Identification of Research Areas to Advance the Adoption of Cross-Laminated Timber in North America

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Abstract

Cross-Laminated Timber (CLT) is emerging as a promising building system that could help revitalize a dwindling forest sector. However, little research has been conducted about CLT, particularly in the marketing realm. Our paper helps bridge this gap. Specifically, we aim to identify research areas that are important to successfully advance CLT as a building material in North America. Our findings, based on a survey of experts, suggest that the level of awareness about CLT among building professionals in general is low. However, architects are considered knowledgeable about the product. Experts consider that the most important barriers to the adoption of CLT are(a) misperceptions held by building industry professionals about wood and CLT, (b) compatibility of building codes with CLT, and (c) the availability of technical information about CLT as a construction system. In terms of most pressing research areas for advancing CLT, experts consider that it is important to shed more light on its seismic and fire performance, and also on proper connectors and fasteners used in CLT-based construction.

Keywords: Cross-Laminated Timber, CLT, engineered wood products, awareness, research needs

1.0 Introduction

1.1 Cross Laminated Timber

Cross-Laminated Timber (CLT) is a building system composed of large-format wood-based panels that can be used as building segments (Lattke and Lehmann 2007). These panels are configured in similar ways that plywood is configured (Figure 1), but with much thicker individual layers. Thus, boards are glued side by side in a single layer into large, individual panels and then glued onto another pre-glued panel placed at right angles with the adjacent layers. This cross-lamination improves rigidity, stability, and mechanical properties of the product (Evans 2013), thereby increasing the range of applications for which wood can be used as a material. CLT panels are made with lumber that has been kiln dried, graded (visually- or machine stress-rated), finger-jointed, and glued together cross-wise to form the final CLT panel. Then, panels are further processed and openings for windows, doors, and service channels, as well as connection spaces and ducts are cut using Computer Numerical Controlled (CNC) routers, which allow high precision and speed. Finally, prior to shipping, the CLT panels are and transported to the construction site, and put into place with cranes. CLT elements are typically connected using metal connectors such as steel angles and metal splines, which are attached to the panels with self-driving screws and dowels (Crespell and Gagnon 2011).

The structural characteristics of CLT allow for considerable architectural freedom during the design process, allowing for different building configurations in terms of openings (numbers, sizes and locations) and providing flexibility to cover long spans without intermediate support or without compromising the structural integrity of the structure, something that would be too complex or impossible to attain using wood in traditional

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Figure 1. CLT panel sections.

ways. For example, a CLT panel with 7 layers (9 inches in thickness) can be used to cover spans of up to 25 feet (Karacabeyli and Douglas 2013, Malczyk 2011)with variations of traditional CLT panels, such as "folded" and "cassette" floors, allowing to cover up to 65 feet-long spans while decreasing the weight of the construction (Crespell and Gagnon 2011,Fountain 2012,Silva et al. 2013). Regarding fire performance, CLT possesses burning properties akin to wood structural elements with large cross-sections. Thus, when exposed to fire, wood forms a layer of char at a predictable rate that acts as a retardant against further degradation of the unburned core, thus slowing down the reduction of load-carrying capacity (Forest Products Laboratory 2015). CLT also has performed well in several studies under seismic conditions (Ceccotti et al. 2013,Quenneville and Morris 2007).

Being a wood-based product, CLT also presents advantages from an environmental perspective (CORRIM 2010, Hubbard and Bowe 2010, Lippke et al. 2004, Wilson et al. 2005). Assuming that forests are managed sustainably, using wood as raw material reduces carbon emissions and creates carbon sinks (Bowyer et al. 2011) and CLT performs well if compared to other building materials. For example, studies that compare environmental performance of CLT and concrete (Chen 2012,Durlinger et al. 2013,John et al. 2008,Robertson 2011) suggest that buildings built with CLT have lower embodied energy than concrete-based buildings and they also performed superior to concrete and steel in respect to ozone depletion, global warming potential, and eutrophication (Chen 2012, Durlinger et al. 2013, John et al. 2008, Robertson 2011).

CLT has been used to erect tall buildings, such as the Stadhaus in London(9 stories,Hopkins 2012,Lattke and Lehmann 2007), the Forte in Melbourne (10 stories,Lend Lease Corporation 2013)or the Wood Innovation Design Center in British Columbia (9 stories,Partnership BC 2013). In the U.S., *Skidmore, Owings & Merrill*, an architectural firm, has developed a conceptual 42-storied building, built in part with CLT (SOM 2013).

The attractiveness of CLT as building material is not only based on its favorable mechanical properties and environmentally preferable characteristics described herewith. The material also allows builders to erect the building with great speed, reducing the disturbances to a site's surroundings and minimizing the cost of labor. Also, CLT offers better insulation properties than competing materials and great ease in adding additional insulation layers to walls and ceilings (Crespell and Gagnon 2011).

1.2 Production Trends

The production capacity of CLT has grown rapidly since its introduction in the early 1990s, and is expected to reach one million cubic meters (m^3) by 2016 by some estimates (Muszyński 2015,Plackner 2015a). While production is currently concentrated in Central Europe (Austria, Germany, and Switzerland represent 80% of global CLT production), most of the growth over the next 10 years will occur outside this region (Plackner 2015b). In North America, as of January 2015, two producers of CLT in Canada exist with a combined production capacity of 110,000 m^3 per year (personal communication with company representatives, March of 2015). In the U.S., three manufacturers exist as May of 2016, and only one certified under the ANSI/APA Standard for Performance-rated CLT (PRG 320, ANSI 2012) to produce CLT panels for construction.

Estimates exist that, for the U.S. alone, the market potential for CLT could be between 2.1 to 6.4 million m^3 annually, mostly for non-residential construction (Karacabeyli and Douglas 2013), which is equivalent to several times the current global production. However, this potential is unlikely to materialize if some conditions are not met, among them the inclusion of CLT into current building codes. Today, the 2015 version of the IBC includes CLT as allowable material to be used for Type IV constructions (e.g., heavy timber constructions; Bland and Coats 2013). However, the adoption of the 2015 version of the IBC by state and local codes is a lengthy process that will likely take several years before this most recent version is implemented. Changes to regulations were recently announced in Québec that will allow the use of lumber can be for buildings up to 12 stories high (Construction Canada 2015). Another necessary condition for CLT to achieve its full potential is for the industry to dedicate considerable, focused effort toward increasing awareness of the material among the construction community (engineers, architects, developers, builders) and the public in general. Research carried out in 2014 among architectural firms in the U.S. has shown a low level of awareness among architects, with only 4.2% reporting to be "very familiar" with CLT (Laguarda-Mallo and Espinoza 2014, Laguarda-Mallo and Espinoza 2015).

1.3 Research Centers for CLT in North America

Growth in research activity about CLT has increased considerably along with the material's increases in market adoption. The first research symposium on CLT in North America held in Vancouver, British Columbia in 2011 included 17 presentations on CLT research (Canadian Wood Council 2011), whereas the joint 2014 World Conference on Timber Engineering and the Forest Products Society International Convention in Quebec City, Canada, listed 8 sessions and over 56 presentations on CLT research (WCTE 2014). In March2016, the Massive Timber Conference took place in Portland, Oregon, with an attendance of more than 500researchers, construction professionals, wood utilization experts, and other stakeholders (Baker 2016), showing the rapidly growing interest in CLT in North America. In fact, today, all major North American wood research entities are actively pursuing CLT research. Table 1 lists institutions involved in CLT research in North America.

1.4 CLT - From a Product Adoption Lens

A number of authors have addressed the process of product adoption (Harvey 1979,Urban and Gilbert 1971); and several models have been proposed (Beal et al. 1957;King 1966,Rogers 2003). Beal et al. (1957) for example, proposed the following five-stage product adoption process: *Awareness* refers to the moment 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* and possible later *adoption* of the product.

Innovation is seen by Wagner and Hansen (2005) as a source of competitive advantage that can benefit the construction industry, providing the critical compo-

Table 1. Research institutions in North America conducting research about CLT.*

Institution	Location	Reference
	Canada	
FPInnnovations	Pointe-Claire, Québec and Vancouver, British Columbia	(FPInnovations 2015a)
Department of Wood Science; University of British Columbia	Vancouver, British Columbia	(UBC 2015)
Department of Civil and Environmental Engineering; University of Waterloo	Waterloo, Ontario	(University of Waterloo 2015)
Département des Sciences du Bois et de la Forêt, Université Laval	Québec, Québec	(Universite Laval 2015)
The Canadian Wood Council	Ottawa, Ontario	(CWC 2015)
	United States	
Department of Wood Science and Engineering; Oregon State University	Corvallis, Oregon	(OSU 2015)
Department of Forest Biomaterials; North Carolina State University	Raleigh, North Carolina	(NCSU 2015)
Department of Sustainable Biomaterials; Virginia Tech University	Blacksburg, Virginia,	(Virginia Tech 2015)
Department of Bioproducts and Biosystems Engineering; University of Minnesota	Saint Paul, Minnesota	(FPMDI 2014)
Forest Products Laboratory	Madison, Wisconsin	(FPL 2015)
The Engineered Wood Association	Tacoma, Washington	(APA 2015)

* Not claimed to be exhaustive. Based on Internet searches, peer-reviewed journals, and consultation with experts

nent for a company's long-term competitive strategy (Slaughter 2000). However, the adoption of innovations is a highly complex process, with limited research having been conducted so far. The risks associated with the adoption of an innovative material or process has been stated by Slaughter (2000) as one of the most important factors that can affect the rate of adoption of a new product. In the construction industry, liability risk is seen as one of the barriers that may hinder the adoption of new materials and technologies in this sector (U.S Department of Housing and Urban Development (HUD), 2005). According to McCoy et al. (2009) the complexity of the adoption process in the construction industry is caused, in part, by the large number of actors (suppliers, manufacturers, design professionals, final users) involved in the decision of adopting an innovation.

Given the emerging nature of the CLT market in North America, market success of this building system will depend to a considerable degree on increasing awareness among stakeholders, particularly construction professionals. Likewise, research and testing is needed to provide these professionals with the design values required to comply with building codes and to assess CLT's performance. This study investigates stakeholders' awareness and views on the research needs about CLT.

2.0 Research Objective

The main purpose of this study was to identify major research needs for the advancement of Cross-Laminated Timber in North America. To accomplish this objective, key stakeholders in United States and Canada were surveyed to learn about the perceived awareness, barriers to adoption, and research needs for CLT. This study follows a similar effort recently conducted for the European market (Espinoza et al. 2015).

3.0 Methods

To collect key stakeholders' opinions on CLT, a web-based survey was conducted. Dillman's Tailored Design Method guidelines for survey design and implementation were followed (Dillman 2009).

3.1 Questionnaire Development

A first draft of a questionnaire was developed, based on a previous study conducted in Europe (Espinoza et al. 2015). The questionnaire was then reviewed by four experts from academia and industry and was incorporated into a web-based survey platform (Qualtrics 2014). After incorporating the feedback obtained from this review process, the final version of the questionnaire was ready for distribution. The questionnaire's main characteristics are presented in Table 2.

3.2 Sample Development

The population of interest for this survey included all North American experts involved with Cross-Laminated Timber (CLT). Thus, the sample included researchers, consultants, industry representatives, and engineers from all over North America. A non-random sampling strategy, or convenience sampling, was used; specifically, several sources of public records were consulted in search for potential participants, namely journals, conference proceedings, industry association directories, industry-supporting organizations' webpages, company websites, university faculty directories, and research grant documents. Experts were also contacted

Table 2. A summary of survey questions.

Topic	Question	Type of response / scale
Demographics	Please select your profession	Multiple selection (9 options and "other")
Awareness	What is, in your opinion, the level of awareness about Cross Laminated Timber (CLT) in North America among the following professionals?	4-point scale: "very low," "low," "high," and "very high"
Barriers to adoption	Which do you think are the most important barriers to the adoption of Cross-Laminated Timber (CLT) in North America?	3-point scale: "large barrier," "may be a barrier," and "not at all a barrier"
Research needs	Please rank the following areas of research about Cross Laminated Timber (CLT) according to their importance (1= Most important, 10=Least important). Select only one ranking position for each research topic.	Ranking 10 research areas in order of importance
	Please list other research topics about CLT that you consider need addressing to support its further development, and that were not included in the previous question.	Open question
Additional comments	Other comments you may want to add about initiatives or actions that are needed for the advancement of CLT in North America?	Open question

and asked for names and contact information of potential participants. A final list of 105 names was compiled and used for the distribution of the survey.

3.3 Survey Implementation and Data Analysis

The survey was implemented according to Dillman's Tailored Design Method (Dillman2009). An email with an introductory message and invitation to participate was sent to all names in the address list in July of 2015. Two reminder emails were sent after one and two weeks, respectively. The survey was closed in August of 2015 and responses were downloaded for analysis. Data analysis was carried out using Microsoft Excel and SPSS. Descriptive statistics were calculated, and qualitative responses were coded and categorized for analysis.

4.0 Results and Discussion

4.1 Survey Implementation and Response Rate

The survey was conducted during July and August of 2015. After the initial email inviting addressees to participate, two reminder emails were sent with one week between each communication. In total, 47 usable responses were received out of 105 in the initial distribution list. A 46.1% adjusted response rate was calculated after accounting for three undeliverable emails. No incomplete responses were received; therefore, all responses were included in the analysis.

4.2 Respondents' Demographics

Table 3 lists the self-reported occupations and professions of respondents. Respondents were allowed to check more than one profession. Most indicated "engineer" or "researcher" as profession (42.6% of all respondents), followed by "educator" (21.3%), "manufacturer or distributor" (19.1%), and "consultant" (10.6%). Only one entry was received for "architect" and one for "builder." This question also allowed participants to enter "other" profession not listed in the questionnaire; three entries were recorded, namely "non-residential wood promotion," "research management," and "sawmill expert." Ten respondents reported two professions, with "engineer" and "researcher" the most frequent pair (4 respondents); and six reported three professions, with "engineer," "research," and "educator" the most frequent combination (4 respondents).

The geographical distribution of respondents and the distribution of the names in the address list can be seen in Table 4. While the initial distribution list was nearly evenly distributed between Canada and the United States (48.0% and 52.0%, respectively), a proportionally higher number of responses were received from participants in the U.S. (66.0% of all respondents). Also, the response rate was much higher in the U.S. (58.5%) than in Canada (32.7%). Looking at specific regions in Canada, a proportionally greater number of responses were received from Quebec Province (50%), while no responses were received from Ontario. In the United States, the geographical distribution of responses resembled more closely the original distribution list, however, slightly higher response rates were achieved from the South (Virginia, South Carolina, Washington DC, North Carolina, and Tennessee) and the Midwest (Montana and Wisconsin) regions.

Table 3. Respondents self-reported professions (N=47).

Occupation	Count	Percent
Engineer	20	42.6%
Researcher	20	42.6%
Educator	10	21.3%
Manufacturer/Distributor	9	19.1%
Consultant	5	10.6%
Architect	1	2.1%
Builder	1	2.1%
Other	3	6.4%

* Multiple responses were possible

Table 4. Geographical distribution of respondents.

Region	Number on distribution list	Number of respondents	Response rate
Canada			
British Columbia	22	4	
New Brunswick	7	4	
Ontario	4	-	
Quebec	16	8	
Canada Total	49 (48.0%)	16 (34.0%)	32.7%
United States			
Midwest	16	11	
Northeast	1	-	
South	18	12	
West	18	8	
U.S. Total	53 (52.0%)	31 (66.0%)	58.5%
TOTAL/PERCENT	102	47	46.1%

4.3 Perceived Level of Awareness

Respondents were asked about their perception of the level of awareness about CLT among developers, contractors, construction managers, engineers, and architects. Responses received are summarized in Figure 2. Overwhelmingly, respondents regarded the level of awareness about CLT among professionals as "low" or "very low" for most professions. Architects are perceived as the professionals most aware of CLT, with 42.6% of respondents indicating that they believe architects have a "high" or a "very high" level of awareness; followed by engineers with 14.9%. Contractors are perceived as the least aware of CLT (78.7% of respondents indicating a "very low" level of awareness), followed by construction managers (70.2%). These answers are consistent with results by Laguarda-Mallo and Espinoza (2015), who surveyed U.S. architecture firms, and reported that 37.9% and 4.3% of 351 architects indicated being "somewhat familiar" and "very familiar," respectively. The difference between the level of awareness between architects and engineers observed in this study (42.6% of architects and 14.9% of engineers are perceived by respondents as having a "high" or a "very high" level of awareness, respectively) could in part be attributed to the different curricula to which architects and engineers are exposed in degree and continuing education programs, as the typical national engineering curriculum does not include information on wood as a building material (Laguarda-Mallo 2014, Laguarda-Mallo and Espinoza 2015).

Respondents were given the opportunity to add a professional category and rate the level of awareness among members of the category added. Seven participants suggested additional categories, including "owners," "investors," "building officials," "foresters," "builders," and "authorities." All these occupations were perceived as having a "very low" or "low" level of awareness about CLT according to the individual respondents, respectively.

For the forest products industry, which may see CLT as a way to grow their market, the level of awareness among all professions indicated must be of major concern (Figure 2). While one can always make efforts to overcome apprehensions that an individual in charge of selecting a building material has over a specific material, one cannot influence somebody who is not aware of that material. Yet, respondents to this study perceived that a "very low" awareness about CLT for contractors (78.7%), for construction managers (70.2%), and for developers (66.0%) exists. Even for architects and engineers, more than half of the respondents perceived their awareness of CLT as being "low" or "very low" (57.5% of architects and 85.1% of engineers were attributed to having a "low" or "very low" awareness by respondents). Thus, increasing the level of awareness about CLT to gain momentum in its adoption as a building material is a high priority for the forest products industry. In fact, first efforts have been initiated by the Canadian and United States governments and industry associations (Table 5). These efforts aim to increase awareness and adoption of emerging wood-based products and building systems, including CLT.

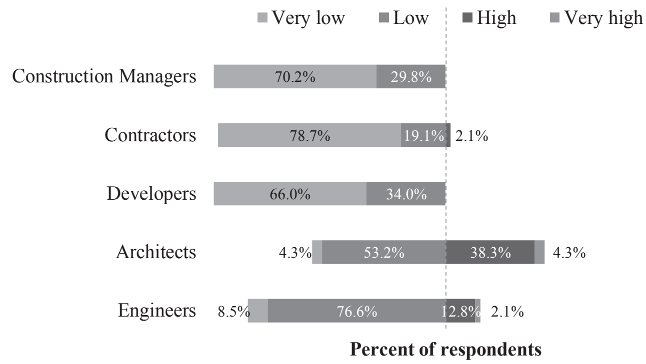

Figure 2. Perceived level of awareness among different occupations (N=47).

4.4 Perceived Barriers for CLT Adoption

The second question in the survey asked respondents to rate a list of potential barriers to increased adoption of CLT in North America. According to CLT experts, major barriers for CLT adoption are the "misperceptions about wood or CLT," the "compatibility of CLT with building codes," and "availability of technical information," which were considered potential barriers or large barriers by 95.7%, 93.6%, and 91.5% of respondents, respectively (Figure 3). The "availability of CLT in the market" and "cost" were, with 87.3% and 86.7%, respectively, considered potential barriers or "large barriers" by respondents and were thus the next highest ranked categories in the list of perceived barriers for CLT Adoption. It is interesting to note that "cost" was the only category that was classified as "may be a barrier" to CLT adoption by more than half of respondents. This may reflect the fact that, while constructing with CLT may be perceived as costlier than with other materials, CLT offers other advantages that potentially offset the relatively high costs. On the other end of the spectrum of "perceived barriers to CLT adoption, the "performance of CLT as building material"

Table 5. Examples of programs and organization that work to increase awareness and adoption of wood-based products and building systems, including Cross-Laminated Timber.*

Program	Funding/Organization	Major Focus	Reference
U.S. Tall Wood Building Prize Competition	United States Department of Agriculture, Softwood Lumber Board, and the Binational Softwood Lumber Council	Competition to design, specify and construct a wood-based building of at least 80 feet in height.	(Anonymous 2015)
WoodWorks	Wood Products Council	Technical support and education for the design of non-residential and multi-family wood buildings.	(Woodworks 2015)
Wood First Program	British Columbia government	Funding for projects that increase the use of wood in public and private projects	(Forestry Innovation Investment Ltd. 2015)
FPInnovations	Canadian government and forest products industry	Research and development to support Canadian forest sector	(FPInnovations 2015b)
The Engineered Wood Association (APA)	Industry Association	Develop and maintain performance standards, promote use of wood	(APA 2015)
American Wood Council (AWC)	Industry Association	Develop building codes and standards for wood design and provide professional education to support implementation	(AWC 2015)

* Not claimed to be exhaustive. Based on Internet searches, peer-reviewed journals, and consultation with experts

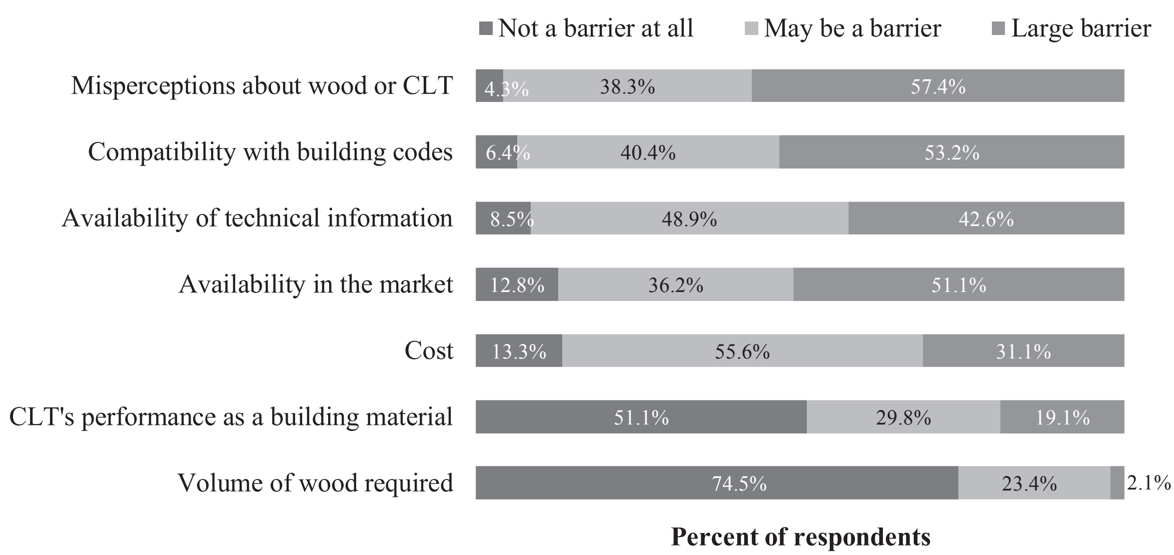

Figure 3. Perceived barriers to CLT adoption (N=47).

and the "volume of wood required" for its manufacture were seen as the least worrisome barriers to the success of CLT in the market place by respondents.

Contrasting this study with experts on CLT with Laguarda-Mallo and Espinoza's (2015) survey of U.S. architecture firms, reveals similarities. U.S. architects agreed with North American CLT experts in that building code compatibility, availability of CLT in the market, and the availability of technical information were large barriers (94.1%, 88.4%, and 77.2% of architects, respectively, considered that these were "large barriers" or "may be barriers"). Similarly, architects did not see the amount of wood required for CLT manufacture as large barrier (only 5.9% considered this as large barrier). However, a larger proportion of architects (e.g., respondents in the study of architecture firms, Laguarda-Mallo and Espinoza (2015), than CLT experts participating in this study, considered cost to be a large barrier or potential barrier (90.9% of respondents). This may be related to the intrinsic characteristics of the architectural profession, in which economic considerations play a critical role on the feasibility of a building project (Hendrickson and Au 1989).

Respondents were given the opportunity to indicate other barriers not listed, in an "other" category. Twenty-three participants entered suggestions, diverse in scope, and some that were already included in the question. Suggested barriers were grouped into the following broad categories: "Fire-related barriers," "Availability of CLT panels," "Seismic performance," and "Others." Table 6 shows the statistics of these answers. Nine respondents' suggestions were related to fire performance of CLT construction, and were further broken down into "Fire performance," "Misperceptions about fire performance," and "Building code issues related to fire performance (Table 6)."

Table 6. Other barriers suggested by respondents.

Barrier	Frequency	
Fire-related barriers		9
Fire performance	4	
Misperceptions about fire performance	2	
Building code issues related to fire performance	3	
Availability of CLT panels		4
Seismic performance		2
Others: "education," "engineering firms expertise with CLT," "construction industry inertia," "field support," "acoustic performance," "connections," "building officials' confidence," and "lack of cost analysis."		8

Summarizing the findings concerning potential barriers to increased adoption of CLT in North America shown in Figure 3 and Table 6, we argue that they represent a favorable story regarding the future adoption of CLT in North America. A majority of respondents (51.1%) indicated that CLT's "Performance as a building material" is not a barrier at all; indicating that they believe the material has no inherent flaws that cannot be addressed. Also, almost four-fifths of respondents (74.5%) do not see the "Volume of wood required" as a barrier. Thus, for the sake of this argument, the two central requirements for potential success, "Performance as a building material" and "Volume of wood required" are not being seen as dominant barriers. However, much work is required to overcome the items ranked as "Large barrier" by respondents such as "Misperceptions about wood or CLT (57.4% ranked this as "large barrier"), "Compatibility with building codes (53.2%)," or "Availability in the market (51.1%)."

4.5 Research Needs

To investigate the research needs that experts judge to exist, participants were presented with a list of 10 potential research topics and asked to rank these topics in order of importance. The questionnaire was set up in a way that forced respondents to select one topic per ranking exclusively (e.g., only one topic could be ranked #1, only one #2, and so forth). Results for this question on research needs are summarized in Figure 4. Since there were 10

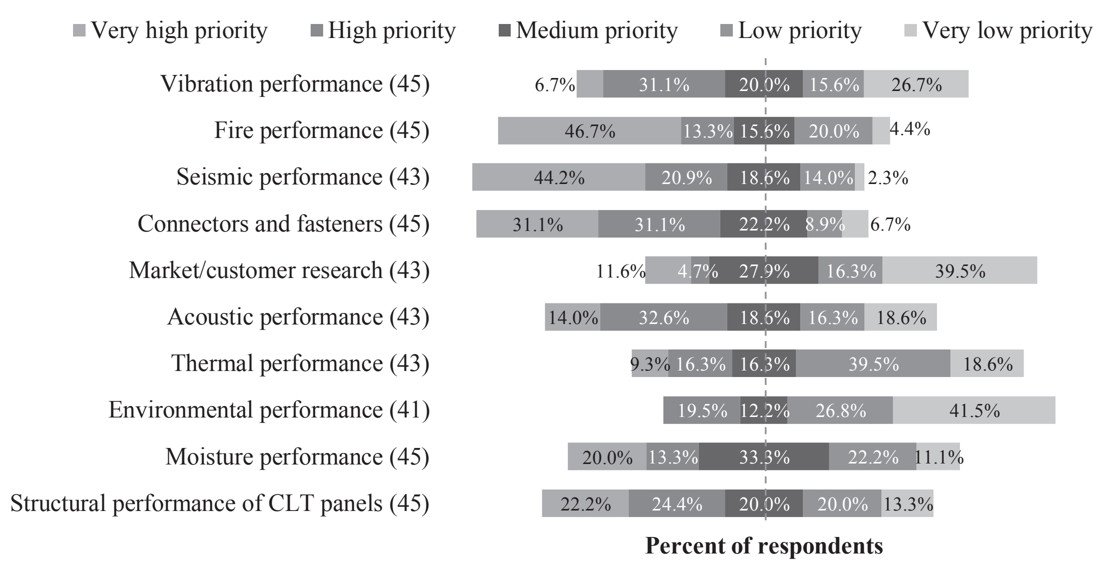

Figure 4. Ranking of research needs. Rankings were grouped into 5 categories: "Very high priority" (ranked 1st and 2nd), "High priority" (3-4), "Medium priority" (5-6), "Low priority" (7-8), and "Very low priority" (9-10). In parentheses is the number of respondents for each item.

ranking positions available, these were grouped into five categories, from "very high priority" for the first and the second ranking, to "very low priority" for the ninth and the tenth ranking positions. Following this rationale, the research topics with the highest priority, according to respondents, were "seismic performance," "connectors and fasteners," and "fire performance;" which were ranked as "very high" or "high" priorities by 65.1%, 62.2%, and 60.0% of respondents, respectively. The research areas with the least need for research are, according to participants, "environmental performance," "thermal performance," and "market/customer research;" which were ranked as "very low" or "low" priority by 68.3%, 58.1%, and 55.8% of respondents, respectively.

A separate field was added to allow respondents to enter other research topics about CLT not included in the previous question that they considered a need addressing to support its further development. In fact, participants could enter as much information as they wanted. The response rate to this question was high, with 27 respondents (close to 60% of total respondents) contributing 54 suggestions. These suggestions were grouped into research areas by the authors and are listed in Table 7 in order of decreasing frequency. Notably, several topics that were included in the previous question (ranking of research needs) were mentioned again by respondents, perhaps with the purpose of adding emphasis and further explaining their positions. For illustrative purposes, examples of specific topics within individual research areas are also listed.

Table 7 lists a vast array of research topics that respondents identified. This may not be surprising, given that CLT is more than just a "new" building material, but in fact represents a new construction philosophy in that it enables the relocation of many tasks from the building site to the factory and in that it requires a new way of thinking when designing loads and forces. Thus, this new construction material requires research in all aspects of building construction and it is, therefore, no surprise to realize the wide array of topics raised by the respondents. However, the prioritization of these needs to achieve the most beneficial outcome for the industry and society is

Table 7. Other research areas and topics suggested by respondents. The frequency column contains the number of times that each specific topic was mentioned by individual respondents.

Research area	Frequency	Specific topic examples
Hybrid systems	7	Lateral load resistance, reinforcement of CLT in high-shear areas, planar shear properties of cross layer(s), and full-scale diaphragms design and testing.
Shear walls and diaphragms	6	Hybrid systems, such as wood/concrete slabs, and mixing CLT with post-frame and light frame construction.
Fire performance	5	Fire performance of connections, need for original research in the U.S., and building code issues related with fire.
Installation/construction	5	CLT construction methodology, and long span applications, construction management.
Seismic performance	3	Need to develop R-factors consistent with ASCE 7 seismic design procedures (Robert Bachman, 2007), and ductility of CLT panels in seismic applications.
Cost and economics	3	Cost comparisons with other building systems, cost optimization, and economic feasibility.
Durability	3	Repair of CLT panels after water-related damage, protection against condensation and plumbing leaks.
Adhesives and gluing	3	Performance of new resins, performance under moisture cycling and fire, and environmental issues of adhesives.
Procurement	2	Supply chain issues, logistics.
Raw material	2	Material specification and reliability of raw material sources.
Tall buildings	2	High-rise building with CLT, building code issues.
Connection systems	2	Connection systems, connection details
Others	11	Changes needed in building code to enable CLT compliance. Product optimization for different applications. Standardization of CLT panels. Prefabricated CLT houses. Costs and performance of CLT-based building core (e.g., elevator shafts, stairs, mechanical rooms). Curtain and window walls. Pre-installation coatings. Business development.

challenging and somewhat unorganized. Only the future will tell how well this task has been managed.

4.6 Other Comments

The last item in the questionnaire provided space for respondents to add any additional comments they had about initiatives or actions needed for the advancement of CLT in North America. Twenty participants offered their comments, which are summarized below.

Education and Promotion. Most comments were related to educating North American construction professionals about CLT. According to respondents, professionals to which these educational efforts should be targeted were engineers, architects, contractors, authorities, building officials, fire departments, and investors. Topics suggested were fire performance, short construction time, the airtight nature of CLT buildings, energy benefits, acoustics, and benefits to the room climate. One respondent suggested education of contractors is particularly needed on installation issues, specifically on running utilities (e.g., electrical, plumbing) through CLT panels. Also, educational efforts should be spent on how to properly insulate CLT structures.

Demonstration Projects. Some respondents suggested that the best promotion of CLT construction is to complete building projects in different parts of the continent. One respondent suggested that building sites or zones across North America should be identified, where a CLT super-structure may have a foundation/sub-structure cost advantage over a reinforced concrete solution. Performance demonstration tests (e.g., fire, acoustic) were also suggested.

Research. Some respondents used the opportunity to suggest additional research topics. One respondent suggested that research is needed for mid-rise buildings in CLT, where this material could become cost-competitive with concrete and steel buildings. At least three comments suggested that interdisciplinary research and collaboration between the different North American institutions is needed. One respondents cited as an example the work that the Forest Products Laboratory is doing in collaboration with other institutions (Dovetail Partners, North Carolina State University, and FPInnovations) to evaluate the environmental performance (by conducting Life Cycle Assessment, or LCA) and economic feasibility (Life Cycle Cost Assessment, or LCCA). This effort also includes studying the construction costs of building a CLT plant and an assessment of regional economic benefits through IMPLAN(an economic impact assessment tool,MIG Inc. 2013). Another contributor suggested that the long-term durability and structural stiffness for midrise buildings needed to be investigated, while still another one suggested that the implications of open floor plans in buildings for ease of reconfiguration without major structural upgrades needed to be investigated.

Government Support. Several respondents suggested that government support is needed to grow the North American CLT industry. Since businesses are hesitant to invest in CLT until solid demand exists, government could offer financial support for manufacturers. Two respondents cited Canadian government efforts as examples to follow, such as the "Wood First Initiative" (Forestry Innovation Investment Ltd. 2015). One respondent suggest that Federal funding is needed to broaden university programs in wood engineering and building science.

Others. One respondent stressed the importance of CLT getting building code recognition. Another indicated that the wood industry needs to overcome its risk-aversion and must start investing into CLT. This participant also mentioned that there is a risk of losing momentum to steel and concrete products. Two respondents suggested that some research areas are related to others, for example connector, vibration and seismic performance.

As visible from the broad array of topics mentioned, the participants of this study hold a wide set of opinions about how to best advance CLT (by research and by other means) in North America. While these opinions are valuable, it may be beneficial for the success of the North American forest products industry that priorities are established. However, how such a list of priorities can be set up and implemented is hard to envision other than the Governments allocating funding to specific areas. Focus can also be expected from the entrepreneurs who are pursuing viable businesses, as their allocation of investments and their support of external efforts will be dictated by what makes their business successful.

4.7 Future Research

This survey on the status of CLT in North America is the second such survey following an almost identical study done in Europe earlier in 2015 (Espinoza et al. 2015). A third such study is currently in preparation covering the remaining parts of the world where known efforts to advance CLT exist. Also, contrasting the opinions expressed by the experts on the different continents and searching for explanations for the differences found is warranted. Longer term, it will also be rewarding to holistically study the actual actions that are undertaken to address some of the issues discovered by these studies. Cross-Laminated Timber (CLT) promises the possibility of a revolution in the building construction industry by reorganizing the way buildings are constructed. In fact, the authors can recall no occasion where the forest products industry, over the last quarter century or so, had an opportunity of this magnitude. Thus, plenty of research topics should emerge.

5.0 Limitations

This study used a non-probability sampling strategy. Thus, generalizations cannot be made based on the results from this survey(Rea 2005). Also, it is acknowledged that researchers in marketing and in other business-related fields were under-represented in the sample. Thus, the results obtained reflect the highly technical focus of the respondents. This focus on engineers and engineering related professionals is partly due to the fact that at this early stage of development of CLT, the population of CLT experts is comprised to a large degree by technically-oriented professionals. Readers also must keep in mind that most of the professionals included in the sample for this survey are involved in one way or another with wood-based materials, and thus might have a natural bias toward wood over other materials. Lastly, limitations pertinent of surveys and stemming from the survey methodology, such as recall bias or the subjective nature of responses given, also apply to this research (Alreck and Settle 2004; Dillman 2009).

6.0 Summary

Cross-Laminated Timber (CLT) is a promising engineered wood material, based on massive, large-format panels that can be used as walls, slabs or roofs. CLT's environmental advantages and design flexibility have generated considerable interest in North America as a material for the construction of commercial and non-commercial mid- and high-rise buildings. Hence, research activities on various aspects of CLT as a building material have been increasing at a rapid rate during the years. This study surveyed North American experts on the most pressing research priorities for the advancement of CLT in North America.

A web-based survey was conducted in the summer of 2015 among 105 CLT experts in North America. A total of 47 usable responses were received, resulting in a response rate of 46.1%. The major findings from the study include:

- In general, respondents rated the level of awareness among building professionals as "low" or "very low." Only for two (architects and engineers) of the five professional groups listed (construction managers, contractors, and developers, respectively) more than 10% of respondents ranked their awareness of CLT as "high" or "very high." Architects were ranked highest, with 42.6% of respondents considering their level of awareness as "high" or "very high."
- The three largest barriers to the adoption of CLT in North America, according to the respondents to this survey, are the misperceptions about wood or CLT, building code compatibility, and the availability of technical information. More than 90% of the respondents rated these three issues as either large barriers or potential barriers. CLT's performance as building material and the amount of wood required for CLT manufacture were not considered large barriers for the adoption of this building system in North America, with less than 50% of respondents ranking them as being "may be a barrier" or "large barrier."
- When given the opportunity to list their own barriers to CLT adoption, almost half of the respondents (23) entered their own topics which ranked from "fire related barriers (9 respondents listed issues related to this topic), availability of CLT panels (4), seismic performance (2), and others (8).
- The research areas most in need of attention, according to respondents, are the seismic and fire performance of CLT, and the connectors and fasteners used in the erection of CLT buildings. The environmental and thermal performance of CLT, and market or customer research, were ranked as low research priorities.
- More than half of the respondents (27) listed their own research areas when given the opportunity. Areas listed include "hybrid systems (7 respondents entered research areas falling into this topic)," "shear walls and diaphragms (6)," "fire performance (5)," and "installation/construction (5)" were all mentioned by at least 5 respondents.

The results of this survey suggest a need to increase educational efforts to raise the level of awareness about CLT in North America. Raising the level of awareness among building professionals would appear to be the first step towards a wider adoption of this novel building material and system on the continent. In this sense, education is essential for the process of public acceptance of CLT, as has been learned with the introduction of other construction materials and systems. It takes time and effort to get professionals and end users to trust new materials and technologies. However, trust can only be gained with proven success stories, thus the importance of successful demonstration projects. Such stories will certainly serve as the best reference for those considering CLT for future applications.

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