (short-term and snow) states. Their research demonstrated that the effect of the DOL on the shear strength of CLT is very different from the effect on lumber. The adjustment factors to take into account the DOL effect on the shear strength were found to be more severe for CLT ( $K_d=0.4-0.6$ ) than for lumber ( $K_d=0.8$ ) (Li & Lam, 2015).

The structural capabilities of CLT and specially it's strength-to-weight ratio has expanded the opportunities for the use of wood in a wide range of buildings, especially as a viable alternative to steel and concrete in mid to high-rise building construction (Fountain, 2012). There are several examples of CLT used in tall buildings, with prominent examples such as the Stadthaus, an 8-story residential building in London (KLH Massivholz GmbH, 2015), and the Forte Building, a 10-story residential building in Melbourne, Australia (Lend Lease, 2013). A recent report by the architecture and engineering firm Skidmore, Owings and Merrill proposed a 42-story CLT-concrete hybrid building in Chicago, called Timber Tower Research Project (SOM, 2013). More recently the architecture studio Rüdiger Lainer and Partners (RLP, 2015) has introduced HoHo Wien, a new 24 story CLT residential building in Vienna. If built, HoHo would be the tallest CLT structure constructed to date (French, 2015).

### *Design flexibility*

According to some authors, the structural characteristics of CLT allow for great architectural freedom during the design process, allowing different building configurations of openings (number, size and location) and providing flexibility in organizing spaces without compromising the structural integrity of the structure (Bejder, 2012; Kwan, 2013). CLT also allows covering long spans without intermediate supports; something that would be too complex or impossible to attain using wood in traditional ways. For example, a CLT panel with 7 layers (9 inch thickness) can be used to cover spans of up to 25 feet (Malczyk, 2011). Some variations of traditional CLT panels, such as “folded” and “cassette” floors have improved the performance of floor structures by decreasing the weight of the

elements, allowing covering up to 65 feet-long spans (Fountain, 2012). Silva, Branco and Lourenço (2013) has evaluated special applications of wall-structures working as deep beams that can help solve long spans without intermediate supports. A study conducted by Jaksch, Fadaei, and Winter (2012) evaluated the use of CLT elements to achieve folded geometries, which they defined as the intersection of two planar surfaces on a specific angle. The study concluded that the use of CLT was not only viable, but also allowed to represent a new type of wooden architectural language based on larger planar surfaces.

### *Fire performance*

Several research studies have focused on CLT's performance under fire situations, given the common perception that wood buildings perform poorly in these situations (Andrea, Fontana, Knobloch, & Bochicchio, 2009; FPInnovations, 2013; Karacabeyli & Douglas, 2013). Authors of these studies state that wooden structural elements of large sections such as CLT panels have desirable fire resistance properties, mainly because of wood's particular charring properties. According to the Forest Products Laboratory (2010), a char depth of 1.5 inches at one hour is generally expected for structural wood members. Correspondingly, experiments performed by Friquin, Grimsbu and Hovde (2010), in which several CLT panels were evaluated under different fire conditions, observed that wood formed a char layer that protected non-charred wood from further thermal degradation and mass loss. This behavior allows the structural element to maintain its strength and dimensional stability without collapsing in an abrupt way, potentially providing time for the evacuation of occupants from the building.

The American Wood Council conducted an ASTM E119 experimental fire resistance test<sup>2</sup> on a series of three CLT walls at an independent fire testing facility in Buffalo, New York (AWC, 2015; Rizzo & Menchetti, 2012). All wall samples lasted more than a 180 minutes before collapsing, which is significantly longer than the required time of ninety minutes set for Type IV (heavy timber) construction in the International Building Code (ICC, 2012). Further research conducted by Frangi, Hugi and Jobstl (2009) on a full-scale 3-story

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<sup>2</sup> The test evaluates the duration for which wood structures contain fire without diminishing their structural integrity.

building showed that providing tighter connections between panels could limit the spreading of smoke and fire, limiting the damage to a room.

Full-scale fire test to evaluate the performance of a CLT wall assembly with fire-retardant-treated plywood sheathing was conducted by Gibbs, Taber, Lougheed, Su and Bénichou (2014). Results from the test showed that even though the sheathing protected the CLT panels during the fire exposure, flames from the fire rose 5.5 m above the wall, which is more than the 0.5m limit established in the 2010 National Building Code of Canada (NRC, 2010). Moreover, from the test it was concluded that panels would not conform to the heat flux (i.e. heat transferred per unit area and time) (Venkatesan, 2014) requirements established by the above mentioned Canadian Code.

When it comes to fire performance and safety, it is also important to evaluate the self-extinguishing properties of wooden elements, which has direct implications in the structural design requirements (Crielaard, 2015). To evaluate these properties, Crielaard (2015) modelled the behavior of exposed CLT members under different burning conditions. It was established that elements go through several stages: flaming combustion, caused flames from the burning of the room contents; smoldering combustion, when contents has been consumed and burning occurs slowly and flameless; and finally, self-extinguishment. Results also showed that delamination greatly affects the fire behavior of CLT elements. When delamination occurs, uncharred wood is exposed and flame combustion is sustained and self-extinguishment cannot be reached, subsequently affecting the overall fire performance of the structure (Crielaard, 2015). In order to account and prevent delamination, authors indicate that the use of a thicker outer lamella could be beneficial.

A recent test conducted by the U.S. Forest Service's Forest Products Laboratory and the American Wood Council evaluated the fire performance of different arrangements of exposed and unexposed CLT on two full scale furnished rooms (Gibson, 2017; Kipfer, 2017). Results proved the self-extinguishing properties of CLT element and showed that these panels could resist the spread of fire to other areas of the building (Kipfer, 2017).

### *Seismic performance*

It has been proposed by several authors that CLT-based constructions perform well under lateral forces and also possess ductility due to its multiple, small connections (Winter, Tavoussi Tafreshi, Fadai, & Pixner, 2010). In one remarkable experiment, the Trees and Timber Research Institute of Italy tested a full-scale seven story CLT building on the world's largest shake table in Japan (Quenneville & Morris, 2007). Even when subjected to a severe earthquake simulation (magnitude of 7.2 in the Richter scale), the structure showed no permanent deformation, with maximum inter-story drifts of 1.5 inches and maximum lateral deformation of 12 inches after the test (measured laterally at the highest point of the 82-foot building). The researchers concluded that the damage to the structure was “negligible” (Quenneville & Morris, 2007). In a similar experiment, Hristovski, Dujic, Stojmanovska and Mircevska (2013) conducted a full-scale shake table test for a CLT building prototype, to verify the computational model they developed to predict the behavior of CLT joints under seismic forces. The results showed that fastening systems help dissipate the seismic energy, which is favorable under seismic conditions. Further research has been conducted by Latour and Rizzano (2014) to develop new innovative connector (XL-stub) that could serve as an alternative to the traditional hold-down connector used in CLT structures.

A full-scale model of a two-story CLT house was tested under seismic conditions by Popovski and Gavric (2015), with the objectives to evaluate the global performance of a CLT structure including: lateral strength, deformability and connectors' performance. The results from the 3D evaluation of the structure showed that critical resistance to lateral forces was almost identical in both directions (longitudinal and transversal). Moreover, the structure showed no structural instability post testing (Popovski & Gavric, 2015). According to the authors, further analysis of the results from this study could be used for as a basis for a future seismic design codes.

More recently, the seismic design of tall wood building is currently being evaluated at the Natural Hazards Engineering Research Infrastructure at the University of California San Diego, where a two story structure is being submitted a range of earthquake intensities (NHERI, 2017). Test will include designs for different locations such as San Francisco,

Berkeley and Seattle. It is expected that these series of tests, (from which no results have, to the time of this writing, been published), will help understand how CLT panels, in particular “rocking walls” behave during seismic events (Diego, 2017).

### *Thermal performance*

One of the measurements used to describe the thermal performance of a material is thermal conductivity, defined as “the rate of heat that flows through one unit of thickness of the material subject to a temperature gradient” (Staube & Burnett, 2005). Thermal conductivity is typically measured in  $\text{Btu}\times\text{in}/(\text{h}\times\text{ft}^2\times^\circ\text{F})$ . The lower the thermal conductivity the less heat the material is able to transfer, which in turn means that the material has better insulating properties. The thermal conductivity of wood is much lower than that of metals and it is about two to four times the thermal conductivity of mineral wool, a material commonly used for thermal insulation (Staube & Burnett, 2005). For example, the conductivity of softwood lumber is about 0.7 to 1.0  $\text{Btu}\times\text{in}/(\text{h}\times\text{ft}^2\times^\circ\text{F})$ , compared with 310 for steel, 6 for concrete, and 0.25 for mineral wool.

Another factor for the thermal performance of a building envelope<sup>3</sup> is thermal mass of the materials used. Since CLT is a solid wood panel, it also provides thermal mass (Cambiaso & Pietrasanta, 2014), thus CLT panels both in the building enclosure and in interior floors and walls act as a thermal mass that stores heat during the day and releases it at night. This property can reduce heating and cooling loads, shifting the time of peak loads, and lowering overall building energy use (Jowett, 2011). The R-value is another measure used to describe a construction material’s thermal performance (Staube & Burnett, 2005). It is a measure of thermal resistance or insulating capacity. This means that materials with higher R-values are preferable since they have higher insulating ability. For wood, the R-value is approximately  $1.25 \text{ ft}^2\times^\circ\text{F}\times\text{hr}/\text{Btu}$  per inch of thickness (Staube & Burnett, 2005). A study conducted by Jowett (2011) determined that a 7 inch-thick CLT panel has an R-value of approximately  $8 \text{ ft}^2\times^\circ\text{F}\times\text{hr}/\text{Btu}$ . For comparison, a concrete wall of similar thickness has,

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<sup>3</sup> Building envelope is the physical separation between the interior (conditioned) and exterior (unconditioned) building space. Exterior walls and the roof are usually part of the building envelope.

according to the American Society of Heating, Refrigeration, and Air-Conditioning Engineers' Handbook (ASHRAE, 2009), an R-value of  $1.35 \text{ ft}^2 \text{ }^\circ\text{F}\times\text{hr}/\text{Btu}$ .

In a similar way to conductivity, “air tightness” of a building is an important characteristic for the building’s thermal performance, because air infiltration can have a significant effect in the indoor climate. According to Staube and Burnett (2005), making a building envelope air-tight can help prevent some problems caused by condensation of humid air from the outside or cold and warm air penetrating or leaking (depending on the season) from the construction. In the International Energy Conservation Code (Internal Code Council, 2009) rigorous requirements are included for air leakage through the building envelope to reduce energy consumption during winter (heating loads) and summer (cooling loads). Regarding this topic, in their study on thermal performance of CLT structures, Skogstad, Gullbrekken and Nore (2011) concluded the main advantage of CLT is that it offers the possibility of creating an airtight construction, due to the large panels, which also make possible using a reduced number of elements and joints through which air could infiltrate or leak.

#### *Design possibilities of CLT*

Construction with CLT panels has resulted in innovative projects. One of the most prominent European examples is the Stadthaus in London. Designed in 2008 by Waugh and Thistleton Architects, the nine-story apartment building includes 19 apartments, ten social housing units and a residential housing office. Foundations and ground floors were built using concrete, while the remaining floors were built in CLT (KLH Massivholz GmbH, 2015; Wells, 2011). Each floor of the building was assembled in 3 days using 4 workers, a task that would have taken more than 45 weeks to be erected in concrete (KLH Massivholz GmbH, 2015).

Over the past few years, many other buildings have demonstrated the structural and aesthetic capabilities of CLT as a building material. The Open Academy, a 3 story educational building in Norwich, England, is a clear example of this. The use of CLT helped achieve long spans, cantilever floors, and a curved roof, which characterize the central space of the building (KLH Massivholz GmbH, 2015). CLT demonstration buildings can be found all over Europe. In Norway, for example, Egenes Park, a mixed-

use building (combines, residential units, public space and a kindergarten annexed to the main building) and the Pulpit Rock Mountain lodge show that complex angular roof designs do not hinder the use of CLT. Both buildings remain as the largest, most impressive CLT buildings in Norway (Mayo, 2015).

Another well-known example of CLT's capabilities is the 10-story Forte building in Melbourne, Australia. The Forte building is the country's first high-rise CLT building and so far, the tallest wooden building in the world. The intrinsic characteristics of CLT were particularly relevant to the Docklands location, since the reduced weight of the structure enabled substantial savings on the foundation construction. It took only twenty-eight days to assemble seven hundred and sixty panels (around twenty five panels per day) of CLT, which were shipped from Austria (Mayo, 2015).

In Canada, CLT has been successfully used in hybrid structures (together with concrete slabs) such as the Earth Sciences Building at the University of British Columbia, the Wayne Gretzky Centre in Ontario (Gauer, 2013) and, more recently, the Wood Innovation Design Center (WIDC) in Prince George by Michael Green Architecture (University of Northern British Columbia, 2015). As of October 2017, only a few projects have been built in the United States: a 78-foot tall church tower in Gastonia, North Carolina, the first non-residential CLT structure in the U.S. (Woodworks, 2016); a 2 story mixed-use facility in Whitefish, Montana, the first commercial building built with locally manufactured CLT (WoodWorks, 2012); the Crossroads building in Madison, Wisconsin, which combines the use of CLT with glulam beams to achieve larger spans while supporting heavily loaded areas (WoodWorks, 2013); the Albina Yard in Portland, Oregon by LEVER Architecture, the first building in the U.S. to use domestically fabricated CLT panels as structural elements (LEVER Architecture, 2017); the Carbon 12 building by PATH Architecture, a 7 story residential building (PATH Architecture, 2017); and the Design Building at the University of Massachusetts, the first CLT higher educational building in the U.S., completed in January 2017 (UMass, 2017).

### *Market opportunity for CLT*

Since its introduction to the European market, the use of CLT has been growing at a fast pace. More recently, sales in Europe have grown more than 20% between 2013 and 2014 (Plackner, 2015a). This recent growth in sales has been influenced by the increased in construction spending in Europe from 2010 to 2012 (Plackner, 2015a). Demand for the system is expected to grow in Europe by 10% annually over the next two years (Plackner, 2015b).

The use of CLT has been growing in popularity in Australia and New Zealand (Rapley, 2013). In North America, the use of CLT has been gaining interest among members of the wood industry and contractor segments because of CLT's structural and environmental performance (FPInnovations, 2015; Karacabeyli & Douglas, 2013). As of 2015, there are two Canadian CLT manufacturing companies. According to personal communications with company representatives (Spickler, 2015; Winkel, 2015), the total production capacity of both plants is around 100,000 m<sup>3</sup>. For comparison, the largest CLT manufacturer in the world, Stora Enso, can produce 120,000 m<sup>3</sup> annually, and is located in Austria (Manninen, 2014).

The success after the recent introduction of CLT in the Canadian market indicates that there is potential for further market penetration in North America (Naturally Wood, 2015). As of October of 2017, there were only two commercial CLT manufacturers in the country certified to produce panels for structural applications. The introduction of CLT in the U.S. market is being supported by many governmental, and by non-profit organizations, such as the American Wood Council's WoodWorks program and The Engineered Wood Association (APA), which led the development of ANSI (American National Standards Institute) product standards for national production of CLT, the ANSI/APA PRG 320-2011 Standard for Performance-Rated Cross-Laminated Timber (ANSI, 2012).

CLT in North America has been presented as an environmentally superior and cost-competitive alternative to concrete (FPInnovations, 2013), the price of which continues to rise at higher rates than the price for softwood lumber. The Producer Price Index (PPI) for precast concrete has increased by 44.8% between December 2003 and December 2013, while the same index for lumber and plywood has only increased 7.2%, in the same period

(Bureau of Labor Statistics, 2015). FPIInnovations (2011) calculated that the cost of production and construction for CLT is, in average, \$17 per cubic foot (assuming a lumber price of \$300 per thousand board feet or MBF) compared to \$22 per cubic foot for a 7-inch post-tensioned concrete slab and frame (McGraw Hill Construction, 2012a, 2012b). These estimates account only for the cost of the panels, connections, insulation, and labor, and do not include the cost of the foundation or the benefits from the time savings when using CLT.

According to FPIInnovations (2011), the potential demand for CT in the U.S. is around \$2 and \$6 billion, assuming a market penetration of 5 and 15% respectively. Their estimation assumed a market in the low-rise (1 to 4 stories) commercial and institutional sector and in the mid-rise (5 to 10 stories) residential multifamily sector.

### ***The process of new product adoption***

Prior to presenting the theoretical framework, objectives and hypotheses of this study, it is important to clarify some basic concepts that will be addressed in this document.

#### ***Innovation***

Many definitions have been used to describe innovation in the literature (Arts, 2008; Baregheh, Rowley & Sambrook, 2009; Cooper & Kleinschmidt, 1987). One common notion behind all definitions is that of “newness” that characterize all innovations (Rogers, 2003). In the marketing sphere, this “newness” is usually defined through the eyes of the consumer; being the consumer, and not the producer, the one that determines if something (product or service) is new or not (Arts, 2008). In this sense, Rogers (2003) defined innovation as “*an idea, practice, or an object that is perceived as new by an individual or other unit of adoption.*”

#### ***Product adoption***

Rogers (2003) defined adoption as “*a decision to make full use of an innovation as the best course of action available.*” Therefore, innovation adoption relates to consumers’

individual decision-making process with regard to the use of new products. This process involves multiple stages, which will be described in the following section.

### *New product adoption process*

The successful introduction of a new product in a market carries significant economic risk for a consumer (or a company if it is an intermediate or industrial product) (Armstrong, Kotler, & He, 2013). A number of authors have addressed the process of product adoption (Harvey, 1979; Urban & Gilbert, 1971); and several models have been proposed (Beal, Rogers, & Bohlen, 1957; King, 1966; Rogers, 2003). Beal et al. (1957) for example, proposed the following five-stage product adoption process:



**Figure 2. Stages of the adoption process, according to Beal et al. (1957).**

*Awareness* occurs when the consumer first becomes aware of the new product's existence and develops preliminary perceptions about the product attributes. This step greatly depends on communication and education (Beal, et al., 1957; King, 1966; Rogers, 2003). Once the potential consumer is aware of the new product, the second step is the development of an interest in the product, during which the consumer seeks *information* and details about the new product (Armstrong, et al., 2013). In the next step, *application*, the consumer evaluates the product's perceived benefits and drawbacks, and assesses if it fits their wants and needs. A positive evaluation potentially leads to the next step, the product *trial*. During the trial period, the product is tested on a limited basis and is further evaluated. Finally, the *adoption* of the product, the final step, is likely to occur if the trial confirms the positive perceptions that the consumer held about the product (King, 1966). According to Gayle (2008), during or after this final stage, the consumer often becomes a strong promoter for the innovation in the community, which is essential to further transmit the knowledge about the product to potential new adopters.

Typically, the adoption of a new product occurs in phases, and a different type of consumer is prevalent in each phase (Robertson, 1967). According to Lindquist and Sirgy (2009) adopters can be categorized into five groups on the basis of the stage of the lifecycle in which they adopt the new product. *Innovators* are usually the first individuals to try new products. The next type of consumer are the *early adopters*, who are the most influential group, because they tend to have more favorable attitudes towards new ideas and are seen as the market leaders and trend-setters. According to Rogers (1976), among early adopters are opinion leaders, who have an important role in transmitting information about the new product to other potential users. Their influence can significantly determine the success or failure of a new product in the market (King, 1966). Therefore, effectively directing the efforts towards the early adopters is perceived as a critical step in launching a successful new product. After the early adopters come the *early majority*, who tend to be more risk-averse in their decisions than innovators and early adopters. The *late majority* group is typically composed of those mainstream consumers that adopt a new product only when it has been firmly established in the market. Finally, *laggards* are those consumers that resist new product adoption until it is soon to be replaced by a new product (Armstrong, et al., 2013).

#### *Innovation adoption in the forest products industry*

The forest products sector is typically seen as conservative towards change and the adoption of innovations, such as new materials and processes (Singh, 2001). However, over the past decades the wood products industry has been facing increasing pressure to innovate due to competition from imports and non-wood product substitutes, a changing raw material, and from a challenging economic environment (Crespell, Knowles, & Hansen, 2006; Hansen, Juslin, & Knowles, 2007).

It is in this environment that engineered wood products have developed a strong presence in the U.S., with the adoption of laminated veneer lumber (LVL), laminated strand lumber (LSL), oriented strand board (OSB), I-beams, among other products (Shrapnel, 2014). The increasing acceptance of structural engineered wood products, and the rapid growth in consumption are two of the factors that are driving new product development in the forest

industry. Also, an increasing realization of the environmental attributes of wood is prompting governments and private companies to invest in research and development of innovative products and technologies derived from this material; resulting in new applications (USDA, 2011). In this context, CLT has potential as an innovative product in the U.S. market to contribute to the competitiveness of the wood products industry, and compete with concrete, steel or brick, as an environmentally friendly building alternative for mid and high-rise commercial buildings (Mikkola, 2014; Karacabeyli, 2013).

#### *Innovation adoption in the construction industry*

Similarly to the forest products industry, the construction industry has often been described as laggard in the adoption of new technologies (Ganguly, Koebel, & Cantrell, 2010; Tangkar & Arditi, 2004; Tatum, 1987). Innovation is seen by Wagner and Hansen (2005) as a source of competitive advantage that can benefit the construction industry, providing a critical component for a company's long-term competitive strategy (Slaughter, 2000). However, the adoption of innovations in the construction industry is a highly complex process, where scarce research has been conducted.

As stated in a report by the U.S. Department of Housing and Urban Development (U.S. Department of Housing and Urban Development (HUD), 2005), the analysis of material or technology adoption in the construction industry started around the 1980s, when researchers realized that the construction industry was fundamentally different to other sectors, and adoption models that apply to other industries did not apply to this sector. Construction materials have to meet certain expectations, such as durability of the materials, their cost, and the potential for economic and human loss associated with their failure, all of which are particular to the construction industry (U.S. Department of Housing and Urban Development (HUD), 2005).

The risk associated with the adoption of an innovative material or process has been stated by Slaughter (2000) as one of the most significant factors that can affect the rate of adoption of a new product. Specifically in the construction industry, liability risk is seen as one of the largest barriers to the adoption of new materials and technologies in this sector (U.S. Department of Housing and Urban Development (HUD), 2005). Design professionals,

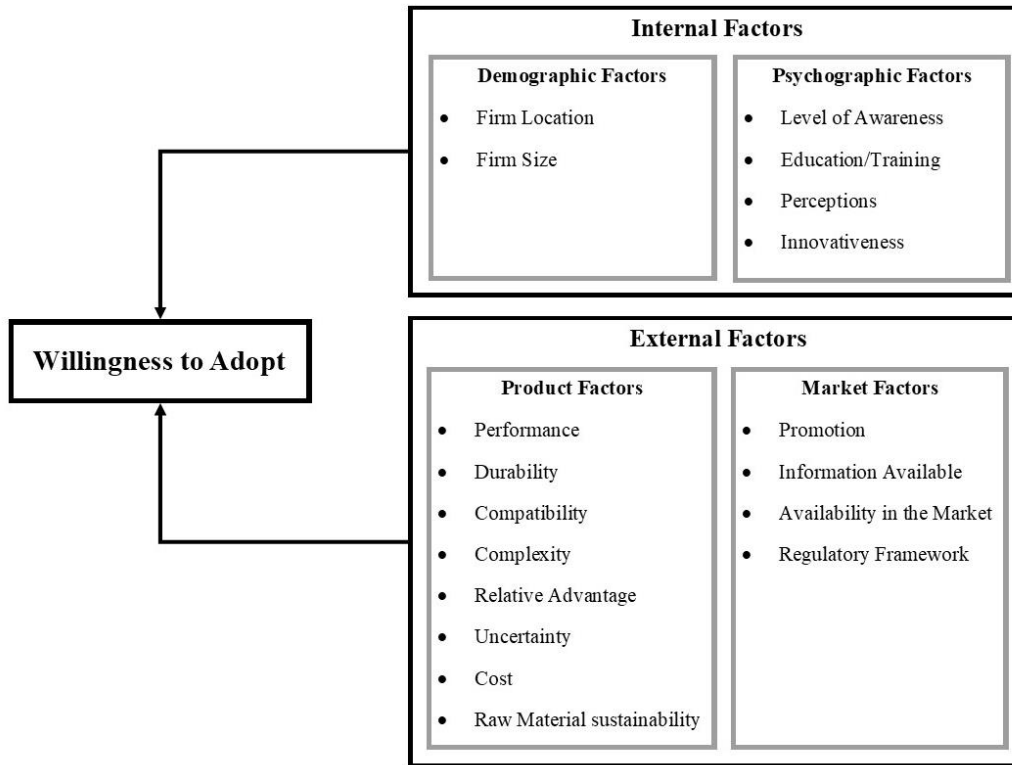
namely architects, engineers and contractors are in the majority of cases responsible for the performance and durability of the buildings and consequently for the specification of the materials to be used, and can face severe penalties when building components fail to perform as expected (Sido, 2006). This liability is frequently shared with product manufacturers (U.S. Department of Housing and Urban Development (HUD), 2005).

According to McCoy, Thabet and Badinelli (2009), the complexity of the adoption process in the construction industry is caused in part by the number of actors (suppliers, manufacturers, design professionals, final users) involved in the decision of adopting an innovation. Although design professionals (architects, engineers, and contractors) are only one group of actors involved in the process, their key role in the supply chain, as specifiers of building requirements and materials, makes them the most influential in the success or failure in the adoption of an innovative material or technology (McCoy, et al., 2009).

The emphasis of this research is on investigating the critical factors in the adoption of new wood based construction materials by engineers and contractors. For this study, CLT was used as a case study. Since the development of CLT in the U.S. is in the embryonic stage (Evans, 2013), it is imperative to focus research efforts in the first stages of new product adoption, namely awareness and interest. As previously discussed, understanding potential adopter's knowledge, perceptions and attributes influencing the decision to adopt an innovative material or technology is vital to enhance the chances of success of a new product in the market.

### ***Theoretical framework***

From the information obtained during the literature review and a previous study conducted by the author (Appendix 1), a conceptual model of the factors influencing the willingness to adopt innovative wood-based construction materials is suggested in Figure 3. An explanation follows.



**Figure 3. Conceptual model for the willingness to adopt innovative wood-based building materials.**

As seen on the previous section of this manuscript, adoption is not just an action, but a very complex process, which depends on many factors. Understanding the consumer’s motivations in adopting a new product or service is of critical importance for market researchers (Hussain, Zaki, & Bukhari, 2014), to provide customer input into the design process and the formulation of marketing strategies.

Over the past three decades, many studies have been conducted to evaluate the factors that influence adoption of new materials by consumers (Gatignon, 2002; Gronross, 1997; Rogers, 2003). A wide range of factors has been addressed, from which “innovation characteristics” and “adopter’s characteristics” stand out (Arts, Frambach, & Bijmolt, 2011; Hussain, et al., 2014). “Innovation characteristics” refers to those products dimensions that potential adopters perceive and are used to evaluate a new product (Hussain, et al., 2014). According to Rogers (2003), relative advantage, compatibility, complexity, “trialability,” observability are among the “innovation characteristics”

perceived by potential adopters. In regards to the “adopter’s characteristics,” or personal traits that can be used to describe a potential adopter of a new product, the most cited dimensions are age, education, and income (Arts, 2008; Gronross, 1997). Hirschman (1980) also stated that within the “adopter’s characteristics” are also “psychographic characteristics” including: awareness, innovativeness, product involvement, opinion leadership, info seeking, and media influence. These psychographic factors were also mentioned by Arts, Frambach and Bijmolt (2011) as vital in predicting the successful adoption of any given innovative product.

From these psychographic factors, innovativeness has been the most studied over the years. Innovativeness is a consumer’s inherent personality trait that depends on many factors (Kim, 2008; Tidd, Bessant, & Pavitt, 1997). It is also defined as a hidden desire for new different and innovative experiences (Roehrich, 2004). Innovativeness is further defined by Strutton, Lumpkin, and Vitell (2011) as the extent to which an individual is an early adopter of a new product. Innovativeness, as a consumer trait is given much significance due to its importance in various researches about consumer behavior and innovation adoption (Arts, et al., 2011). In particular, Cotte and Wood (2004) evaluated consumer’s innovativeness attributes and concluded that it has a strong effect on innovation acceptance. According to Kim (2008), innovativeness is a personality trait that depends on several factors that had also been studied by other authors in the past (Childers, Houston, & Heckler, 1985; Goldsmith & Hofacker, 1991; Kim, 2008; King & Summers, 1970; Leavitt & Walton, 1975; Leavitt & Walton, 1988; Raju, 1980), such as (a) openness of information; and (b) exploratory tendencies. To this factors, Gore (2010) also added that (a) transfer processes, (b) stakeholder relationships, (c) corporate culture, and (d) financial resources available, are also factors used to measure innovativeness.

Based on the above discussion, it is hypothesized that the critical factors that influence willingness to adopt innovative wood-based construction materials by construction firms can be grouped into two categories: internal and external factors. Internal factors are those over which the firm has control and influence, while external factors are the ones that are beyond the company’s control.

The Internal Factor's category include: (a) demographic factors, including location and size of the firm, and types of buildings the firm specializes on; and (b) psychographic factors, namely, the firms' level of awareness and perceptions about innovative materials, and the company's innovativeness, defined by Hirschman (1980) as "*a driver of adoption intention and adoption behavior as it captures the propensity of consumers to adopt new products.*" To measure the firm's perceived innovativeness, the author took innovativeness dimensions cited in the literature and adapted them to the construction industry, such as (a) employee encouragement to research new materials; (b) collaboration within the firm, with other firms, with universities, research centers, or suppliers; (c) employee training; (c) reflection on past projects; (d) innovation as part of the corporate strategy.

A previous study conducted by the author (Appendix 1) has shown that demographic characteristics of U.S. architecture firms (location and size of the firm) can influence the perceptions and therefore the willingness to adopt innovative wood-based construction materials such as CLT. The study also concluded that there is a statistically significant relationship between psychographic factors, such as level of awareness and perceptions about CLT, and the willingness to adopt the system in the future. A summary of the results obtained from the above mentioned study can be found in Appendix 1.

The External Factor category includes two subcategories: (a) product factors, related to the intrinsic characteristics of the material, such as: performance, cost, compatibility, complexity (ease of use), relative advantage in comparison to other materials, cost and uncertainty; and (b) market factors, which are those related to the market environment of the firm, including promotion, availability of information, availability of the product in the market and regulatory framework in place (e.g. building codes).

A previous study (Appendix 1) showed that product factors, such as performance, greatly influences the likelihood of adoption. Other product factors such as compatibility, and complexity were also evaluated by other authors (Ostlund, 1974; Rogers, 2003). Several studies have also investigated the effect that price and promotion of a new product have on new product adoption. For example, Kalish (1985) stated that pricing and advertising over time can greatly influence potential adopters' willingness to adopt a product. Therefore, these factors were also added to the hypothesized conceptual model used in this study.

## ***Hypotheses***

To increase the understanding about the factors that influence the willingness to adopt innovative wood-based materials, the following hypotheses are proposed:

*Hypothesis 1:* Firms' demographic characteristics are associated with the willingness to adopt innovative wood-based materials used in construction.

*Hypothesis 2:* Firms' psychographic characteristics are associated with the willingness to adopt innovative wood-based materials used in construction.

*Hypothesis 3:* External factors to the firm are associated with the willingness to adopt innovative wood-based materials used in construction.

*Hypothesis 4:* Distinct market segments exist in the construction industry based on the awareness, perception and willingness to adopt innovative wood-based building materials.

## ***Problem Statement***

The adoption of innovative wood-based construction materials is a complex process, which involves many decision makers and is influenced by a number of factors. There is much debate about the factors that influence the successful adoption of new products. Studies have focused on different stages of the adoption decision process and on a variety of independent factors that influence these decisions. The literature review on this subject has shown that, as of now, no adoption model for this has been developed that can accurately explain the factors that influence the willingness to adopt wood based materials in commercial buildings by the construction industry.

There is an abundance of information on the technology of building with Cross-Laminated Timber (CLT). Research is being carried out at several research institutions on various technical aspects of this relatively new construction system. However, one area that has received limited attention has been the potential adopters' perceptions and willingness to adopt CLT, which will ultimately lead to trial and adoption of this new construction system. This study addresses the lack of information in this area and provides important

information for entrepreneurs interested in entering the CLT market, and other stakeholders with interests on CLT's success. No previous research has been reported or is underway analyzing the adoption of CLT by major decision makers in the construction industry. This research contributes to a better understanding of the adoption process and market potential for CLT and other innovative wood-based construction materials in the U.S. Information obtained from this research is important to evaluate the possibilities of successful and sustainable implementation of CLT in the U.S.

### ***Research Objectives***

This dissertation builds on previous research by the author (Appendix 1) by analyzing critical actors in the material selection process in the construction industry. The population of interest for this study was comprised of structural engineering and construction firms, who are major decision-makers in the material selection process of commercial and multi-family building construction in the U.S.

*The main objective of this research is to investigate the critical factors that affect the willingness to adopt innovative wood-based building materials in the U.S.* Cross Laminated Timber was used as the material for this case study. To accomplish this goal, the following specific objectives were proposed:

1. Investigate the level of awareness, perceptions, and willingness to adopt CLT among structural engineers and construction firms.
2. Develop a conceptual model including the most critical factors that influence the adoption of innovative wood-based construction materials among structural engineers and construction firms.
3. Identify the barriers to the adoption of CLT in the U.S.
4. Identify distinct market segments for CLT adoption in the U.S.

## ***Research Contributions***

Results from this dissertation contribute to the body of knowledge in the fields of wood science and technology and sustainable building practices. The author also believes that this research will have direct business implications. An explanation of the expected scientific and practical contributions follows.

### *Contributions to the field of wood science and technology*

This study enhances the knowledge in the field of wood science and technology by investigating major issues in the adoption process for innovative wood-based building materials by the construction industry. Findings also help to understand how the perceptions of potential adopters of these products affect the adoption process. Results from this study lead to a better understanding of critical factors that affect the adoption of wood-based building materials. As of today, little research effort exists in the U.S. that addresses the adoption of new wood-based materials used in commercial buildings by the U.S. construction industry. Learning about the major issues in the adoption of innovations by the construction industry is of critical importance to ensure market success and will help to accelerate technology adoption through well-designed education programs, demonstration projects, marketing strategies, and policy incentives.

### *Contributions to the field of sustainable building*

The growing concern for environment degradation, climate change, and energy independence, has led to a renewed considerations of wood as construction material (Omer, 2013). Numerous programs to promote wood-based construction have been implemented in parts of the world to promote this shift towards more environmentally conscious and sustainable building construction (Espinoza, 2013; Fund, 2002; Karjalainen, 2005). Governmental initiatives have also been implemented in the U.S. Specifically, the Department of Agriculture's Forest Service is exploring new ways to increase research on areas related to the development of sustainable building materials, while establishing its preference to select wood-based materials in new building construction (especially federal

government facilities and buildings) and maintaining its commitment to sustainable building standards (USDA, 2011). In this context, results obtained from this research help government officials and organizations to promote the use of wood in construction, could also find the results from this study helpful to develop new and improve existing educational programs.

### *Practical contributions and business implications*

This dissertation addresses some key questions that must be answered to understand the viability of CLT in the U.S. This study provides important information regarding the most attractive market segments for CLT, which can be used by entrepreneurs interested in entering the CLT industry. By understanding the major factors and actors in the construction material selection process, entrepreneurs and industry suppliers will be able to develop better marketing strategies to target potential adopters of their products and better serve their customers.

Results from this research are directed to industry suppliers, participants, and government officials in the construction and wood products industries. The adoption of new wood-based construction materials, such as CLT, helps the U.S. wood industry by increasing the demand of wood-based construction materials and supports the creation of employment in a sector of critical importance to the U.S. economy.

## ***Outcomes***

The outcomes of this study are:

1. Identification of the key attributes that influence the adoption of wood-based building materials, such as CLT, in commercial and multifamily building construction.
2. Estimation of the level of awareness, perceptions and willingness to adopt CLT among U.S. engineering and construction firms.
3. Identification of the barriers to the adoption of CLT.

4. Identification of the market segments that offer the most attractive opportunities for CLT.

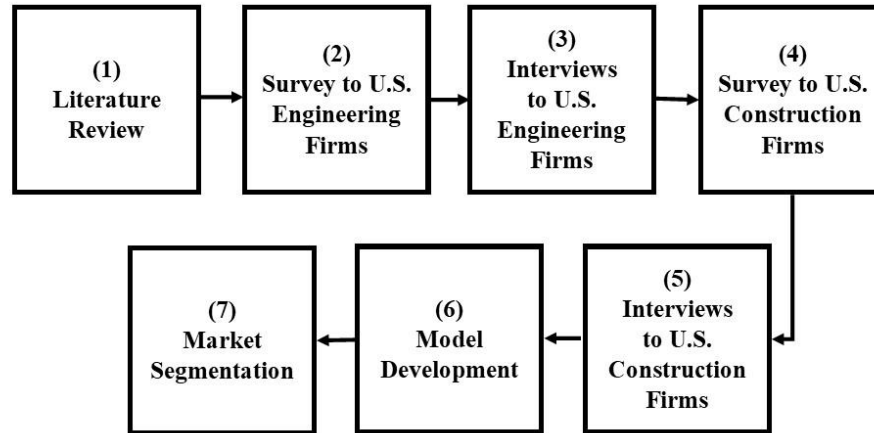
## ***Deliverables***

Results from this research were used to generate the following outputs:

1. A doctoral dissertation in fulfillment of the requirement for the Degree of Doctor of Philosophy in Bioproducts and Biosystems Engineering, Marketing and Management.
2. Two peer-reviewed articles.
3. An industry-oriented summary of results, will be posted on the Forest Products Management Development Institute's webpage (examples at <http://fpmdi.bbe.umn.edu>).
4. Poster and oral presentations at international conferences, such as the Mass Timber Conference (March 2017 in Portland, Oregon) and the IUFRO Division 5 Conference (June 2017 in Vancouver, British Columbia, Canada).

## ***Research Methods***

To achieve the objectives of this research, the project was carried out in seven stages (Figure 4) A more exhaustive methodology section is available in each Chapter of this dissertation.



**Figure 4. Dissertation methodology.**

*(1) Literature review*

The first part of this study consisted of an in-depth literature review. The review was concentrated on topics such as: technical attributes of CLT, adoption of CLT, adoption of new materials by the construction industry, market assessment of building materials, among others. To gather this information, several sources were consulted, such as governmental reports published by the USDA Forest Service, peer-reviewed articles published in the journals such as Wood Fiber Science, Forest Products Journal, Journal of Product Innovation Management, Journal of Market Research, among others. Over 730 sources of information (managed using EndNote software (EndNote, 2017)) were consulted and used for this study.

*(2) Survey of U.S. engineering firms*

The second part of the study consisted of a nation-wide survey of engineering firms. The objective of this quantitative study was to learn the level of awareness, perceptions and willingness to adopt CLT by U.S. engineering firms, and to find the factors that influence the adoption of innovative wood-based construction materials.

According to preliminary interviews conducted by the author and available in Appendix 1, engineers often work with architects in the determination of a building's structural system, and therefore they are considered a critical group for the adoption of CLT. Furthermore,

based on the information obtained from these interviews and preliminary market and economic analysis conducted by Karacabeyli and Douglas (2013), it was concluded that multi-family and commercial buildings are the most likely applications for CLT, accounting for most of the potential demand in the U.S. Therefore, a decision was made to focus on U.S. civil engineering firms that work with multi-family and commercial buildings. The population of interest was a subset of the category Engineering Services, listed under the NAICS code 541330.

A list of potential respondents was compiled from the database managed by the American Council of Engineering Companies (ACEC, 2014) one of the largest associations of engineering firms in the U.S. The mailing list of names and contact information was compiled randomly. Assuming that 384 respondents corresponds to an expected response rate of 25%, an initial sample of 1,536 firms was calculated and rounded up to 1,540 firms. A questionnaire were drafted taking into consideration the set of questions used for the study conducted by the author of this dissertation (Laguarda-Mallo, 2014) to CLT experts and U.S. architecture firms. Once a first version of the questionnaire was created, a draft was sent to five experts (including engineers and researchers) to obtain their feedback regarding clarity and consistency of the questions, potential errors, and suggestions for improvement. A copy of the questionnaire can be found in Appendix 2.

The survey was delivered through the Internet using Qualtrics software (Qualtrics, 2016). The first reminder was sent a week after the first email was sent to request a response from those who did not replied. Three weeks after the first questionnaire went out, a second reminder was sent. Since a low response rate was obtained from the online survey, the author decided to call engineers to ask them to participate in the survey personally, and therefore improve the response rate.

### *Data analysis*

After closing the survey, data obtained was analyzed using standard statistical techniques, such as descriptive statistics, inferential statistics and charts. Categorical data was evaluated using Chi-square test. All statistical tests are going to be evaluated at a 0.05 alpha level. Excel (Microsoft, 2017) and SPSS (IBM, 2017) were used for the analysis. In order

to evaluate the existence of non-response bias, Chi-square tests were run for three of the survey questions. This test compared responses obtained online with those obtained via phone. A more complete description of the methods used in this section can be found in Chapter 2.

### *(3) Interviews of U.S. engineering firms*

A set of 30 semi-structured phone interviews was conducted with U.S. engineering firms that specialize in multi-family residential and commercial building construction and that are familiar, but not necessarily have worked, with CLT. Interviews were conducted after concluding the survey, to expand and gather more in-depth information about the perception of U.S. engineering firms to verify and clarify some topics that may have come up from the survey. A questionnaire with 11 open-ended questions was developed. A copy of the questionnaire can be found in Appendix 3.

A list of participants was compiled using the same database and procedure as the one used to compile the list used to conduct the survey to U.S. engineering firms.

Participants were contacted via email and phone to arrange a convenient date and time for the interview. Interviews were conducted via phone during the fall of 2015.

The interviews were audio-recorded with the consent of the participants and notes were taken as a backup. Each interview recording was fully transcribed. Transcriptions of the interviews were coded by topics, mentioned by participants.

### *Data analysis*

Established qualitative research methods for thematic content analysis using the constant comparative method (Bruce, 200; Burnard, 1991) were used to analyze and to identify major themes from the transcripts. Organization of the responses and analysis was carried out using Excel spreadsheet software (Microsoft, 2017). Although specific information expected from the interviews depended on the topics that arise from the survey, much of these interviews served as means to expand on the information regarding: firm innovativeness, and critical factors that influence the willingness to adopt innovative wood-

based building materials. A more complete description of the methods used in this section can be found in Chapter 3.

#### *(4) Survey of U.S. construction firms*

The role of the contractors is essential during the construction of any type of building. Personal communications with an architecture firm in the Minneapolis area (Hargens, 2013), showed that for some architecture firms, the contractor's knowledge about certain materials can greatly influence their material selection for their buildings.

The fourth part of the study consisted of a nation-wide phone survey of construction companies, specifically firms specializing in multi-family residential and commercial building construction. The population of interest was a subset of the category Commercial and Institutional Construction, listed under the NAICS code 236220. The objective of this part of the study was to gain insight of the level of awareness, perceptions and willingness to adopt CLT by U.S. construction firms.

In this case, the list of U.S. construction firms was compiled randomly, using the online database managed by the Associated General Contractors of America (AGC of America, 2014).

For this part of the study, the same sample size calculated for the survey to U.S. engineering firms, was used. A list of 1,540 U.S. construction firms was compiled. Likewise, Institutional Review Board (IRB) at the University of Minnesota approval was requested (Appendix 4). Once the approval was granted, the survey was delivered through the internet, following the procedure and the questionnaire covered the same topics as the previous part of the study. However, some questions targeted specifically to construction firms were added. For the survey to construction firms, questions regarding the perceptions about CLT's attributes emphasized the economic performance of CLT in comparison to alternative materials. A copy of the questionnaire can be found in Appendix 2.

#### *Data analysis*

Data obtained from the survey was analyzed using the same statistical techniques used for the survey to engineering firms. Results from the survey to construction firms was also

compared with those from the study to engineering and architecture firms (Appendix 1). A more complete description of the methods used in this section can be found in Chapter 4.

#### *(5) Interviews of U.S. construction firms*

Similarly to stage (3) of this study, a set of 30 semi-structured phone interviews is was conducted with U.S. construction firms that specialize in multi-family residential and commercial building construction and are familiar.

A list of 132 potential interviewees was compiled thanks to the help of Professor Renee Cheng from the School of Architecture at the University of Minnesota and Professor Peter Hilger, Director of the Construction Management Program at the University of Minnesota. Participants were contacted via phone and email to ask them to participate in the study. A total of 30 semi-structured interviews were conducted via phone in the Spring of 2016. Data collection and analysis was carried out in the same way as in stage (2). A copy of the questionnaire can be found in Appendix 3. A more complete description of the methods used in this section can be found in Chapter 5.

#### *(6) Model development*

From the stages (2) and (4) from this study, factors that influence the willingness to adopt innovative wood-based building materials were identified. These factors were compared with those proposed in the hypothesized conceptual model presented in the theoretical framework section of this manuscript. The goal is to construct a final conceptual model including all the critical factors influencing the willingness to adopt innovative wood-based building materials in the U.S.

#### *Data Analysis*

To accomplish this goal, factor analysis was used to ensure that the inclusion of the hypothesized factors can be justified in the final model (Field, 2009). Factor analysis was also used in data reduction, to remove redundant or highly correlated variables. Among the different types of Factor Analysis techniques discussed in the literature, an Exploratory Factor Analysis (EFA) was chosen to evaluate the validity and reduce variables, without

imposing predetermined structure (Child, 2006). Polychoric correlation and ordinal regression, both used when working with ordinal data, were used for the hypothesis testing. A more complete description of the methods used can be found in Chapter 6.

#### *(7) Market segmentation for CLT in the U.S.*

The fourth and last part of this dissertation consisted of a market segmentation analysis for the CLT market. As previously stated in the document, a preliminary study conducted by FPInnovations (2011) evaluated market opportunity for CLT under a limited number of parameters (market penetration, type of construction), without taking into consideration the adopters' level of awareness, perceptions of new product; which are the main drivers of any product acceptance process. This dissertation aimed to incorporate these elements, as well as others such as firm demographic characteristics, to identify the most promising markets segments for this innovative wood-based building system in the country.

The term "market segmentation" was first introduced by Smith (1956), who defined it as "*viewing a heterogeneous market as a number of smaller homogeneous markets, in response to differing preferences, attributable to the desires of consumers for more precise satisfaction of their varying wants*".

Results from the survey of potential adopters was analyzed and used to identify the most promising market segments for CLT. From the surveys, firms' demographic and psychographic information was collected and used as bases for the segmentation.

#### *Data Analysis*

In marketing, cluster analysis is commonly used for market segmentation (Wendel, 2000). The analysis was carried out using SPSS statistical software (IBM, 2017). This method divides a complex and heterogeneous sets of data into smaller homogenous subsets or groups (Wendel, 2000). A more complete description of the methods used in this section can be found in Chapter 7.

## *Structure of the Dissertation*

This dissertation consists of eight chapters and three appendices. Chapter 1 introduces the reader to this dissertation, with a literature review, theoretical background, and a summary of methods. Chapter 2 and 4 include the quantitative studies (surveys) conducted to U.S. engineering and construction firms, respectively. Chapter 3 and 5 include the qualitative studies (interviews) conducted to U.S. engineering and construction firms, respectively. Chapter 6 presents the findings from the model development, to determine the most critical factors that influence the willingness to adopt innovative wood-based construction materials by the U.S. construction industry. Chapter 7 presents the information obtained from the market segmentation from CLT. Chapter 8 summarizes the results and conclusions from all the findings. Chapter 8 also contains strategic recommendations and ideas for future research.

# Chapter 2

## U.S. Engineering Firms Survey

## *Introduction*

This chapter describes the methods, analysis, and conclusions from survey research aimed at assessing the market potential for CLT in the United States by investigating the level of awareness, perceptions and willingness to adopt CLT by U.S. structural engineering firms. Structural engineers are key actors in the structural material decision process. Given the importance of engineers in the material selection process, they were the population of interest for this study. Based on the information from previous research by the author (Appendix 1) and preliminary economic analysis conducted by FPInnovations (2011), it was decided to focus on U.S. structural engineering firms that work primarily with commercial (which includes office buildings, retail, hospitals, restaurants and hotels, and others), industrial, institutional, and educational buildings (NAICS code 541330).

## *Methodology*

A nation-wide survey of U.S. structural engineering firms was carried out, with the purpose of learning about this community's perceptions and awareness about CLT. The survey was conducted through the internet, which is a cost-effective approach that allows reaching large geographic areas at an affordable cost (Dillman, 2011; Sue & Ritter, 2012). There are several tools for the design, implementation, and data analysis of online surveys. For this study, the Qualtrics software was used (Qualtrics, 2016).

### *Sample size determination*

The mailing list of names and contact information was compiled randomly. Choosing the sample size is a critical decision in any survey research. The objective is to select the smallest sample size that allows for an adequate confidence level and margin of error. The correct sample size will help decrease the occurrence of sampling error and sampling bias (Dillman, 2011). According to Dillman (2011), sample size can be estimated as follows:

$$\text{Sample size} = \frac{Z^2 s^2}{H^2}$$

Where Z is the inverse of the normal distribution, which at a desired level of confidence of 95 percent is 1.95. H represents the confidence interval, set at 5% for this research (H=0.05). To obtain the sample size for the worst case scenario, s, which is the expected standard deviation, takes the value of 0.5.

$$\text{Sample size} = \frac{1.95^2 \times 0.5^2}{0.05^2} = 384$$

Assuming that 384 respondents corresponds to an expected response rate of 25%, an initial sample of 1,536 firms was calculated and rounded up to 1,540 firms. The number of firms from each state to be included in the list was calculated as a proportion of the state's population.

### *Sample development*

The target audience for this survey were U.S. structural engineering firms that work primarily with commercial construction. The population of interest was a subset of the

category Engineering Services, listed under the NAICS code 541330. A list of 1600 U.S. structural engineering firms was compiled, using the online database managed by the American Council of Engineering Companies (ACEC, 2016). According to personal communications with the Chair of Membership of the ACEC (2016), this association represents licensed engineers of all fields including civil structural engineering firms. The ACEC's member directory provides search tools to generate lists of firms using criteria such as geographic location, type of engineering firm, and zip code. There are currently over 5,000 firms in the ACEC's database, representing more than 500,000 employees throughout the country (ACEC, 2016), from a total of 94,500 engineering firms in existence, according to the U.S. Census Bureau (2017). To the best knowledge of the author, there is no information available regarding how many of these engineering firms are structural engineering firms.

#### *Questionnaire development*

A first draft of the survey questionnaire was developed, using the questionnaire from a previous study of U.S. architecture firms as starting point, conducted in 2015 (Appendix 1). The first version of the questionnaire contained 15 questions, six of which were of multiple-choice, eight Likert scales, and one open-ended question. The questionnaire covered the following topics:

- Company demographic information: location and size of firm.
- Sources of information used to investigate about new structural materials, firm's perceived innovativeness, type of buildings and structural materials the firm works with.
- Awareness of CLT in the Engineering Community: familiarity with CLT, how participants learned about the system.
- Perceptions about CLT: how participants perceive the environmental, structural and economic benefits of the system.
- Willingness to adopt the CLT building system.

To assess clarity and relevance, the draft questionnaire was sent to four researchers with experience in survey design and implementation. These engineers and experts were asked to evaluate the clarity and consistency of the questions, identify potential errors, and provide suggestions and recommendations. Changes were made to the questionnaire based on the reviewers' feedback.

The survey instrument included an introductory email to inform participants about the study and ask for their participation, including a link to access the web-based survey. The questionnaire started with a welcome page with information about the study as well as a confidentiality statement. Questions were grouped according to the topics mentioned above. A final "Thank you" message was presented to those participants who completed the questionnaire. Participants were also asked whether they were interested in receiving a summary of the survey results, and those who answered positively to this question provided an email address where they wanted the summary to be sent. A copy of the survey questionnaire can be found in Appendix 2.

#### *Survey pretest*

Prior to the survey implementation, forms and questionnaires were submitted to the Institutional Review Board (IRB) at the University of Minnesota for approval (Appendix 4). After IRB approval, a survey pre-test was delivered through the Internet. The pre-test was conducted by sending the survey to seven U.S. structural engineering firms, to identify issues that were overlooked during the questionnaire development and expert evaluation. These companies were asked to provide feedback about the survey's clarity and potential errors. After a week, a reminder was sent to those participants who did not answer. All seven firms' representatives answered the pretest. The analysis of the pretest responses did not suggest difficulty or problems in completing the questionnaire and only minor changes in wording were made.

#### *Survey implementation*

A first email was sent to all companies in the distribution list in February 2016. Reminder emails were sent to those participants that did not complete the questionnaire, one, two and

three weeks after the initial email. Thus, the survey was closed after four weeks of the initial email. Due to the low response rate obtained during the first iteration of the study, personal phone calls to all non-respondents were conducted over the course of three weeks after the last reminder, to obtain more responses.

#### *Data analysis*

After the survey was closed, response data was downloaded to be analyzed using standard statistical techniques. Descriptive statistics and charts were calculated. Categorical data was evaluated using Chi-square tests. All tests were evaluated at a 0.05 alpha level. Excel (Microsoft, 2017) and SPSS (IBM, 2017) were used for the analysis.

### ***Limitations***

As with any other research method, there are limitations and potential sources of error (Dillman, 2011; Sue & Ritter, 2012). The most important are listed below.

- *Measurement error*: survey question and answer options could lead to inaccurate data because certain answer options may be interpreted differently by participants. While this source of error cannot be eliminated, an attempt was made to minimize its magnitude by seeking the input and feedback from experts, and by doing a survey pre-test.
- *Non-response bias*: which means estimating a population characteristic based on a sample in which certain types of respondents are under or not represented. This was addressed by the sampling strategy and by testing for non-response bias.
- *Coverage error*: using the ACEC database to compile the mailing list for this survey could introduce a source of coverage error, since not all U.S. structural engineering firms are associated with the ACEC (only 5.3% of all engineering firms in the U.S. are part of the ACEC), and some differences may exist between companies that belong to this association and non-members.

- In order to make inferences about the relationship between firm location and respondents perceptions, a “multi-region” category was created, grouping those companies with operations in more than one region. Thus some region-related information was lost from those firms grouped into this category.
- Technical problems could also arise. Some respondents may be unable to complete the survey due to a browser freeze or server crash, resulting in missing data.
- Limitations inherent to any internet-based survey apply to this study (Dillman, 2011). Importantly, answers received represent the knowledge of a single professional in an engineering firm that may employ many individuals. Since the population of interest is comprised of engineering firms that work primarily with commercial buildings, conclusions do not necessarily apply to the entire engineering community.
- Due to low response rate (see next section “Results and Discussion”) generalizations to the population of interest cannot be made.

## ***Results and discussion***

### *Response rate*

The questionnaire was sent to 1,601 U.S. structural engineering firms, and 113 usable responses (75 responses were received online and 38 were received through personal phone calls) were received. Accounting for 110 firms that declined to participate or were not part of our targeted population (e.g., bridge engineering firms, consultants, etc.), 202 undeliverable emails, 1 duplicate address, and 12 incomplete (unusable) responses, the adjusted response rate calculated was 8.8%.

### *Non-response bias assessment*

Non-response bias refers to error in estimating a population characteristic based on a sample in which, due to non-response, certain types of respondents are under or not represented (Berg, 2005). To assess non-response bias, respondents of this study were

separated in two groups, or “waves”: early respondents (those answering online) and late respondents (those answering after the personal phone calls). Late respondents were used as a proxy for non-respondents. Early and late respondents were compared based on three attributes: firm location, firm size, and familiarity with CLT.

Early and late respondents were compared using Pearson’s Chi-square tests with a significance value of 0.05. The test performed under the location criteria resulted in a Chi-square value of  $X^2=0.467$  and a p-value of 0.993 ( $p>0.05$ ), which shows that there is no relationship between the time of response and the location of the firm. The evaluation of association between time of response and size of the company also shows that there is no statistically significant association between these two variables ( $X^2=4.536$  and p-value =0.338). Similarly, no significant relationship was found between timing of the response and level of awareness ( $X^2=1.270$  and p-value of 0.736). With this analysis, it was concluded that no significant bias existed between respondents and non-respondents.

#### *Company demographics*

Participants were asked to indicate the region where they operated (from a list of five U.S. regions) and the number of employees (used as a proxy for company size). Participants were able to check more than one location to indicate that they operated in more than one region. Firms with operations in more than one region were grouped into a new category, called “Multi-region,” for the analysis. Table 1 shows the counts and percentages of respondents for each region and firm size.

**Table 1. Location and number of employees, as reported by survey respondents. N=113.**

<b>Firm Characteristic</b>	<b>Count of Respondents</b>	<b>Percentage</b>
<b>--- Company Location (U.S. Region) ---</b>		
Multi-region	38	33.6%
Midwest	24	21.2%
West	21	18.6%
South	20	17.7%
Northeast	10	8.8%
Alaska/Hawaii	0	0.0%
<b>Total</b>	<b>113</b>	<b>100.0%</b>
<b>--- Firm Size (Number of Employees)---</b>		
1 to 4 employees	18	15.9%
5 to 9 employees	14	12.4%
10 to 19 employees	25	22.1%
20 to 99 employees	28	24.8%
100 employees or more	28	24.8%
<b>Total</b>	<b>113</b>	<b>100.0%</b>

*Sources of information*

To assess how firms learn about new building materials and evaluate which methods of communication are more efficient for this type of audience, engineers were asked to indicate their preferred sources of information. Table 2 shows that most firms learn about new materials from the internet and industry events (93.8% and 78.8%, respectively), and 64.6% from magazines. Least mentioned media were webinars, with only 19.5% of respondents indicating that they used this source to learn about new materials. These results show an opportunity to promote innovative materials through articles and reports published on the internet and magazines, as well as by introducing them in industry related events.

**Table 2. Sources of information used to learn about new building materials. N=113.**

Source of information	Count of respondents	Percentage*
Internet	106	93.8%
Industry Events	89	78.8%
Magazines	73	64.6%
Academic Journals	70	61.9%
Research Academics	61	54.0%
Seminars	60	53.1%
Books	58	51.3%
Expos	42	37.2%
Workshops	41	36.3%
Conferences	39	34.5%
Manufacturer's Websites	37	32.7%
Webinars	22	19.5%
Unanswered	3	2.7%

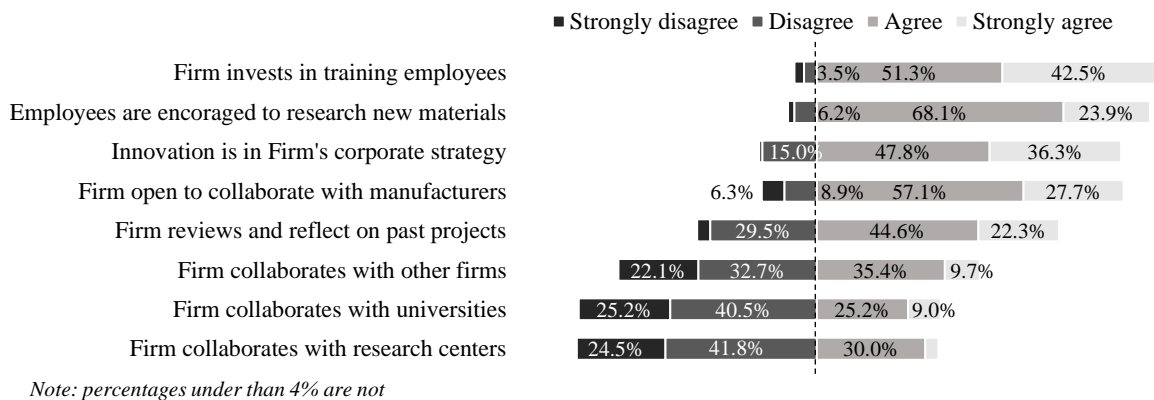
\* Multiple responses were possible

### *Innovativeness*

Over the past three decades many studies have been conducted to evaluate the factors that influence adoption of new materials by consumers (Gatignon H., 2002; Gronross, 1997; Rogers, 2003). A wide range of factors have been addressed, of which “innovation characteristics” and “adopter’s characteristics” stand out. In regards to “adopter’s characteristics,” the most commonly cited dimensions are age, education, and income (Arts, 2008; Gronross, 1997). Hirschman (1980) stated that “psychographic characteristics” are part of “adopter’s characteristics,” and include innovativeness, defined by the author as “*a driver of adoption intention and adoption behavior as it captures the propensity of consumers to adopt new products.*”

To understand how innovative structural engineering firms perceive themselves, and investigate how innovativeness relates to the willingness to adopt innovative wood-based materials, survey participants were asked to rate their agreement with a number of statements, including training of employees, the incorporation of innovation in the firm’s strategy, and collaboration with other organizations. Results for this questions are shown in Figure 5. Research conducted on organizational innovativeness shows that encouraging employee’s freedom to explore and innovate influence innovative behavior at the individual, team and organizational levels (Anderson, 2014; Shalley & Gilson, 2004).

Results from the survey indicate that the majority of respondent firms invest in the training of their employees, with 93.8% of firms agreeing or strongly agreeing with this statement. This is not surprising given that professional engineers must fulfil continuing education requirements. Similarly, 92.0% of respondents indicated that their firms encourage employees to research new materials. The inclusion of innovation in the corporate strategy seems to apply also to a great majority of firms, since 84.1% of respondents agreed or strongly agree with this statement. Statements with which respondents indicated the most disagreement, were those related to collaboration with other institutions or companies, with 66.3% of respondents stating they “strongly disagree” or “disagree.” One explanation for the lack of collaboration relates to the market-driven nature of the engineering industry, where instances for research and development of new technologies or materials is scarce and the main goal is to deliver the final product, to the clients specifications, within the stipulated time and cost, while minimizing the risk for the firm.



**Figure 5. Level of agreement with statements about firm innovativeness. N=113. Bars represent the percentage of respondents.**

A Pearson’s Chi-square test ( $\alpha=0.05$ ) was performed to determine if there was a significant relationship between innovativeness and other demographic factors. Table 3 shows items for which a statistical difference was found. No statistical difference was found between location and innovativeness. However, a significant relationship was found between

innovativeness and size of firm. However, as in any sector, the successful introduction of an innovation usually implies some upfront investment and therefore carries economic risk (Armstrong, Kotler, & He, 2013). It is hypothesized that larger firms tend to invest more in innovation than smaller firms do. It is possible that larger firms that have more financial resources could be more open to collaboration and innovation due to their greater ability to invest in innovation, which could be more risky for smaller firms.

**Table 3. Statistically significant associations between size of the firm and innovativeness factors, as per Pearson’s Chi-square test.**

Innovativeness dimension	p-value	Chi-square
"Firm collaborates with other firms"	0.003	16.017
"Firm collaborates with research centers"	0.008	13.745
"Firm open to collaborate with manufacturers"	0.001	17.576
"Firm collaborates with universities"	0.002	17.361

#### *Type of buildings*

Respondents were asked what types of building their firms works with. Responses to this question are shown in Table 4. As expected, per our sampling method, two-thirds (66.4%) of respondents indicated that they work with commercial construction. Other frequent responses were “Industrial” (46%), “Educational” (45.1%) and “Multi-family” (44.2%). Only 23.9% work with single-family residential buildings.

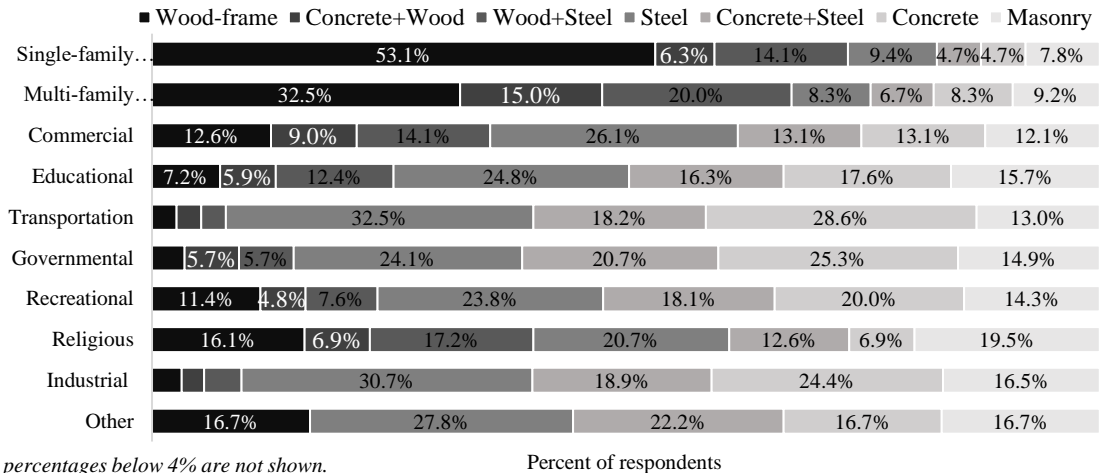
**Table 4. Type of buildings in which participant firms specialize. N=113.**

Type of building	Count of respondents	Percent*
Commercial	75	66.4%
Industrial	52	46.0%
Educational	51	45.1%
Multi-family residential	50	44.2%
Recreational	43	38.1%
Government	35	31.0%
Transportation	30	26.5%
Religious	29	25.7%
Single-family residential	27	23.9%
Non responses	19	16.8%

\* Multiple responses were possible

### *Materials used by type of construction*

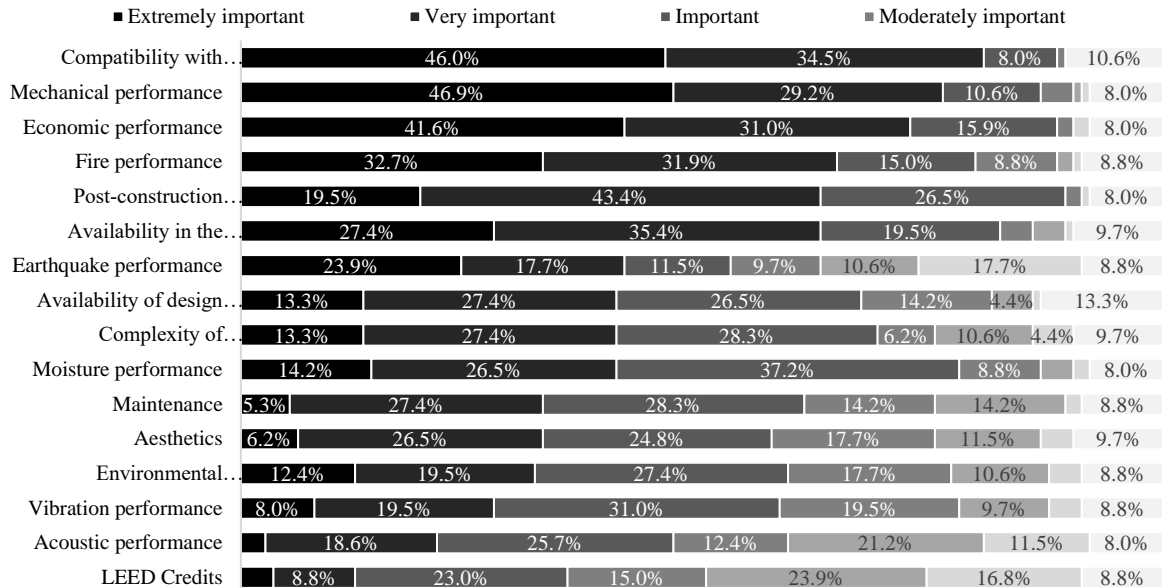
According to an exploratory study conducted by the author of this study (Laguarda-Mallo & Espinoza, 2016), the decisions about the structural material to be used in a commercial, industrial, institutional or educational construction project are frequently done very early on in the design process. These decisions are influenced by many factors such as cost, code and structural requirements. When asked about the materials used for different types of construction, participants indicated light wood-frame as the main type of material used for single-family residential construction and multi-family residential building construction above foundation (53.1% and 32.5%, Figure 6.) For single and multi-family buildings, light wood-frame construction is in the majority of cases the most cost-competitive material compared to concrete or steel alternatives (Laguarda-Mallo & Espinoza, 2016). For buildings over 5-6 stories with complex geometries and greater dead loads (i.e. stationary loads, such as self-weight of structural members), live loads (i.e. loads assumed by the intended use or occupancy of the building), rain, wind, snow, or even, in some cases, earthquake loads (ICC, 2015) other materials, become more cost-effective. This is the case of commercial, institutional, transportation, and governmental buildings. Results shown in Figure 6 indicate that for these types of construction, steel, concrete and a mix of both are typically selected. Due to the low data count for each category tested, Chi-square tests could not be performed to evaluate the relationship between materials used by type of construction and other items in the questionnaire.



**Figure 6. Structural materials (or combination of materials) typically used by respondents for building types listed on the left. N=113.**

### *Importance of materials characteristics*

Decisions about the choice of a construction material for a construction project are highly influenced by the priorities and perceptions of the engineers regarding the attributes of different materials. Thus, participants to this study were asked to rate the importance of a number of characteristics when specifying a construction material. A 6-point Likert scale was used, ranging from “very important” to “not at all important.” Figure 7 summarizes the responses to this question.



Note: Percentages below 4% are not shown. Percent of respondents  
 Characteristics on the left are sorted using the two highest importance ratings with the largest percentage at the top .

**Figure 7. Importance of the characteristics listed on the left for specifying a structural material. N=113.**

The results (Figure 7) indicate that the most important characteristics that engineers look for in a construction material are “compatibility with building code” (76.1% of respondents rated this attribute as “extremely important” or “very important”), “mechanical properties” (72.6%), “economic performance” (76.1%), “fire performance” (64.6%), “post-construction maintenance” (62.9%) and “availability in the market” (62.8%). LEED credits and acoustic performance did not seem to be high in the engineers' priorities when selecting a material, with only 28.3% of respondents rating these characteristics as “extremely important” or “very important.” It is presumed that features such as mechanical and fire performance, which are related to the structural performance of a structure, were rated the highest because of safety concerns and the liability implications that a structural failure might have (Pealer, 2007; Sido, 2006). Respondents rated high the importance of features such as “economic performance,” “availability in the market,” and “post-construction

maintenance,” possibly because of their influence on the economic feasibility of a project and its long-term success over the years.

Results from this and a previous study conducted by the author (Appendix 1) were compared to identify similarities and differences between architects and engineers. Both professionals place a high importance on cost and structural capabilities of construction materials, but show very different opinions towards the aesthetic performance of materials. Aesthetics was rated by 94.0% of architects that participated in the study conducted in 2015 as “Very Important” or “Important” (Appendix 1), and by 6.2% of engineers that participated in the study discussed in this paper.

The results from two previous studies conducted by the author of this study (Appendix 1) suggested that geographical location may have strong influence on construction professionals’ priorities. Therefore, Chi-square tests ( $\alpha = 0.05$ ) were performed for each material characteristic to determine if location and size of a firm may have had an effect in the way each characteristic was rated. Tests showed statistically significant differences between the responses from firms in different locations only for “earthquake performance” ( $p\text{-value} = 0.000$ ,  $\text{Chi-square} = 21.027$ ). This can be understood in light of the fact that some regions experience seismic events with more frequency and intensity (Dieterich & Okubo, 1996; Koyanagi, Endo, & Ward, 1976) than other regions. In regards to firm size, responses were significantly different for “earthquake performance” ( $p\text{-value} = 0.006$ ,  $\text{Chi-square} = 14.601$ ) and “vibration performance” ( $p\text{-value} = 0.027$ ,  $\text{Chi-square} = 10.961$ ). These results may suggest that smaller firms, which are more likely to be commissioned projects such as single and multi-family residential buildings, could be placing a higher importance on vibration; a greater concern for these types of buildings than others.

#### *Level of awareness*

The adoption of a product depends to a great degree on the awareness about the product among potential adopters. Therefore, one of the main objectives of this study was to determine the level of awareness about CLT in the U.S. structural engineering community. Participants were asked to indicate their familiarity with CLT, using a 4-point Likert familiarity scale, ranging from “very familiar” to “never heard about it.” The results to this

question, presented Table 5 show that the overall level of awareness about CLT among U.S. structural engineering firms is intermediate. A combined 59.3% of respondents indicated being “not very familiar” or that they “have not heard about CLT.” This indicates that there is a need for education and training about CLT among the engineering community if this product is going to be more widely adopted in the U.S.

**Table 5. Familiarity with Cross-Laminated Timber reported by respondents? N=113.**

<b>Familiarity with CLT</b>	<b>Count of respondents</b>	<b>Percent</b>
Very familiar	13	11.5%
Somewhat familiar	29	25.7%
Not very familiar	45	39.8%
Have not heard about it	22	19.5%
Unanswered	4	3.5%

Due to the low data count for each category tested, Chi-square test could not be performed to evaluate the relationship between level of awareness and location and size of the firm. Since the rest of survey questions required some knowledge of CLT, a “skip logic” (Appendix 2) was set up in the questionnaire to direct those participants that “have not heard about CLT” to a short description about CLT, its characteristics and claimed advantages, followed by two questions, one regarding their interest to learn more about CLT and another one regarding the likelihood of adopting the system for their projects in the future. Out of the 22 respondents indicating not knowing about CLT, 12 indicated to be “somewhat interested” in learning more about it. In regards to the perceived adequacy of CLT for the respondents’ projects, five respondents indicated that it could be likely adequate while seven indicated uncertainty. This uncertainty is consistent with the low familiarity of these respondents with the CLT system.

The following section will explore the responses of those participants of the study that reported having some familiarity with CLT. To assess how firms learn about CLT and evaluate which methods of communication are more efficient for this type of audience, engineers were asked to indicate how they learned about CLT. The results in Table 6 show

that most firms learned about CLT from the internet, magazines and conferences (37.9%, 36.8% and 36.8%, respectively). Although magazine names were not asked, it is hypothesized that architectural and engineering magazines with a focus on structural materials could have been the source of such information. The least mentioned media were: radio, television, newspaper and word-of-mouth, each of them selected by less than 7% of the respondents. Respondents were also given the option to indicate whether they heard about CLT from another source. Two respondents indicated that they learned about CLT from a “design partner,” one mentioned “PE (The Principles and Practice of Engineering) Exam,” another indicated “salesman,” and one respondent wrote that they heard about CLT through this survey. Subtracting 22 respondents that indicated not knowing about CLT from the 113 respondents to the survey, 87 answers were left for analysis.

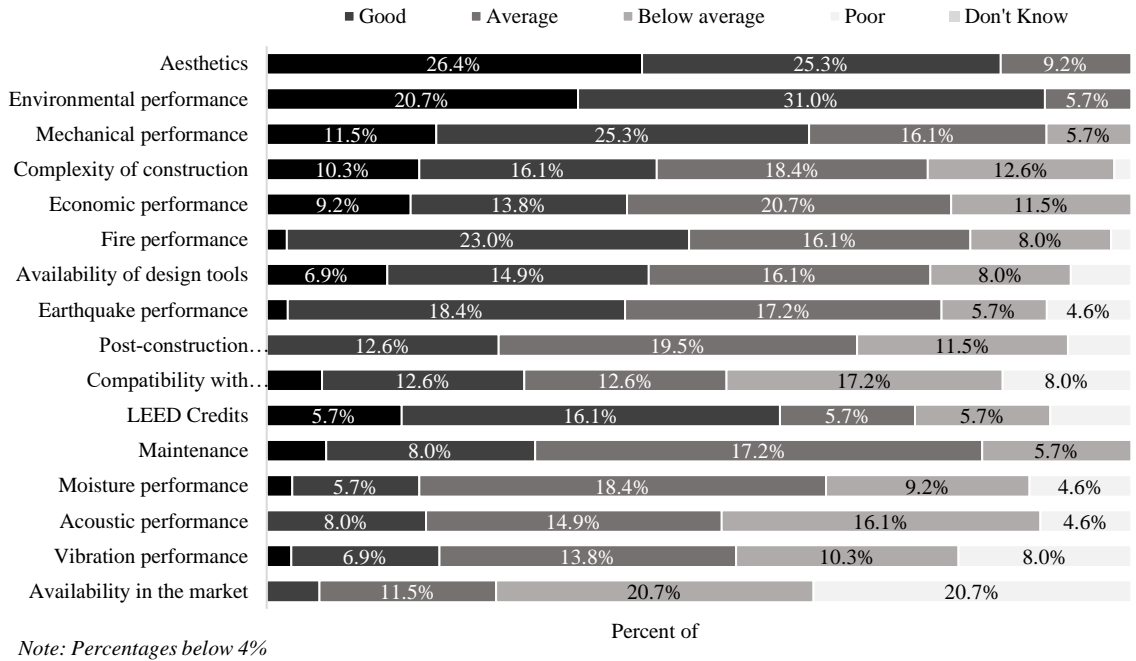
**Table 6. Sources of information from which respondents learned about Cross-Laminated Timber (CLT) for the first time. N=87.**

<b>Source of information</b>	<b>Count of respondents</b>	<b>Percent</b>
Internet	33	37.9%
Magazine	32	36.8%
Conference	32	36.8%
Academic Journal	8	9.2%
Relative/ Friend	6	6.9%
Newspaper	5	5.7%
Television	1	1.1%
Radio	0	0.0%
Non responses	3	3.4%

### *Perceptions about CLT*

Perceptions are fundamental in new product adoption, because what professionals feel and believe about a product can be just as important as what that product actually provides in terms of technical performance (Cooney, 2014). Therefore, it is essential to learn how potential adopters, such as engineers, view CLT's characteristics as a building material (Armstrong, et al., 2013). With this purpose, participant firms were asked to evaluate CLT's performance compared with other materials (e.g., steel and concrete), on eleven attributes,

using a 5-point Likert scale going from “excellent” to “poor.” Respondents were also given the option to select a “don't know” choice. Results for this question are presented in Figure 8.



**Figure 8. Respondents’ perceptions about performance of Cross-Laminated Timber compared to other materials (e.g. steel, concrete). N=87.**

The highest-rated features of CLT were “aesthetics,” “environmental performance,” and “mechanical performance;” perceived as “good” or “average” by 51.7%, 51.7%, and 36.8% of respondents, respectively. This is in agreement with the results from a previous study of U.S. architecture firms (Appendix 1), in which aesthetics, environmental and structural performance were also the highest ranked CLT attributes. The lowest ranked characteristics were “availability in the market,” “acoustic performance,” and “vibration performance,” perceived as “good” or “average” by only 3.4%, 8.0% and 9.9% of respondents, respectively. Recent research found that thanks to its massive nature, CLT-based systems achieve good acoustic performance and provide adequate noise control for both airborne and impact sound transmissions, especially if sealant and other types of acoustic membranes are used to provide air tightness and improve sound insulation at the interfaces

between the floor and wall plates (Sylvain Gagnon, 2011; S. Gagnon & Karacabeyli, 2013). In regards to the availability in the U.S. market, as of October 2017, CLT panels are not yet widely available. Only three U.S. manufacturer exist, only two of which is certified to produce CLT panels for construction under the ANSI/APA Standard for Performance rated CLT (PRG 320, (ANSI, 2012)). Due to the low data count for each category tested, Chi-square tests could not be performed to evaluate the relationship between how CLT attributes are perceived and other questions within this survey.

*Willingness to adopt CLT*

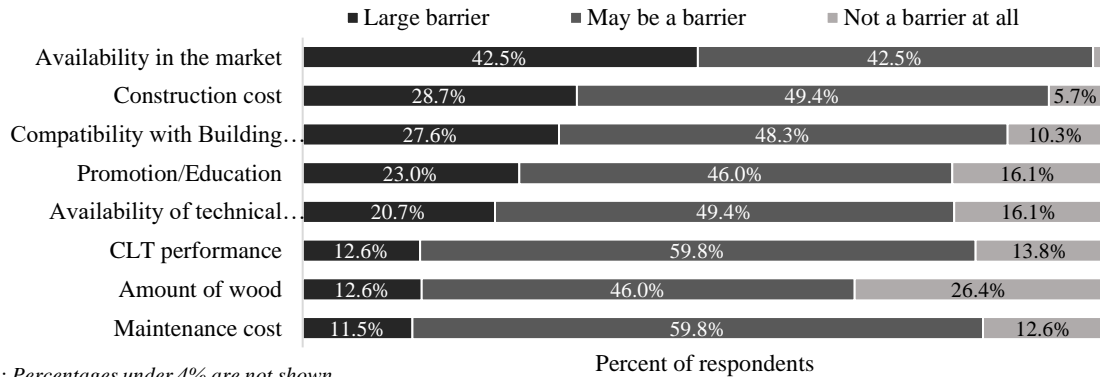
The third objective of this study was to determine if the population of interest would be willing to adopt CLT if it were available in the market. This information is essential to evaluate the potential market success of CLT in the U.S. Table 7 shows the participants’ responses to this question. More than half of respondents (57.8%) indicated that they were “very likely” or “likely” adopt CLT in one of their future building projects if it were available in the U.S.; 35.6% were “uncertain” and 12.6% indicated “unlikely” or “very unlikely” to adopt the system in the future. These findings are consistent with the level of awareness reported previously, as more than a third of professionals would be hesitant to adopt a material with which they are not very familiar.

**Table 7. Willingness to adopt CLT by respondents, if it were “readily available” in the U.S. for one of the participants’ building projects in the near future? N=87.**

<b>Willingness to adopt</b>	<b>Count of respondents</b>	<b>Percent</b>
Very likely	12	13.8%
Likely	32	36.8%
Uncertain	31	35.6%
Unlikely	8	9.2%
Very unlikely	3	3.4%
Non responses	1	1.1%

### *Barriers to the adoption of CLT*

To understand the market opportunities of CLT in the U.S., it is important to identify the perceived barriers to its adoption. Respondent firms were asked to rate five possible barriers, using a 3-point Likert scale, including “large barrier,” “may be a barrier,” and “not a barrier.” The largest barrier according to respondents is the lack of availability of CLT in the market (85.0% of respondents considered it a large barrier or a potential barrier). Overall, 78.1% of respondents saw cost as a large or potential barrier to the adoption of CLT in the U.S (Figure 9). Compatibility with the building code was considered a potential barrier to the implementation of the system in the U.S., with 75.9% of respondents indicating that the building code is a “large barrier” or “may be a barrier.” Results listed in Figure 9 show that the availability (or lack thereof) of technical information about the system “may be a barrier” or was a “large barrier.” This represents an opportunity for organizations promoting CLT to improve and increase the information available among possible adopters of the system. The results from the survey also indicate that more than half of respondents (58.6%) consider that the amount of wood required for the manufacture of the panels was a “large barrier” or “may be a barrier.” From the 10 experts interviewed for the study conducted by the author in 2014 (Appendix 1), six agreed that the main disadvantage of Cross-Laminated Timber (CLT) is the large volume of wood required for its manufacture. One interviewee with experience in design and calculation of CLT structures estimated that CLT panels use three times more wood than a wood-frame system solution. However, the amount of wood necessary to manufacture CLT panels was not seen as one of the possible barriers to the architecture firms for a later study (Appendix 1), which calls for a lack of knowledge about the amount of wood required in the production of CLT. This is not surprising given the low level of familiarity with the system, with only 4.3% of respondents indicating they were “very familiar” with CLT (Appendix 1). For the present study, respondents were also given the opportunity to indicate other perceived barriers not listed in the questionnaire. “Other” barriers listed were: “no experience,” and “contractor education.”



**Figure 9. Perceived barriers to adoption of Cross-Laminated Timber in the U.S. N=87.**

Lastly, “promotion/education” were ranked as barriers (considered by 69.0% as “large barrier” or “maybe a barrier”) to the adoption of CLT in the U.S. These finding opens the opportunity for organizations to continue their work promoting the use of wood in general, and mass timber systems in particular, and educating U.S. construction professionals. Chi-square tests (alpha = 0.05) were performed to determine if there was a significant relationship between firm level of awareness and the different barriers. Tests showed that there is a statistical relationship between the level of awareness and the participants’ perception of CLT’s availability in the market (p-value =0.022, Chi-square= 14.732), and between awareness and the amount of wood required to manufacture CLT panels (p-value = 0.008, Chi-square=17.370). Chi-square tests were performed to identify a possible relationship between barriers and likelihood of CLT adoption among those that indicated knowledge about the system. Results show a significant relationship between likelihood of adoption and availability of technical information (p-value =0.032, Chi-square = 13.767) as well as CLT performance (p-value =0.003, Chi-square = 19.965), stressing the importance information has in the adoption process. Results indicate that there is an opportunity to improve the likelihood of adoption by making information about CLT available to potential adopters.

## *Conclusions*

The main goal of this part of the study was to assess the level of awareness, perceptions and willingness to adopt CLT by structural engineering firms in the United States. Specifically, this study assessed the level of awareness about CLT in the U.S. engineering community, an important group for material specification in construction projects, their perceptions about CLT, and their willingness to adopt CLT-based construction systems in the future. For this purpose, a web-based survey was conducted among U.S. structural engineering firms that work primarily with commercial buildings.

The results show that the level of awareness in the U.S. structural engineering community is intermediate, since 11.5% of respondents indicated to be “very familiar” with the system. When asked about how the participants heard about CLT, 37.9% firms indicated that they obtained the information from the internet, 36.8% from magazines and 36.8% at conferences, seminars or workshops. These findings are consistent with the results obtained from a similar study conducted by the author with U.S. architecture firms (Appendix 1).

Information obtained from the survey indicates that the highest ranked features of CLT are its aesthetic characteristics, and its environmental and structural performance, which makes the system highly competitive against concrete or steel. On the other hand, availability in the market was one of the lowest ranked features of the product, which coincides with the current state of CLT supply in the U.S., where, so far, only three manufacturing companies exist. Regarding the perceived barriers, respondents indicated that CLT's availability in the market, its initial cost and compatibility issues with the building code were the largest hurdles to wide adoption of the system in the U.S. A considerable percentage of participants of this study perceived that the CLT performance and maintenance cost could were barriers to the adoption of CLT in the U.S. This is in accordance with the lack of experience about CLT among U.S. construction professionals. The results from the survey show that engineers are hesitant to adopt CLT.

Results from this study highlight the importance that information and education can have on the adoption of CLT. Research has proven that the rate of diffusion is dependent on potential adopters' perceptions of the product attributes, thus a future commercial adoption

of CLT is only possible if consumers' awareness and positive attitude and acceptance towards the product exists. From these results, we conclude that the future success of a CLT-based construction system in the U.S. depends in part on the information about the product reaching the target audience (i.e. U.S. construction industry professionals, such as architects, engineers, contractors and even developers and the general public). Proven success stories will also be important to develop confidence among potential adopters. A series of demonstration projects have been built over the past few years in the U.S. and in Canada. The experiences of professionals that worked in the design and construction of these projects, as well as the experience and perceptions of the inhabitants of these buildings should be used to educate professionals and users on the possibilities of the systems and promote its wide adoption in the U.S. It is also important to increase the system's availability in the country, so that professionals interested in trying the system are not deterred by the costs of having to import the product from Canada or Europe. The author hypothesizes that tax credits for embracing CLT will also help with acceptance of this construction system in the U.S., while showcasing CLT's capabilities in demonstration buildings. The results from this research benefit entrepreneurs with interest in entering the CLT market (as suppliers, designers, or manufacturers), by providing them with important information about engineers' perceptions about CLT and their willingness to adopt it as a building material. Outcomes also inform organizations supporting the forest products industry, such as non-profits, government agencies, and industry associations.

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# Chapter 3

## U.S. Engineering Firms Interviews

## *Introduction*

The main objective of this part of the study was to follow up on the survey conducted to U.S. structural engineering firms (Chapter 2) and gain a deeper understanding of the level of awareness, perceptions and willingness to adopt CLT by these firms, one of the key actors in the structural material decision process. This qualitative study also aimed to investigate how the structural material decision process takes place and who are the most influential actors. Based on the information from the interviews to experts (Appendix 1) and preliminary economic analysis conducted by Crespell and Gaston (2011), a decision was made to focus on U.S. engineering firms that work primarily with commercial construction (NAICS code 541330).

## *Methodology*

The research approach followed for this study comprised a set of semi-structured interviews with the purpose of collecting insights and in-depth information about the selection process for structural materials, and the awareness and perceptions about CLT among U.S. structural engineers. The population of interest was a subset of the category Engineering Services, listed under the NAICS code 541330. A list of 100 U.S. structural engineering firms was compiled using the online database managed by the American Council of Engineering Companies (ACEC, 2016), with the aim to recruit 30 firms for the interviews. This association represents engineering companies, including structural engineering firms. The ACEC's member directory provides search tools to identify firms using criteria such as state, type of engineering firm, type of buildings they engage with and zip code. There are currently over 5,000 firms in the ACEC's database, representing more than 500,000 employees throughout the country (ACEC, 2016). Selection of 100 potential participants was carried out randomly from the ACEC database.

### *Questionnaire design*

A semi-structured questionnaire was used to obtain information and insights on topics relevant to existing and potential markets for CLT in the U.S. A questionnaire with 13 open-ended questions was developed. The topics included in the questionnaire are listed in Table 8. A copy of the questionnaire can be found in Appendix 3. In order to assure the relevance, consistency and clarity of the questions, the questionnaire was reviewed by academics with extensive experience in interviews design and implementation.

**Table 8. Topics included in the questionnaire.**

<b>Topic category</b>	<b>Topic</b>
Firm and respondent characteristics	Position of the interviewee within the firm Years of experience in the U.S. engineering industry Size of the firm Location Type of constructions the firm works with Structural materials most frequently used
Professionals' roles	Roles of architects, engineers and contractors Influence in the structural material decision process
Sources of information	How the firm gathers information about structural materials
Wood as a structural material	Frequency the firm uses wood as a structural material Perceptions about wood as a structural material
Innovativeness	Perceptions about the firm's innovativeness
Cross-Laminated Timber (CLT)	Familiarity with CLT Perceived advantages and disadvantages of CLT Perceived factors influencing the adoption of CLT in the U.S. Willingness to adopt CLT in the future

### *Interview implementation*

Companies in the list generated in a previous step were contacted via phone and invited to participate in the study. A short description of the study was used to inform potential participants of the objectives of the research. Those firm's representatives that agreed to participate were then asked for a convenient date and time to conduct the interviews. Interviews were conducted via phone in the summer and fall of 2016, and recorded with the consent of participants. Recordings were transcribed, coded and analyzed using Excel spreadsheets (Microsoft, 2017), and following the standard guidelines for qualitative research (Berg & Berg, 2001).

### *Limitations*

A number of limitations may have affected the results obtained from this study, including:

- A secondary objective of this qualitative study was to explore and identify perceptions about the use of wood-based structural systems, in particular CLT. Thus, generalizations to the population of interest are not possible.

- The absence of visual cues via telephone results in loss of contextual and nonverbal data, which may cause some loss of information (Opdenakker, 2006).
- Telephone interviews usually need to be kept short, thus reducing in-depth discussion (Chapple, 1999).

## ***Results and discussion***

### *Demographic information*

Thirty interviews to U.S. engineering firm representatives were conducted. The characteristics of the interviewees was diverse. Table 9 shows demographic information of respondents and their companies. Most participants work as “structural engineers,” and have between 5 and 29 years of experience. Companies were mostly in the mid-range size of 10 to 49 employees, and were evenly distributed in the four U.S regions.

**Table 9. Interviewee characteristics (30 interviews).**

<b>Interviewee Characteristics</b>	<b>Frequency</b>
<b>-- Position in the Firm * --</b>	
Structural Engineer	13
Senior Structural Engineer	6
Senior Project Engineer	2
Project Engineer	7
Structural Design Engineer	2
Associate	5
Director	3
Principal	6
<b>-- Years of Experience --</b>	
Less than 5 years	2
Between 5 and 9 years	10
Between 10 and 19 years	7
Between 20 and 29 years	6
More than 30 years	5
<b>-- Size of the Firm --</b>	
Less than 5 employees	0
Between 5 and 9 employees	5
Between 10 and 49 employees	16
Between 50 and 99 employees	6
More than 100 employees	3
<b>--Location of the Firm *--</b>	
South	11
Midwest	7
Northeast	6
West	11

\* Multiple answers were possible.

### *Type of buildings*

Participants were asked to indicate the types of buildings that their firm works with. A great majority of the interviewees (22 of 30 participants) indicated that their firm worked with commercial buildings (e.g. office buildings, restaurants, retail stores, hotels, markets, malls, etc.) and 12 indicated working with residential building developments (e.g. Multi-family residential complexes, condos, duplexes, dormitories, town-homes, etc.). Of the 30 engineers interviewed, eight had worked with educational and cultural buildings (e.g. schools, colleges, libraries, museums, theaters, etc.) in the past, and six with industrial buildings (e.g. parking ramps, storage buildings, factories, power plants, etc.). Four participants indicated having experience with religious and institutional buildings and only

two participants indicated being involved in the design and construction of governmental, healthcare facilities or single-family residential buildings.

*Type of structural materials used*

In order to evaluate the firm’s attitudes towards different structural materials, interviewees were asked about the materials frequently used for a number of building types, and the reasons for their choice. Responses to this question are summarized in Table 10.

**Table 10. Predominant structural materials (or combination of materials) by building type.**

<b>Building type</b>	<b>Structural materials primarily used</b>
Single-family residential	light-wood frame
Multi-family residential <i>(e.g. condos, apartment buildings, townhouses, etc.)</i>	light-wood frame, concrete, and light-steel frame
Commercial buildings <i>(e.g. offices, restaurants, retail stores, hotels, etc.)</i>	concrete, steel, light-steel frame, and precast concrete
Educational buildings <i>(e.g. schools, universities, libraries, etc.)</i>	wood-frame, concrete, steel, light-steel frame, and precast concrete
Transportation buildings <i>(e.g. airport, bus/train stations, etc.)</i>	concrete, steel
Governmental buildings <i>(e.g. city halls, courthouses, embassies, etc.)</i>	concrete, steel
Recreational buildings <i>(e.g. gymnasiums, stadiums, pools, ice rinks, etc.)</i>	concrete, steel
Religious buildings <i>(e.g. churches, temples, chapels, etc.)</i>	concrete, steel, light-wood frame, and engineered-wood products
Industrial buildings	concrete, steel, and precast concrete

When respondents were asked to elaborate about the reasons for each selection, they indicated that the main drivers for selecting the materials were: cost compared to other solutions; building code and fireproofing requirements; building and program characteristics (buildings requirements); height; characteristics of the enclosed environment (e.g. pools); architectural form (e.g. emblematic structures); and security (e.g.

embassies). Regarding the main drivers for selecting materials, one interviewee that works in residential construction mentioned that *“for single-family residential [...] wood is most often used. Multi-family residential buildings tend to be [built with] wood too but we do have a lot of mixed-use going on, with commercial on the bottom floor. In those cases, due to code requirements, you see a lot of concrete podiums, and wood is used over that.”* As for commercial buildings, another engineer mentioned, *“a lot of times, restaurants and retail stores tend to be light-steel frame with steel joist for the roof, just for economics. Code also tends to drive the decision to go with steel versus wood.”* That same interviewee continues saying that code and fireproofing requirements play a big role in the material selection: *“whether a building has to be fireproofed or not, that lends itself to the type of construction and the structural material selected.”* One engineer with experience in governmental buildings stated that building security concerns (e.g. explosions, etc.) could also influence the structural material selection: *“You need to try to make sure the [governmental] building has enough resiliency to withstand that. Concrete is natural for that [purpose] because its nature is redundant; with steel you can do that too [but] you have to spend a little bit more time detailing.”*

Resiliency was mentioned by one interviewee as a factor influencing the material selection process in their firm. “Resilient design” has been gaining interest over the past decade. Construction professionals are now aware that the effects of climate change (e.g. extreme heat, sea level rise, natural disasters, etc.) present significant challenges for building and are starting to take these factors into consideration during the design and material selection processes (AIA, 2017; Minnery, 2015; Resilient Design Institute, 2017). One engineer interviewed stated that they have been requested by several clients to *“...create durable and resilient buildings that can maintain livable conditions in the event of a hurricane or typhoon. All of these conditions greatly influence the project design and the materials used.”*

When talking about wood construction, out of the 30 engineers interviewed, 21 indicated having used light-frame construction or a combination of light-frame and other materials (e.g. concrete or steel) in the past. Two interviewees mentioned using engineered-wood

products such as glulam beams and columns for particular projects, where wood was used for its environmental and aesthetic characteristics.

### *Perceptions about wood as a structural material*

When asked about the benefits of using wood for construction, two-thirds of the interviewees mentioned wood's favorable environmental performance as the main benefit of the material. One interviewee stated that *"Many people are now concerned with the environment. We had a few clients requesting wood for this reason."* Wood-based construction materials have been gaining significant attention due to wood's renewable nature, their ability to store carbon, and the less energy and water required to manufacture wood products. Additionally, extensive research conducted over the past couple of decades has shown that wood members have lower greenhouse gas emissions, energy input, and water usage when compared to equivalent elements made of concrete or steel (Cabeza, 2014; Robertson, Lam, & Cole, 2012; Ximenes, 2013). Lower material cost, in comparison to concrete and steel, was also mentioned by half of participants as a major benefit of wood-based construction materials, with one interviewee saying that: *"Wood offers the best cost-benefit ratio. For residential buildings, we evaluated different options in the past but nothing comes out as cost-effective as wood-framing;"* and another one declaring: *"Cost is our main driver for choosing wood over other alternatives."* Six engineers interviewed saw the aesthetic characteristics and faster construction times as additional advantages of wood construction. *"Time restrictions are always there...building with wood can be faster than with concrete because [structural] elements can be prefabricated,"* said one of the engineers interviewed. A previous study conducted by the author (Laguarda-Mallo & Espinoza, 2016), in which architects and engineers at a Midwestern architecture firm were interviewed, also found that wood, and in particular engineered wood products, tend to be the preferred material for churches and temples due to the *"[...] warmth factor that wood has that works nice for religious buildings."* One of the respondents also mentioned familiarity with the material and its workability as an advantage of wood over other materials, saying that, *"Both our contractor and our team is very confident in their ability to work with wood. We know what we can do, what we can't, and how to solve certain*

issues. We know how to properly detail wood buildings to avoid some issues, and the contractor is already familiar with our solutions, so the process tends to run smoothly.”

In regards to wood’s perceived disadvantages, poor durability was mentioned as the least favorable characteristic of wood by about one-third of the participants, with one interviewee saying: “[Wood] is not as dimensionally stable or durable as other options. Detailing to avoid water and moisture issues in the long term is sometimes extremely time-consuming.” According to a previous study (Appendix 1), CLT experts believe that a sizable percentage of the general population still does not completely trust the durability of wood as a building material. In particular, construction professionals tend to believe that wood is not able to withstand time and that its biological nature implies more frequent and costly maintenance, since it is susceptible to moisture and biological degradation (Lehmann, 2011). Several participants indicated fire and structural performance of wood elements as disadvantages of wood-based materials. One of the respondents mentioned that “Concrete and steel are both monolithic and stronger [than wood] and with the right protection, the risk for fire and fire propagation is almost non-existent.” Table 11 shows a summary of all the perceived advantages and disadvantages of wood as a construction material.

**Table 11. List of advantages and disadvantages of wood as a construction materials by interviewees in order of frequency (highest frequency on top) (30 interviews).**

Advantages of wood	environmentally friendly
	cost-competitive
	fast construction
	familiarity
	aesthetics
	design versatility
	workability
Disadvantages of wood	structural performance
	durability
	fire performance
	structural performance
	dimensional stability
acoustic performance	

### *Roles of construction professionals*

During the interviews, participants were asked about the roles of architects, engineers and contractors in the structural material decision process. Almost half of respondents mentioned that while there is a constant communication between the different professionals; architects, engineers and contractors have distinct and separate roles. Architects were considered the main design professionals, in charge of planning and designing the building according to the program (building specific requirements) and any particular client requirements, and of guaranteeing the functionality of the finalized building. Structural engineers are in charge of the design and calculation of the structural elements according to the architect's specifications. Contractors plan and advise on issues regarding cost, constructability and labor; in other words, they manage the actual implementation of the design, taking into consideration the budget set by the owner or developer. However, depending on the firm, the differences between the roles of the architects and structural engineers are often not clear; and there is frequently collaboration between the two professionals. For example, one engineer stated, *"It is hard to separate architecture and structure because they are sewn together."*

When asked which of the construction professionals have the most influence when it comes to deciding the type of structural material, there was an almost unanimous consensus among engineers interviewed that both architects and structural engineers are the main decision-makers during the structural material decision process. Two engineers interviewed also added that this process could vary depending on the type of firm and project. One respondent stated, *"Depending on the kind of firm, [the material selection] could be a sequential process or could be a collaborative process. The level of collaboration is often project-specific"*. To stress this idea of collaboration another respondent said, *"Structural elements could ruin the design, the aesthetics of the building. So we always need to talk to the architects, check with them before specifying a structural element and get to an agreement."*

### *Sources of information*

To assess how firms learn about new building materials and evaluate which methods of communication are more effective for this type of audience, structural engineers interviewed were asked to indicate what their preferred sources of information were. The responses (Table 12) show that most firms learn about new materials from the internet, trade shows, books, and direct communications with manufacturers. Least mentioned sources were research papers, word-of-mouth, and research conducted within the company. These results show an opportunity to promote innovative materials through articles and reports published on the internet and presentations during expos and other industry-related events.

**Table 12. Sources used to gather information about structural materials in order of frequency (30 interviews).**

<u>Sources of information</u>
Internet
Books
Manufacturers
Trade show
Magazines
Conferences
Webinar
Journals/Papers/Research
Colleagues
<u>Research within the company</u>

### *Innovativeness*

Over the past three decades many studies have been conducted to evaluate the factors that influence adoption of new products by consumers (Gatignon H., 2002; Gronross, 1997; Rogers, 2003). A wide range of factors has been addressed, of which “innovation characteristics” and “adopter’s characteristics” stand out. Innovation characteristics refer to the product dimensions that potential adopters perceive. The most frequently cited adopter characteristics were demographic characteristics of the potential adopter, such as experience, educational background, size, and location (Arts, 2008; Gronross, 1997). Capatina (2014) also included the “psychographic characteristics” of adopters, such as

innovativeness (defined by Hirschman (1980) as *“a driver of adoption intention and adoption behavior, as it captures the propensity of consumers to adopt new products”*); opinion leadership; price consciousness; and familiarity with the brand.

To evaluate to what extent structural engineers perceive their firms as innovative, interviewees were asked to indicate the importance that innovation plays within their firm. Of the 30 engineers interviewed, seven indicated that innovation was of “great importance” for their firm; the same number of participants indicated that innovation has “moderate importance,” and nine consider innovation to be of “low importance” to the company. When asked to expand on the reasons for their statements, two engineers mentioned that innovation is part of their firm’s strategic planning, because innovation is considered a competitive advantage. One engineer said, *“Innovation is something that we strive for. Research of new materials and solutions is valued and encouraged among team members. That is the only way to improve, to be better and to stay current. It is our way to have a competitive advantage in a very risk-averse industry.”* All interviewees that stated innovation to be of “low importance,” mentioned risk and liability issues as the main factors preventing them from adopting newer solutions. One interviewee mentioned, *“Sometimes it is difficult to take a chance and trust a new technology or even a process that has not been around for too long, and we have no experience with.”* In the construction industry, liability risk is as one of the largest barriers to the adoption of new materials and technologies (HUD, 2005). Construction professionals, namely architects, engineers and contractors are, in the majority of cases, responsible for the performance of buildings and consequently for the specification of the materials to be used, and can face severe consequences when building components fail to perform as expected (Sido, 2006). Liability is frequently shared with product manufacturers (U.S. Department of Housing and Urban Development (HUD), 2005). According to McCoy, Thabet and Badinelli (2009), the complexity of the adoption process in the construction industry originates in part in the number of actors (suppliers, manufacturers, design professionals, final users) involved in the decision of adopting an innovation. Although construction professionals (architects, engineers, and contractors) are only one group of actors involved in the process, their key role in the supply chain, as specifiers of building requirements and materials,

makes them the most influential in the adoption of an innovative material or technology (McCoy, et al., 2009).

### *Level of awareness*

The adoption of a product depends to a great degree on the awareness about the product among potential adopters. Therefore, participants were asked to indicate their familiarity with CLT. Overall level of awareness about CLT among U.S. structural engineering firms included in the study is low, with only five of the participants indicating some knowledge about CLT, and the remaining 25 saying that they have not heard about it . These results are consistent with the findings from the survey to U.S. architecture and engineering firms conducted by the author (Appendix 1 and Chapter 2), in which a combined 57.5% of architects and a combined 59.3% of engineers were either “not very familiar” or “have not heard about CLT.”

Following the question about awareness, interviewees were divided into two groups: those with some familiarity with CLT and those that never heard about it. Those respondents in the first group were asked a series of questions to evaluate their perceptions and willingness to adopt CLT in the future. Participants with no prior knowledge of CLT, were read a short paragraph explaining what CLT was, after which they were asked to express their perceptions and likelihood to adopt CLT if it were widely available in the U.S. market. The following sections present the responses obtained from both subgroup of interviewees.

### *Perceived benefits and disadvantages of CLT*

All five engineers that indicated having some familiarity with CLT, explained that the main advantage of CLT relates to faster construction. Some of these participants indicated that the fact that CLT is a wood-base structural system makes its environmental performance superior to concrete or steel-based building systems. One interviewee stated that, “*The fact that [wood] is a natural material that can be regrown, is a plus.*” The environmental qualities of wood, and CLT in particular, have been contrasted with other materials, such as steel and concrete (Chen, 2012; Darby, Elmualim, & Kelly, 2013; Dodoo, Gustavsson, & Sathre, 2014; Durlinger, Crossin, & Wong, 2013; John, Nebel, Perez, & Buchanan,

2009; S. Lehmann, 2012a; O'Connor, Mahalle, & Berry, 2011). For example, the results from a comparative study of two mid-rise office buildings conducted by John et al. (2009) indicated that CLT has a favorable environmental performance, in all impact categories (ozone depletion, global warming potential, eutrophication), compared to a similar building constructed with concrete. The same study also concluded that the carbon sequestration potential associated with CLT would allow the building to operate for the first 12 years with no net CO<sub>2</sub> emissions. Research conducted by Darby, et al. (2013) in the United Kingdom showed that a reinforced concrete six-story building contains more embodied CO<sub>2</sub> than an equivalent CLT building (1661 vs. 655 U.S. tons). CLT has about two-fifths (39.4%) of the embodied carbon of a concrete alternative. However if carbon sequestration is taken into account, the CLT building turns out to be carbon-negative, with a value of approximately -2,314 U.S. tons of embodied CO<sub>2</sub> for the six-story building. By achieving a negative balance of embodied CO<sub>2</sub> emission compared with other alternative, CLT building are able to reduce the carbon footprint, locking carbon in their mass. For this reason, massive timber construction systems, such as CLT, offer the opportunity to turn buildings into “carbon sinks” (Lehmann, 2012b).

The design versatility and aesthetic qualities of CLT were also mentioned as advantages by two interviewees. One of the engineers interviewed mentioned *“The versatility of the system is also an advantage. Some of the buildings in Europe that I have seen are impressive.”* According to some authors, the structural characteristics of CLT enable great architectural freedom during the design process, allowing different building configurations of openings (number, size and location) and providing flexibility in organizing spaces without compromising the structural integrity of the structure (Bejder, 2012; FPInnovations, 2013). CLT also allows covering long spans without intermediate supports, something that would be too complex or impossible to attain using wood in traditional ways. For example, a CLT panel with 7 layers (9 inch thickness) can be used to cover spans of up to 25 feet (Malczyk, 2011).

Regarding the perceived disadvantages of CLT, three participants with familiarity with the system indicated fire performance as the main drawback to the use of CLT for structural applications. Several research studies have focused on CLT’s fire performance, given the

common perception that wood buildings perform poorly in these situations (Crielaard, 2015; Frangi, Bochicchio, Ceccotti, & Lauriola, 2008; Gibbs, Taber, Lougheed, Su, & Bénichou, 2014; Schmid, Klippel, Just, & Frangi, 2014). Authors of these studies state that wooden structural elements of large sections such as CLT panels have adequate fire resistance properties, mainly because of wood's particular charring properties (Forest Products Laboratory, 2010). Correspondingly, experiments performed by Frangi et al. (2009), in which several CLT panels were evaluated under different fire conditions, observed that wood formed a char layer that protected non-charred wood from further thermal degradation and mass loss. This behavior allows the structural element to maintain its strength and dimensional stability without collapsing in an abrupt way, potentially providing time for the evacuation of occupants from the building (Phan et al., 2010). CLT's fire performance was also recently studied by the American Wood Council (2016). During the testing phase of the above mentioned study, a 16x12 ft CLT room with typical fuel load from furniture and other contents concluded that gypsum-protected CLT (2 layers of 5/8" Type X gypsum wallboard used in this study) can achieve nearly damage-free performance during a fire burn out event.

Other disadvantages mentioned were durability issues, weak connections and maintenance. Regarding maintenance requirements and cost, one interviewee indicated that he had not "seen any information about maintenance" and questioned, "What happens when these buildings need maintenance? Water leakages and subsequent moisture problems are important and very common issues that need to be considered." In a previous study (Appendix 1), in which CLT experts were interviewed, durability was also frequently mentioned as a possible disadvantage of the system, especially since wood is susceptible to moisture-related problems.

#### *Perceived factors affecting the adoption of CLT in the U.S.*

Participants to this study familiar with CLT were asked to share their views about what they perceived could be major barriers hindering the adoption of CLT in the U.S. by construction professionals. Table 13 summarizes all the perceived factors affecting the adoption of CLT in the U.S. mentioned by participants during the interviews.

**Table 13. List of perceived factors affecting the adoption of CLT in the U.S. mentioned by interviewees (30 interviews). Factors are listed in order of frequency (most frequently mentioned at the top).**

<b>Factors affecting the adoption of CLT</b>
Information about design methods
Research on user's experience
Research on professional's experience
Building code compatibility
Acoustic performance
Availability in the market
Construction cost
Information about manufacturers
Information on maintenance schedule and cost

According to interview responses, there is little or no research on inhabitants' experience for CLT buildings and about construction professionals' experience of working with CLT. This represents a research opportunity. These results are consistent with findings presented in a previous study by the author (Appendix 1), where CLT experts were asked about perceived barriers to the wide implementation of CLT in the U.S. Barriers mentioned by the respondents in said study were building code compatibility, availability of CLT in the domestic market, and existing misperceptions about wood as a building material.

Barriers to the adoption of CLT have been studied by other authors (Riala & Ilola, 2014; Schmidt & Griffin, 2013). Contrasting their findings with the information obtained from the present study reveals some similarities. A survey conducted by Schmidt and Griffin (2013) to Oregon stakeholders involved with the design of multi-family residential buildings, highlights a number of barriers to the use of CLT in multi-family residential buildings, such as: lack of knowledge about attributes and capabilities of CLT, building code and construction cost. Similarly, Riala and Ilola (2014) concluded that the building code compatibility, cost competitiveness and doubts about the performance of wood as a building materials are some of the largest barriers that hinder the adoption of new technologies, such as CLT.

#### *Likelihood of adoption*

When the five interviewees familiar with CLT were asked about the likelihood of them adopting the system for future projects, if it were available in the market, there was a

consensus that they would “*likely*” adopt it. However, when the 25 interviewees that indicated no familiarity with the system were informed about CLT and asked if they would consider CLT for their future projects, 11 and 14 said that they were “*likely*” and “*unlikely*” to adopt it, respectively (Table 14).

**Table 14. Likelihood to adopt CLT in the future (30 interviews).**

Willingness to adopt CLT in the future	Count of respondents
<i>-- U.S. engineers familiar with CLT (N=5) --</i>	
Likely	5
Unlikely	0
<i>-- U.S. engineers not familiar with CLT (N=25) --</i>	
Likely	11
Unlikely	14

These results are in agreement with the findings reported in previous studies of U.S. architecture and engineering firms by the author (Appendix 1 and Chapter 2), which concluded that the willingness to adopt CLT by U.S. construction professionals is uncertain and that there is a significant relationship between the level of awareness and the willingness to adopt the system in the future. In other words, the more familiar professionals are with the system, the more likely they are to adopt it. This indicates that much work still needs to be done to efficiently distribute information and educate the different actors that influence the material decision process, such as engineers.

## *Conclusions*

This qualitative study was conducted with the purpose of following up on the information obtained from the survey conducted to the same population of interest (U.S. engineering firms) and presented in Chapter 2. This study aimed at gaining a deeper understanding about the level of awareness, perceptions and willingness to adopt CLT by U.S. structural engineering firms, considered key actors, together with architects, in the structural material decision process. The author of this chapter also aimed to investigate how structural

material decisions process take place and who are the major actors with the most influence during this process. To accomplish these objectives, 30 interviews were conducted with U.S. structural engineers to learn about their insights.

Results from this study show that the material selection process varies greatly depending on the type of building and the cost of the material selected. Security (in regards to the ability to withstand explosions or other attacks to the structural integrity of the building) and resiliency (in regards to the ability to withstand natural disasters related to climate change, such as hurricane, flooding, etc.) were mentioned as factors influencing the material decision process. According to the responses, during the material selection process, architects and engineers are the actors with the most influence. Contractors, on the other hand, were seen as advisors and are incorporated later on in the decision process. Collaboration between these professionals was also mentioned as a key part of the material decision process.

According to the information gathered during the interviews, it was found that the level of awareness about CLT among U.S. engineers was low, with only 5 participants out of 30 indicating some familiarity with CLT. When asked about the perceived benefits of CLT, engineers interviewed indicated that the main benefits of CLT-based systems come from using a natural, renewable resource as opposed to energy-intensive and non-renewable materials like concrete or steel. Another important benefit of CLT-based systems over traditional construction systems (e.g., concrete and steel) is the shorter construction time needed since CLT is a prefabricated system, in which panels come to the construction site ready to be installed. Other benefits cited were CLT's aesthetic qualities and design versatility. Respondents with previous knowledge about CLT also mentioned durability and fire resistance, connector, and maintenance requirements and cost as potential drawbacks of the system.

Barriers to the wide adoption of CLT-based construction systems in the U.S. mentioned by the respondents were lack of information about design methods, users/occupants experience, professionals experience working with a CLT-based structural system, and availability of CLT in the domestic market. These results show that, even though there has been extensive research carried out about CLT properties, more information is needed

about how to design, detail and build with CLT and user's experience living and working in these buildings. Future research on these topics, as well as more demonstration projects, would greatly improve the confidence of construction professionals evaluating the possibility of adopting CLT for their projects.

The willingness to adopt CLT for future project, among those professionals familiar with the system, was high. Engineers showed interest to choose CLT if it were widely available in the U.S. market at a competitive price. The willingness to adopt CLT for future projects among those professionals unaware of the system, was intermediate, with 11 respondents indicating to be "likely" to adopt CLT, and 14 respondents "unlikely" or "very unlikely" to adopt CLT in the future.

Results presented in this paper show that future commercial adoption of CLT will only possible if decision makers' are aware of the product. Wide adoption of CLT in the U.S. will also depend on a positive attitude and acceptance towards the product. From these results, we conclude that the future success of a CLT-based construction system in the U.S. depends in part on the information about the product reaching decision makers, mainly architects and structural engineers. The current level of awareness and perceived disadvantages of the material make it difficult to create a market for CLT. It also takes time and effort to get professionals to trust the material. However, trust can only be gained after proven success stories that can help U.S. construction professional confidently design and build CLT buildings.

# Chapter 4

## U.S. Construction Firms Survey

## ***Introduction***

This chapter describes the methods, analysis, and conclusions from survey research aimed at assessing the market potential for CLT in the United States by investigating the level of awareness, perceptions and willingness to adopt CLT by U.S. construction firms. Construction firms are key actors in the structural material decision process. Given their importance in the material selection process (Laguarda-Mallo & Espinoza, 2016), they were the population of interest for this study. Based on the information from the interviews with experts (Appendix 1) and preliminary economic analysis conducted by FPInnovations (2011) that concluded that commercial buildings are the most adequate for CLT, a decision was made to focus on U.S. construction firms that work primarily with commercial buildings (NAICS 236220).

## *Methodology*

A nation-wide survey of U.S. construction firms was conducted with the purpose of learning about this community's perceptions and awareness about CLT. The survey was conducted over the phone, which is a cost-effective approach that allows reaching large geographic areas (Marcus & Crane, 1986). Another advantage of phone surveys relates to the interviewer control. In contrast to mail or internet-based surveys, phone interviewers can encourage respondents to answer all the questions, and clarify questions to participants (Salant & Dillman, 1994).

### *Sample size determination*

Choosing the sample size is a critical decision in any survey research. The objective is to select the smallest sample size that allows for an adequate confidence level and margin of error, and helps to decrease the occurrence of sampling error and sampling bias (Dillman, 2011). For this study the sample size was estimated at a desired confidence level of 95% and an expected standard deviation of 0.5 (Dillman, 2011; Salant & Dillman, 1994). Using these parameters, and an expected response rate of 25%, an initial sample of 1,525 firms was calculated and rounded up to 1,600 firms. The number of firms from each state to be included in the list was calculated as a proportion of each state's population.

### *Sample development*

The target audience for this survey were U.S. construction firms that work primarily with commercial construction. The population of interest was a subset of the category Commercial and Institutional Construction, listed under the NAICS code 236220. A list of 1,600 U.S. construction firms was randomly selected using the online database managed by the Associated General Contractors of America (AGCA, 2017). The AGCA's member directory provides search tools to generate lists of firms using criteria such as firm's name, geographic location, type of engineering firm, zip code, and keywords. There are currently over 26,000 member firms in the AGCA's database, all through a nationwide network of chapters, from a total of 773,614 construction firms in existence, according to the U.S. Census Bureau (2017), thus representing about 3.3% of all construction firms in the U.S.

### *Questionnaire development*

A survey questionnaire was developed based on the study's objectives and the literature review. The first version of the questionnaire contained an introductory paragraph and 17 questions, 16 of which were of the multiple-choice variety, and one open-ended question. The questionnaire included the topics presented in Table 15. A copy of the survey questionnaire can be found in Appendix 2.

**Table 15. Topics included in the questionnaire for U.S. construction firms.**

<b>Topic category</b>	<b>Topic</b>
Firm and respondent characteristics	Size of the firm
	Location
	Type of constructions the firm works with
	Structural materials most frequently used
Professionals' roles	Roles of architects, engineers and contractors
	Influence in the structural material decision process
Sources of information	How the firm gathers information about structural materials
Wood as a structural material	Frequency the firm uses wood as a structural material
	Perceptions about wood as a structural material
Innovativeness	Perceptions about the firm's innovativeness
Cross-Laminated Timber (CLT)	Familiarity with CLT
	Perceived advantages and disadvantages of CLT
	Perceived factors influencing the adoption of CLT in the U.S.
	Willingness to adopt CLT in the future

### *Survey Pretest*

Prior to the survey implementation, forms and questionnaires were submitted to the Institutional Review Board (IRB) at the University of Minnesota for approval (Appendix 4). After IRB approval, a survey pre-test was delivered through the Internet. The pre-test was conducted by sending the survey to five U.S. construction firms, to identify issues that were overlooked during the questionnaire development and expert evaluation. These companies were asked to provide feedback about the survey's clarity and potential errors. After a week, a reminder was sent to those participants who did not answer. Three firms' representatives answered the pretest. The analysis of the pretest responses did not suggest difficulty or problems in completing the questionnaire and only minor changes in wording were made.

### *Survey implementation*

The phone survey was conducted following the process determined by Lavrakas (1987). Data collection started on December 5<sup>th</sup>, 2016. All 1,600 representatives of the construction firms in our distribution list were contacted via phone and asked to participate in the study. Companies that agreed to participate were asked a convenient date and time for the phone survey. From all the participants, 36 agreed to answer the survey at the time of the initial call and 70 requested to be called at a different day or time. From this subset of respondents, only 32 agreed to participate after the second call. Therefore, the phone survey resulted in a total of 68 complete responses, for a response rate of 4.28%. Many studies published in the literature involving the construction industry have faced the challenge of low response rates (Abul-Rahman et al., 2006; Cao, Li, Guangbin, & Zhang, 2016; Loosemore & Lee, 2002), thus indicating that this industry is very reticent to the participation in surveys. The last phone survey was conducted on February 24<sup>th</sup>, 2017. Data from the surveys was recorded by hand in hardcopies of the survey questionnaire.

### *Data analysis*

After the survey was closed, response data was entered in Excel spreadsheets (Microsoft, 2017) to be analyzed using standard statistical techniques. Descriptive statistics and charts were calculated. Categorical data was evaluated using Chi-square tests. All statistical tests were evaluated at a 0.05 alpha level. Excel (Microsoft, 2017) and SPSS (IBM, 2017) were used for the analyses.

## ***Limitations***

As with any other research method, phone surveys have their limitations and potential sources of error (Dillman et al., 2009; Sue et al., 2012). The most important are listed below.

- *Measurement error:* survey question and answer options could lead to inaccurate data because certain answer options may be interpreted differently by participants.

While this source of error cannot be eliminated, an attempt was made to minimize its magnitude by seeking the input and feedback from experts, and by doing a survey pre-test.

- *Coverage error:* using the AGCA database to compile the mailing list for this survey could introduce a source of coverage error, since not all U.S. construction firms are associated with the AGCA, and some differences may exist between companies that belong to this association and non-members. Also, trends of telephone coverage are always a concern (Lepkowski et al., 2008), since many firms might not have a landline listed with the AGCA.
- In order to make inferences about the relationship between firm location and respondents perceptions, a “multi-region” category was created, grouping those companies with operations in more than one region. Thus, some region-related information was lost from those firms grouped into this category.
- Limitations inherent to any telephone survey apply to this study (Dillman, 2009). Importantly, answers received represent the knowledge of a single professional in a construction firm that may employ many individuals.

## ***Results and discussion***

### *Company demographics*

Participants were asked to indicate the region where they operated (from a list of five U.S. regions) and the number of employees (used as a proxy for company size). Participants were able to check more than one location to indicate that they operated in more than one region. Firms with operations in more than one region were grouped into a new category, called “Multi-region,” for the analysis. Table 16 shows the counts and percentages of respondents for each region and firm size.

**Table 16. Survey participants' responses when asked about the location and size (by number of employees) of their firms. N=68.**

<b>Firm Characteristic</b>	<b>Count of Respondents</b>	<b>Percentage (%)</b>
<b>-- Company Location (U.S. Region) --</b>		
Northeast	10	14.7%
South	15	22.1%
Midwest	13	19.1%
West	12	17.6%
Alaska/Hawaii	2	2.9%
Multi-region	16	23.5%
<b>Total</b>	<b>68</b>	<b>100.0%</b>
<b>-- Firm Size (Number of Employees) --</b>		
1 to 4 employees	12	17.6%
5-9 employees	10	14.7%
10 to 19 employees	14	20.6%
20 to 99 employees	25	36.8%
100 or more employees	7	10.3%
<b>Total</b>	<b>68</b>	<b>100.0%</b>

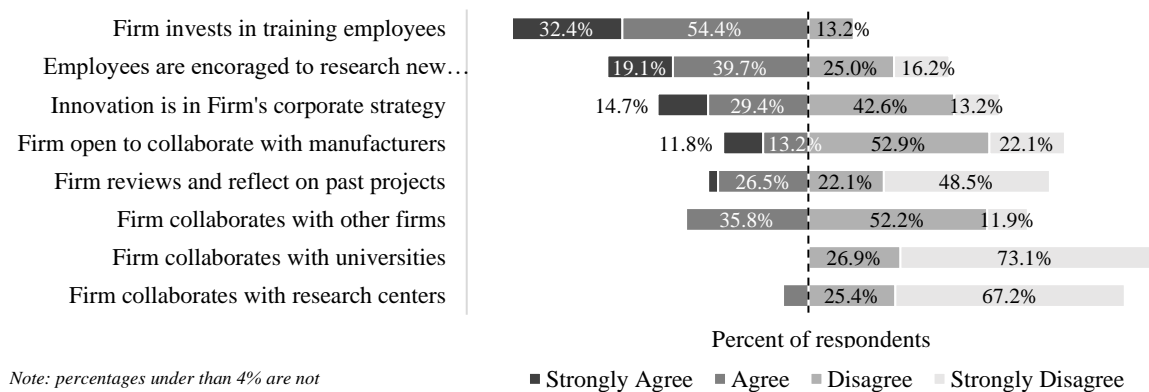
### *Innovativeness*

Firm innovativeness has been cited by many authors as a characteristic that could influence the adoption of new materials by professionals (Gatignon H., 2002; Gronross, 1997; Laguarda-Mallo & Espinoza, forthcoming-a; Rogers, 2003). To understand how innovative the firms perceive themselves to be, and to investigate how innovativeness relates to the likelihood to adopt innovative wood-based materials in the future, construction firm's representatives participating in this study were asked to rate their agreement with a series of eight statements (Figure 10).

Results for these questions are shown in Figure 10. Research conducted on organizational innovativeness, shows that encouraging employees to explore and innovate within the company influence innovative behavior at the individual, job, team and organizational levels (Anderson, 2014; Shalley & Gilson, 2004). Results indicate the majority of firms invest in the training of their employees, with 86.8% of firms agreeing or strongly agreeing to this statement. This is not surprising since contractors have to fulfil special continuing education requirements to renew their license (MN Department of Labor and Industry, 2017). More than half (58.8%) of firms encourage employees to research new materials. The inclusion of innovation in the corporate strategy was reported by 44.1% of

respondents. Of all the statements, those that most respondents seem to be in disagreement were related to collaboration with universities and research centers, with 100.0% and 92.6% disagreeing or strongly disagreeing with these statements, respectively. Similar results for this question were found when the author surveyed U.S. engineering firms (Chapter 2), when 66.3% and 65.7% of participants disagreed or strongly disagreed to collaborating with research centers or universities, respectively.

Interestingly, 25% of respondents strongly agreed or agreed with the statement about being open to collaborate with manufacturers. The author hypothesizes that this could be related to the fact that these collaborations could be technical in nature and could help improve the delivery time and quality of the building. This relative openness of construction firms to collaborate with manufacturers could represent an opportunity for innovative wood-based construction materials manufacturers to reach out to construction firms directly to try out new materials or processes.



**Figure 10. Please rate your agreement with the following statements about your firm. N=68.**

A Pearson’s Chi-square test ( $\alpha=0.005$ ) was performed to determine if there was a significant relationship between innovativeness and other demographic factors. No statistical difference was found between location and innovativeness. However, a significant relationship was found between firm size and all but one item (“Our Firm has a systematic procedure in place to review and reflect on past projects”) measuring

innovativeness. Table 17 shows items for which a statistical difference were found. In the construction community, innovation is seen as a competitive advantage (Farshchi, 2012); however, as in any sector, the successful introduction of an innovation usually implies some upfront investment and therefore carries economic risk (Armstrong, Kotler, & He, 2013). Similarly to what happens among engineering firms (Chapter 2) it is possible that larger firms could be more open to innovation than small firms due to their greater ability to invest in innovation.

**Table 17. Statistically significant association between size of the firm and innovativeness, as per Pearson’s Chi-square test.**

<b>Innovativeness Dimension</b>	<b>P-Value</b>	<b>Chi-square</b>
"Employees in our Firm are encouraged to research new materials"	0.011	13.076
"Our Firm collaborates with universities to investigate new materials"	0.000	46.313
"Our Firm collaborates with research centers and governmental agencies to investigate new materials"	_*	_*
"Our Firm is open to find innovative solutions by collaborating with materials suppliers/manufacturers"	0.001	18.948
"Our Firm invests in the training and development of its employees"	0.011	13.080
"Innovation is incorporated in our Firm's corporate strategy"	0.000	28.549
"Our Firm is receptive to changes and new technologies"	0.014	12.438
"Our Firm has a systematic procedure in place to review and reflect on past projects"	0.066	8.810

*\*Analysis could not be performed due to low response count.*

### *Type of buildings*

Respondents were asked about the main type of building their firm works with. Responses to this question are shown in Table 18. As expected, per our sampling method, more than half (67.2%) of respondents indicated that they work primarily with commercial construction and 22.4% with single-family residential buildings.

**Table 18. What are the main type of buildings your firm works with? Please, mark all that apply. N=68.**

<b>Type of Building</b>	<b>Count of Respondents</b>	<b>Percentage (%)</b>
Commercial	45	67.2%
Multi-family residential	34	50.7%
Educational	20	29.9%
Recreational	19	28.4%
Industrial	19	28.4%
Single-family residential	15	22.4%
Others	10	14.9%
Transportation	6	9.0%
Governmental	2	3.0%
Religious	2	3.0%
Non-response	1	1.5%

*Note: More than one option was possible (percentages add to more than 100%)*

### *Materials used by type of construction*

According to an exploratory study conducted by Laguarda-Mallo and Espinoza (2016), the decisions about the structural materials are made early on in the design process, during the pre-design phase. These decisions are influenced by many factors such as type of building and budget, among others. When asked about the materials used by type of construction, all participants indicated wood-frame as the main type of materials used for single-family and multi-family residential building construction. From all respondents, 89.5% also indicated wood-frame being used for educational buildings. Due to the smaller scale (less complex and low to mid-rise buildings) and lower structural requirements of single and multi-family building, light wood-frame construction is, in the majority of cases, more cost-competitive material than concrete or steel alternatives (Laguarda-Mallo & Espinoza, 2016). Due to the modular nature of educational buildings (Burnett, 2014), prefabricated wood-frame elements are usually chosen to increase the speed of construction and reduce project cost. According to respondents, for buildings with more complex structural requirements, such as transportation, recreational, industrial and governmental buildings, concrete and steel (or a hybrid of both) are usually selected as main structural materials. As for commercial buildings, Table 19 shows the results for this category.

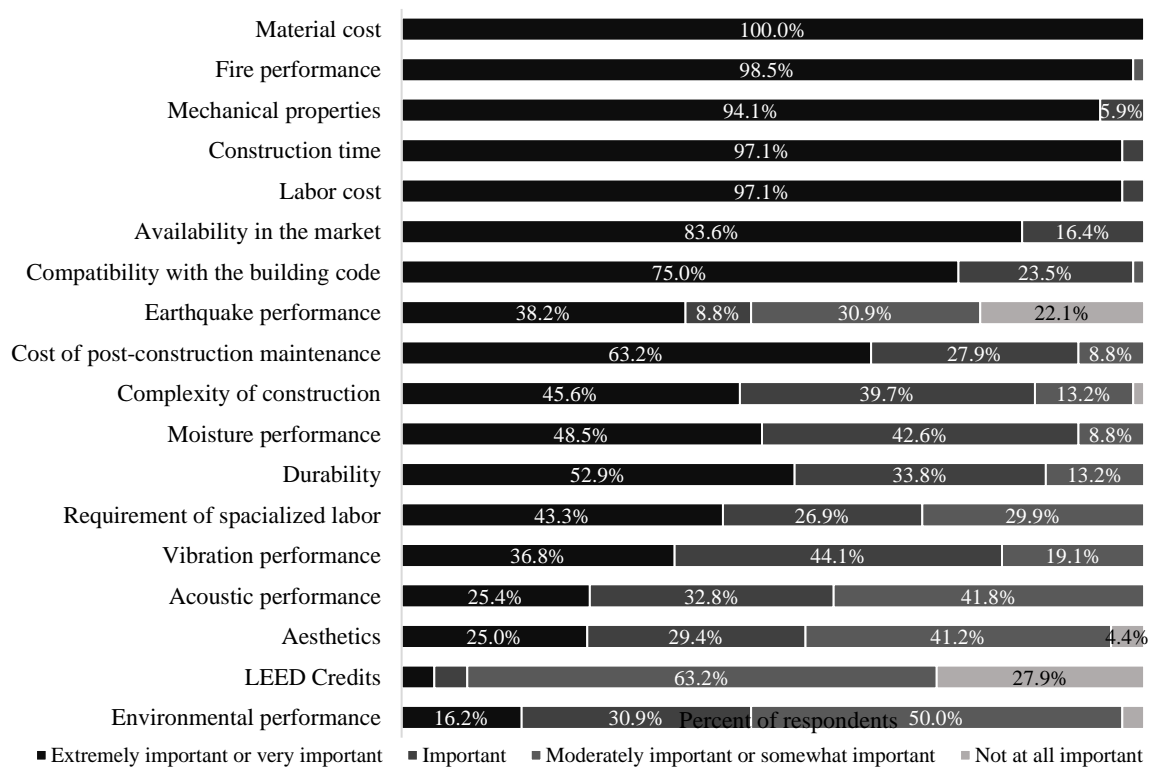
**Table 19. Please indicate what are the structural materials (or combination of materials) you typically use above the foundation, for commercial buildings. N=68.**

<b>Materials</b>	<b>Percentage (%)</b>
Wood	34.1%
Concrete	36.4%
Steel	40.9%
Masonry	0.0%
Concrete + Wood	9.1%
Steel + Wood	2.3%
Concrete + Steel	6.8%

Results in Table 19 indicate that for commercial buildings, wood, steel and concrete are most frequently chosen for the structure above foundation, while 9.1% use a mix of concrete and wood and 6.8% a mix of concrete and steel. Due to the small number of responses for each question category, a Chi-square test could not be performed to evaluate the relationship between materials used and other items in the questionnaire.

#### *Importance of materials characteristics*

Decisions about the choice of a structural material for a construction project are influenced by the priorities and perceptions of the construction professionals regarding the attributes of different materials. Thus, participants to this study were asked to rate the importance of a number of characteristics when specifying a structural material. A 4-point Likert scale was used for the responses, from “extremely important” to “not at all important”. Figure 11 shows the results to this question.



**Figure 11. Please rank the importance of the following characteristics at the time of specifying a structural material. N=68.**

These results indicate that the most important characteristics that engineers look for in a construction material are material cost (100% of respondents rated this attribute as “extremely important” or “very important”), fire performance (98.5%), mechanical properties (94.1%), construction time (97.1%), and labor cost (97.1%). LEED credits and earthquake performance did not seem to be high in the contractors' priorities when selecting a material, with 27.9%, and 22.1% of respondents rating these characteristics as “not at all important.” It is possible that the high importance placed on the economic performance of structural materials (e.g. material and labor cost, construction time, availability in the market and cost of post-construction maintenance) relates to the fact that contractors are

usually in charge of controlling the project's time, cost and quality (Betts, Brandon, & Nfa, 2003).

It is presumed that features such as mechanical and fire performance, which are also related to the structural performance of a structure, were rated the highest because of concern for the occupants' safety and the liability implications (Laguarda-Mallo & Espinoza, forthcoming-a; Pealer, 2007; Sido, 2006).

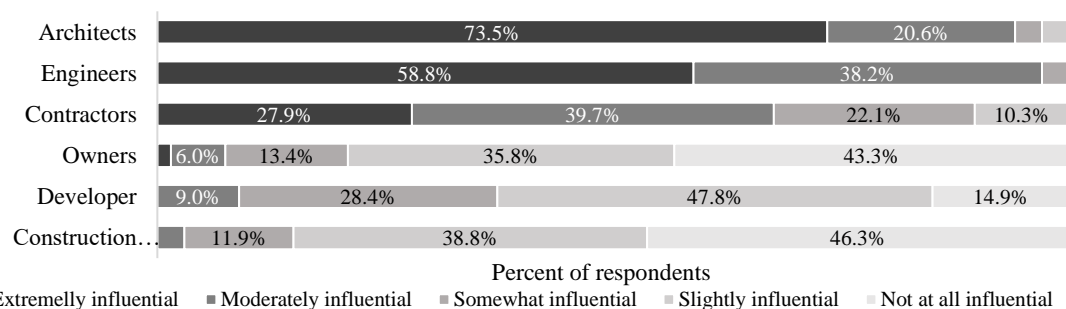
Aesthetics, which was highly rated by architects in a previous study (Appendix 1), was considered of very low importance for the construction firms surveyed, with only 25.0% of participant indicating that this is extremely or very important at the time of selecting a structural system. This response can be understood considering that contractors are, in most cases, not as directly involved with the design of the building as architects or structural engineers (Chapter 3). LEED Credits were rated as "extremely important or very important" feature of a structural material by a very low percentage of respondents (4.4%). Similarly, this item was also rated high ("extremely important" or "very important") by only 4.8% of architects and 3.5% of engineers surveyed in previous studies (Appendix 1 and Chapter 2). It is hypothesized that the low importance placed on the LEED Certification during the material selection process is associated with the fact that only 1 point (out of the 69 possible points available to obtain the LEED Certification) is awarded if wood (structural and non-structural) is used in the building. This suggests that rising the relevance of wood in the "Materials and Resources" category would encourage construction professionals interesting in LEED certification to use more wood in their projects (Bland, 2010).

Results from this research can be compared with those obtained by similar studies about U.S. architecture and engineering firms (Appendix 1 and Chapter 2). Construction professionals in general place high importance on cost and structural capabilities of the materials, but show different attitudes toward aesthetic performance. Aesthetics was rated "very important" by 94.0% of architects, 6.2% of engineers, and 4.4% of contractors that participated in the aforementioned studies. Conclusions from previous studies cited suggested that geographical location may have strong influence on engineers' priorities. Therefore, Chi-square tests ( $\alpha = 0.05$ ) were performed for each material characteristic

to determine if location and size of a firm have an effect in the way each characteristic was rated. Tests showed statistically significant differences between the responses from firms in different locations for earthquake performance (p-value = 0.049 and Chi-square = 6.019). This can be understood in light of the fact that some regions, mainly those on the Pacific coast, seismic events are more of a concern than in other regions of the country (Dieterich & Okubo, 1996; Koyanagi, Endo, & Ward, 1976).

### *Influence in the material decision process*

In order to learn about the role of different actors in the structural material decision process, U.S. construction firms' representatives surveyed were asked to rate the level of influence that architects, engineers, contractors, construction managers, developers, and owners have during this process. Figure 12 summarizes the responses to this question. As expected, architects and engineers were considered "extremely influential" by 73.5% and 58.8% of participants, respectively. Contractors, on the other hand, were considered "extremely influential" by only 27.9% of U.S. construction firms representatives. When engineers interviewed in a previous study (Chapter 3) were asked which professionals (architects, engineers or contractors) has the most influence when it comes to deciding which structural material is selected, there was an almost unanimous consensus that architects and structural engineers are the main decision-makers during this process.



*Note: Percentages below 4% are not shown.*

**Figure 12. Please, indicate the level of influence these actors have during this structural material selection process. N=68.**

As for the least influential actors, construction managers and owners were seen as “not at all influential” by almost half of respondents (46.3% and 43.3% respectively). This could be understood by the fact that construction manager’s function is to manage and oversee the day-by-day construction of the project (e.g. on time material delivery, tool availability, personnel availability and safety, etc.) (Smith & Roth, 1991) and are not usually involved in the design phase, therefore their influence in the materials decision process is very limited. In regards to owners, their role greatly depends on the type of owner (e.g. individual, private company, or public agency) and specific project characteristics (Hendrickson, 2008). As stated by Hendrickson (2008), there are two types of owners. The first are owners that have in-house professionals capable to handle the work in every stage of the entire construction process. In this case, the owners influence is extremely high. The second type of owners are those that hire outside professionals for the work in all stages from planning, design, to construction. This type of owner is usually less involved in the design process and therefore has minimum influence during the structural material selection process. The author hypothesizes that this could be the reason why 7.5% of respondents indicated that owners are extremely or moderately influential during the material selection process.

#### *Level of awareness*

The adoption of a product depends to a great degree on the awareness about the product that exists in the target market. Therefore, one of the main objectives of this study was to determine the level of awareness about CLT in the U.S. construction community. Participants were asked to indicate their familiarity with CLT, using a 4-point Likert familiarity scale, from “very familiar” to “never heard about it.” The results to this question, presented in Table 20 show that the overall level of awareness about CLT among U.S. construction firms is low. A combined 88.3% of respondents indicated being “not very familiar” or that they “have not heard about CLT.” This indicates that there is a clear need for education and training about CLT in the construction community if this product is going to be more widely adopted in the U.S.

**Table 20. How familiar are you with Cross-Laminated Timber (CLT)? N=68.**

<b>Level of Awareness</b>	<b>Count of Respondents</b>	<b>Percentage (%)</b>
Very familiar	2	2.9%
Somewhat familiar	6	8.8%
Not very familiar	8	11.8%
Have not heard about it	52	76.5%

If we compare the results from the present study of U.S. construction firms with previous studies (Chapter 2 and Appendix 1), it can be seen that the level of awareness about CLT among contractors is far lower than for architects and engineers. Among architects, 42.2% of respondents indicated to be “very familiar” or “somewhat familiar” with CLT; and this percentage among structural engineers was 37.2%. However, only 11.7% of contractors surveyed for this study indicated to be “very familiar” with CLT. A possible explanation for the low awareness could be associated with how new the system is in the U.S. market and insufficient education efforts towards contractors. Another explanation could be associated with the lower level of “innovativeness” among construction firms, in comparison to engineering firms (Chapter 2).

A Pearson’s Chi-square test ( $\alpha=0.005$ ) was performed to determine if there was a significant relationship between the level of awareness and demographic factors. No statistical difference was found between location and awareness. However, a significant relationship was found between awareness and size of firm (p-value = 0.017 and Chi-square = 24.515). A plausible explanation is that larger firms have more financial resources to allocate to the education and training of their employees, which could be associated to more opportunities to attend professional meetings conferences or workshops where the latest developments in materials and construction practices are discussed.

Since the following questions required some knowledge of CLT, those participants that reported no prior knowledge of CLT were read a short description about CLT. The “CLT primer” was followed by two questions, one regarding the participants’ interest in learning more about the system and a question regarding the adequacy of the system for their future projects. From the 52 respondents that indicated not knowing about the system, 26 said they were “very interested” or “interested” in knowing more about it. In regards to the

suitability of CLT for the respondents' future projects, 14 indicated that CLT could be “very likely” or “likely” adequate while 22 indicated uncertainty. This uncertainty is consistent with the low familiarity of these respondents with the system.

The following section will explore the responses of the 16 participants of the study that indicated having some familiarity with CLT. To assess how firms learn about CLT and evaluate which methods of communication are more efficient for this type of audience, contractors were asked to indicate how they heard about CLT. The results in Table 21 show that most firms learned about CLT from the internet, conferences/workshops, and word-of-mouth (10, 6 and 4 responses respectively). Radio, academic journals, magazines, and television did not get responses from any of the participants.

**Table 21. How did you hear about Cross-Laminated Timber (CLT) for the first time? N=16.**

Sources	Count of Respondents
Internet	10
Conference/Seminar/Workshop	6
Relative or Friend	4
Newspaper	1
Other	1
Television	0
Magazine	0
Academic Journal	0
Radio	0

*Note: More than one option was possible (percentages add to more than 100%)*

### *Perceptions about CLT*

Perceptions are fundamental in new product adoption, because what consumers feel and believe about a product can be just as important as what that product actually provides in terms of performance (Cooney, 2014; Laguarda-Mallo & Espinoza, forthcoming). Therefore, it is essential to learn how potential adopters, such as contractors, view CLT's characteristics as a building material. With this purpose, participant firms were asked to evaluate their perceptions of CLT's performance compared with other materials (e.g., steel and concrete), on eleven attributes, using a 5-point Likert scale going from “excellent” to “poor.” A “don't know” option was also possible. Results for this question are presented in Table 22.

**Table 22. Attributes of CLT in order of the highest rated (on top). N=16.**

Attributes of CLT	Environmental performance
	Aesthetics
	Labor cost
	Complexity of construction
	Construction time
	Mechanical properties
	Requirement of specialized labor
	Earthquake performance
	Fire performance
	Building Code
	LEED Credits
	Durability
	Moisture performance
	Vibration performance
	Acoustic performance
	Availability in the market
Material cost	
Cost of post-construction maintenance	

As Table 22 shows, CLT’s environmental performance, aesthetics and labor cost were rated very highly by respondents with previous knowledge about CLT. This is in agreement with the results from the study of U.S. architecture and engineering firms (Appendix 1 and Chapter 2), in which aesthetics, environmental were also the highest ranked CLT attributes. The lowest ranked characteristics by U.S. contractors were availability in the U.S. market, material cost, and acoustic and vibration performance. Even though CLT’s acoustic and vibration performance have been considered by many professionals as a drawbacks of the system, according to a study conducted to U.S. architecture firms by the author of this study (Appendix 1), acoustic problems could occur due to, for example, shortcomings in the installation and the lack of proper linings. In regards to the availability in the U.S. market, CLT panels are not yet widely available, only two manufacturers are certified to produce CLT panels for structural use under the ANSI/APA PRG 320 Standard for Performance rated CLT (ANSI, 2012).

Most respondents (15 respondents out of 16) indicated no knowledge of CLT’s maintenance cost. Similarly, 11 contractors indicated not knowing about LEED Credits applicable for CLT constructions and 10 indicated not knowing about CLT’s moisture performance or material cost. A great opportunity exists for researchers and organizations to look into these topics and bridge the existing information gaps. Due to low response rate

for this question, Chi-square tests could not be performed to evaluate the relationship between how CLT attributes are perceived and other questions within this survey.

#### *Willingness to adopt*

The third objective of this study was to determine if the population of interest would be willing to adopt CLT if it were available in the market. This information is essential to evaluate the potential market success of CLT in the U.S. From the 16 respondents to this question, 10 indicated to “very likely” or “likely” adopt CLT in one of their building projects if it was available in the U.S.; five were “uncertain” and one indicated to be “unlikely” or “very unlikely” to adopt the system in the future. These findings are consistent with the level of awareness reported previously, as more than a third of professionals would be hesitant or “very unlikely” to adopt a material with which they are not very familiar.

#### *Barriers to the adoption of CLT*

To understand the market opportunities of CLT in the U.S., it is important to determine and understand the perceived barriers to its adoption. Respondent firms were asked to rate ten possible barriers, using a 3-point Likert scale going from “large barrier” to “not a barrier.” The largest barrier according to respondents is the lack of availability of CLT in the market (11 respondents considered it a large barrier or a potential barrier). Overall, 10 respondents saw the amount of wood required to manufacture the panels as a large or potential barrier to the adoption of CLT in the U.S (Table 23).

Compatibility with the building code and maintenance costs were seen as potential barriers by almost all respondents (14) to this question. Table 23 shows that the promotion and education, as well as availability (or lack thereof) of technical information about the system “may be a barrier” or was a “large barrier.” These findings open the opportunity for organizations to continue their work promoting the use of wood in general, and mass timber systems in particular, and educating U.S. construction professionals. Due to low response rate for this question, Chi-square tests could not be performed to evaluate the relationship between how CLT attributes are perceived and other questions within this survey.

**Table 23. Perceived barriers in order of the highest rated (on top). N=16.**

Barriers to the adoption of CLT	Availability in the market
	Amount of wood required
	Promotion/Education
	Material cost
	Availability of technical information
	Maintenance cost
	Compatibility with Building Code
	CLT performance as a construction system
	Labor cost
	Construction time

## *Conclusions*

The main goal of this study was to assess the level of awareness, perceptions and willingness to adopt CLT by construction firms in the United States. For this purpose, a phone survey was conducted among U.S. construction firms that work primarily with commercial buildings.

The results show that the level of awareness among construction firms is low in the U.S, since only two respondents, out of 68, indicated to be “very familiar” with the system. When asked about how the participants heard about CLT, ten firms indicated that they obtained the information from internet, six from conference, webinar or workshops and four through a friend or relative. These findings are consistent with the results obtained from a similar study conducted by the author with U.S. architecture firms (Appendix 1) and U.S. engineering firms (Chapter 2).

Information obtained from the survey indicates that the highest ranked features of CLT are its reduced labor costs, aesthetic characteristics, and its environmental performance, and faster construction time. On the other hand, availability in the market was one of the lowest ranked features of the product, which coincides with the current state of CLT market in the U.S. Interestingly, most of our respondents indicated to have no knowledge about the cost of post-construction maintenance, which opens the opportunity for research institutions and universities to further the research in this area. Regarding the perceived barriers, respondents indicated that CLT's availability in the market, the amount of wood requires as well as the promotion/education (or lack of thereof) were the largest hurdles to wide

adoption of the system in the U.S. A considerable percentage of participants of this study perceived that the material's cost, compatibility with the building code and maintenance cost could be potential barriers to the adoption of CLT in the U.S. This is in accordance with the lack of experience about CLT among U.S. construction professionals. Findings from this study also show that similarly to architect and engineers, contractors are hesitant to adopt CLT if it were available in the market.

The results stress the need for improved educational resources available for potential adopters, such as contractors. For example, there could be an opportunity to include seminars or workshops about CLT construction as part of the existing continuing education requirements for licensed contractors. Findings indicate that there are many research needs that should be addressed prior to a wide adoption of the system in the U.S., in particular in regards to maintenance requirements, schedule and cost. Further research should also be carried out in regards to material cost in comparison to other structural systems, such as concrete and steel, and LEED Credits.

As with any new product adoption, it will take time and effort to get people to trust the material. This can only be done by increasing the system's availability in the U.S. market, and promoting the use of CLT among potential adopters.

# Chapter 5

## U.S. Construction Firms Interviews

## ***Introduction***

The main objective of this part of the study was to follow up on the survey conducted to U.S. construction firms (Chapter 4) and gain a deeper understanding of the level of awareness, perceptions and willingness to adopt CLT by these firms, one of the key actors in the structural material decision process. This qualitative study also aimed to investigate how the structural material decision process takes place and who are the most influential actors. Based on the information from the interviews to experts (Appendix 1) and preliminary economic analysis conducted by Crespell and Gaston (2011), a decision was made to focus on U.S. construction firms that work primarily with commercial construction.

## *Methodology*

The research approach followed for this study, similarly to the study presented in Chapter 3, is comprised a set of semi-structured interviews carried out with the purpose of collecting insights and in-depth information about the structural material selection process, and awareness and perception about CLT, among U.S. contractors. A list of 130 U.S. construction firms was compiled based on recommendations from construction industry representatives, construction academics from the School of Architecture and Construction Management Program at the University of Minnesota, with the aim to recruit 30 firms for the interviews. Three participants of the Mass Timber Conference held in Portland in March 2017, were also recruited for this study.

### *Questionnaire design*

A semi-structured questionnaire was used to obtain information and insights on topics relevant to existing and potential markets for CLT in the U.S. A questionnaire with 13 open-ended questions was developed. A copy of the questionnaire can be found in Appendix 3. In order to assure the relevance, consistency and clarity of the questions, the questionnaire was reviewed by academics with extensive experience in interviews design and implementation. The topics included are listed in Table 24.

**Table 24. Topics included in the questionnaire to construction firms.**

<b>Topic category</b>	<b>Topic</b>
Firm and respondent characteristics	Position of the interviewee within the firm Size of the firm Location Type of constructions the firm works with Structural materials most frequently used
Professionals' roles	Roles of architects, engineers and contractors Influence in the structural material decision process
Sources of information	How the firm gathers information about structural materials
Wood as a structural material	Frequency the firm uses wood as a structural material Perceptions about wood as a structural material
Innovativeness	Perceptions about the firm's innovativeness
Cross-Laminated Timber (CLT)	Familiarity with CLT Perceived advantages and disadvantages of CLT Perceived factors influencing the adoption of CLT in the U.S. Willingness to adopt CLT in the future

*Interview implementation*

Firms in the list generated in a previous step were contacted via phone and invited to participate in the study. A short description of the study was used to inform potential participants of the objectives of the research. Firm representatives that agreed to participate were then asked for a convenient date and time to conduct the interviews. Ten representatives agreed to respond to the questionnaire via email due scheduling conflicts. The rest of the interviews were conducted via phone in the spring of 2017. Phone interviews lasted 15 minutes on average. Interviews were recorded with the consent of participants, and notes were also taken as backup. Recordings and notes were then coded and analyzed using Excel Spreadsheets (Microsoft, 2017), and following the standard guidelines for qualitative research (Berg & Berg, 2001).

***Limitations***

A number of limitations may have affected the results obtained from this qualitative study. Limitations include:

- Due to the small sample size, generalization of the conclusions to the population of interest is not feasible. The main purpose of this qualitative study was to explore the material decision process in the construction industry and evaluate the level of awareness, perceptions and willingness to adopt CLT by U.S. contractors.
- The absence of visual cues via telephone results in loss of contextual and nonverbal data, which may cause some loss of information (Opdenakker, 2006).
- Telephone interviews typically need to be short, thus reducing in-depth discussion (Chapple, 1999).

## ***Results and discussion***

### *Demographic information*

Thirty interviews to U.S. construction firm's representatives were conducted. Table 25 shows the demographic information of respondents and their companies. Most participants work as "construction project managers," and work in mostly medium-size to large companies, with over 100 employees. From the 30 firms participating in this study, half (15) indicated to have offices and clients in more than one region of the country.

**Table 25. Interviewee characteristics (30 interviews).**

<b>Interviewee Characteristics</b>	<b>Frequency</b>
<b>-- Position in the Firm * --</b>	
General Manager	3
Vice President	7
Senior Project Manager	4
Chief Operating Officer	2
Construction Project Manager	11
Partner/Owner	2
Project Superintendent	1
<b>-- Size of the Firm --</b>	
Less than 5 employees	0
Between 5 and 9 employees	2
Between 10 and 49 employees	4
Between 50 and 99 employees	1
More than 100 employees	23
<b>--Location of the Firm *--</b>	
South	9
Midwest	10
Northeast	4
West	5

*\* Multiple answers were possible.*

### *Type of buildings*

Participants were asked to mention which types of buildings their firm works on. A great majority of the interviewees (25 of 30 participants) indicated that their firm work primarily with commercial buildings (e.g. office buildings, restaurants, retail stores, hotels, markets, malls, etc.) and 14 indicated working with residential building developments (e.g. Multi-family residential complexes, condos, duplexes, dormitories, town-homes, etc.). Of the 30 engineers interviewed, 12 had worked with healthcare facilities (e.g. hospitals, clinics, outpatient medical centers, dental offices, etc.). From all participant of this study, 10 had been engaged in the construction of industrial (e.g. manufacturing facilities, storage, energy plants, etc.) and educational (e.g. schools, colleges, libraries, museums, theaters, etc.) in the past. Six participants indicated having experience with institutional buildings, three had experience with governmental buildings, and only two participants indicated being involved in the construction of religious buildings.

*Very weak*Type of structural materials used

To evaluate the firm's attitudes towards different structural materials, interviewees were asked about the materials frequently used for a number of building types, and the reasons why they believed each material was selected. Responses to this question are summarized in Table 26.

**Table 26. Predominant structural materials (or combination of materials) by building type.**

<b>Building type</b>	<b>Materials primarily used</b>
Multi-family residential <i>(e.g. condos, apartment buildings, townhouses, etc.)</i>	light-wood and steel frame
Commercial buildings <i>(e.g. offices, restaurants, retail stores, hotels, etc.)</i>	concrete, steel, light-wood and steel frame, and precast concrete
Educational buildings <i>(e.g. schools, universities, libraries, etc.)</i>	Light wood and steel frame, concrete, steel, and masonry
Governmental buildings <i>(e.g. city halls, courthouses, embassies, etc.)</i>	concrete, steel, and precast concrete
Religious buildings <i>(e.g. churches, temples, chapels, etc.)</i>	concrete, steel, light-wood frame
Healthcare facilities <i>(e.g. hospitals, clinics, etc.)</i>	concrete, steel, precast concrete and masonry

Of the 30 construction firm's representatives interview an overwhelming majority (29 respondents) indicated to use concrete, 23 indicated to use steel and 18 light wood-frame construction. From the 18 professionals that had worked with wood-frame construction in the past, two indicated to have used mass timber solutions (e.g. glulam elements) "*...for aesthetic reasons.*" Ten interviewees mentioned having used prefabricated concrete elements in their buildings in the past (e.g. pre-cast and/or pre-stressed beams, columns and planks; hollow core slabs, etc.). One interviewee indicated that "*... [these prefabricated concrete elements] are often used to reduce the cost and time of construction. A pre-cast element can cost in average 20% less than an identical cast-in-place element,*

*and that makes a tremendous difference in the overall cost of the construction.*” The positive perceptions about prefabricated concrete elements could play a favorable role in the adoption of prefabricated wood-based structural system, since they have many attributes in common. Previous research conducted by the author of this dissertation has shown that the use of CLT elements could help reduce an average of 20% of construction cost and 40% of construction time depending on the characteristics of the project, thus making them attractive for construction firms looking to reduce the overall cost of building developments (Laguarda-Mallo & Espinoza, 2016).

When respondents were asked to elaborate about the reasons for each selection, they indicated that the main drivers for selecting the materials were material, labor and maintenance costs compared to other solutions; availability of material and workforce; and durability and longevity. One interviewee that works in residential construction mentioned that, *“concrete and structural steel are usually used for industrial, healthcare and office buildings. Durability and longevity go together, and of these structures is always key to select materials that can perform well over time. For housing projects, we work a lot with student housing and senior living facilities, the lifespan is about 50 years. In these cases, concrete podium and light wood-frame solution has been frequently selected, among other things, to reduce the cost of the project, while still guaranteeing the longevity of the structure.”* Another contractor said that *“[wood is] usually viewed as a 30-40 year building material where concrete/masonry/steel are viewed as 150+ year building materials. 30-40 year construction is ideal for a private developer, but would be completely unacceptable for a public building.”* The main factor affecting the longevity of wood buildings is durability, in particular related to moisture issues of structural elements (Morris & Wang, 2011). Research to measure the longevity of wood buildings is scarce (Stauder, 2013), however, construction professionals can improve the longevity of a building by carefully designing and detailing the projects taking into consideration location, and weather and soil conditions at the site (FPInnovations, 2011; Morris & Wang, 2011). By including elements such as cladding, moisture barriers, and adequate air spaces around the CLT panel, rainwater can easily be deflected and drained, allowing a fast drying and

guaranteeing the durability of the wooden elements (Straube, Ge, McClung, & Lepage, 2013).

The influence of material and labor availability in the construction cost is a well-known factor that can discourage new developments (Wellington, Fillmore, & Robert, 2003). The escalating cost of many construction materials, the shortage in labor, and inflation have been slowing new commercial construction and pressuring construction firms throughout the country and in particular more remote areas of the U.S. (AGCA, 2017; Kyle, 2017). In regards to material and workforce availability, one interviewee mentioned “...*location of the building site always influences the material selection. It is important to consider what we have available in the region or if we need to bring materials or workers from other states. These decisions can make or break a budget.*” Similarly, two other contractors working in the Midwest indicated that the “...*regional [carpentry] unions are relatively small, which makes it harder to find workers.*” In contrast, an interviewee working in other regions stated that “...*with the current boom in wood framed commercial projects, the labor force that can support wood framed structures has grown significantly which improves labor pricing.*” These statements indicate that the ease in the use of wood is highly dependent on the location where the project is located.

#### *Perceptions about wood as a structural material*

When asked about the perceived benefits of using wood for construction, eight interviewees mentioned wood’s favorable economic performance as the first most mentioned benefit of the material. Wood is an abundant and readily available material nationwide, that can be usually sourced locally and delivered to site quickly (AFF, 2017). Wood is also a significantly lighter material when compared to concrete or steel which makes wood-based buildings require less complex and expensive foundations (Adams, 2017; AFF, 2017). Additionally, many wood element used in construction can be prefabricated off-site which helps reduce construction time and therefore help keep construction costs down (ReThink Wood, 2012).

Regarding the advantageous economic performance of wood, one interviewee stated that wood “...*is cost effective, easy to work and insulates better than steel stud framing,*

*therefore it is used almost whenever possible.*” Another interviewee also added that, *“wood tends to be cheaper than other options and the construction usually goes faster.”* Interestingly a contractor working mainly with commercial and residential construction declared *“wood serves an important role in meeting a cost initiative while offering sufficient structural integrity to meet the demands of multi-story buildings.”* Another participant of this study also stated that the economic benefits of wood construction can also be seen during the end-stage of the building life-cycle: *“It's inexpensive, lightweight, workable, uses lower cost labor than some other materials, and is less costly to demolish someday.”* Responses from these questions show that construction time and cost seem to be the most advantageous benefits of wood construction for U.S. construction. The author of this dissertation believes that an innovative wood-based construction system that capitalizes on these benefits could be well accepted by construction professionals in the country.

The environmental performance of wood was the second most mentioned perceived benefit of this material. Interviewees stated that the natural, renewable and energy efficient nature of wood are all advantages over traditional building materials such as concrete and steel. Similarly to what is presented in Chapter 3, where some U.S. engineering firms stated that their clients requested them environmentally-friendly materials, *“many of our clients are concerned with the environment and the effect materials have in the health of the building occupants, are specifically asking for more natural and chemical-free construction materials, and in that sense nothing compares to wood.”* A number of studies conducted over the past decades have concluded that wooden elements have lower greenhouse gas emissions, and require less energy input and water usage when compared to equivalent concrete or steel elements (Cabeza, 2014; Robertson, Lam, & Cole, 2012; Ximenes, 2013).

Five interviewees also stated that another benefit of wood relates to its workability (defined by Campean, Ispas and Porojan (2008) as *“the absorbed power and specific resistance to cutting during milling”*) in comparison to traditional materials. One contractor stated that *“the ease of workability of wood cannot be compared with any other material.”* In contrast to the study conducted to U.S. engineering firms presented in Chapter 3, where some

engineers interviewed saw the aesthetic characteristics as an additional advantage of wood construction, only one contractor interviewed for this study considered this attribute an advantage over other materials. This can be explained in part by the fact that contractors are not usually involved in the design of projects and join later during the construction phase.

In regards to wood's perceived disadvantages, wood's natural defects and poor durability were mentioned as the least favorable characteristic of wood by six participants of this study, with one interviewee saying: "*Wood is a fine structural material, but has more factors like shrinkage or warping to consider.*" Another contractor added that "*[wood] can be strong, but has a greater potential for imperfections in the material (splitting boards, knots, etc.)*" The same respondent also added that wood "*...is also more susceptible to fire, termites [and to] damage from strong winds and tornados, compared to a concrete or steel structure.*" Another participant said that, "*[wood] is not preferred due to quality control concerns and preference for working with more durable structural materials.*" Several participants indicated fire and structural performance of wood elements as their main concerns regarding of wood-based materials. One respondent mentioned that, "*historically [wood] has had trouble overcoming fireproofing concerns.*" However, according to one interviewee, wood's inherent challenges can also be overcome by creating hybrid options where wood and concrete work together: "*In previous projects I've seen wood and concrete toppings used to achieve structural and fire-resistive needs.*" Table 27 shows a summary of all the perceived advantages and disadvantages of wood as a construction material and the frequency in which they were mentioned by respondents.

**Table 27. List of advantages and disadvantages of wood as a construction materials most commonly mentioned by construction firms (30 interviews). Responses are listed by frequency. Mostly mentioned items are at the top.**

Advantages of wood	<hr/> cost-competitive environmentally friendly workability structural performance fast construction design versatility good insulator readily available familiarity aesthetics lightweight dependable <hr/>
Disadvantages of wood	<hr/> durability fire performance expensive dimensional stability structural performance limited spans/height limited union in Midwest quality assurance issues biological attack susceptible to wind damage <hr/>

### *Roles of construction professionals*

During the interviews, participants were asked about the roles of architects, engineers and contractors in the structural material decision process. Most of the contractors interviewed indicated that collaboration between architects, engineers and contractors is crucial for the success of the building construction. For example, one contractor stated, “[collaboration] varies from job to job and procurement approach. We generally prefer a collaborative approach where the architect, engineer and contractor work together to find the most cost effective solution that takes into account aesthetics, performance, and cost.”

When asked which of the construction professionals have the most influence when it comes to deciding the type of structural material, most contractors interviewed indicated that both architects and structural engineers are the main decision-makers during the structural material decision process. One contractor stated that, “Initial selections are typically made by the architect and engineer in the conceptual stages with input from the builder.” More specifically, another contractor indicated that “...typically the architects determine which

*structural material are chosen with consultation from the structural engineer. We are asked about budget and schedule concerns for the material.*” Similarly, another participant said that, *“The architects and engineers have the primary role in selecting materials for the projects we work on. We provide feedback with regards to material availability, project sequencing, and other logistic which may sway the decision.”* These results confirm the findings from the previous study conducted by the author of this dissertation about U.S. engineering firms and presented in Chapter 3. Non-profit organizations committed to providing information about the use of wood for commercial construction to potential adopters should focus their efforts in reaching out to architects and engineers first, as these are the professionals with the most influence during the material decision process. In a second stage, effort should be directed to contractors, developers and the public as their influence is less prominent.

#### *Sources of information*

To assess how firms learn about new building materials and evaluate which methods of communication are more effective for this type of audience, contractors interviewed were asked to indicate what their preferred sources of information were. The responses (Table 28) show that most firms learn about new materials from colleagues and peers, web searchers and conferences, which were considered by one contractor interviewed as *“...a great source to be able to get first-hand information.”* One participant stated that information gathered is dependent on *“...the suppliers and distributors of those materials and the amount of 'advertising' they do.”* Adding that *“this can be done in multiple ways; internet, magazines, workshops, conferences, etc.”* Least mentioned media were books, educational sessions (e.g. Lunch and Learn sessions) and webinars. These results show an opportunity to promote innovative materials through articles and reports published on the internet, presentations during conferences and by reaching out to other construction professionals such as architects and engineers.

**Table 28. Sources used to gather information about structural materials (30 interviews). Responses are listed by frequency. Mostly mentioned items are at the top.**

Sources of information
Colleagues/Peers
Internet
Conferences
Magazines
Suppliers/Manufacturers
Past experience/projects
Subcontractors
Journals/Papers/Research
Webinar
Educational sessions
Books

### *Firm's innovativeness*

As stated in previous chapters, over the past three decades many studies have been conducted to evaluate the factors that influence adoption of new products by consumers (Gatignon H., 2002; Gronross, 1997; Rogers, 2003). A wide range of factors have been found to potentially influence the adoption of new products (for further information about this, refer to Chapter 1 - Literature Review). One of these factors is firm's innovativeness, defined by Hirschman (1980) as *"a driver of adoption intention and adoption behavior, as it captures the propensity of consumers to adopt new products."*

To evaluate to what extent contractors that participated in the study perceive their firms as innovative, interviewees were asked to indicate the importance that innovation plays within their firm. Of the 30 engineers interviewed, nine firms indicated that their firm was very innovative, five participants indicated to be somewhat innovative and fifteen consider their firm not innovative at all. When asked to expand on the reasons for their statements, two contractors mentioned that innovation is key part of their firm's culture and projects. For example, one of these contractors stated that he considered their firm innovative *"...because of the fact that we build some of the most technically complex facilities."* Regarding this question another contractor said: *"We do a fair share of our volume working on design-build projects, so we have the opportunity to be very innovative when looking at the best options for certain types of material to incorporate into the project and still meet the project goals and requirements."* Interestingly, one interviewee that indicated to work for an innovative firm declared, *"In this business we are always trying to find cheaper and*

*faster ways to delivering construction projects. However some items still use the old "Brick and Mortar" because it is tried and true."* This comment shows that the adoption of innovative wood-based construction materials such as CLT could be hindered simply by the fact that it is a new material that does not have the widespread proven trajectory of traditional material materials. This could be associated with the "network effect", a phenomenon where a new product gains additional value as the number of users grows (Sundararajan, 2017).

All interviewees that stated innovation to be not at all important mentioned risk as the main factor preventing them from adopting newer solutions. One interviewee declared, *"In all honesty, [...] I don't know many clients/engineers who want to be innovative. There has to be a big benefit for us to want to use something innovative. And, our client's would agree since they have to live with the result of that material for decades after construction."* As previously mentioned in Chapter 3, in the construction industry, liability risk is seen as one of the largest barriers to the adoption of new materials and technologies. Construction professionals, are responsible for the performance of buildings and consequently for the specification of the materials to be used, and could face severe consequences when building components fail to perform as expected (Sido, 2006).

#### *Level of awareness*

The adoption of a product depends to a great degree on the awareness about the product among potential adopters. Therefore, participants were asked to indicate their familiarity with CLT. Overall level of awareness about CLT among U.S. construction firms included in the study is low, with one third of the contractors interview indicating some knowledge about CLT, and the remaining 20 saying that they have not heard about it . A similar level of awareness was reported from the qualitative study conducted by the author of this dissertation of U.S. engineering firms and presented in Chapter 3.

Following the question about awareness, interviewees were divided into two groups: those with some familiarity with CLT and those that never heard about it. Those respondents in the first group were asked a series of questions to evaluate their perceptions and willingness to adopt CLT in the future. Participants with no prior knowledge of CLT, were read a short

paragraph explaining what CLT was, after which they were asked to express their perceptions and likelihood to adopt CLT if it were widely available in the U.S. market. The following sections present the responses obtained from both subgroup of interviewees.

#### *Perceived benefits and disadvantages of CLT*

Two of the six contractors interviewed that indicated having some familiarity with CLT, explained that the main advantages of CLT relates to its aesthetic qualities and the design possibilities of CLT, with one saying that “...*the advantage is that the material can help achieve attractive designs while maintaining structural integrity.*” Another contractor with experience in industrial buildings also added that, “*For our type of work, longer span lengths are definitely an advantage.*”

As mentioned in the last paragraph, structural integrity was also seen as a benefit of using CLT panels. CLT panels are manufactured with layers orthogonal to each other, in a way similar to plywood. With this configuration, adjacent layers act as reinforcement of the whole panel, adding to dimensional stability and allowing panels to span and carry load in both directions, similar to a concrete slab (Turner, 2010; Van de Kuilen, Ceccotti, Xia, He, & Li, 2010). Cross-lamination also enhances dimensional stability, as individual layers constrain the expansion and contraction of the adjacent layers (Evans, 2013).

Many researchers have extensively studied the environmental properties of CLT panels. However only one interviewee mentioned environmental performance as an advantage. The environmental qualities of wood, and CLT in particular, have been contrasted with other materials, such as steel and concrete (Chen, 2012; Darby, Elmualim, & Kelly, 2013; Dodoo, Gustavsson, & Sathre, 2014; Durlinger, Crossin, & Wong, 2013; John, Nebel, Perez, & Buchanan, 2009; Lehmann, 2012a; O’Connor, Mahalle, & Berry, 2011). One of the main advantages of CLT relate to the carbon sequestration potential of CLT. The system turns out to have more than a third (39.4%) of the embodied carbon of a concrete alternative. However if carbon sequestration is taken into account, the CLT building turns out to be carbon-negative. By achieving a negative balance of embodied CO<sub>2</sub> emission compared with other alternative, CLT building are able to reduce the carbon footprint,

locking carbon in their mass, and transforming buildings in “carbon sinks” (Lehmann, 2012b).

One respondent also mentioned, “*We also see for our temporary formwork and falsework needs the advantages in the CLT.*” In construction, formwork, used to contain and mold, to specific dimensions, poured wet concrete, while it sets (cures) (Richardson, 1986). Temporary formwork is composed of elements that are removed once the concrete sets and can be reused. Permanent formwork are elements that stay in place even after the concrete has cured. Falsework, on the other hand, is defined as the temporary construction that hold the formwork in place, carrying the vertical load until the structure is able to support it-self (Richardson, 1986). This indicates that panel could also could have non-structural uses that professionals could find appropriate for the type of work that they are involved with.

Regarding the perceived disadvantages of CLT, three participants with familiarity with the system indicated the lack of wide availability of the product in the U.S. market as the main drawback to the use of CLT for structural applications. As of August 2017, only two companies in the U.S. (Smartlam and DR Johnson Wood Innovations) have received APA/ANSI PRG 320 certification to manufacture structural CLT panels (DR Johnson Wood Innovations, 2017; Smartlam, 2017). Moreover, two contractors also mentioned that since the product is new, there is a lack of skilled workers able to design, detail and install the system in the U.S. One contractor indicated that, “*[CLT] needs to get a proven track record in the US and it will need to be done in multiple locations due to the varying climates in the U.S.*”

Concerns about the fire performance of CLT were also mentioned as drawbacks of the system. One interviewee said, “*I am unsure as to how liability insurance industry addresses the risk of fire in these buildings.*” Several research studies have focused on CLT’s fire performance (Crielaard, 2015; Frangi, Bochicchio, Ceccotti, & Lauriola, 2008; Gibbs, Taber, Loughed, Su, & Bénichou, 2014; Schmid, Klippel, Just, & Frangi, 2014). Conclusions from these studies suggest that wooden structural elements of large sections such as CLT panels have adequate fire resistance properties, mainly because of wood’s particular charring properties (Forest Products Laboratory, 2010). A recent test conducted by the U.S. Forest Service’s Forest Products Laboratory and the American Wood Council

evaluated the fire performance of different arrangements of exposed and unexposed CLT on two full scale furnished rooms (Gibson, 2017; Kipfer, 2017). Results proved the self-extinguishing properties of CLT element and showed that these panels could resist the spread of fire to other areas of the building (Kipfer, 2017).

Other disadvantages mentioned were durability issues, especially those related to moisture, and lead time of delivery on site. Regarding durability, one interviewee indicated that he was not “[sure] of the impact related to the exposure to moisture during the construction process,” and questioned, “Is there the potential for mold growth if panels have been saturated for a period of time? On-site protection of CLT panels is particularly important to guarantee the durability and in-service performance of the panels (FPInnovations, 2011). Scarce research has been conducted over the past decade on the hygrothermal properties of CLT panels during the building’s life cycle (AlSayegh, 2012; Lepage, 2012; McClung, Ge, Straube, & Wang, 2014). Furthermore, very limited information is available regarding maintenance of structural elements in cases of moisture related problems.

For those respondents with no previous knowledge and who were introduced to CLT at the time of the interview, the environmentally-friendly characteristics of the material, and in particular in regards to the reduced carbon footprint, was the most frequently mentioned advantage. Many interviewees also mentioned that the design flexibility and the fact that CLT’s “*structural characteristics enable shapes and openings with diverse sizes and forms.*” Additionally, CLT’s aesthetic attributes and structural soundness were also mentioned as an advantage over traditional building materials. In regards to the disadvantages mentioned by interviewees with no previous knowledge, findings show that fire performance is seen as the main disadvantage of CLT. Another drawback seen by a third of the interviewees is related to durability, with one interviewee stating: “*I would be concerned about the possibility of mold growth and other kind of biological attack.*” As seen before this is an issue brought up by both professionals that are familiar and not familiar with the system. The author believes that it would be important for manufacturers and organizations in charge of promoting the use of wood and specifically CLT in construction to stress the design strategies in place to avoid this kind of issues in CLT-based buildings. Other disadvantages mentioned were the fact that CLT is not “as well-known or established as

other *[traditional] materials in the market*”, and that it would be *“difficult to convince engineers to vary from what has been more typical design methods.”*

*Perceived factors affecting the adoption of CLT in the U.S.*

Participants to this study familiar with CLT were asked to share their views about what they perceived could be major barriers hindering the adoption of CLT in the U.S. by construction professionals. Table 29 summarizes all the perceived factors affecting the adoption of CLT in the U.S. mentioned by participants during the interviews.

**Table 29. List of perceived factors affecting the adoption of CLT in the U.S. mentioned by interviewees (30 interviews).**

<b>Factors affecting the adoption of CLT</b>
Limited availability of suppliers
U.S. construction industry is generally slow to embrace change
Not well established as traditional materials
Lack of pilot projects
Material cost
Lack of education on Mass Timber

According to interview responses, contractors that had previous knowledge about CLT view scarce availability of the system in the U.S. market as the largest barrier by. One interviewee stated, *“There is a limited number of suppliers of the product. In addition, concrete and steel are well established technologies.”* Another contractor said that, *“If there were already manufacturers capable of producing custom units in the U.S., the use would be much more widely implemented.”* Adding to this, one interviewee mentioned, *“Supply is scarce and not many structural engineers willing to deviate from the standard.”* This statements add another important factor potentially influencing wide adoption of CLT in the U.S. market, is the fact that the U.S. construction industry is particularly resistant to change, with one interviewee declaring that: *“The U.S. is in my opinion always on [the] back side of looking at innovative solutions in the construction industry compared to the Europeans and our neighbors to the North and South. We lag far behind in the post*

*tioning of building and structures compared to the European countries. It could well be that we do not invest in R&D as well as other countries or we are just slow to embrace change.”* This could indicate that organizations educating these professionals on the benefits related to the use CLT panels could face significant challenges in changing misperceptions about the material. The change-averse nature of this industry is also related to the liability risks that professional must take, as one interviewee said, *“It is unfortunate, but the construction industry evolves at a much slower pace than the rest of the world; we are still largely using the same building systems that have been common since the industrial revolution. There is a lot of risk associated with the design, construction, and operation of large-scale buildings. Fortunes can be lost in an instant when things don't work out right. The construction industry is all based around risk. We price risk, mitigate risk, and shift liability around to minimize potential losses and maximize gains. This doesn't foster innovation.”* This statement is in line to what was mentioned in Chapter 1 (section: Innovation adoption in the construction industry), related to the risk associated with the adoption of an innovative material or process. According to Slaughter (2000), this risk as one of the most significant factors that can affect the rate of adoption of a new product. Specifically in the construction industry, liability risk is particularly important as it is seen as one of the largest barriers to the adoption of innovations in this sector (U.S. Department of Housing and Urban Development (HUD), 2005). Construction professionals, such as those interviewed for this part of the study, are in the majority of cases responsible for the performance of the buildings and consequently for the specification of the materials to be used (Sido, 2006).

Another important factor that was considered by one interviewee to be hindering the wide adoption of CLT in the U.S. was the lack of demonstration projects and educational opportunities to learn how to design and build with CLT. It is important to mention that over the past two years many buildings have been erected using this system in the U.S. More recently the first high-rise building made of CLT in the U.S. (Framework building designed by LEVER Architecture) was granted a building permit by the City of Portland, Oregon (LEVER Architecture, 2017; Rosenstock, 2017; USDA, 2015). The project won a \$1.5 million U.S. Tall Wood Building award sponsored by the U.S. Department of

Agriculture, a sum that will be destined to conduct research to prove the performance and durability of CLT in comparison to traditional materials (USDA, 2015). The author of this dissertation believes that if more information about these projects becomes available to construction professionals, it could help them make informed decisions about the potential adoption of the system for their own buildings in the future.

*Likelihood of adoption*

When the six interviewees familiar with CLT were asked about the likelihood of them adopting the system for future projects if it were available in the market, there was an almost complete consensus that they all would “*likely*” adopt it. However, when the 24 interviewees that indicated no familiarity with the system were informed about CLT and asked if they would consider CLT for their future projects, 16 and 8 said that they were “*likely*” and “*unlikely*” to adopt it, respectively (Table 30).

**Table 30. Likelihood to adopt CLT in the future (30 interviews).**

Willingness to adopt CLT in the future	Count of respondents
<i>-- U.S. contractors familiar with CLT (N=6) --</i>	
Likely	5
Unlikely	1
<i>-- U.S. contractors not familiar with CLT (N=24) --</i>	
Likely	16
Unlikely	8

These results are in agreement with the findings reported in previous studies of U.S. architecture, engineering and construction firms by the author (Appendix 1 and Chapters 2,3 and 4), which concluded that the willingness to adopt CLT by U.S. construction professionals is uncertain but steadily growing. Findings of this study indicate that there is an increasing potential for adoption among U.S. constructors if some conditions (e.g. cost-competitive, available in the market, etc.) are met, and more information about the system and demonstration projects were readily available through the most relevant communication channels for the audience. Also, more suppliers are needed who will make

the system available throughout the U.S. One interviewee stated, *“This is a product that I would be willing to adopt. The biggest problem is that if it is not already massively used in this market, the cost will be high. Once something like this is produced at a larger scale and the per-unit price becomes cheaper, you will begin to see contractors recommending this product in lieu of steel or concrete.”* Results from this study show that even though contractors are not particularly influential during the material decision process, they frequently collaborate and communicate with architects and engineers. By educating contractors there is an opportunity that this knowledge will be reach other construction professionals through word-of-mouth. As one interviewee stated *“...more awareness is needed in the engineering community.”* Regarding the likelihood of adoption one contractor also pointed out that: *“It's a chicken vs. the egg argument. We would endorse it, but not until after we have used it. But, we would be less likely to use it until after we have endorsed it. My advice would be to find a unique application to build familiarity with the product, and then grow it into more broad applications.”*

## ***Conclusions***

The main goal of this research was to assess the market potential and barriers to adoption of Cross-Laminated Timber (CLT) in the United States. Specifically, this qualitative study aimed at investigating the level of awareness, perceptions and willingness to adopt CLT by U.S. construction firms, commonly considered key actors, together with architects, and engineers in the structural material decision process. The author of this dissertation also aimed to investigate how structural material decisions process take place and who are the major actors with the most influence during this process. To accomplish these objectives, 30 interviews were conducted with U.S. construction firm representatives to learn about their insights.

Results from this study show that the material selection process varies greatly from firm to firm. However most factors influencing the material selection process among firms were similar. Interviewees stated that material, labor and maintenance cost compared to other solutions; availability of material and workforce; and durability and longevity, are the main

characteristics they take into consideration when selecting a structural system for their projects.

According to the information gathered during the interviews, it was found that the level of awareness about CLT among U.S. construction firm representatives was low, with only six participants out of 30 indicating they had been knowledgeable about CLT. Four interviewees indicated they had heard about the system in the past but when asked about their perceptions they were not able to respond due to lack of knowledge. When asked about the perceived benefit of CLT, U.S. construction firm representatives interviewed indicated that the main benefits of CLT-based systems come from the aesthetic qualities. Another important benefit of CLT-based systems over traditional light wood-frame construction are the design possibilities and structural capabilities, in particular related to the opportunity to span longer distances without intermediate supports. Respondents with previous knowledge about CLT also mentioned durability and fire resistance, lack of suppliers and skilled professionals able to design, detail and install the product, as potential drawbacks of the system.

Barriers to the wide adoption of CLT-based construction systems in the U.S. mentioned by the respondents were the limited availability of the product in the market, the slow pace at which the construction industry adopts new products, the fact that as a newer material it is not as well established as concrete or steel, and the lack of demonstration projects and mass timber education opportunities within the U.S. Similarly to what was mentioned in previous chapters, the author of this dissertation believes stronger educational programs, as well as more built demonstration projects, would greatly improve the confidence of construction professionals evaluating the possibility of adopting CLT for their projects.

The willingness to adopt CLT for future projects, among the professionals familiar with the system, was high. Contractors showed interest and likelihood to select CLT if it were widely available in the U.S. market at a competitive price. The willingness to adopt CLT for future projects, among those professionals unaware of the system, was intermediate, with 16 respondents indicating they were “very likely” or “likely” to adopt CLT, and a total of 8 respondents indicating “unlikely” or “very unlikely” to adopt said system in the future.

Results presented in this chapter indicate that there is still considerable work to be done to educate construction professionals about CLT. From these results, we conclude that the future success of a CLT-based construction system in the U.S. depends in part on the information about the product reaching the main decision makers in the material selection process (architects and structural engineers) and their collaborators (contractors). The current level of awareness and some misconceptions about wood as a structural materials make it difficult to increase the market for CLT. It is also important to realize that, as many interviewees stated, the construction industry is very risk and change averse, so it will takes time and effort to get professionals to trust the material.

### *Acknowledgements*

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# **Chapter 6**

**Factors that Influence the Willingness  
to Adopt Innovative Wood Products among  
U.S. Engineering and Construction Firms**

## ***Introduction***

This chapter presents the results obtained from the conceptual model development and evaluation of the factors that influence the willingness to adopt innovative wood-based products by the U.S. Construction Industry. For this purpose, responses from two surveys (to U.S. engineering and construction firms) were analyzed using a series of statistical methods. The development of the hypothesized model, the methodology followed to test the proposed conceptual model, and the results and conclusions are presented in the following sections. From the information obtained from the literature review and a previous study conducted by the author (Appendix 1) a conceptual model of the factors influencing the willingness to adopt new wood-based construction materials is suggested in Figure 13. An explanation of the factors included in the hypothesized conceptual model can be found in Chapter 1 (Theoretical framework).

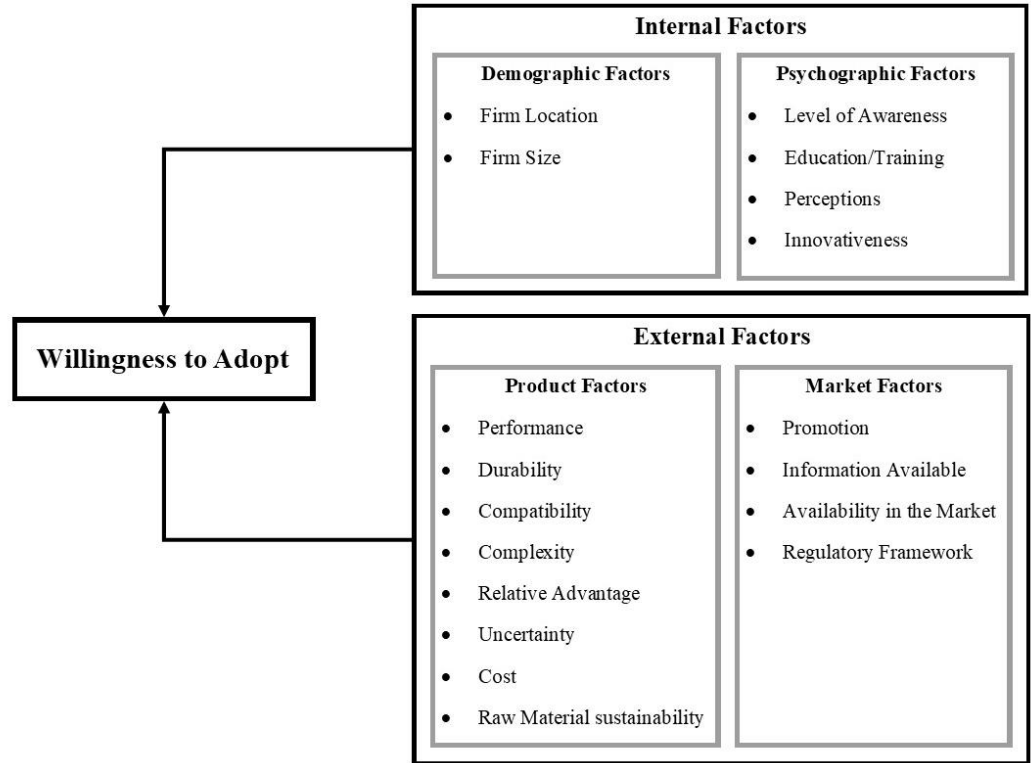


Figure 13. Conceptual model for the willingness to adopt innovative wood-based building materials.

## ***Research hypotheses***

The main objective of this chapter was to investigate the critical factors that affect the willingness to adopt innovative wood-based building materials in the U.S. To accomplish this goal, a conceptual model was developed which includes the critical factors that influence the adoption of innovative wood-based construction materials by U.S. structural engineers and construction firms. To understand the factors that influence the willingness to adopt innovative wood-based materials, the following hypotheses were proposed:

*Hypothesis 1:* Firms' demographic characteristics are associated with the willingness to adopt innovative wood-based materials used in construction.

*Hypothesis 2:* Firms' psychographic characteristics are associated with the willingness to adopt innovative wood-based materials used in construction.

*Hypothesis 3:* External factors to the firm are associated with the willingness to adopt innovative wood-based materials used in construction.

## ***Methodology***

To accomplish the goals and test the hypotheses listed above, data was collected from U.S. engineering and construction firms via nation-wide surveys, which were presented in Chapters 2 and 4 of this dissertation, respectively. To validate the conceptual model (Figure 13), five questions from the survey were used for the analysis (Table 31). These questions were selected based on the specific objectives and hypotheses for this part of the study. A copy of the survey questionnaires can be found in Appendix 2.

**Table 31. Survey questions analyzed.**

	<b>Hypotheses</b>	<b>Questions analyzed</b>		
		<b>Code</b>	<b>Survey Question</b>	<b>Topic</b>
H1	Firms' demographic characteristics are associated with the willingness to adopt innovative wood-based materials used in construction.	Q1	In which of the following regions does your firm operate?	Location of Firm
		Q2	Which of the following firm size categories best describes your firm?	Size of Firm
H2	Firms' psychographic characteristics are associated with the willingness to adopt innovative wood-based materials used in construction.	Q4	Please rate your agreement with the following statements about your firm's innovativeness.	Innovativeness
H3	External factors to the firm are associated with the willingness to adopt innovative wood-based materials used in construction.	Q8	How familiar are you with Cross-Laminated Timber (CLT)?	Awareness
		Q7	Please rank the importance of the following characteristics at the time of specifying a structural material.	Material's characteristics

Cronbach's alpha and exploratory factor analysis were used for the purification (eliminate items that affect the internal consistency of the scales) and reduction of the data obtained from the surveys to U.S. engineering and construction firms. Once these methods were

applied, hypothesis testing was carried out using Chi-square, polychoric correlation and ordinal regression to test the relationships of factors included in the proposed conceptual model and determine the factors that should be included in the final model. Figure 14 shows a schematic representation of the methodology used in this Chapter. All analyses were carried out using statistical software SPSS (IBM, 2017). A more detailed description of the data purification and hypothesis testing methods employed follows.

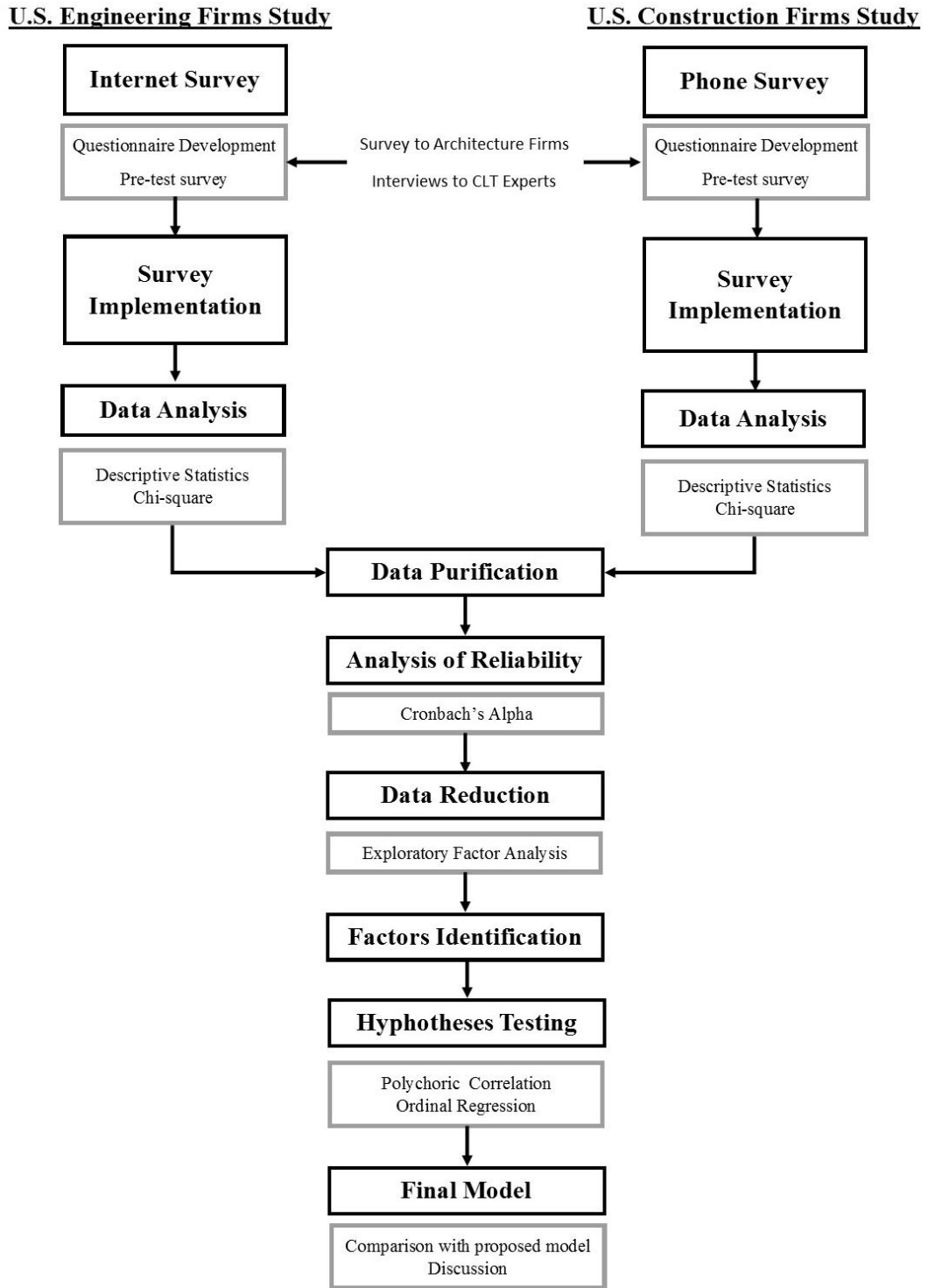


Figure 14. Methodology followed to evaluate determine the factors influencing the adoption of innovative wood-based construction materials among U.S. engineering and construction firms.

### *Analysis of reliability: Cronbach's alpha*

Reliability refers to the extent to which a set of items in a questionnaire produces consistent and reliable measure of a certain concept (Goforth, 2015). One way to measure the strength of this consistency is through the calculation of Cronbach's alpha (Villenas, 2014). The alpha coefficient is calculated by correlating the scores for each item with the total score for each observation, and then comparing these with the variance for all individual scores (Goforth, 2015). According to Fields (2009), a Cronbach's alpha lower than 0.60 means poor reliability, values between 0.6 and 0.7 are acceptable, and values that are higher than 0.70 indicate good scale reliability. In cases where the alpha is low, a stronger internal consistency (i.e. higher alpha coefficient) can be achieved by eliminating items looking at the column "Cronbach's Alpha if Item is Deleted" on the SPSS output (Field, 2009).

### *Data reduction: Exploratory Factor Analysis*

Exploratory Factor Analysis is a statistical method used to discover the number of factors influencing variables and for reducing a large number of variables to a set of more manageable categories (Mahmoodi & Esfandiari, 2016; Stapleton, 1997). This method is particularly useful when working with large datasets where it may be easier to focus on just the main factors that explain many variables, rather than having to evaluate many independent variables (Yong & Pearce, 2013). Therefore, the goal is to find the smallest number of factors that will explain the largest percent of variables, also referred as Principal Component Analysis (PCA) (Abdi & Williams, 2010; Yong & Pearce, 2013). For this study PCA was used as extraction method and Varimax rotation to better distinguishing of factor loadings among factors. This research is focused on using factor loadings bigger or equal to 0.40 as suggested by Field (2009).

### *Hypothesis testing*

Once the analysis of reliability and data reduction were performed, hypotheses shown in Table 32 were tested using a series of statistical test. Tests performed are dependent of the type of data that need to be analyzed (e.g. ordinal or nominal). Below is an explanation of the methods selected for the analysis of each question (Table 32).

**Table 32. Methods used to analyze the relationship of Independent and dependent variables.**

<b>Hypotheses</b>	<b>Independent variable</b>	<b>Type of independent variable</b>	<b>Dependent variable</b>	<b>Type of dependent variable</b>	<b>Method used</b>
H1	Location of Firm	Nominal	Willingness	Ordinal	Chi-square
H1	Size of Firm	Nominal	Willingness	Ordinal	Chi-square
H2	Innovativeness	Ordinal	Willingness	Ordinal	Polychoric correlation and ordinal regression
H2	Level of awareness	Nominal	Willingness	Ordinal	Chi-square
H3	Material's characteristics	Ordinal	Willingness	Ordinal	Polychoric correlation and ordinal regression
H3	Environment characteristics (availability in the market and building code)	Ordinal	Willingness	Ordinal	Polychoric correlation and ordinal regression

*Polychoric correlation*

Correlation is a statistical test used to measure the association or relationship between two quantitative variables (Field, 2009; Statistics Solutions, 2017a). Given that the questions analyzed with factor analysis (Questions Q4 and Q7 in Table 32) are Likert scales, and are considered ordinal, Pearson’s correlation cannot be used. Instead, a polychoric correlation was used to estimate the correlation between these two ordinal variables (Innovativeness/Material’s Characteristics and Willingness) (Uebersax, 2015).

Since the generic SPSS software does not allow performing polychoric correlations, a recently developed program for SPSS called POLYMAT-C was used to carry out this analysis. POLYMAT-C is a free noncommercial program that can be run from the SPSS Syntax window (Lorenzo-Seva & Ferrando, 2014). Parameters used in the analysis can be easily configured by the user following the manual provided by the developers (Lorenzo-Seva & Ferrando, 2014).

### *Ordinal regression*

Regression analysis was used to validate the proposed conceptual model. In general terms, regression is used to describe and assess the relationship between a dependent variable and one or more independent variables (Field, 2009; Sullivan, 2004), such as the ones listed in Table 32. Regression can also be used to identify which variable (independent variable) can estimate the outcome of another variable (dependent variable) (Field, 2009). Because the items analyzed are ordinal (Likert scale), a traditional linear regression approach cannot be used (Laerd Statistics, 2017; Williams, 2017). Instead, an ordinal regression was used. It is important to point out that the output of an ordinal regression is not one  $R^2$  value, like in a traditional linear regression, but three  $R^2$  values, because variance is split into categories (Bartlett, 2014; Statistics Solutions, 2017b). Therefore, Cox and Snell's, Nagelkerke's and McFadden's pseudo  $R^2$  statistics are reported.

### *Chi-square*

One of the ways to test the relationship between two categorical variables is through a Chi-square statistic test (Diener-West, 2008). For this study, Pearson's Chi-square test was used to analyze nominal variables that could not be analyzed through factor analysis (location, size of firm and level of awareness – Table 32). All statistical tests were evaluated at a 0.05 alpha level using SPSS software.

## ***Limitations***

A number of limitations may have affected the results from this part of the study.

- *Sample size:* The relatively small sample size from both the U.S. Engineering and Construction firm's survey makes it difficult to obtain reliable and generalizable statistical results. The recommended sample size to conduct an exploratory factor analysis is at least 300 respondents, and all the items included in the analysis should each have at least 5 to 10 observations (Comrey & Lee, 1992; Pearson & Mundform, 2010). The same issue arises when performing the hypotheses testing.

As stated by numerous authors (Kalla, 2009; Kaplan, Chambers, & Glasgow, 2014; Marley, 2017), larger samples will provide more accurate and reliable results for the polychoric correlation, and the ordinal regression and the Chi-square analyses. However, the author believes that results presented herein provide a good approximation that could be useful for stakeholders looking to enter the innovative wood-based materials market and target U.S. engineering and construction firms.

- *Naming Factors*: One of the limitations of the exploratory factor analysis technique is that naming the factors can be problematic. Factor names may not accurately reflect the variables within the factor. Furthermore, some variables are difficult to interpret because they may load onto more than one factor which is known as “split loadings” (Asthana, 2016; Yong & Pearce, 2013), which make the naming more challenging.

## ***Results and discussion***

The section below describes the results from the data purification and reduction, as well as the hypotheses testing. The results are organized by question: (a) Material characteristics, (b) Innovativeness, and (c) Location, Size and Level of Awareness. For each question, the results for U.S. engineering and construction firms are presented.

### *(a) Materials characteristics*

#### *U.S. engineering firms*

Results (Table 33) from the data purification for the question regarding material’s characteristics show a high reliability of the scale, with a Cronbach’s alpha above 0.800. After analyzing the “Cronbach’s Alpha if Item Deleted” column of the output, it was decided not to exclude items from the analysis, since this would not improve reliability of the scale (i.e., result in a higher alpha). Table 33 presents the SPSS output for the analysis.

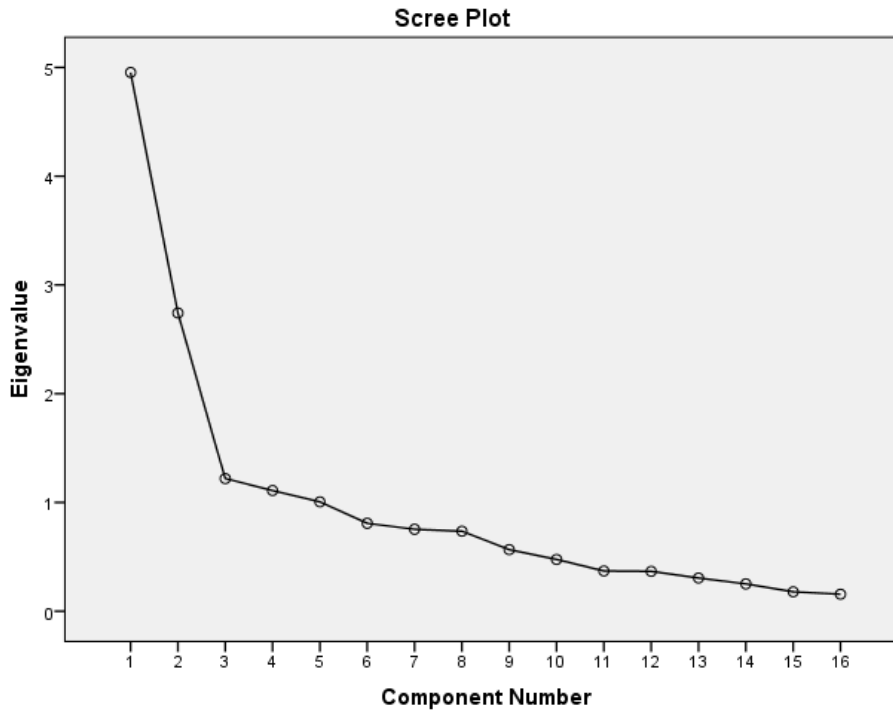
**Table 33. Cronbach's Alpha results.**

<b>Material's Characteristics</b>	<b>Raw Cronbach's Alpha</b>	<b>Standardized Cronbach's Alpha</b>
Environmental Performance		
Mechanical Performance		
Economic Performance		
Aesthetic Performance		
Fire Performance		
Earthquake Performance		
Availability in the Market		
Acoustic Performance	0.837	0.838
Maintenance requirement		
Durability		
LEED Credits		
Moisture Performance		
Vibration Performance		
Complexity of Construction		
Availability of Design Tools		
Building Code		

A principal component analysis was then conducted on the 16 items with orthogonal rotation (Verimax). The Kaiser-Meyer-Olkin measure verified the sampling adequacy for the analysis (KMO = 0.752). The Barret's test of sphericity Chi-square (120) = 483.154 and p-value = 0.000, indicated that the correlation between elements was sufficiently high for the principal component analysis. An initial analysis was run to obtain the eigenvalues for each component (factors) in the data. According to Field (2009), eigenvalues represent the amount of variation, and eigenvalues of 1 or more represent a high variation, thus being preferable. Five components had eigenvalues larger than the Keaiser's criterion of 1 (Table 34). However, when looking at the scree plot, it showed a pronounced inflection on the first three components that could justify retaining only three factors instead of the original five (Figure 15).

**Table 34. Eigenvalues obtained from the analysis.**

<b>Factor</b>	<b>Eigenvalue</b>	<b>Percentage of Variance explained (%)</b>
<b>1</b>	<b>4.954</b>	<b>30.962</b>
<b>2</b>	<b>2.742</b>	<b>48.100</b>
<b>3</b>	<b>1.220</b>	<b>55.723</b>
4	1.110	62.659
5	1.006	68.947



**Figure 15. Scree plot of the analysis.**

After determining how many factors to keep, loading factors were obtained and components were analyzed. A decision was made to show only those loadings higher than 0.4, in order to improve the readability of the results. Table 35 shows the factor loadings after the Varimax rotation. Bolded are the items that have the strongest influence on each factor. The naming of each component was done by looking at the bolded loading factors trying to find a common topic among them. Hence, the items that cluster on the same component suggest that component 1 represents “Constructability,” component 2 “Longevity,” and component 3 “Performance.”

**Table 35. Loading factors obtained.**

Material's characteristics	Factors		
	1	2	3
	Constructability	Longevity	Performance
Complexity of Construction	<b>0.841</b>		
Vibration Performance	<b>0.837</b>		
Availability in the Market	0.673		
Durability	0.623	0.500	
Availability of Design Tools	0.605		
Maintenance requirement	0.597		
Earthquake Performance	0.592		
Environmental Performance		<b>0.822</b>	
Moisture Performance		<b>0.683</b>	
Fire Performance			<b>0.758</b>
Acoustic Performance			<b>0.748</b>
LEED Credits		0.533	0.571
Aesthetic Performance		0.451	0.479
Mechanical Performance			0.412
Economic Performance			
Building Code			

Results from the ordinal regression presented in Table 36 verify the goodness of fit of the model (p-value = 0.000). The SPSS output also indicates a strong association between independent and dependable variables with  $R^2$  values over 0.90. In regards to the polychoric correlation, results show that for U.S. engineering firms there is a relationship between willingness to adopt innovative wood-based construction materials and aesthetics, LEED, moisture and vibration performance, and the availability of design tools (Table 36), which will be the material characteristics included in the final conceptual model for U.S. engineering firms.

**Table 36. Hypothesis testing results.**

Independent variables	Dependent variable	Polyc. corr.	Ordinal Regression				
			p-value	Pseudo R <sup>2</sup>			
				Cox and Snell	Nelgelkerke	McFadden	
	Environmental	-0.064					
	Mechanical	0.002					
	Economic	-0.095					
	Aesthetics	<b>0.148</b>					
	Fire	0.003					
	Earthquake	0.063					
	Availability	-0.075					
Material's characteristics	Acoustic	Willingness	0.057	0.000	0.939	1.000	1.000
	Maintenance						
	Durability						
	LEED	<b>-0.103</b>					
	Moisture	<b>-0.155</b>					
	Complexity	-0.014					
	Building Code	-0.053					
	Design Tools	<b>0.139</b>					
	Vibration	<b>-0.101</b>					

*U.S. construction firms*

Similarly to U.S. engineering firms, for construction firms, the results from the data purification for the question regarding material's characteristics, shows a high reliability of the scale, with a Cronbach's alpha above 0.800. When analyzing the "Cronbach's Alpha if Item Deleted" column of the output, it was decided to exclude 5 items (material cost, earthquake performance, complexity of construction, compatibility with the Building Code and requirement of specialized labor) of the 18 items from the analysis to help improve reliability of the scale (i.e. have a higher alpha). Table 37 presents the SPSS output for the analysis.

**Table 37. Cronbach's Alpha results.**

<b>Material's Characteristics</b>	<b>Raw Cronbach's Alpha</b>	<b>Standardized Cronbach's Alpha</b>
Environmental Performance		
Mechanical Performance		
Labor Cost		
Maintenance		
Aesthetics		
Fire Performance	0.850	0.850
Availability in the Market		
Acoustic Performance		
Durability		
LEED		
Moisture Performance		
Vibration Performance		
Construction Time		

A principal component analysis was conducted on the 13 remaining items, listed in Table 33, with orthogonal rotation (Verimax). After two iterations, three more items were removed. The Kaiser-Mayer-Olkin measured with the remaining 10 items verified the sampling adequacy for the analysis (KMO = 0.603). The Barret's test of sphericity Chi-square (36) = 39.722 and p-value = 0.308, indicated that the correlation between elements was not sufficiently high for the principal component analysis. This issue arises due to the small sample size and observation counts utilized for the analysis. Due to the low reliability of the factor analysis results for these questions, it was decided not to report factor loadings.

**Table 38. Hypothesis testing results.**

Independent variables	Dependent variable	Polyc. corr.	Ordinal Regression			
			p-value	Pseudo R <sup>2</sup>		
				Cox and Snell	Nelgelkerke	McFadden
Material's characteristics	Mechanical	-0.011	0.000	0.911	1.000	1.000
	Labor cost	<b>-0.106</b>				
	Maintenance	<b>-0.229</b>				
	Availability	0.086				
	LEED	<b>0.280</b>				
	Vibration	<b>0.332</b>				
	Const. Time	-0.076				
	Durability	<b>-0.200</b>				
	Moisture	-0.086				

Results from the ordinal regression presented in Table 38 verify the goodness of fit of the model (p-value = 0.001). The SPSS output also indicates a strong association between independent and dependable variables with R<sup>2</sup> values over 0.900. In regards to the polychoric correlation, results show that for U.S. construction firms there is a relationship between willingness and labor cost, maintenance requirements, LEED credits, vibration and durability performance (Table 38). Consequently, these will be the material characteristics included in the final conceptual model for U.S. construction firms.

*(b) Innovativeness*

*U.S. engineering firms*

Results from the data purification for the question regarding innovativeness shows a low reliability of the scale, with a Cronbach's alpha slightly below 0.600 (Table 39). After analyzing the "Cronbach's Alpha if Item Deleted" column of the output, the author of this dissertation decided not to exclude items from the analysis, since this would not improve reliability of the scale (i.e., a higher alpha). It is presumed that the low reliability of the scale relates to the fact that there are only eight items in the question. It has previously been reported by Cortinas (1993) and Field (2009) that the coefficient alpha highly depends on the number of items included. The more items, the higher the coefficient. Table 39 presents the SPSS output for the analysis.

**Table 39. Cronbach's Alpha results.**

<b>Innovativeness</b>	<b>Raw Cronbach's Alpha</b>	<b>Standardized Cronbach's Alpha</b>
Employees are encouraged to research new materials		
Firm collaborates with firms		
Firm collaborates with universities		
Firm collaborates with research centers	0.568	0.575
Firm open to collaborate with manufacturers		
Firm invests in training employees		
Innovation is part of the firm's corporate strategy		
Firm reviews and reflects on past projects		

A principal component analysis was conducted on the eight items with orthogonal rotation (Verimax). The Kaiser-Mayer-Olkin measure verified the sampling adequacy for the analysis (KMO = 0.621). The Barret's test of sphericity Chi-square (28) = 57.103 and p-value = 0.001, indicated that the correlation between elements was sufficiently high for the principal component analysis. An initial analysis was run to obtain the eigenvalues for each component (factors) in the data. Three factors had eigenvalues larger than the Keaiser's criterion of 1 (Table 40). This criteria was verified by looking at the scree plot (Figure 16). Table 41 shows the factor loadings after the Verimax rotation. The items that cluster on the same component suggest that component 1 represents "employee motivation", component 2 "collaboration" and component 3 "openness to change". Naming of the factor is left to the researcher's judgement.

**Table 40. Eigenvalues obtained from the analysis.**

<b>Factor</b>	<b>Eigenvalue</b>	<b>Percentage of Variance explained (%)</b>
1	2.094	26.177
2	1.188	41.029
3	1.051	54.161

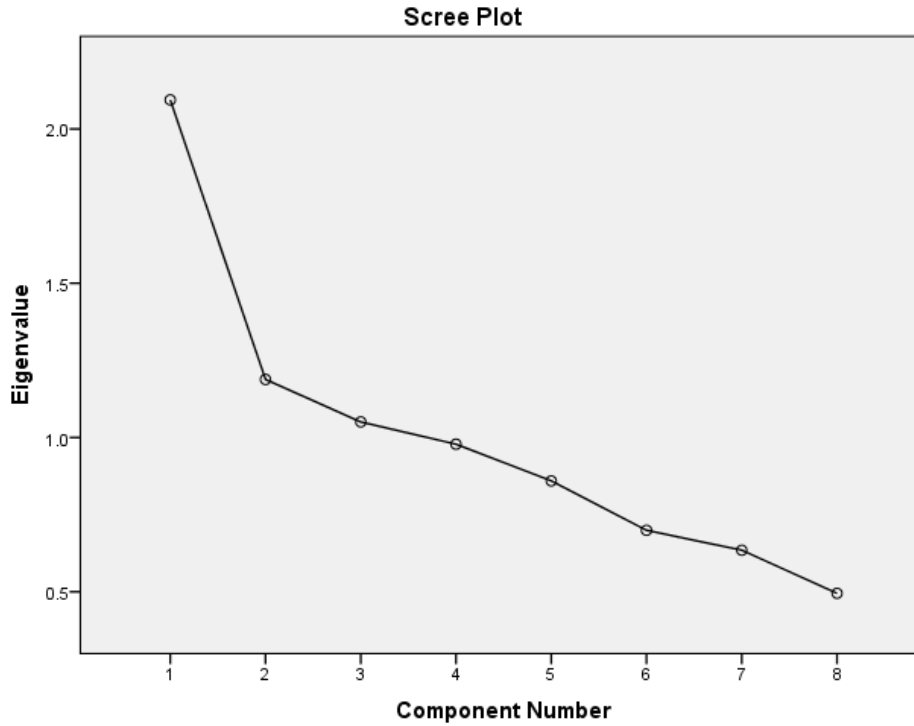


Figure 16. Scree plot of the analysis.

Table 41. Loading factors.

Innovativeness	Factor		
	1 Employee motivation	2 Collaboration	3 Openness to change
Employees are encouraged to research new materials	<b>0.825</b>		
Innovation is part of the firm's corporate strategy	0.690		
Firm collaborates with firms	0.583		
Firm collaborates with research centers		<b>0.794</b>	
Firm collaborates with universities		0.690	
Firm open to collaborate with manufacturers			<b>0.718</b>
Firm reviews and reflects on past projects			0.662
Firm invests in training employees			0.477

Results from the ordinal regression presented in Table 42 indicate that there is a poor goodness of fit of the model (p-value = 0.450). The SPSS output also indicates a poor association between independent and dependable variables with  $R^2$  values of 0.113, 0.120 and 0.043. For this reason, the dimensions of innovativeness used in this study will not be

included in the final conceptual model for U.S. engineering firms. Further research should be conducted to evaluate other dimensions of innovativeness that might have a stronger association with willingness.

**Table 42. Hypothesis testing results.**

Independent variables	Dependent variable	Polyc. corr.	p-value	Ordinal Regression		
				Pseudo R <sup>2</sup>		
				Cox and Snell	Nelgelkerke	McFadden
Innovativeness	Encourage Firms	<b>0.186</b>	0.450	0.113	0.120	0.043
	Universities	<b>-0.146</b>				
	Government	<b>-0.163</b>				
	Suppliers	-0.005				
	Training	0.065				
	Strategy	-0.067				
	Reflect	0.052				
		<b>-0.144</b>				

*U.S. construction firms*

Data purification analysis for the question regarding innovativeness for U.S. construction firms, shows that there is high reliability of the scale, with a Cronbach’s alpha slightly over 0.800. After analyzing the “Cronbach’s Alpha if Item Deleted” column of the output, it was decided to exclude three of the eight items from the analysis, since this would it help improve reliability of the scale. Table 43 shows the results from this analysis.

**Table 43. Cronbach's Alpha results.**

Innovativeness	Raw Cronbach’s Alpha	Standardized Cronbach’s Alpha
Employees are encouraged to research new materials	0.808	0.813
Firm open to collaborate with manufacturers		
Firm invests in training employees		
Innovation is part of the firm's corporate strategy		
Firm reviews and reflects on past projects		

A principal component analysis was conducted on the remaining five items with orthogonal rotation (Verimax). The Kaiser-Meyer-Olkin verified the sampling adequacy for the analysis (KMO = 0.649). The Barret's test of sphericity Chi-square (10) = 29.944 and p-value = 0.001, indicated that the correlation between elements was sufficiently high for the principal component analysis. However, results for the factor analysis show that only one factor was found. Table 44 also shows that all factor loadings calculated are below the 0.400 recommended by the literature. For this reason, it was decided not to report any factors for this question since the one factor found is not strong enough to represent the sample.

**Table 44. Loading factors obtained.**

<b>Innovativeness</b>	<b>Factor</b>
Employees are encouraged to research new materials	0.305
Firm open to collaborate with manufacturers	0.220
Firm invests in training employees	0.216
Innovation is part of the firm's corporate strategy	0.297
Firm reviews and reflects on past projects	0.261

Results from the ordinal regression presented in Table 45 verifies the goodness of fit of the model (p-value = 0.000). The SPSS output also indicates a strong association between independent and dependable variables with  $R^2$  values over 0.800. In regards to the polychoric correlation, results show that for U.S. construction firms there is a relationship between willingness and the encouragement and training of employees, the collaboration with suppliers, innovation as part of the firm's strategy, and reviewing and reflecting on past projects. Consequently, these will be the psychographic characteristics related to innovativeness to be included in the final conceptual model for U.S. construction firms.

**Table 45. Hypothesis testing results.**

Independent variables	Dependent variable	Polyc. corr.	Ordinal Regression			
			p-value	Pseudo R <sup>2</sup>		
				Cox and Snell	Nelgelkerke	McFadden
Innovativeness	Encourage Supplier	<b>-0.651</b>	0.000	0.823	0.903	0.715
	Training	<b>-0.490</b>				
	Strategy	<b>-0.577</b>				
	Review	<b>-0.712</b>				
		<b>-0.487</b>				

*(c) Location and size of the firm, and level of awareness*

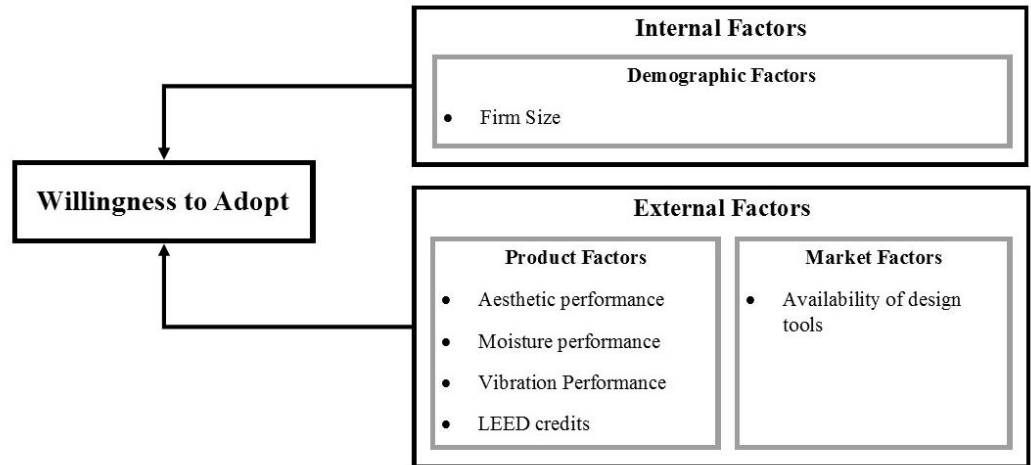
Results from the analysis of the categorical variables included in the proposed conceptual model show that there is an association between willingness to adopt innovative wood-based construction materials and the location of U.S. construction firms. An association between willingness and size of the firms was found among U.S. engineering firms. Finally, when evaluating the relationship between level of awareness and willingness to adopt innovative wood-based construction systems, an association was found for U.S. construction firms. A summary of all Chi-square and p-values for the interactions is presented in Table 46.

**Table 46. Results of the Chi-square tests.**

Hypothesis	Independent variable	Dependent variable	U.S. engineering firms		U.S. construction firms	
			Chi-square	p-value	Chi-square	p-value
H1	Location of Firm	Willingness	8.159	0.429	18.926	<b>0.004</b>
	Size of Firm		23.799	<b>0.002</b>	6.267	0.180
H2	Level of Awareness		7.732	0.258	9.601	<b>0.048</b>

*Comparison of models*

Figures 17 and 18 show the final models after performing the data purification and reduction and hypotheses testing. Below is a comparison of the two conceptual models.



**Figure 17. Final conceptual model for U.S. engineering firms.**

From the data analysis conducted it was found that there are three main factors (demographic, product and market factors) influencing the willingness to adopt innovative wood-based construction materials among U.S. engineering firms. Within the demographic factors, firm size appears to be associated with the willingness to adopt. It was hypothesized that larger firms that have more investment (financial) power tend to be more willing to try new materials, something that for smaller firms (with less employees) could imply more resources and economic risk. This could also be related to the idea that larger firms have more employees to conduct research on new materials and technologies.

Interestingly, while innovativeness is seen in the literature as one of the main factors influencing innovation adoption (Lu, Yao, & Yu, 2005; Nalevanko, 2015; Yun-Hee, 2008; Yun, Verma, Pysarchik, Yu, & Chowdhury, 2008), results from the analysis presented previously suggests no association between innovativeness and willingness to adopt. It is important to point out that these results were obtained taking into account the innovativeness dimensions presented in Chapter 1 (Theoretical Background). Further research on this particular topic should be conducted to gain a deeper understanding of how other dimensions of the firm’s perceived innovativeness relates to their willingness to adopt new products.

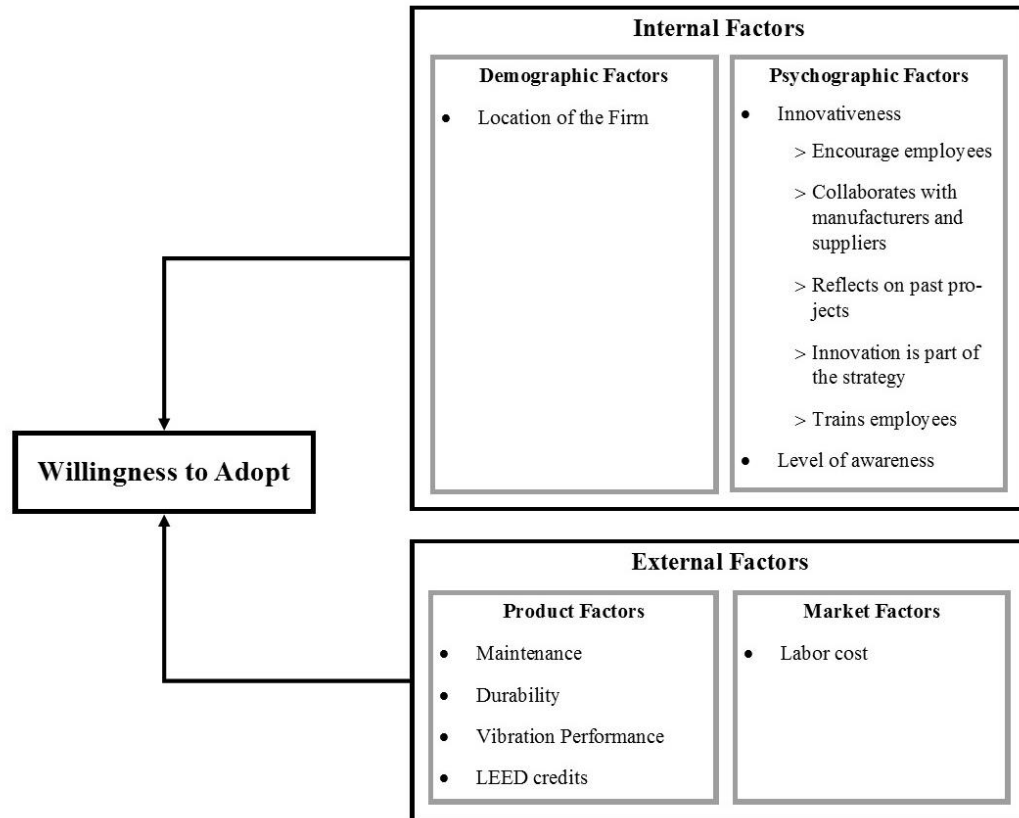
In regards to the product factors, it was concluded that aesthetics, moisture and vibration performance as well as LEED credits are associated with willingness. These results are in

accordance with the information presented in Chapter 2 and 3 regarding the roles of engineers during the structural material decision process. As previously seen, engineers, in collaboration with architects, are usually in charge of the design and calculation of structural elements (Chapter 4 and 5). In previous chapters (Chapter 2 and 3) of this dissertation, the aesthetics of a material, is an important factor considered during the material the selection process. Therefore, it is not surprising that this characteristic appears as one of the critical factors influencing the likelihood to adopt innovative materials.

The author hypothesizes that moisture and vibration performance are both factors included in the conceptual model because they relate the overall performance and longevity of buildings, which are factors that engineers place high importance on due to safety and liability implications.

The possibility of getting LEED Credits is also seen as a factor affecting the willingness to adopt innovative materials, this is expected given that the population of interest for this study was structural engineers that works in commercial building construction. This type of construction is usually the most commonly certified by the Green Building Council (Green Building Council, 2017b). Over the past two decades, LEED Certification was seen as a way for companies to differentiate themselves as environmentally responsible, therefore creating a competitive advantage. Complying with the LEED Certification also represents a way for building owners and investors to get tax credits and deduction that could make their investment more profitable (Department of Energy, 2017; Green Building Council, 2017a; LLP, 2012).

According to the results, within the market factors, availability of design tools turned out to be the only influencing the willingness to adopt innovative wood-based materials. In an interview with a structural engineer conducted for a study published by the author of this dissertation in 2016 (Laguarda-Mallo and Espinoza, 2016), availability of design tools was seen as essential when choosing a material. If existing software and design processes (e.g. BIM) are not compatible with the new material, is makes it very unlikely for professionals to favor it (M. Laguarda-Mallo & Espinoza, 2016).



**Figure 18. Final conceptual model for U.S. construction firms.**

For the final conceptual model for U.S. construction firms, four critical factors were obtained from the data analysis: demographic, psychographic, product and market. The model including these factors are represented in Figure 18. Within the demographic factors, location of the firm appears to be associated with the willingness to adopt innovative wood-based construction materials. This could be associated with the materials available at each location and also with labor costs associated with said materials.

Unlike the conceptual model for engineering firms, in which no psychographic factors appeared to be influencing the adoption of new materials, for construction firms these factors seem to have a stronger effect. The psychographic factors associated with the willingness to adopt were innovativeness and the level of awareness. Among the sub-factors related to innovativeness, the author found that 6 of the 8 innovativeness dimensions (encouragement of employees to explore new materials, the firm's openness to

collaboration with manufacturers and material's suppliers, the firm's systematic review and reflect on past projects, the inclusion of innovation as part of the firm's corporate strategy and the investment in training of employees) are associated with the willingness to adopt innovative wood-based materials. These sub-factors clearly show a commitment for continuous improvement and growth by firms, which directly affect the likelihood of adoption.

The level of awareness appears to be associated with willingness to adopt. Previous research conducted by the author (Appendix 1) has shown that the likelihood of adoption of a construction material grows with awareness and perception about that material.

As for the product's factors, the study showed evidence that the maintenance cost, durability, vibration performance and the possibility to gain LEED Credits, are associated with likelihood of adoption. As mentioned in Chapter 4 and 5, contractors are usually in charge of controlling the construction time, cost and quality of a building. Therefore, it is not surprising that these factors would be included in the final conceptual model for U.S. construction firms. Similarly, within the market factors, labor costs turned out to be the only one influencing the willingness to adopt innovative wood-based materials. This factor also intrinsically relates to one of the tasks performed by contractors during the construction process: to manage and control workers on site. This also includes the hiring of the labor force needed to complete a project within a pre-established budget.

## ***Conclusions***

The objective of this chapter was to develop conceptual models of the critical factors for the adoption of innovative wood-based construction materials by U.S. Engineering and construction firms. In order to accomplish this goal, the information collected from two nationwide surveys was purified, reduced and analyzed using a series of statistical methods, such as reliability tests, factor analysis, polychoric correlation and ordinal regression analysis.

Many parallels can be drawn between the final conceptual model for U.S. engineering firms (Figure 17) and that for U.S. construction firms (Figure 18). Similarities between the two

are evident when comparing the product-related factors influencing the willingness to adopt new materials. In both cases, LEED credits and vibration performance are present. These factors are related to the in-service performance of buildings, something that both engineers and contractors strive to achieve and control during the building design and construction.

Many differences between both conceptual models can also be distinguished, mainly in regards to the demographic, psychographic and market factors. Even though it could be expected that for both engineering and construction firms, size of the company would have an influence in the likelihood of adoption of new materials, results show that this is the case only for U.S. engineering firms. The author believes that further research should be conducted, with a larger sample size. Similarly, results show that innovativeness, which is a known factor driving adoption in other industries, and was included in the hypothesized conceptual model for both professionals, was only a critical factor for construction firms, but not for engineering firms.

Even though the small sample size obtained for this part of the study makes it difficult to generalize results and draw conclusions for such a large and diverse population of interest, it is believed that the results and analysis presented provide a better understanding of the critical factors that affect the adoption of wood-based building materials. Learning about the major issues in the adoption of innovations by the construction industry is of critical importance to ensure market success and will help to accelerate technology adoption through well-designed education programs, demonstration projects, marketing strategies, and policy incentives.

### ***Acknowledgements***

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# Chapter 7

## Market Segmentation for CLT in the U.S.

## ***Introduction***

The objective of this chapter was to identify distinct market segments for CLT adoption in the U.S. For this purpose, responses from two surveys (to U.S. engineering firms and construction firms) was used to conduct a cluster analysis using Marketing Engineering, educational software developed by Decision Pro Inc. This study will also provide information regarding market segment attractiveness, which can be used by entrepreneurs interested in entering the CLT market and organizations supporting the industry. By understanding what influences main actors in the construction material selection process, entrepreneurs and industry suppliers will be able to develop more effective marketing strategies to target potential adopters and provide more customized services and products.

## *Methodology*

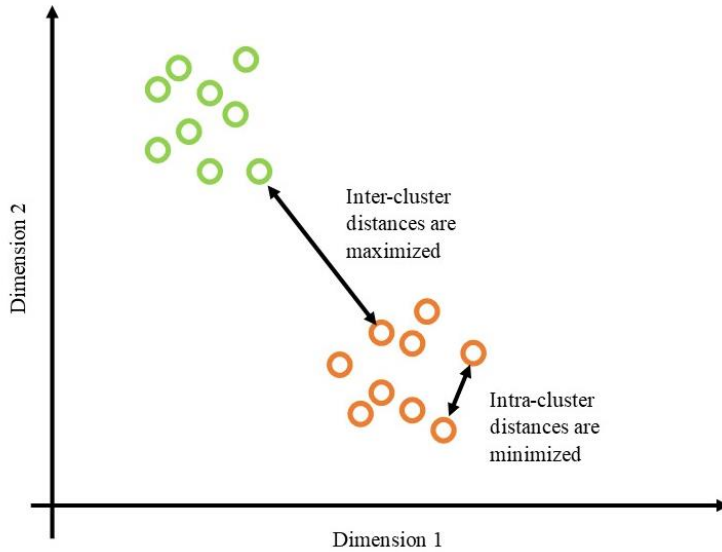
To understand the market potential of a new product, it is important to identify distinct segments of customers in that market, to allow targeted product and marketing strategy development. This part of the research aims to incorporate potential adopters' perceptions about CLT, as well as firm demographic characteristics, to identify the most promising markets segments for CLT.

The term “market segmentation” was first introduced by Smith (1956), who defined it as “*viewing a heterogeneous market as a number of smaller homogeneous markets, in response to differing preferences, attributable to the desires of consumers for more precise satisfaction of their varying wants*”. Since then, market segmentation has become essential for marketing strategy formulation, as a way for companies to serve their customers' demands more effectively (Do, 2011). Market segmentation highly depends on bases (variables) and methods (Wendel, 2000). There are numbers of market characteristics that can be chosen as bases for market segmentation, which leads to many ways to segment a market (Do, 2011). The approach chosen for this study was cluster analysis.

### *Cluster Analysis*

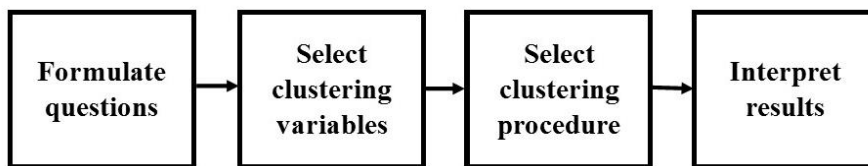
Results from the survey of potential adopters was used to identify distinct market segments for Cross-Laminated Timber (CLT). Firm demographic and psychographic information was used as bases for market segmentation.

To accomplish this goal, a cluster analysis was performed. Cluster analysis is a widely used tool for market segmentation (Wendel, 2000). In cluster analysis, observations are “clustered” into groups, minimizing the inter-cluster distance and maximizing intra-cluster distances (Figure 19). Cluster analysis, also called taxonomy analysis (MathWorks, 2017), has been used in academic research and marketing to: (a) better understand buyer behavior, (b) identify groups of buyers, (c) identify niche markets, and (d) identity new product opportunities (Punj & Stewart, 1983).



**Figure 19. Cluster analysis diagram.**

Conducting a cluster analysis involves four steps. Figure 20 shows a summary of the procedure (Lilien & Rangaswamy, 2004; Mooi & Sarstedt, 2011).



**Figure 20. Generic cluster analysis methodology.**

The first step is to decide what the objective of the cluster analysis is, and what kind of information we would like to obtain from the analysis. Step 2 involves the selection of the clustering variables (segmentation variables) to be used as basis for the segmentation; and discriminant variables, which will describe the observations in each segment. In a similar way to the methodology followed to perform the factor analysis presented in Chapter 6, five questions from the surveys to engineers and contractors were used to segment the CLT market. Table 47 summarizes those questions.

**Table 47. Variables used in the cluster analysis.**

<b>Clustering variables</b>	<b>Code</b>	<b>Question</b>	<b>Variable</b>	<b>Type of question</b>
Discriminant variable	Q1	In which of the following regions does your firm operate?	Location of firm	Multiple choice
	Q2	Which of the following firm size categories best describes your firm?	Size of firm	Multiple choice
	Q3	What are the main type of buildings your firm works with?	Type of construction	Multiple choice
Segmentation variables	Q5	Please rate your agreement with the following statements about your firm's innovativeness.	Innovativeness	Likert scale
	Q7	Please rank the importance of the following characteristics at the time of specifying a structural material.	Importance of material's characteristics	Likert scale

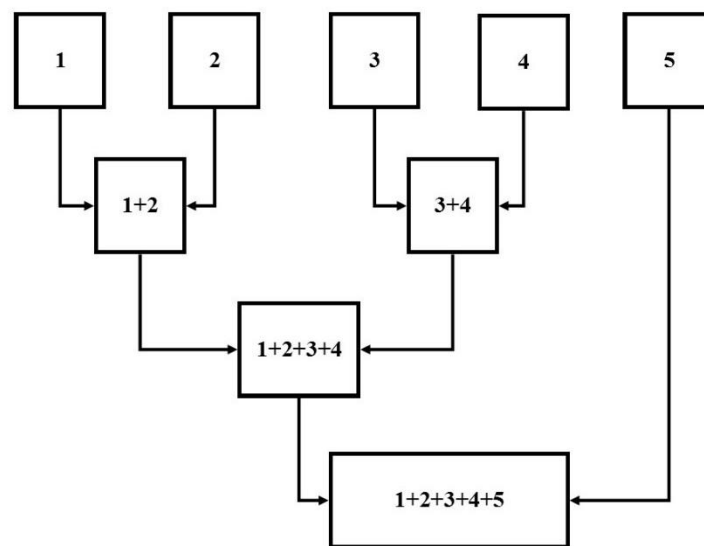
Discriminant variables, also called descriptors, are observable variables that are used to describe or to profile a segment (Lilien & Rangaswamy, 2004). These variables tell researchers who is, or who is not likely to belong to a specific segment. Segmentation variables, on the other hand, are latent variables that are used to define each segment. These variables suggest the researcher why respondents make certain decisions or purchases (Lilien & Rangaswamy, 2004). For this research, location, size of firm, and type of constructions were used as discriminant variables, while innovativeness and perceptions about material's characteristics were chosen as segmentation variables (Table 47). These two segmentation variables were chosen given their importance as main drivers of any product acceptance process.

After determining the clustering variables, the third phase a cluster analysis is the selection of the clustering procedure (Mooi & Sarstedt, 2011). There is a wide variety of clustering algorithm, such as Fuzzy c-means, Gaussian and k-means. According to Mooi and Sarstedt (2011), these procedures can minimize the within-cluster variance (hierarchical method), or maximize the distance between clusters (partitioning method).

#### *Hierarchical method*

Hierarchical clustering, also called nesting clustering (Khan, 2016), is characterized by the grouping of items in a multi-level tree-like structures or dendrograms (MathWorks, 2017). Most hierarchical techniques fall into a category called agglomerative clustering (Adamson

& Bawden, 1981; Mooi & Sarstedt, 2011). This technique starts with each observation representing an individual cluster, which are the sequentially merged depending on how similar they are to each other. Similarity is evaluated using a measure of “distance;” which can in turn be calculated by several methods, such as the Euclidian distance. Initially, the two most similar clusters are merged to form a new cluster at the top of the hierarchy (Borgatti, 1994). Then, another pair of clusters is merged and linked to a lower level of the hierarchy. The procedure continues until no more clusters can be merged. Figure 21 illustrates this process.



**Figure 21. Hierarchical method.**

*Partitioning method*

Another clustering method is the partitioning technique (Ayramo & Karkkainen, 2006; Wilson, Boots, & Millward, 2002). This is the most common type of clustering method used. This clustering process starts by randomly assigning objects to clusters (Mooi & Sarstedt, 2011). The rest of the observations are then sequentially assigned into one of the mutually exclusive clusters to minimize the inter-cluster distance variation. One of the most frequently used partitioning clustering algorithms is k-means clustering, which requires number of clusters as input (k) before running the algorithm (Indika, 2011). In general, the

k-means is regarded as superior to hierarchical methods, because it is less affected by outliers or of unrelated clustering variables (Mooi & Sarstedt, 2011).

For this research, the partitioning (k-means) method was used. To determine the number of clusters to be used for the analysis, “elbow plots” were used (explained later). The analysis was carried out using Marketing Engineering, an educational software (Marketing Engineering, 2017).

### ***Limitations***

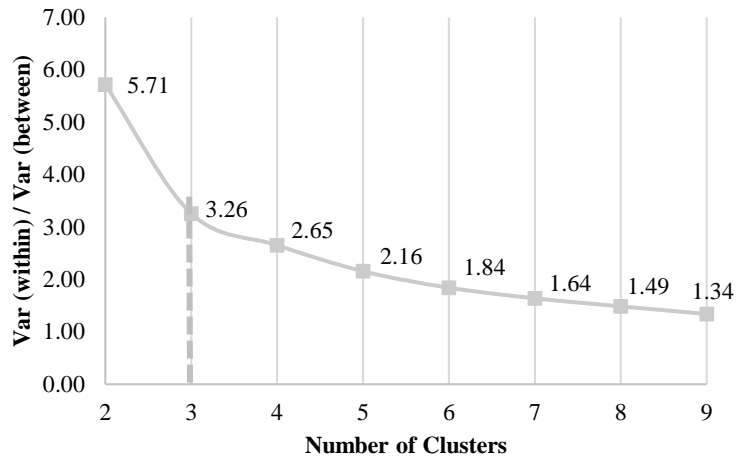
As with any statistical analysis, there are some limitations when conducting a cluster analysis in regards to the sample size required. Unfortunately, there is no universally recognized rule of thumb regarding minimum sample size required to ensure the validity to the analysis (Mooi & Sarstedt, 2011). However, Formann (1984) provided a guidance by recommending a sample size of at least  $2^n$ , where  $n$  equals the number of clustering variables. It is also important to mention that cluster analysis is an exploratory procedure, and it requires making some decisions based on judgement (Espinoza, 2017).

### ***Results and discussion***

Two segmentations, one for U.S. engineering firms and one for U.S. construction firms, were conducted for this study. An explanation of the results obtained follows.

#### ***(a) U.S. engineering firms***

To evaluate the number of clusters, eight hierarchical analyses were performed to obtain the ratio between the within-cluster and the between-cluster variances. The goal is to minimize the ratio of within-cluster variance (Martin, 2013). This numbers were then graphed in an “elbow diagram” (Figure 22). As seen in Figure 22, gains in information become marginal after three clusters. Therefore, it was decided to work with three clusters for the analysis.



**Figure 22. Elbow diagram for U.S. engineering firms.**

After determining the number of clusters, the analysis of the segmentation and discriminant data was run again. Results of the analysis for the segmentation variables are shown in Table 48. The output for the analysis of discriminant variables (firms' demographic information) is presented in Table 49. The information in Tables 48 and 49 is then used to describe each segment.

**Table 48. Segmentation variables for U.S. engineering firms.**

Segmentation variables	Cluster 1	Cluster 2	Cluster 3
<b>-- Material's characteristics --</b>			
Environmental Performance	2.55	3.58	3.08
Mechanical Performance	1.77	2.03	1.32
Economic Performance	1.77	2.24	1.32
Aesthetics	2.72	3.45	3.40
Fire Performance	1.77	3.00	1.24
Earthquake Performance	2.47	3.68	3.64
Availability in the Market	2.25	2.03	2.16
Acoustic Performance	3.38	4.42	3.20
Maintenance	2.92	3.26	3.20
Durability	2.00	2.26	2.28
LEED Credits	3.38	5.03	3.72
Moisture Performance	2.45	2.89	2.52
Vibration Performance	2.67	3.45	3.56
Complexity of Construction	2.65	2.82	3.24
Compatibility Building Code	1.38	1.68	1.80
Availability of Design Tools	2.50	2.42	3.40
<b>-- Innovativeness --</b>			
Employees in our Firm are encouraged to research new materials	1.50	2.03	2.08
Our Firm collaborate with other firms to investigate new materials	1.98	2.74	3.60
Our Firm collaborates with universities to investigate new materials	2.25	2.87	3.72
Our Firm collaborates with research centers and governmental agencies to investigate new materials	2.35	2.87	3.68
Our Firm is open to find innovative solutions by collaborating with materials suppliers/manufacturers	1.42	1.97	2.56
Our Firm invests in the training and development of its employees	1.17	1.95	1.88
Innovation is incorporated in our Firm's corporate strategy	1.30	2.16	1.96
Our Firm has a systematic procedure in place to review and reflect on past projects	1.58	2.68	2.04

*Note: Numbers are average responses. The scale for the material's characteristics goes from 1 to 6, with 1 being "extremely important" and 6 being "not at all important". The scale for innovativeness goes from 1 to 4, with 1 being "strongly agree" and 4 being "strongly disagree". Colors denote statistical differences between segments. Green represents significantly higher values, and red significantly lower values.*

**Table 49. Discriminant variables for U.S. engineering firms.**

Discriminant variables	Cluster 1	Cluster 2	Cluster 3
<b>-- Location of Firm --</b>			
Northeast	37.5%	26.3%	40.0%
South	45.0%	42.1%	44.0%
Midwest	62.5%	44.7%	40.0%
West	57.5%	28.9%	40.0%
Alaska/Hawaii	12.5%	0.0%	12.0%
<b>-- Size of Firm --</b>			
1 to 4	7.5%	18.4%	24.0%
5 to 9	12.5%	13.2%	8.0%
10 to 19	20.0%	23.7%	24.0%
20 to 99	25.0%	26.3%	24.0%
100 or more	35.0%	18.4%	20.0%
<b>-- Type of construction --</b>			
Single-family residential	25.0%	34.2%	16.0%
Multi-family residential	42.5%	47.4%	44.0%
Commercial	60.0%	71.1%	68.0%
Educational	37.5%	52.6%	48.0%
Transportation	40.0%	18.4%	24.0%
Governmental	35.0%	36.8%	24.0%
Recreational	37.5%	42.1%	36.0%
Religious	27.5%	31.6%	24.0%
Industrial	52.5%	44.7%	36.0%

*Cluster 1*

Cluster 1 contains 38.8% of the engineering firms in the sample. According to Table 49, 62.5% of the firms in this group have offices in the Midwest and more than half (57.5%) in the West. Over one third (35.0%) of the firms in cluster 1 are large firms (with 100 or more employees), and only 7.5% of the firms in this cluster were small firms with 1 to 4 employees. As for the type of projects, 60.0% of the firms in cluster 1 work primarily with commercial buildings. Additionally, more than half of the firms (52.5%) also work with industrial buildings. In regards to the segmentation variables, it is important to mention that the numbers in Table 48 are averages of responses on a scale from 1 to 6 for material's characteristics (with 1 being "extremely important" and 6 being "not at all important"), and from 1 to 4 for innovativeness (with 1 being "strongly agree" and 4 being "strongly disagree"). The most important material characteristic for firms in this segment seems to be the compatibility with the building code (1.38). Companies in cluster 1 also rated highly the importance of mechanical, fire, and economic performance (all rated an average of 1.77) (Table 48). In contrast, they do not regard as highly important the ability to obtain

LEED credits (3.38), acoustic performance (3.38), and maintenance (2.92). However, firms in cluster 1 care about LEED Credits and vibration performance to a higher degree than the other clusters. In regards to their perceived innovativeness, respondents in cluster 1 consider themselves highly innovative, since they highly agreed with almost all innovativeness dimensions evaluated (Table 48), and particularly with “Our Firm invests in the training and development of its employees” (1.17), and with “Innovation is incorporated in our Firm’s corporate strategy” (2.35). Furthermore, firms in cluster 1 agreed to all innovativeness dimensions to a higher degree than the other clusters (Table 48).

### *Cluster 2*

Cluster 2 contains 36.9% of the engineering firms in the sample. This segment has a large percentage of respondents from medium-sized (between 20 and 99 employees) firms that are predominantly located in the Midwest and South of the U.S. (Table 49). As seen in Table 49, firms in cluster 2 works mainly with commercial and educational buildings with 71.0% and 52.6% of respondents selecting these types of construction, respectively. The most important material characteristic for firms in this segment are mechanical properties (2.03), availability in the market (2.03), and building code compatibility (1.68). In contrast, they do not regard as highly important the ability to obtain LEED credits (5.03), and acoustic performance (4.42) (Table 48). Firms in cluster 2 care about economic, fire and acoustic performance, and the LEED Credits to a lower degree than the other clusters. Participants represented in cluster 2 consider themselves somewhat innovative, since the average for the innovativeness dimensions is between 1.95 and 2.87, on a scale from 1 to 4 (Table 48). In a similar way as firms in cluster 1, engineering firms in cluster 2 highly agreed with the statement “Our Firm invests in the training and development of its employees” (1.95). Innovativeness dimensions related to collaboration (with other firms (2.74), with universities (2.87) or with research centers (2.87)) received low agreement ratings by firms in cluster 2 (Table 48). Firms in cluster 2 disagree to three of the eight innovativeness dimensions (training and development of employees, innovation

incorporated in the firm's strategy, and review and reflect on past projects) to a higher degree than the other clusters.

### *Cluster 3*

Cluster 3 contains 24.3% of the engineering firms in the sample. Firms in cluster 3 are more evenly distributed geographically than clusters 1 and 2 (Table 49). Firms in this cluster do not have a distinct size (measured by number of employees), and work mainly with commercial construction. The most important material characteristic for firms in this segment are mechanical (1.32) economic (1.32) and fire performance (1.24), and compatibility with the building code (1.80). In contrast, they do not regard as highly important earthquake (3.64) and vibration performance (3.56), and ability to obtain LEED credits (3.72) (Table 48). Firms in cluster 3 care about mechanical, economic, and fire performance to a higher degree, and about availability of design tools to a lower degree than the other clusters. In regards to their perceived innovativeness, respondents in cluster 3 do not consider themselves very innovative, since they highly disagree with almost all but three innovativeness dimensions evaluated, particularly those related to collaboration (with other firms (3.60), universities (3.72) or research centers (3.68)). Firms in cluster 3 disagree to five of the eight innovativeness dimensions to a higher degree than the other clusters. Interestingly, firms in this cluster showed the highest disagreement among all engineering clusters, with the statement: "Our Firm is open to find innovative solutions by collaborating with materials suppliers/manufacturers" (2.56). A summary of the characteristics of each cluster is presented in Table 50.

**Table 50. Summary of cluster characteristics for U.S. engineering firms.**

U.S. engineering firms						
Cluster	Location of firm	Size of firm	Type of Building	Material's characteristics		Innovativeness
				Highest rated	Lowest rated	
Cluster 1	Midwest and West	Large (100 or more employees)	Commercial and industrial	Mechanical, economic and fire performance and compatibility with building code	Acoustic performance and LEED credits	Very innovative
Cluster 2	South and Midwest	Medium (between 10 and 99 employees)	Commercial and educational	Mechanical and economic performance, availability in the market, and compatibility with the building code	Acoustic performance, and LEED credits	Moderately innovative
Cluster 3	All regions	Small, medium and large	Commercial and educational	Mechanical performance, economic performance, fire performance and compatibility with building code	Earthquake and vibration performance, and LEED credits	Not very innovative

*Comparison of U.S. engineering firm clusters*

Many similarities and differences can be seen among the three clusters created for U.S. engineering firms. Table 50 shows a comparative summary of the results. A clear distinction between clusters can be noted when comparing firm size; firms in cluster 1 tend to be larger than those in cluster 2, and firms of all sizes are represented in cluster 3. However, the differences in regards to the location of the firms in each cluster are not as clear, and this is due in part because companies were able to select multiple locations where they operate.

Regarding the type of buildings that companies specialize in, most companies mentioned commercial construction as their primary market, which comes from the sample development, when a decision was made to focus on firms that work in commercial construction. However, firms in cluster 1 tend to also work with industrial buildings and those in cluster 2 with educational buildings.

Regarding material characteristics, firms in all clusters rated mechanical and economic performance and compatibility of the material with the building code as highly important during the material selection process. However, cluster 2 also rated the importance of

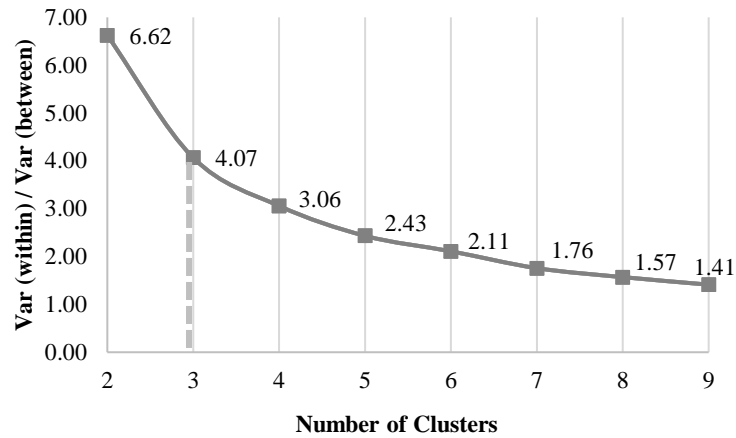
durability as high, indicating that this segment might be more concerned with the longevity and in-service performance of buildings. On the other hand, all clusters seem to consider LEED credits less important than other structural material's attributes during the material decision process, and firms in cluster 2 seemed to be the least concerned with LEED credits.

The main differences among the segments are in innovativeness. Firms in cluster 1 consider themselves as highly innovative, while firms in cluster 3 tend to disagree with most of the statements related to innovativeness. One possible explanation for these results could be that, in general, larger firms with more investment capability usually have more employees dedicated to the research of new materials and procedures. More employees may also lead to a more active exchange of diverse ideas.

Firms in cluster 1 rated the importance of environmental performance higher than firms in cluster 2 and 3. This indicates that firms in cluster 1 tend to work with an audience that is more interested in environmental sustainability, which may be an opportunity to emphasize the environmental attributes of innovative wood-based construction materials, such as CLT.

*(b) U.S. construction firms*

Below is the elbow diagram used to determine the number of cluster used in the market segmentation of U.S. construction firms. As seen in Figure 23, the most pronounced inflection in the graph happens for three clusters. Therefore, three was also selected as the number of clusters for the segmentation of construction firms.



**Figure 23. Elbow diagram for U.S. construction firms.**

After determining the number of clusters, the analysis of the segmentation and discriminant data was run again. Results from the analysis of the segmentation variables are shown in Table 47. The output for the analysis of discriminant variables (firms' demographic information) is presented in Table 48.

**Table 51. Segmentation variables for U.S. construction firms.**

Segmentation variables	Cluster 1	Cluster 2	Cluster 3
<b>-- Material's characteristics --</b>			
Environmental Performance	2.43	4.10	4.04
Mechanical Performance	1.07	1.40	1.62
Labor cost	1.14	1.53	1.67
Material cost	1.00	1.37	1.12
Cost of post-construction maintenance	1.71	2.17	2.54
Aesthetics	2.43	3.37	4.12
Fire Performance	1.14	1.07	1.58
Earthquake Performance	2.79	3.50	4.08
Availability in the market	1.21	1.90	1.79
Acoustic Performance	2.36	3.37	3.71
Durability	2.29	2.07	3.12
LEED Credits	3.71	5.30	4.75
Moisture Performance	1.93	2.27	3.00
Vibration Performance	2.71	2.43	3.33
Complexity of construction	2.36	2.87	2.29
Compatibility with the building code	1.79	2.20	1.79
Construction time	1.36	1.63	1.12
Requirement of specialized labor	2.50	3.13	2.54
<b>-- Innovativeness --</b>			
Employees in our Firm are encouraged to research new materials	2.00	2.87	2.08
Our Firm collaborates with research centers and governmental agencies to investigate new materials	2.57	3.67	3.75
Our Firm is open to find innovative solutions by collaborating with materials suppliers/manufacturers	2.64	3.50	3.17
Our Firm invests in the training and development of its employees	1.29	2.80	2.92
Innovation is incorporated in our Firm's corporate strategy	2.00	2.80	2.29
Our Firm has a systematic procedure in place to review and reflect on past projects	1.43	2.50	2.33
Our Firm is receptive to changes and new technologies	2.93	2.53	2.46

*Note: Numbers are average responses. The scale for the material's characteristics goes from 1 to 6, with 1 being "extremely important" and 6 being "not at all important". The scale for innovativeness goes from 1 to 4, with 1 being "strongly agree" and 4 being "strongly disagree". Colors denote statistical differences between segments. Green represents significantly higher values, and red significantly lower values.*

**Table 52. Discriminant variables for U.S. construction firms.**

Discriminant variables	Cluster 1	Cluster 2	Cluster 3
<b>-- Location of Firm --</b>			
Northeast	50.0%	10.0%	33.3%
South	50.0%	40.0%	29.2%
Midwest	14.3%	40.0%	29.2%
West	35.7%	23.3%	29.2%
Alaska/Hawaii	0.0%	3.3%	4.2%
<b>-- Size of Firm --</b>			
1 to 4	0.0%	26.7%	16.7%
5 to 9	7.1%	16.7%	16.7%
10 to 19	28.6%	20.0%	16.7%
20 to 99	21.4%	33.3%	50.0%
100 or more	42.9%	3.3%	0.0%
<b>-- Type of Construction --</b>			
Single-family residential	21.4%	16.7%	29.2%
Multi-family residential	64.3%	40.0%	54.2%
Commercial	78.6%	50.0%	79.2%
Educational	35.7%	20.0%	33.3%
Transportation	0.0%	16.7%	4.2%
Governmental	0.0%	3.3%	4.2%
Recreational	42.9%	23.3%	25.0%
Religious	7.1%	0.0%	4.2%
Industrial	42.9%	20.0%	29.2%

*Cluster 1*

Cluster 1 contains 20.6% of the construction firms in the sample. Results (Table 52) indicate that cluster 1 is comprised of firms located in the Northeast and South regions. Results also show that 42.9% of this cluster are large firms of 100 or more employees. According to the analysis, a small percentage of this segment are small firms of between one and nine employees. A majority (78.6%) of cluster 1 consists of construction firms that work with commercial buildings (Table 52). More than half (64.3%) of represented firms work with multi-family residential buildings. In regards to the segmentation variables, the most important material characteristic for firms in this segment are mechanical performance (1.07), labor (1.14), material (1.00) and post-construction cost (1.71), availability of the material in the market (1.21), and construction time (1.36) (Table 51). In contrast, they do not regard as highly important the ability to obtain LEED credits (3.71), vibration (2.71) and earthquake performance (2.79). Construction firms in cluster 1 care about environmental, mechanical, acoustic and moisture performance, labor, material and maintenance cost, as well as LEED Credits and availability in the market to a higher degree

than the other clusters. In regards to their perceived innovativeness, respondents in cluster 1 consider themselves very innovative, since they highly agreed with almost all innovativeness dimensions evaluated, in particular “Our Firm invests in the training and development of its employees” (1.29). The statements regarding collaboration, in particular those related to collaboration with manufacturer and suppliers and research centers were rated relatively low (2.64 and 2.57, respectively) in comparison to other innovativeness dimensions (Table 51). Construction firms in cluster 1 agree to all but one (“Our firm is receptive to changes and new technologies”) of the innovativeness dimensions analyzed to a higher degree than the other clusters.

### *Cluster 2*

Cluster 2 contains 44.1% of the construction firms in the sample. Over a third of the firms (33.3%) in cluster 2 are medium-sized (between 20 and 99 employees), and are predominantly located in the Midwest (40.0%) and the South (40.0%) (Table 52). The most important material characteristic for firms in this segment are mechanical properties (1.40), material cost (1.37), fire performance (1.07), as well as construction time (1.63) (Table 51). In contrast, they do not regard as highly important the ability to obtain LEED credits (5.30) and environmental performance (4.10). Construction firms in cluster 2 care about durability and vibration performance to a higher degree, and about material cost, construction time and LEED Credits to a lower degree than the other clusters. In regards to their perceived innovativeness, construction firms in cluster 2 consider themselves somewhat innovative, since they moderately agreed with almost all innovativeness dimensions evaluated (Table 51). U.S. construction firms in cluster 2 agreed with the statement regarding the existence of a procedure in place to review and reflect on past projects (2.50). Table 51 also shows that dimensions of innovativeness related to collaboration (with suppliers/manufacturers (3.50), or research centers (3.67)) were the statements with which respondents in this cluster showed the least agreement. This cluster showed the highest disagreement among all construction firm clusters with the statement: “Employees in our Firm are encouraged to research new materials” (2.87).

### *Cluster 3*

Cluster 2 contains 35.3% of the construction firms in the sample. Firms in this cluster are evenly distributed in all U.S. regions (Table 52). However, a slightly larger percentage of firms (33.3%) in this segment are located in the northeastern region of the U.S. This cluster contains firms of all sizes that work mainly in commercial construction. The most important material characteristic for firms in this segment are mechanical performance (1.62), labor costs (1.67), material cost (1.12), availability in the market (1.79), and construction time (1.12) (Table 51). However, results show that, similarly to cluster 2, firms in cluster 3 do not regard as highly important environmental and earthquake performance (4.04 and 4.08 respectively), aesthetics (4.12), as well as the ability to obtain LEED Credits (4.75) (Table 51). Firms in cluster 3 care about construction time to a higher degree, and about aesthetics, fire, moisture and vibration performance, and durability to a lower degree than the other clusters. Similarly to cluster 2 of construction firms, firms in cluster 3 consider themselves somewhat innovative, since they moderately agreed with almost all innovativeness dimensions evaluated (Table 51). Collaboration does not seem to be a priority for this cluster. Firms in cluster 3 highly disagreed with almost all innovativeness dimensions evaluated, particularly those related to collaboration (with research centers (3.75), and suppliers/manufacturers (3.17). Interestingly, firms in this cluster showed the highest disagreement with the statement: “Our Firm invests in the training and development of its employees” (2.92). A summary of the characteristics of each cluster is presented in Table 53.

**Table 53. Summary of cluster characteristics for U.S. construction firms.**

Cluster	Location of firm	Size of firm	Type of construction	Material's characteristics		Innovativeness
				Highest rated	Lowest rated	
Cluster 1	Northeast and South	Large (100 or more employees)	Commercial and multi-family residential	Mechanical and fire performance, labor, material, and maintenance cost, availability in the market, and construction time	Earthquake and vibration performance, and LEED credits	Very innovative
Cluster 2	South and Midwest	Medium (between 20 and 99 employees)	Commercial	Mechanical and fire performance, labor and materials cost and construction time	Environmental performance, and LEED credits	Somewhat innovative
Cluster 3	All regions	Medium (between 20 and 99 employees)	Commercial	Mechanical and fire performance, labor and material cost, and construction time	Environmental and earthquake performance, aesthetics, and LEED credits	Somewhat innovative

*Comparison of U.S. construction firm clusters*

Differences between the three clusters created for U.S. construction firms are subtle. On one hand, many similarities can be seen between cluster 2 and 3 in regards to size of firm, the type of buildings the firms are involved with, and their perceived innovativeness. The main difference between these two groups relates to the material characteristics rated with the lowest importance during the material decision process. Both cluster 2 and 3 appear to be less environmentally focused (rating environmental performance and LEED credits low) than firms in cluster 1. Firms in cluster 3 seem to be less interested in aesthetics than firms in the other two clusters.

Cluster 2 is distinctively composed of large and very innovative firms that place great importance on performance and cost. Availability in the market and construction time, both associated with the final cost of construction are included among the highest rated characteristics. In a similar way to clusters 2 and 3, firms in cluster 1 rated LEED credits low in importance.

## *Positioning*

### *U.S. engineering firms*

According to the results from this study, U.S. engineering firms in cluster 1 rated highly the importance of mechanical, fire, and economic performance of materials; as well as building code compatibility. A positioning statement that highlights the structural capabilities of CLT and how this innovative structural system could allow for significant construction time and cost reductions, when compared to traditional building materials would be important to increase adoption of CLT among professionals in this cluster. Since this group also prioritizes the compatibility with the building code, a positioning statement highlighting that CLT has recently been included in the Building Code (AWC, 2015), could help promote the adoption of the system among these segments.

Engineering firms in cluster 2 rated high the importance of mechanical properties, building code compatibility, and availability during the material decision process. A positioning statement for this cluster should be focused on providing information about CLT performance and manufacturing companies supplying CLT panels.

Similarly, respondents that belong to cluster 3 place a high importance on mechanical, economic and compatibility with the building code, as well as fire performance, when selecting materials for construction. There is opportunity to gain market share from the U.S. engineering firm's segments by stressing the benefits of CLT in regards to its fire performance.

Interestingly, U.S. engineering firms in all clusters strongly agree with the statement regarding their investment in the training and development of their employees. Organizations looking to target firms in cluster 3 should also focus their efforts in offering more and improved educational opportunities, that could count towards the renewal of these professionals licenses, for the these the firms in these clusters.

### *U.S. construction firms*

Cluster 1 is comprised of respondents that rate mechanical, and labor and material cost very high in importance during the material decision process. Availability of the material

in the market and construction time were also rated highly by firms in this cluster. It can be speculated that a positioning statement that emphasized the structural and economic benefits of adopting CLT in comparison to traditional materials, such as concrete or steel, could greatly improve the chances of adoption of this system among firms in this cluster. It would also be important to make information about CLT suppliers readily available for this group, as they place high importance on the availability of material in the domestic market.

U.S. construction firms in cluster 2 rated fire performance and material and labor cost as the material's characteristics with the highest importance during the material decision process. Firms in this cluster also rated construction time and mechanical performance highly. This indicates that for this cluster a positioning statement focusing on the advantages of CLT as a structural material in regards to fire performance, faster construction time, lower construction cost could help increase the adoption of CLT among the firms in this group.

Similarly to clusters 1 and 2, firms in cluster 3 also rated material cost, construction time and fire performance as the material's characteristics with the highest importance, when selecting structural materials for their buildings. Therefore, a similar positioning approach as the one mentioned for the two previous clusters should be followed.

## ***Conclusion***

The objective of this chapter was to identify distinct market segments for CLT adoption in the U.S. Responses from two surveys (Chapter 2 and Chapter 4) were used to conduct a cluster analysis. Using this method, distinct market segments were identified in the two populations of interest (U.S. engineering and construction firms). From this analysis, priorities and demographics of those segments were identified.

Results from the cluster analysis show that segments of U.S. engineering firms are comprised of companies, which work primarily with commercial, industrial and educational buildings. Firms in these clusters consider mechanical and economic performance of materials and compatibility with the building code to be the most important

attribute during the material decision process. A positioning statement that emphasizes the structural capabilities of CLT and the similarities and advantages between CLT and traditional building materials, such as concrete, may prove important to increase adoption of CLT among these groups. It appears to be an opportunity to gain market share from these U.S. engineering firm's segments by stressing the benefits of CLT in regards to its fire performance. Since engineering firm's clusters prioritize the compatibility with the building code, a positioning statement should also highlight that CLT has recently been included in the 2015 International Building Code.

Findings from the analysis of U.S. construction firms, show that firms in these clusters are highly cost-sensitive. These clusters comprise of firms that usually work with commercial and multi-family residential buildings. As seen in Chapter 4, U.S. construction firms are also the construction professionals with the lowest familiarity with CLT. For this reason, a positioning statement for construction firm's clusters should be focused, first at increasing the familiarity and confidence in CLT, and second, at stressing the economic benefits (i.e. less labor cost and construction time) (Laguarda-Mallo & Espinoza, 2016). Before these clusters begins to adopt, it will be important to overcome the industry's negative perception of CLT's availability in the market and material cost (Laguarda-Mallo & Espinoza, forthcoming; Laguarda-Mallo & Espinoza, 2016; Laguarda Mallo & Espinoza, 2015).

The information obtained from this chapter is useful to develop effective marketing strategies to target potential adopters and provide customized services and products. In the case of U.S. construction firms, which as seen in Chapters 4 and 5 are the population with the least familiarity with CLT, it would be important to first focus the efforts in educating these professionals before directing any marketing strategies towards them.

# **Chapter 8**

**Conclusions, Implications,  
Strategic Recommendations  
and Future Work**

## ***Introduction***

This research builds on previous work by the author, to gain insights about the critical factors associated with the adoption of innovative wood-based building materials by U.S. engineering and construction firms. Cross-Laminated Timber (CLT) was used as a case to study. Inputs from major decision makers in the material selection process, namely structural engineering firms and construction firms, were collected and analyzed. Based on the information gathered from surveys and interviews, a conceptual model of the critical factors that influence the willingness to adopt innovative wood-based construction systems was developed. The results were also used to identify distinct market segments for CLT in the U.S. In this chapter, the most important conclusions and implications from each component of the research project are presented. The chapter ends listing some topics for future research.

## *Summary of results*

### *Chapter 2 - Survey to U.S. engineering firms*

The main goal of this part of the thesis was to assess the level of awareness, perceptions and willingness to adopt CLT by structural engineering firms in the U.S. To accomplish this objective, a web-based survey was conducted among U.S. structural engineering firms that work primarily with commercial buildings. A total of 113 usable responses were received.

The results from this quantitative study show that the level of awareness in the structural engineering community is intermediate, with a combined 59.3% of respondents indicating very little or no knowledge of CLT. When asked about how participants heard about CLT, respondents indicated that they obtained the information primarily from the internet (37.9%), magazines (36.8%), and conferences (36.8%). Information obtained from the survey indicates that the highest ranked features of CLT are its aesthetic characteristics, its environmental attributes, and its structural performance. On the other hand, availability in the market was one of the lowest ranked features of the product, consistent with the existence of only three manufacturing companies in the country at the time of writing. Regarding the perceived barriers for CLT adoption, respondents indicated that CLT's availability in the market, its initial cost, and compatibility issues with the building code were the largest hurdles to the wide adoption of the system. A considerable percentage of participants also indicated that CLT's performance (72.4%) and maintenance costs (71.3%) could constitute barriers to its adoption. The results from the survey showed that engineers were hesitant to adopt CLT (with 35.6% saying they are uncertain if they would use it in the future) if it were available in the market.

### *Chapter 3 - Interview to U.S. engineering firms*

The objective of this part of the thesis was to follow up on the information obtained from the survey of U.S. engineering firms, and gain in-depth insights about the level of awareness, perceptions and willingness to adopt CLT by U.S. structural engineering firms. This qualitative study also aimed to investigate how the structural material decision process

takes place and who are the actors with the most influence during this process. To accomplish these objectives, 30 interviews with U.S. structural engineers were conducted. Results from this study show that the material selection process varies greatly depending on the type of building and the cost of the material selected. During the interviews, many participants indicated that building security and resiliency requirements were factors that influence strongly the material decision process. According to their responses, architects and engineers are the most influential actors in the material selection process, and collaborate closely in the design process. U.S. construction firms, on the other hand, were seen as “advisors,” who are incorporated later on in the decision process. Findings from the interviews confirm and complement the information obtained from the survey, indicating that the level of awareness about CLT among U.S. engineers is intermediate. When asked about the perceived benefits of CLT, engineers interviewed indicated that the main benefits of CLT-based systems come from using a natural, renewable resource as opposed to energy-intensive and non-renewable materials like concrete or steel. Another important benefit of CLT-based systems noted by the engineers is the shorter construction time and labor needed since CLT is a prefabricated system, in which panels come to the construction site ready to be installed. In addition to this, participants mentioned that the aesthetic qualities, such as a “natural” look and warmth (when CLT is left exposed) and CLT’s design flexibility, are strong advantages of CLT in comparison to concrete or steel. When asked about the perceived barriers to CLT adoption in the U.S., respondents with previous knowledge about CLT mentioned durability issues, fire resistance, maintenance requirements and cost as potential drawbacks of CLT. The most frequently mentioned barriers to the wide adoption of CLT-based construction systems in the U.S. were the lack of information about design methods and procedures specific to CLT; lack of information about users and occupants’ experience living in these buildings; little experience working with CLT-based structural systems; and availability of CLT in the domestic market. Interviewees familiar with CLT were optimistic and positive about their willingness to adopt the system in the future if it were widely available in the U.S. market at a competitive price.

#### *Chapter 4 - Survey to U.S. construction firms*

A survey of U.S. construction firms was conducted in this part of the study, to understand the current level of awareness about CLT, perceptions about this material, and construction firms' willingness to adopt CLT. A phone survey was used as data collection method, and U.S. construction firms that work primarily with commercial buildings were the target audience. A total of 68 usable responses were received.

The results from this quantitative study show that the level of awareness among construction firms is low, with a combined 88.3% of respondents indicated being "not very familiar" or that they "have not heard about CLT." When asked about how the participants heard about CLT, 10 from the 16 participants familiar with CLT indicated that they obtained information mostly from the internet, six from conferences, webinar or workshops, and four through a friend or relative. Information obtained from the survey indicates that the highest ranked features of CLT are its reduced labor costs, aesthetic characteristics, environmental performance, and faster construction time. On the other hand, availability in the market was one of the lowest ranked features of the product. Regarding the perceived barriers, respondents indicated that CLT's availability in the market, the amount of wood required for its manufacture, as well as the promotion/education (or lack of thereof) were the largest hurdles to wide adoption of the system in the U.S. Moreover, participants familiar with CLT perceived that CLT's cost, compatibility with the building code and maintenance costs are potentials barriers to the adoption of CLT in the U.S. Findings from this study also show that U.S. construction firms familiar with CLT are likely to adopt CLT if it were available in the market, with 10 out of 16 being "very likely" or "likely" to adopt CLT in the future.

#### *Chapter 5 - Interviews to U.S. construction firms*

To follow up on the information obtained from the survey to U.S. construction firms and gain in-depth insights about this population, this qualitative study aimed at investigating the level of awareness, perceptions and willingness to adopt CLT by U.S. construction firms. The interviews conducted were also intended to gain a deeper understanding of how structural material decisions take place, and who are the most influential actors in this

process. To accomplish these objectives, 30 interviews were conducted with U.S. construction firm representatives.

Most interviewees that participated in this study stated that the material selection process varies greatly from firm to firm, and depends on the type of project. When asked about the major factors influencing this selection process, interviewees stated that relative cost (including material, labor and maintenance) of the available solutions, product availability, availability of trained workforce, durability, and longevity, are the main characteristics they take into consideration when selecting a structural system for their projects. Among the construction firm representatives interviewed for this study, the level of awareness about CLT was low, confirming results from the survey to the same population of interest. When asked to expand on what they perceived as benefits of CLT, U.S. construction firm's representatives indicated that previous knowledge about CLT indicated that the main benefits of CLT-based systems come from its aesthetic qualities. Another important benefit of CLT-based systems over traditional light wood-frame construction that was mentioned are the design possibilities and structural capabilities, in particular related to the opportunity to span longer distances without intermediate supports. When asked about the downsides of CLT, many U.S. construction firm representatives mentioned durability, poor fire resistance, and lack of suppliers and skilled professionals able to design, detail and install the product, as potential drawbacks of the system. When asked about the perceived barriers to the wide adoption of CLT-based construction systems in the U.S., respondents mentioned the limited availability of the product in the market; the slow pace at which the construction industry adopts new products as the main potential barriers. Other factors affecting the adoption of CLT mentioned by respondents were that CLT is not as well established as concrete or steel; the lack of demonstration projects; and the lack of "mass timber" education opportunities within the U.S. The willingness to adopt CLT for future projects, among the professionals familiar with the system, was high. U.S. construction firm representatives showed interest in adopting CLT if it were widely available at a competitive cost in the U.S. market, and if more demonstration projects were available.

### *Chapter 6 - Model development*

The objective of this part of the research was to develop a conceptual model of the critical factors affecting the adoption of innovative wood-based construction materials by U.S. engineering and construction firms. To accomplish this goal, the information collected from two nationwide surveys was purified (process that eliminates items that affect the internal consistency of the scales), reduced and analyzed using a series of statistical methods.

The final conceptual model for U.S. engineering firms shows that the main internal factor that affects the willingness to adopt innovative wood-based construction materials is firm size. In regards to the external factors, aesthetics, moisture, and vibration performance, LEED Credits, and availability of design tools, are associated with the willingness to adopt these products.

As for the conceptual model for U.S. construction firms, the main internal factors that influence willingness are location, perceived innovativeness of the firm, and level of awareness. Within innovativeness, the most important sub-factors are encouragement and training of employees, collaboration with manufacturers and suppliers, review of past projects, innovation as part of the firm's corporate strategy. In regards to external factors, maintenance requirements, durability, vibration performance, labor cost and LEED Credits, are associated with the willingness to adopt CLT.

### *Chapter 7 - Market segmentation*

The goal of this part of the dissertation was to identify distinct market segments for CLT adoption in the U.S. For this purpose, responses from the surveys to engineers and construction firms were used to conduct a cluster analysis. Three distinct segments were identified in each group.

Results from the cluster analysis show that segments of U.S. engineering firms are comprised of companies, which consider mechanical and economic performance of materials and compatibility with the building code to be the most important attributes during the material decision process. A positioning statement that emphasizes the structural capabilities of CLT and the similarities and advantages between CLT and traditional

building materials, as well as the benefits of CLT in regards to its fire performance such as concrete, will be important to increase adoption of CLT among these groups.

Findings from the analysis of U.S. construction firms, show that firms in clusters are cost- and time sensitive. For this reason, a positioning statement for this cluster should be focused on stressing the economic benefits (i.e. less labor cost and construction time). Similarly to the clusters of U.S. engineering firms, U.S. construction firms also place high importance on mechanical and fire performance as well as availability in the market. A positioning statement that highlights CLT's mechanical and fire performance capabilities as well as informs about domestic CLT suppliers would help increase the adoption of this system among U.S. construction clusters.

#### *Final remarks*

The research presented herein aimed at increasing the understanding about the factors that influence the willingness to adopt innovative wood-based materials. Hypotheses proposed in Chapter 1 were evaluated and results led the author to accept them. An explanation follows.

*Hypothesis 1:* Firms' demographic characteristics are associated with the willingness to adopt innovative wood-based materials used in construction.

*Decision:* Accept

It was found that Size of firm for U.S. engineering firms and Location of firm for U.S. construction firms were demographic factors influencing the willingness to adopt innovative wood-based construction materials.

*Hypothesis 2:* Firms' psychographic characteristics are associated with the willingness to adopt innovative wood-based materials used in construction.

*Decision:* Accept

It was found that firm's innovativeness and level of awareness of U.S. construction firms were psychographic factors influencing the willingness to adopt innovative wood-based construction materials.

*Hypothesis 3:* External factors to the firm are associated with the willingness to adopt innovative wood-based materials used in construction.

*Decision:* Accept

It was found that external factors to the company such as availability of design tools for U.S. engineering firms, and labor cost for U.S. construction firms, were issues influencing the willingness to adopt innovative wood-based construction materials.

*Hypothesis 4:* Distinct market segments exist in the construction industry based on the awareness, perception and willingness to adopt innovative wood-based building materials.

*Decision:* Accept

A total of six distinct market segments were identified among U.S. engineering and construction firms.

Results from this dissertation indicate that U.S. engineering firms would likely be the greatest proponents for CLT in the country. Interviews to engineering and construction firm's representatives revealed that engineers are, in most cases, the main actors together with architects during the structural material decision process. The nationwide survey to engineering firms also showed that this population is also more familiar and would be more willing to adopt CLT if it were widely available in the market, than construction firms. Engineering firms' priorities in regards to the most important attributes taken into consideration when selecting structural materials, appear to be in line with the most advantageous characteristics of CLT. Results from this research show that mechanical, economic and fire performance, as well as building code compatibility are the most important characteristics that engineers look for in construction material. Marketing strategies and educational programs targeted to U.S. engineering firms should highlight the benefits of selecting CLT in regards to its structural performance, the potential labor cost and construction time reductions, the fact that it has been included in the 2015 International

Building Code and its proven advantageous fire performance when compared to traditional building materials.

A long term look into the adoption of CLT among U.S. construction professionals, should not only include engineering firms but also construction firms. Even though their influence during the material decision process is more limited, they usually work closely with architect and engineers and their knowledge about the system could potentially help these professionals make better decisions. However, findings from this dissertation show that construction firms are largely unfamiliar with CLT. Therefore, before focusing any marketing strategies towards this population, it would be important to concentrate all efforts in improving the level of awareness and education about this system among construction firms.

### ***Implications***

The outcomes from this research help fill the gap in the knowledge about market adoption process for innovative wood-based materials in the construction industry, especially those used in the commercial construction sector. This study also contributes to the advancement the development of the CLT industry in the U.S., by adding to the body of knowledge in the fields of wood science and technology, and sustainable building practices.

This research enhances the knowledge in the field of wood science and technology by investigating major issues in the adoption of innovative wood-based building materials by the construction industry, by helping to understand how the perceptions of potential adopters of these products affect the adoption process. This research also contributes to the development of new sustainable building materials and practices, by providing information about the perceived barriers to the adoption of CLT in the U.S. market. Results from this study provide relevant information about the most attractive market segments for CLT in the U.S., to help stakeholders in the wood and construction industry interested in entering the CLT market and developing other innovative wood-based construction materials and practices. It is believed that information obtained from this study will help

accelerate technology adoption through well-designed education programs, demonstration projects, marketing strategies, and policy incentives.

Results from this research are also directed to industry suppliers, participants, and government and building officials in the U.S. construction and wood products industries. The author of this dissertation believes its findings will help them accelerate the adoption of CLT through well-designed education programs, demonstration projects, marketing strategies, and policy incentives. The potential wide adoption of innovative wood-based construction materials, such as CLT, could help U.S. wood industry by increasing the demand of wood-based construction materials and support the creation of locally based employment opportunities in a sector of critical importance to the U.S. economy.

### *Strategic recommendations*

Since its arrival in the U.S market, the future of CLT has been gaining momentum and looks promising. The development of the CLT market is the result of extensive efforts by academia, industry, organizations supporting forest products and governmental agencies. However, to continue this development and incentivize the wide adoption of the system in the U.S., the author recommends the following strategic recommendations.

#### *Education*

Awareness is the first step towards the adoption of any new product. Findings from this research show that a large percentage of U.S. construction professionals are not familiar with CLT, and therefore are hesitant about adopting it in the future. Efforts should be directed toward the education of professionals, and future professionals, in the U.S. construction industry. In order to guide these efforts, the development of an education plan for architects, engineers and contractors is imperative. In addition, further support is needed in adding courses, certifications and degrees focused on wood construction in universities and other educational institutions. Collaboration should be fostered among educational institutions and industry representatives to enable training opportunities in this field. As the results from the interviews conducted to U.S. engineering and construction firms

revealed, there is a lack of education on the following topics: a) general mass timber construction, b) construction professional's experience designing, detailing and building with CLT, c) user's experience working and living in CLT buildings, and d) maintenance requirements, cost and procedures.

#### *Tax credits and incentives*

Results from the surveys and interviews to U.S. engineering and construction firms have shown that cost is one of the main factors influencing the material decision process. The author believes that making CLT more cost-competitive against traditional materials would greatly improve its chances of success in the U.S. market. There is a need to explore the possibility of tax credits and incentives to make the costs of manufacturing CLT, and designing, building and maintaining CLT projects more accessible to potential adopters. By reducing the costs associated with the use of CLT (mentioned by many participants of this study as one of the factors that have the most influence during the material selection process), professionals interested in adopting it for their buildings would be more likely to select CLT.

#### *Building code*

Findings from this dissertation and previous work conducted by the author shows that construction professionals in the U.S. still perceive that the Building Code could be a barrier to the wide adoption of the system in the country. The 2015 International Building Code, currently in use, allows for CLT to be used in most types of building occupancies (classification that categorizes buildings bases on their usage. e.g. commercial, educational, residential, institutional, etc.) and construction type IV (heavy timber) and V (not fire-rated) (AWC, 2015). However, height restrictions exist for these types of buildings, limiting their construction to 6 stories. Research has shown that CLT could be cost-competitive for buildings over 6 stories as an environmentally-friendly alternative to concrete and steel structures. Implementing new changes in the building code to allow taller wood buildings could make CLT more attractive to construction professionals

looking to reduce the carbon footprint of their buildings. It is also important to educate building code officials about this innovative wood-based structural system.

#### *Demonstration projects*

Results from this study show that pilot and demonstration projects are key elements that could be used to endorse innovative wood-based construction materials such as CLT. As seen in this manuscript, professionals in U.S. construction industry are risk- and change-averse, and success stories in the form of successful building projects, would create awareness and make professionals more interested and receptive to this new technology.

#### ***Future work***

Based on the results from this thesis, recommendations for further research are made in this section to advance the knowledge of innovative wood based materials.

Findings from this research show that U.S construction professionals perceive a lack of information about maintenance procedures and cost. In particular, professionals are interested in learning more about the eventuality of maintenance or corrective actions in case of moisture or other problems within the structure.

Some participants to the surveys and interviews stated not knowing if this system is cost competitive with other more established materials for the type of projects they work with. The author conducted one case study to evaluate how the cost of a CLT structure compares to a hybrid concrete-steel structure for the same building (Laguarda-Mallo & Espinoza, 2016), however much more research is needed to estimate material, labor, and maintenance costs for different building types. It would be useful for professionals to have information about the cost of CLT structures depending on the region where the building is located.

Results show that U.S. construction professionals are interested in gaining information about professionals' experience in designing, detailing and building with CLT, as well as building occupants' experience living or working in these buildings. As mentioned before, the construction industry in the U.S. is very risk- averse and the availability of information about demonstration projects and previous experiences would be an important resource to increase professionals' confidence in the adoption of this system for their own projects.

From the survey to U.S. engineering firms it was also found that building resiliency is becoming a topic of interest among clients and professionals. Construction professionals are starting to pay close attention to materials that can withstand the impacts of hurricane, tornadoes, floods, earthquakes, among others natural disaster events. As mentioned in the introduction of this dissertation, much of the work that has been conducted on CLT over the past few years has been related to the earthquake and fire performance of the system. However, information is needed regarding the performance of CLT-based buildings under hurricane and flooding conditions.

U.S. engineering and construction firms considering the adoption of CLT for its environmental attributes could also find information about the sustainability of the fabrication of CLT panels, in regards to the amount of wood required to manufacture the elements important during their material decision process. Previous studies conducted by the author have shown that the amount of raw material used in CLT is seen by many professionals as a large barrier to the wide implementation of the system in the U.S. market. Systematic information about the U.S. forest inventory (growth rate and removal rates) and timber volume requirements for a sustained development of a CLT market should be addressed and made available to professionals and stakeholders interested in working with CLT.

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# Appendix 1

## *Summary of Master's Thesis results*

The author of this dissertation conducted interviews to CLT experts and a nationwide survey to U.S. architecture firms during 2013-2014 with the purpose of learning about the perspectives of experts about the awareness, perceptions, and willingness to adopt CLT by the U.S. architecture community. Results from these two studies were published in two peer-reviewed articles (Laguarda-Mallo & Espinoza, 2014, 2015). A summary of the conclusions obtained from both studies is presented below.

### *Interviews with CLT experts*

Semi-structured interviews were conducted, recorded, transcribed and analyzed to gain some insight from CLT experts, about the level of awareness, perceptions, barriers and willingness to adopt CLT by the U.S. construction industry. Results show that the main benefits of CLT-based systems, based on expert interviews, come from using a natural, renewable resource like wood as opposed to energy-intensive and non-renewable materials like concrete or steel. According to experts, another important benefit of CLT-based systems over traditional construction systems is the shorter construction time needed, since CLT is a prefabricated system in which panels come to the construction site ready to be installed. Interviewees emphasized that CLT-based systems reduce labor time, on-site waste, the occurrence of accidents, and disturbances to the site's surroundings, all of which have a positive effect on total construction costs. Structurally, CLT offers performance comparable with concrete or steel, with a reduction of the weight (Evans, 2013). Regarding the panel's structural performance, interviewees indicated that the layered configuration of CLT grants the panels good rigidity, stability, and mechanical properties, allowing CLT to be used as walls, floors, roofs, elevator shafts, and stairways, to name a few possible applications.

Experts interviewed mentioned that CLT has technical drawbacks such as its acoustic and vibration performance, especially when the design does not require insulation layers. According to experts, construction professionals should never use bare CLT floors without acoustic membrane on one side or without ceiling. Another concern voiced by several

respondents was the volume of wood utilized in the manufacture of CLT panels. According to one expert, CLT panels use three times more wood than a wood-frame system.

Regarding the level of awareness about CLT-based construction systems among architecture professionals, there was almost universal consensus among interviewees that the awareness is still low in the U.S. Reasons suggested for this lack of awareness include the novelty of the system and regional variances in tradition of working with wood-based construction.

Barriers to adoption of CLT-based construction systems in the U.S. mentioned by respondents were building code compatibility, availability of CLT in the domestic market, and misconceptions about wood as a building material. In particular, the current absence of CLT manufacturing operations in the U.S. requires that CLT elements must be imported from Canada or Europe, which adds to the total costs.

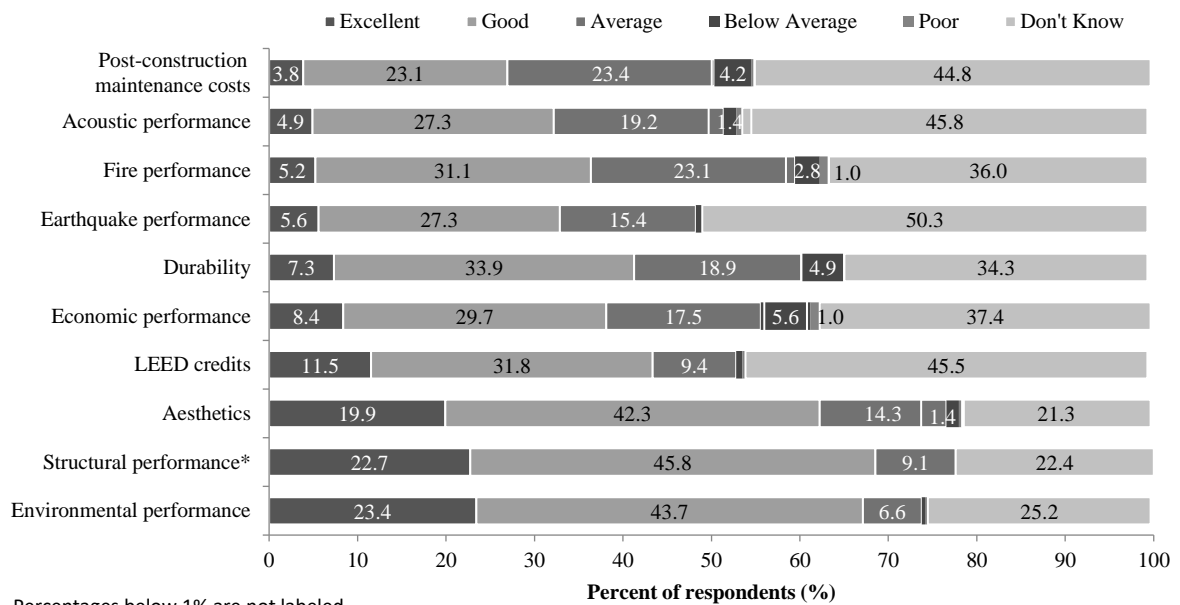
Regarding cost-competitiveness of cross-laminated timber, experts mentioned that it could be a cost-competitive alternative to concrete structures, especially for buildings over six stories high. This is in great part due to the dramatically reduced construction time needed for CLT-based systems. Most experts agreed that CLT is cost-competitive for high-rise commercial or multi-family residential buildings and low-rise commercial and industrial buildings, where a wood-frame system cannot be used. Respondents also agree that the system will not be cost-competitive for applications where light wood-frame construction is an option.

Experts indicated that the future of CLT is promising and that the adoption of the system nationwide is possible and currently happening. However some participants showed some skepticism, based on their experience with the adoption of CLT-based systems in other parts of the world. These skeptics stated that CLT-based systems can end up finding a niche market in some regions while acceptance of the system will be rather difficult in regions with a tradition of construction in concrete, masonry, or steel.

#### *Survey to U.S. architecture firms*

A web-based survey to U.S. architecture firms that work with commercial building construction was conducted to determine the level of awareness, perceptions, and

willingness to adopt CLT in the U.S. A total of 351 usable responses were received, resulting in an adjusted response rate of 22.7%. The results show that the level of awareness in the architecture industry is low in the U.S., since only 4.3% of 351 respondents indicated to be “very familiar” with the system. When asked about how the participants heard about CLT, a majority (42.3%) of firms indicated that they obtained the information from magazines, 20.3% from the internet and 17.5% at conferences, seminars or workshops. Information obtained from the survey indicates that the highest ranked features of CLT are its environmental and structural performance and its aesthetic characteristics, which makes the system highly competitive against concrete or steel (Figure 24). On the other hand, post construction maintenance cost was one of the lowest ranked features of the product, which is consistent with the common belief that wood is susceptible to deterioration due to its organic nature, and therefore requires more maintenance (Figure 24).



**Figure 24. Survey participants’ responses regarding the perceived performance of CLT on ten dimensions. N=286.**

Regarding the perceived barriers (Table 54), respondents indicated that CLT’s availability in the market, its initial cost and compatibility issues with the building code were the largest hurdles to wide adoption of the system in the U.S. A considerable percentage of participants to this study perceived that the lack of awareness and information available about CLT were barriers to the adoption of CLT in the U.S.

**Table 54. Survey participants’ responses regarding their perceived barriers to the implementation of CLT in the U.S. N=286.**

Barrier	Large Barrier	May be a Barrier	Not a Barrier
<i>--- percent of respondents ---</i>			
Availability in the market	37.8	56.3	2.8
Compatibility with Building Code	26.2	62.2	7.7
Initial Cost	23.1	67.8	4.5
Availability of technical information	20.6	56.6	19.6
Amount of wood required	5.9	54.2	35.3

*Note: Sum of percentages for each barrier is not 100% because not all participants rated all the items.*

Regarding respondents’ perceptions as the most appropriate types of building for CLT application, CLT would be very appropriate for residential single-family buildings. CLT was ranked highly for recreational and residential multi-family buildings (Laguarda-Mallo & Espinoza, 2014). The results from the survey show that architects are uncertain about adopting CLT for their projects if it were available in the market (Table 55). Similarly, they were uncertain about the prospect of utilizing CLT as a construction system for high-rise building construction. The results stress the importance of information and education on the adoption of CLT by professionals, as architects that are more knowledgeable about the system tend to be more willing to use the system.

**Table 55. Survey participants' responses regarding the likelihood of them adopting CLT in the future. N=286.**

<b>Likelihood of adoption</b>	<b>Count of respondents</b>	<b>Percent of respondents (%)</b>
Very likely	25	8.7
Likely	92	32.2
Uncertain	145	50.7
Unlikely	15	5.2
Very unlikely	4	1.4

*Note: Percentages do not add to 100% because 5 participants did not answer this question.*

# Appendix 2

## *CLT SURVEY – U.S. engineering firms 2015*

*Welcome to the Survey "Adoption of Innovative Wood-Based Building Materials by the U.S. Construction Industry" PhD Dissertation Project*

The objective of this study is to investigate the critical factors that influence the adoption of innovative wood-based building materials, such as Cross-Laminated Timber (CLT), in the United States. Your firm has been selected because it is part of the population of interest for this study, consisting of the major material specifiers in the construction industry. For this research to be successful, it is very important that we receive your input. The responses given are **strictly confidential**, data will be used only for the purposes of the study, and no company information will be disclosed. Results will be reported only in aggregate manner.

Completing this survey will take approximately 10 minutes. You could receive a report of the results from this nation-wide survey. Should you have any questions, please contact me at [lagua006@umn.edu](mailto:lagua006@umn.edu)

The time invested in helping us is greatly appreciated!  
Sincerely,

**Maria Fernanda Laguarda Mallo**

PhD Candidate

Bioproducts and Biosystems Engineering Department

University of Minnesota

1. In which of the following regions does your firm operate? Check more than one region, if appropriate.
  - Northeast
  - South
  - Midwest
  - West
  - Alaska/Hawaii
  
2. Which of the following firm size categories best describes your firm?
  - 1 to 4 employees
  - 5 to 9 employees
  - 10 to 19 employees
  - 20 to 99 employees
  - 100 employees or more
  
3. Please, indicate what sources of information you and your firm use to investigate about new building materials. Please, mark all that apply.
  - Internet
  - Books
  - Magazines
  - Academic Journals
  - Research Academics
  - Manufacturer's websites
  - Industry Events
  - Expos
  - Workshops
  - Conferences
  - Seminars
  - Webinars

1. Please rate your agreement with the following statements about your firm:

	Strongly Disagree	Disagree	Agree	Strongly Agree
Employees in our Firm are encouraged to research new materials	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Our Firm collaborates with other firms to investigate new materials	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Our Firm collaborates with universities to investigate new materials	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Our Firm collaborates with research centers and governmental agencies to investigate new materials	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Our Firm is open to find innovative solutions by collaborating with materials suppliers/manufacturers	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Our Firm invests in the training and development of its employees	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Innovation is incorporated in our Firm's corporate strategy	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Our Firm has a systematic procedure in place to review and reflect on past projects	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

2. What are the main type of buildings your firm works with? Please, mark all that apply.

- Single-family residential
- Multi-family residential (e.g. town-homes, duplexes, apartment buildings, etc.)
- Commercial buildings (e.g. offices, restaurants, retail stores, hotels, etc.)
- Educational buildings (e.g. schools, universities, libraries, etc.)
- Transportation buildings (e.g. airport, bus/train stations, etc.)

- Governmental buildings (e.g. city halls, courthouses, embassies, etc.)
- Recreational buildings (e.g. gymnasiums, stadiums, pools, ice rinks, etc.)
- Religious buildings (e.g. churches, temples, chapels, etc.)
- Industrial buildings (e.g. factories, storage, etc.)
- Other (please specify): \_\_\_\_\_

3. Please indicate what are the structural materials (or combination of materials) you typically use above the foundation, for these buildings.

	W	C	S	M	C+W	W+S	C+S	N/A
Single-family residential	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Multi-family residential	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Commercial buildings	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Educational buildings	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Transportation buildings	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Governmental buildings	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Recreational buildings	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Religious buildings	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Industrial buildings	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Other (please specify):	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

*W=wood*

*C=concrete*

*S=steel*

*M=masonry*

*C+W=concrete and wood*

*S+W=steel and wood*

*C+S=concrete and steel*

4. Please rank the importance of the following characteristics at the time of specifying a structural material.

	Extremely important	Very important	Important	Moderately important	Somewhat important	Not at all important
Environmental performance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Mechanical properties	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Economic performance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Aesthetics	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Fire performance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Earthquake performance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Availability in the market	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Acoustic performance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Cost of post-construction maintenance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Durability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
LEED Credits	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Moisture performance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Vibration performance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Complexity of construction	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Compatibility with the building code	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Availability of design tools and resources	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Other (please specify):	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

5. How familiar are you with Cross-Laminated Timber (CLT).

- Very familiar
- Somewhat familiar
- Not very familiar
- I have not heard about it

**Skip Logic:**

If *Not very familiar* is selected, then skip to *How did you hear about Cross-Laminated Timber*.

If *I have not heard about it* is selected, then skip to *Please, read the following information*.

If *Very familiar* is selected, then skip to *How did you hear about Cross-Laminated Timber*.

If *Somewhat familiar* is selected, then skip to *How did you hear about Cross-Laminated Timber*.

6. Please, read the following information and answer the questions below

**What is Cross-Laminated Timber?**

One of the most recent innovations in Engineered Wood Products is Cross-Laminated Timber (CLT). This structural system is based on the use of multi-layered panels made from solid wood boards glued together, with the grain direction of successive layers placed at 90° angles, similar to plywood, but with final thicknesses between 4 and 20 inches. This configuration improves rigidity, dimensional stability, and mechanical properties. Structurally, CLT offers performance comparable to concrete or steel, with panels suitable for use as walls, floors, roofs, and other applications.

The use of CLT panels has become a popular and successful method of construction in Europe since its introduction. It is currently used for all kinds of structures ranging from houses, barns, power line towers, churches and bridges to high-rise apartment and office buildings, adding visibility and reputation to the system.

The benefits of CLT are well documented. The structural characteristics of CLT enables design professionals to achieve shapes and openings with the most diverse sizes and forms, without compromising the structural integrity of the structure. Regarding the fire resistance of CLT-based elements, tests have shown satisfactory performance, in great part due to the predictable charring properties of large-section wood components. CLT members burn at a predictable rate and form a char layer that initially protects non-charred wood, allowing structural components to keep significant strength and dimensional stability. Being a solid wood system, CLT also offers the possibility of reducing the thermal loads of the building and consequently the energy costs, due to its thermal inertia. This construction technology enables the construction of airtight buildings, with fewer elements and thus fewer joints where air could infiltrate, which is a key aspect in reducing the energy requirements. Moreover, CLT has proven to be an adequate option for construction in seismic regions. Regarding environmental performance, Life Cycle Analysis (LCA) research has demonstrated that, as with most wood-based products, CLT has a smaller carbon footprint, and lower impact compared to concrete or steel in regards to ozone depletion, global warming potential, eutrophication.

7. After reading the information presented above, please indicate if you would be interested in learning more about the system.
- Very Interested
  - Interested
  - Somewhat interested
  - Not interested at all
8. If you are not interested about the system. Please briefly describe why not.
9. If Cross-Laminated Timber (CLT) were readily available in the U.S., you believe Cross-Laminated Timber would be adequate for your future projects?
- Very likely
  - Likely
  - Uncertain
  - Unlikely
  - Very unlikely
10. Please, indicate the reasons for your selection.
11. How did you hear about Cross-Laminated Timber (CLT) for the first time? Please, mark all that apply.
- Internet
  - Television
  - Newspaper
  - Magazine
  - Academic Journal
  - Radio
  - Relative or friend
  - Conference/Seminar/Workshop
  - Other (please specify): \_\_\_\_\_

12. Please rate the following features of Cross-Laminated Timber, compared to other materials (e.g. steel, concrete).

	Excellent	Good	Average	Below average	Poor	Don't know
Environmental performance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Mechanical properties	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Economic performance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Aesthetics	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Fire performance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Earthquake performance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Availability in the market	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Acoustic performance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Cost of post-construction maintenance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Durability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
LEED Credits	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Moisture performance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Vibration performance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Complexity of construction	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Compatibility with the building code	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Availability of design tools and resources	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Other (please specify):	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

13. If Cross-Laminated Timber (CLT) were readily available in the U.S.

- Very likely
- Likely
- Uncertain
- Unlikely
- Very unlikely

14. Please, indicate the reasons for your selection.

15. Which do you think are the most important barriers to adoption of Cross-Laminated Timber in the U.S.?

	Large Barrier	May be a barrier	Not a barrier at all
Amount of wood required	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Availability in the market	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Construction cost	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Availability of technical information	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Compatibility with Building Code	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Promotion/Education	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
CLT performance as a construction system	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Maintenance cost	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Other (please specify):	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

16. Any comments you may want to add about the potential barriers to the adoption of Cross-Laminated Timber in the U.S.?

17. Any comments you may want to add about Cross-Laminated Timber?

## ***CLT SURVEY – U.S. construction firms 2016***

***Welcome to the Survey "Adoption of Innovative Wood-Based Building Materials by the U.S. Construction Industry" PhD Dissertation Project***

The objective of this study is to investigate the critical factors that influence the adoption of innovative wood-based building materials, such as Cross-Laminated Timber (CLT), in the United States. Your firm has been selected because it is part of the population of interest for this study, consisting of the major material specifiers in the construction industry. For this research to be successful, it is very important that we receive your input. The responses given are **strictly confidential**, data will be used only for the purposes of the study, and no company information will be disclosed. Results will be reported only in aggregate manner.

Completing this survey will take approximately 10 minutes. You could receive a report of the results from this nation-wide survey. Should you have any questions, please contact me at [lagua006@umn.edu](mailto:lagua006@umn.edu)

The time invested in helping us is greatly appreciated!

Sincerely,

**Maria Fernanda Laguarda Mallo**

PhD Candidate

Bioproducts and Biosystems Engineering Department

University of Minnesota

1. In which of the following regions does your firm operate? Check more than one region, if appropriate.
- Northeast
  - South
  - Midwest
  - West
  - Alaska/Hawaii
2. Which of the following firm size categories best describes your firm?
- 1 to 4 employees
  - 5 to 9 employees
  - 10 to 19 employees
  - 20 to 99 employees
  - 100 employees or more
3. What are the main type of buildings your firm works with? Please, mark all that apply.
- Single-family residential
  - Multi-family residential (e.g. town-homes, duplexes, apartment buildings, etc.)
  - Commercial buildings (e.g. offices, restaurants, retail stores, hotels, etc.)
  - Educational buildings (e.g. schools, universities, libraries, etc.)
  - Transportation buildings (e.g. airport, bus/train stations, etc.)
  - Governmental buildings (e.g. city halls, courthouses, embassies, etc.)
  - Recreational buildings (e.g. gymnasiums, stadiums, pools, ice rinks, etc.)
  - Religious buildings (e.g. churches, temples, chapels, etc.)
  - Industrial buildings (e.g. factories, storage, etc.)
  - Other (please specify): \_\_\_\_\_

1. Please indicate what are the structural materials (or combination of materials) you typically use above the foundation, for these buildings.

	W	C	S	M	C+W	W+S	C+S	N/A
Single-family residential	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Multi-family residential	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Commercial buildings	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Educational buildings	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Transportation buildings	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Governmental buildings	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Recreational buildings	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Religious buildings	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Industrial buildings	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Other (please specify):	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

*W=wood*

*C=concrete*

*S=steel*

*M=masonry*

*C+W=concrete and wood*

*S+W=steel and wood*

*C+S=concrete and steel*

2. Please, indicate the level of influence these actors have, during this structural material selection process.

	Extremely influential	Moderately influential	Somewhat influential	Slightly influential	Not at all influential
Architects	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Engineers	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Contractors	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Construction Managers	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Developers	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Owners	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

3. Please rank the importance of the following characteristics at the time of specifying a structural material.

	Extremely important	Very important	Important	Moderately important	Somewhat important	Not at all important
Environmental performance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Mechanical properties	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Labor cost	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Material cost	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Cost of post-construction maintenance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Aesthetics	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Fire performance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Earthquake performance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Availability in the market	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Acoustic performance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Durability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
LEED Credits	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Moisture performance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Vibration performance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Complexity of construction	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Compatibility with the building code	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Construction time	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Requirement of specialized labor	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

4. Please rate your agreement with the following statements about your firm:

	Strongly Disagree	Disagree	Agree	Strongly Agree
Employees in our Firm are encouraged to research new materials	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Our Firm collaborates with universities to investigate new materials	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Our Firm collaborates with research centers and governmental agencies to investigate new materials	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Our Firm is open to find innovative solutions by collaborating with materials suppliers/manufacturers	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Our Firm invests in the training and development of its employees	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Innovation is incorporated in our Firm's corporate strategy	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Our Firm has a systematic procedure in place to review and reflect on past projects	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Our Firm is receptive to changes and new technologies	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

5. How familiar are you with Cross-Laminated Timber (CLT)?

- Very familiar
- Somewhat familiar
- Not very familiar
- I have not heard about it

**Skip Logic**

If *Not very familiar* is selected, then skip to *How did you hear about Cross-Laminated Timber?*

If *I have not heard about it* is selected, then skip to *Please, read the following information.*

If *Very familiar* is selected, then skip to *How did you hear about Cross-Laminated Timber?*

If *Somewhat familiar* is selected, then skip to *How did you hear about Cross-Laminated Timber?*

6. Please, read the following information and answer the questions below

**What is Cross-Laminated Timber?**

One of the most recent innovations in Engineered Wood Products is Cross-Laminated Timber (CLT). This structural system is based on the use of multi-layered panels made from solid wood boards glued together, with the grain direction of successive layers placed at 90° angles, similar to plywood, but with final thicknesses between 4 and 20 inches. This configuration improves rigidity, dimensional stability, and mechanical properties. Structurally, CLT offers performance comparable to concrete or steel, with panels suitable for use as walls, floors, roofs, and other applications.

The use of CLT panels has become a popular and successful method of construction in Europe since its introduction. It is currently used for all kinds of structures ranging from houses, barns, power line towers, churches and bridges to high-rise apartment and office buildings, adding visibility and reputation to the system.

The benefits of CLT are well documented. The structural characteristics of CLT enables design professionals to achieve shapes and openings with the most diverse sizes and forms, without compromising the structural integrity of the structure. Regarding the fire resistance of CLT-based elements, tests have shown satisfactory performance, in great part due to the predictable charring properties of large-section wood components. CLT members burn at a predictable rate and form a char layer that initially protects non-charred wood, allowing structural components to keep significant strength and dimensional stability. Being a solid wood system, CLT also offers the possibility of reducing the thermal loads of the building and consequently the energy costs, due to its thermal inertia. This construction technology enables the construction of airtight buildings, with fewer elements and thus fewer joints where air could infiltrate, which is a key aspect in reducing the energy requirements. Moreover, CLT has proven to be an adequate option for construction in seismic regions. Regarding environmental performance, Life Cycle Analysis (LCA) research has demonstrated that, as with most wood-based products, CLT has a smaller carbon footprint, and lower impact compared to concrete or steel in regards to ozone depletion, global warming potential, eutrophication.

7. After reading the information presented above, please indicate if you would be interested in learning more about the system

- Very interested
- Interested
- Somewhat interested
- Not interested at all

**Skip Logic**

If *Very interested* is selected, then skip to If Cross-Laminated Timber (CLT) were available...?

If *Interested* is selected, then skip to if *Cross-Laminated Timber (CLT) were available...?*

If *Somewhat interested* is selected, then skip to *If Cross-Laminated Timber (CLT) were...?*

If *Not interested at all* is selected, then skip to *If you are not interested about the sytem...?*

8. If you are not interested about the system. Please briefly describe why not.

9. If Cross-Laminated Timber (CLT) were readily available in the U.S., do you believe Cross-Laminated Timber would be adequate for your future projects?

- Very likely
- Likely
- Uncertain
- Unlikely
- Very unlikely

10. Please, indicate the reasons for your selection.

11. How did you hear about Cross-Laminated Timber (CLT) for the first time? Please, mark all that apply.

- Internet
- Television
- Newspaper
- Magazine
- Academic Journal
- Radio
- Relative or friend
- Conference/Seminar/Workshop
- Other (please specify): \_\_\_\_\_

12. Please rate the following features of Cross-Laminated Timber, compared to other materials (e.g. steel, concrete).

	Excellent	Good	Average	Below average	Poor	Don't know
Environmental performance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Mechanical properties	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Labor cost	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Material Cost	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Cost of post-construction maintenance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Aesthetics	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Fire performance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Earthquake performance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Availability in the market	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Acoustic performance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Durability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
LEED Credits	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Moisture performance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Vibration performance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Complexity of construction	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Compatibility with the building code	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Construction time	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Requirement of specialized labor	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Other (please specify):	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

13. If Cross-Laminated Timber (CLT) were readily available in the U.S., would you consider it for one of your building projects in the near future?

- Very likely
- Likely
- Uncertain
- Unlikely
- Very unlikely

14. Please, indicate the reasons for your selection.

15. Which do you think are the most important barriers to adoption of Cross-Laminated Timber in the U.S.?

	Large Barrier	May be a barrier	Not a barrier at all
Amount of wood required	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Availability in the market	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Labor cost	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Material cost	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Maintenance cost	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Availability of technical information	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Compatibility with Building Code	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Promotion/Education	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
CLT performance as a construction system	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Construction time	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Other (please specify):	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

16. Any comments you may want to add about the potential barriers to the adoption of Cross-Laminated Timber in the U.S.?

17. Any comments you may want to add about Cross-Laminated Timber?

18. If you would like to receive a report of the results of this study, please enter your email address below.

# Appendix 3

## *U.S. engineering firms interview questionnaire*

### **Demographic questions**

1. Would you please indicate your role within the company and your years of experience?
  - a) What's the approximate size (in number of employees) of the company?
  - b) Does your company work predominantly in a certain region?
2. What are the predominant types of buildings your firm works with?
3. What kind of structural materials does your company use for these types of buildings?
4. Could you briefly describe the roles of architects, engineers and constructors during the process of structural material selection?
  - Which of these actors would you say has the most influence when it comes to deciding which type of structural material is selected?
5. When evaluating a structural material, what are the main attributes you consider?
6. What sources of information do you use to obtain How does your company gather information about structural materials? (e.g. web, magazines, journals, peers, workshops, conferences, etc.)
7. How frequently does your firm work with wood-based structural systems for its buildings?
8. What are your perceptions about wood as a structural material?
9. Do you consider your firm innovative in regards to structural materials use? Why?

### **Cross-Laminated Timber**

10. Are you familiar with Cross Laminated Timber?

#### If they are not familiar:

*One of the most recent innovations in Engineered Wood Products is Cross-Laminated Timber (CLT). This structural system is based on the use of multi-layered panels made from solid wood boards glued together, with the grain direction of successive layers placed at 90° angles, similar to plywood, but with final thicknesses between 4 and 20 inches. This configuration improves rigidity, dimensional stability, and mechanical properties. Structurally, CLT offers*

*performance comparable to concrete or steel, with panels suitable for use as walls, floors, roofs, and other applications.*

*The use of CLT panels has become a popular and successful method of construction in Europe since its introduction. It is currently used for all kinds of structures ranging from houses, barns, power line towers, churches and bridges to high-rise apartment and office buildings, adding visibility and reputation to the system.*

*The benefits of CLT are well documented. The structural characteristics of CLT enables design professionals to achieve shapes and openings with the most diverse sizes and forms, without compromising the structural integrity of the structure. Regarding the fire resistance of CLT-based elements, tests have shown satisfactory performance, in great part due to the predictable charring properties of large-section wood components. CLT members burn at a predictable rate and form a char layer that initially protects non-charred wood, allowing structural components to keep significant strength and dimensional stability. Being a solid wood system, CLT also offers the possibility of reducing the thermal loads of the building and consequently the energy costs, due to its thermal inertia. This construction technology enables the construction of airtight buildings, with fewer elements and thus fewer joints where air could infiltrate, which is a key aspect in reducing the energy requirements. Moreover, CLT has proven to be an adequate option for construction in seismic regions. Regarding environmental performance, Life Cycle Analysis (LCA) research has demonstrated that, as with most wood-based products, CLT has a smaller carbon footprint, and lower impact compared to concrete or steel in regards to ozone depletion, global warming potential, and eutrophication. From the description you heard, what would you say are the main advantages and disadvantages of the system?*

1. If the product were available in the market, would you be willing to adopt it in future projects? Why or why not?

If they are familiar:

11. What are, in your opinion, the main advantages and disadvantages of CLT?
12. What are, in your opinion, the factors influencing the adoption of CLT in the U.S.?
13. If the system were widely available in the U.S. market, would you consider it as a construction system for your buildings?

14. Any other comments about the adoption of new structural systems by engineering firms or CLT you might want to add?

## *U.S. construction firms interview questionnaire*

### **Demographic questions**

1. Would you please indicate your role within the company?
  - c) What's the approximate size (in number of employees) of the company?
  - d) Does your company work predominantly in a certain region?
2. What are the predominant types of buildings your firm works with?
3. What kind of structural materials does your company use for these types of buildings?
4. Could you briefly describe the roles of architects, engineers and constructors during the process of structural material selection?
  - Which of these actors would you say has the most influence when it comes to deciding which type of structural material is selected?
5. What sources of information do you use to obtain How does your company gather information about structural materials? (e.g. web, magazines, journals, peers, workshops, conferences, etc.)
6. How frequently does your firm work with wood-based structural systems for its buildings?
7. What are your perceptions about wood as a structural material?
8. Do you consider your firm innovative in regards to structural materials use? Why?

### **Cross-Laminated Timber**

9. Are you familiar with Cross Laminated Timber?

#### **If they are not familiar:**

*One of the most recent innovations in Engineered Wood Products is Cross-Laminated Timber (CLT). This structural system is based on the use of multi-layered panels made from solid wood boards glued together, with the grain direction of successive layers placed at 90° angles, similar to plywood, but with final thicknesses between 4 and 20 inches. This configuration improves rigidity, dimensional stability, and mechanical properties. Structurally, CLT offers performance comparable to concrete or steel, with panels suitable for use as walls, floors, roofs, and other applications.*

*The use of CLT panels has become a popular and successful method of construction in Europe since its introduction. It is currently used for all kinds of structures ranging from houses, barns,*

*power line towers, churches and bridges to high-rise apartment and office buildings, adding visibility and reputation to the system.*

*The benefits of CLT are well documented. The structural characteristics of CLT enables design professionals to achieve shapes and openings with the most diverse sizes and forms, without compromising the structural integrity of the structure. Regarding the fire resistance of CLT-based elements, tests have shown satisfactory performance, in great part due to the predictable charring properties of large-section wood components. CLT members burn at a predictable rate and form a char layer that initially protects non-charred wood, allowing structural components to keep significant strength and dimensional stability. Being a solid wood system, CLT also offers the possibility of reducing the thermal loads of the building and consequently the energy costs, due to its thermal inertia. This construction technology enables the construction of airtight buildings, with fewer elements and thus fewer joints where air could infiltrate, which is a key aspect in reducing the energy requirements. Moreover, CLT has proven to be an adequate option for construction in seismic regions. Regarding environmental performance, Life Cycle Analysis (LCA) research has demonstrated that, as with most wood-based products, CLT has a smaller carbon footprint, and lower impact compared to concrete or steel in regards to ozone depletion, global warming potential, and eutrophication.*

10. From the description you heard, what would you say are the main advantages and disadvantages of the system?
11. If the product were available in the market, would you be willing to adopt it in future projects? Why or why not?

**If they are familiar with CLT:**

12. What are, in your opinion, the main advantages and disadvantages of CLT?
13. What are, in your opinion, the factors influencing the adoption of CLT in the U.S.?
14. If the system were widely available in the U.S. market, would you consider it as a construction system for your buildings?
15. Any other comments about the adoption of new structural systems by engineering firms or CLT you might want to add?

# Appendix 4

# IRB Approval

VERY IMPORTANT - Question about need for IRB approval

Jp <perke001@umn.edu>

Jun 1, 2015, 9:45 AM

to:  
Marfa Laguarda <lagua006@umn.edu>

cc:  
Cynthia McGill <mcgill018@umn.edu>

Hi Maria,

I'd say this could be easily covered by an Exempt category 2 application since the data is not private or sensitive. The exempt applications are on our website under the Forms link; the submission instructions are there as well. Please allow 10-15 business days for review.

Jeffery  
...

On Mon, Jun 1, 2015 at 9:37 AM, Marfa Laguarda <lagua006@umn.edu> wrote:

Good morning Cynthia,

My name is Maria Fernanda Laguarda Mallo and I am a Graduate Research Assistant at the Department of Bioproducts and Biosystems Engineering.

At the moment I am participating in a research project regarding the level of awareness, barriers and future research of a new wood-based construction system. In order to accomplish this goal we will be conducting a survey. Attached you can find my draft questionnaire.

Questions to be asked do not involve sensitive company or personal information, only general opinions and perceptions. No identifying information will be collected.

Would you please tell me whether any these surveys need IRB approval?

Looking forward to your prompt response,

Maria Fernanda Laguarda Mallo

—

**University of Minnesota**  
Graduate Research Assistant  
Bioproducts and Biosystems Engineering Department  
College of Food, Agricultural and Natural Resource Sciences  
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2004 Folwell Ave  
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Web: <http://www.bbe.umn.edu/>  
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—

Jeffery Perkey, MLS, CIP  
Research Compliance Supervisor, Social Behavioral Sciences IRB  
[Human Research Protection Program](#)  
University of Minnesota  
direct line [612-626-5922](tel:612-626-5922)  
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[irb@umn.edu](mailto:irb@umn.edu)

UNIVERSITY OF MINNESOTA  
**RESEARCH EXEMPT FROM IRB COMMITTEE REVIEW**  
 SURVEYS/INTERVIEWS, STANDARD EDUCATION TESTS &  
 OBSERVATIONS OF PUBLIC BEHAVIOR  
 EXEMPT CATEGORY 2

Version 6.2

Updated January 2015, check <http://www.irb.umn.edu> for the latest version

Based on the information provided, this project does not meet the regulatory definition of human subjects research. **Additional IRB review is NOT required.**

Jeffery  
Perkey

Digitally signed by Jeffery Perkey  
 DN: cn=US, st=Minnesota, l=Minneapolis,  
 ou=Human Research Protection Program,  
 email=perke001@umn.edu, o=University  
 of Minnesota, c=Jeffery Perkey  
 Date: 2015.10.01 14:14:11 -0500

Submit this application, along with all required appendices and supplemental documents to the University of Minnesota IRB.		IRB Use Only IRB Study # <a href="#">click here to enter text.</a>
Electronic Submission (preferred): Submit to: <a href="mailto:rspperev@umn.edu">rspperev@umn.edu</a> PI must submit request using University of Minnesota e-mail Account.	U.S. Mail Address: Human Research Protection Program MMC 820 420 Delaware St. SE Minneapolis, MN 55455-0392	For more information please visit our website <a href="http://www.research.umn.edu/irb/index.html">http://www.research.umn.edu/irb/index.html</a> Contact our office Phone: 612-626-5654 Email: <a href="mailto:rspperev@umn.edu">rspperev@umn.edu</a> Fax: 612-626-6061
<b>Project Title</b>		
If the project is funded, the Sponsored Project Administration (SPA) project title must match the IRB project title. If the project is funded by multiple grants, provide all grant titles below:		
Critical factors in the adoption of innovative wood-based building materials in the construction industry: The case of CLT		
<b>Section 1 <a href="#">Principal Investigator</a></b>		
Name	Highest Earned Degree:	
Maria Fernanda Laguarda Mallo	Master's Degree	
Preferred contact information: <a href="mailto:lagua006@umn.edu">lagua006@umn.edu</a> Preferred email or phone number at which the PI may be contacted by IRB staff or reviewers to resolve questions or concerns.		
Affiliation and contact information		
<input checked="" type="checkbox"/> University of Minnesota (complete contact info section 1 only) <input type="checkbox"/> Fairview (complete contact info section 2 only) <input type="checkbox"/> Gillette (complete contact info section 2 only)		
Required Contact information  Section 1 - U of M only	U of M Internet ID (x.500):	lagua006
	U of M Employee/student ID Number:	4652203
	University Department:	Department of Bioproducts and Biosystems Engineering
Required contact information Section 2 Non-U of M only	Address:	Phone number: