Innovation Research

Potential of Hardwood Lumber in Cross Laminated Timber in North America: A CLT Manufacturer's Perspective

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The objectives of this research are to study the current manufacturing practices for Cross Laminated Timber (CLT) in North America and record manufacturers' perspectives to identify the opportunities and challenges of using hardwood lumber in their existing set-up. Face-to-face interviews and industry visits were used to collect data on current production practices and manufacturers' opinions regarding the potential use of hardwood lumber in CLT manufacturing. To date, only two United States-based CLT manufacturers have used hardwood lumber in specific projects. The only issues with using hardwoods for the two manufacturers, compared to softwood operations, were quick dulling of cutting tools because of higher hardwood density and a longer pressing time. Other factors, such as moisture content, various dimensions of the lumber, and the caustic nature of some species, were highlighted as limitations for the use of hardwood lumber in CLT panels. The primary concern of the manufacturers was the availability of hardwood lumber in the required quality and quantity. While there is abundance of non-dimensional grade hardwood lumber available, none of this hardwood lumber can be used in its current state, as it does not meet the minimum requirements for CLT manufacturing, or those that meet the specifications are of higher grade and are not cost-competitive. Using non-dimensional grade hardwood lumber requires additional value-added and material removal work, and such work would significantly reduce productivity and increase costs. All CLT manufacturers agreed that the first step to the successful implementation of hardwood or hardwood-softwood hybrid CLT would require the production of dimensional grade hardwood lumber by hardwood sawmills.

Keywords: *Mass Timber Construction; Cross Laminated Timber, Manufacturers Perspectives on CLT, CLT Status; Hardwood CLT; CLT Raw materials*

Mass timber construction has evolved as a new and promising alternative to more traditional forms of construction in recent years (Kremer et al., 2015). Mass timber is defined as large engineered wood products manufactured with multiple layers of lumber or other wood products to create solid panels by lamination and compression. Mass timber is considered as a sustainable alternative for the construction industry for building mid- and high-rise buildings (Lehmann, 2012; Grasser, 2015; Espinoza et al., 2016). Its use in construction provides a solution to the increased cost of construction material and reduces onsite labor. Of the various mass timber opportunities, the Cross Laminated Timbers (CLTs) system has been recognized as excellent construction material in recent years (Kremer et al., 2015; Mohammad et al. 2015; Grasser, 2015). CLTs are wood panels comprised of several layers of lumber that is kiln-dried to a moisture content of 12±3% at the time of the manufacturing, with boards stacked crosswise at 90-degree angles (ANSI/APA, 2012). Glue, nails, or wooden dowels are used to fasten the CLT lamella. An odd number of layers, three to seven layers per panel, is the common practice to fabricate CLTs (ANSI/APA, 2012), and some of the companies in Europe are manufacturing up to nine layers. Commonly, lumber used for CLTs ranges from 5/8 inches to 2 inches in thickness and 2.4 to 9.5 inches in width. Fabricating the layers parallel to the outside layer of CLTs, the lumber grades are required to be a minimum of visually graded No. 2 softwood and visually graded No. 3 softwood for the perpendicular layers (ANSI/APA, 2012).

CLTs can compete with other construction materials in terms of mechanical performance, fire resistance, construction costs, carbon footprint, construction lead times, and aesthetic beauty. CLT construction is now used in 48 states in the US, and approximately 708 projects are currently being built or are in design stages (Woodworks, 2020). Currently, commercial construction industries are the primary consumers of structural grade CLTs and are expected to be the primary consumer in the coming years.

There are two standard CLT products available on the market, structural grade, and non- structural grade. Structural grade of CLTs are used for engineering construction. They are manufactured under the specification established by American National Standard for Performance-Rated Cross-Laminated Timber (APA/ANSI PRG 320), hereafter referred to as PRG 320. To produce structural grade CLTs, each company must have the process and product certified by the Engineered Wood Association (APA). However, there is no standard design specification for manufacturing CLTs for non- structural applications such as road mats, or crane mats. Manufacturers for non- structural applications can choose any tree species and adhesives to fabricate CLT panels if the product meets the consumers' needs. ISO 16696-1:2019 also lack detailed explanation on designing industrial grade (for non-structural application) CLTs (ISO, 2019) but explained the allowable defects on the CLT surface.

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Production of CLT panels for the structural market was projected to grow at a compounded annual growth rate (CAGR) of 16.2% starting in 2017, with a market value of $1.833 billion by 2024 (Energias, 2018). Energias (2018) also estimated that the North American region would have the highest CAGR over the following seven years, starting in 2017. The Beck-Group (2018) estimated that the CLT production capacity in the US in 2020 would reach approximately 257,700 m3, provided all the CLT manufacturing facilities were running at full capacity. They stated that fabricating CLTs to meet the 2020 demand would require approximately 1.95 billion bf of lumber. They also estimated a dimensional grade CLT demand of 515,400 m3 by 2025, which would require approximately 3.9 billion bf of nominal size lumber.

In the US, 38.41 billion bf of softwood lumber and 7.87 billion bf of hardwood lumber were consumed by various wood-based industries in 2017. Approximately 24.4 billion bf of softwood and 8.32 billion bf of hardwood lumber were produced in the same period (Howard et al., 2018). Lumber produced from species that are angiosperms are defined as softwood lumber, and lumber from species that are gymnosperms are defined as hardwood lumber. Softwood lumber production in the US is insufficient to meet the domestic demand. Thus, softwood lumber has to be imported from other countries. The current production of hardwood lumber in the US surpasses domestic demand. To meet the predicted demand for CLTs in 2025 would require approximately 17% of the total softwood lumber produced in the US. This estimation is based on the lumber production capacity of the US remaining the same as in 2017. The estimated lumber volume count doubles the volume of lumber required to meet the predicted demand of 2020, which required the additional importation of softwood lumber. The demand for and insufficient supply of softwood lumber could also be an opportunity to begin the production of dimensional grade lumber from some hardwood species. As a structural solution, CLT and its components have experienced exponential growth, and an adequate supply of the lumber is necessary to meet the continuously increasing demand (Muszyński et al., 2017). CLT manufacturing companies need to find an alternative source to meet their increasing demand.

CLTs were first introduced in Europe. In the beginning, the CLT panel was designed to be manufactured from a single wood species. Single species was chosen to avoid possible design failure due to differences in mechanical and strength properties of the wood (ANSI/APA, 2012; Grasser, 2015). North American manufacturers can use multiple species in a single CLT panel (ANSI/APA, 2012). The use of multiple lumber species in a single panel is allowed if the lumber has similar mechanical and strength properties. However, this definition excludes lumber from hardwood species. The revised version of PRG 320 in 2015, 2017, and 2020 does not recognize hardwood lumber as raw material. With the rise in interest for using lumber from different species and the need for an adequate and sustainable supply of raw materials, CLTs from hardwood lumber could be an option to softwood lumber (Grasser, 2015).

In recent years, there have been some significant studies that promote the use of hardwood lumber for use in CLTs. Aicher (2016) studied three-layered hybrid CLT built with spruce outer layers and an inner cross-layer of beech wood. The author reported significantly higher rolling shear for hybrid CLTs compared to those made with softwood only. Wang et al. (2015) studied the mechanical properties of hybrid hardwood CLT fabricated from a combination of both lumber and laminated strand lumber (LSL). Wang et al. (2015) found that modulus of elasticity (MOE) was 19% higher. Modulus of rupture (MOR) was 36% higher for hybrid CLT, compared to the control sample with LSL in the outer layers.

Additionally, hardwood CLTs with LSL as the core layer had 13% and 24% higher MOE and MOR, respectively. Kramer et al. (2013) also tested three-layered hardwood CLT panels fabricated from low specific gravity hybrid poplar. They evaluated the bending strength and stiffness of the CLT panels. The results indicated that the MOR of hybrid CLT was higher than E3-grade CLT, but the MOE value was lower than the minimum requirements specified by PRG 320. Mohammad et al. (2015) fabricated three-layer CLT panels using a 6/4-inch National Hardwood Lumber Association (NHLA) grade 2-common yellow poplar lumber. This study concluded that CLTs made from yellow poplar compared well with V1 and V2 grade CLT with significantly higher stiffness, bending strength, and interlaminar shear capacity. These studies suggested that hardwood CLTs would be crucial in structural applications when there is a need for higher stiffness and bending strength. Also, hardwood CLTs can solve design problems that require higher interlaminar shear strength. The results from experimental research based on mechanical performance support this unique concept, but the industrial production of this unique product from the existing production system should be evaluated.

There are various technologies and practices in the CLT production process. The overall production line for CLTs can be generalized, despite the different technologies used by manufacturing companies, which is shown in Figure 1. It is necessary to evaluate the production procedures that need to be adopted based on the current technology of CLTs pressing, finger joint technology, and CNC technology for the change in lumber types. The glue bond performance of hardwood lumber from the existing CLT manufacturing technology needs scrutiny at a basic level to manufacture hardwood CLTs for dimensional application. Hardwood lumber currently available in the market requires various value-added work, so it is crucial to identify the technology required to prepare hardwood lumber for CLT application.

Hardwood CLTs for dimensional applications are an additional material choice for designers and architects, and an incredible opportunity for the hardwood lumber market. However, the production of hardwood CLTs on a large scale is only possible if manufacturers have information and willing to accept hardwood lumber. In addition to manufacturers' acceptance of hardwood lumber as raw material, it is also necessary for manufacturers to have adequate technology to process hardwood CLTs. Understanding the current practices used in CLT manufacturing and identifying the potential to use hardwood in CLT manufacturing are the first steps toward successful implementation. If the current technology used by manufacturers is not adequate to begin hardwood CLT production, it is necessary to quantify the scale and level of modification required to use hardwood lumber. Thus, the objective of this research is to study the current manufacturing practices for CLTs in North America and record manufacturers' perspectives to identify the opportunities and challenges of using hardwood lumber in the existing set-up of CLT manufacturers. The following section will discuss the methodology used for data collection to complete this research.

Method

Our present research utilized a case study design to understand the current practices of CLT manufacturers and their perspectives on using hardwood lumber in CLT panels. The authors chose to

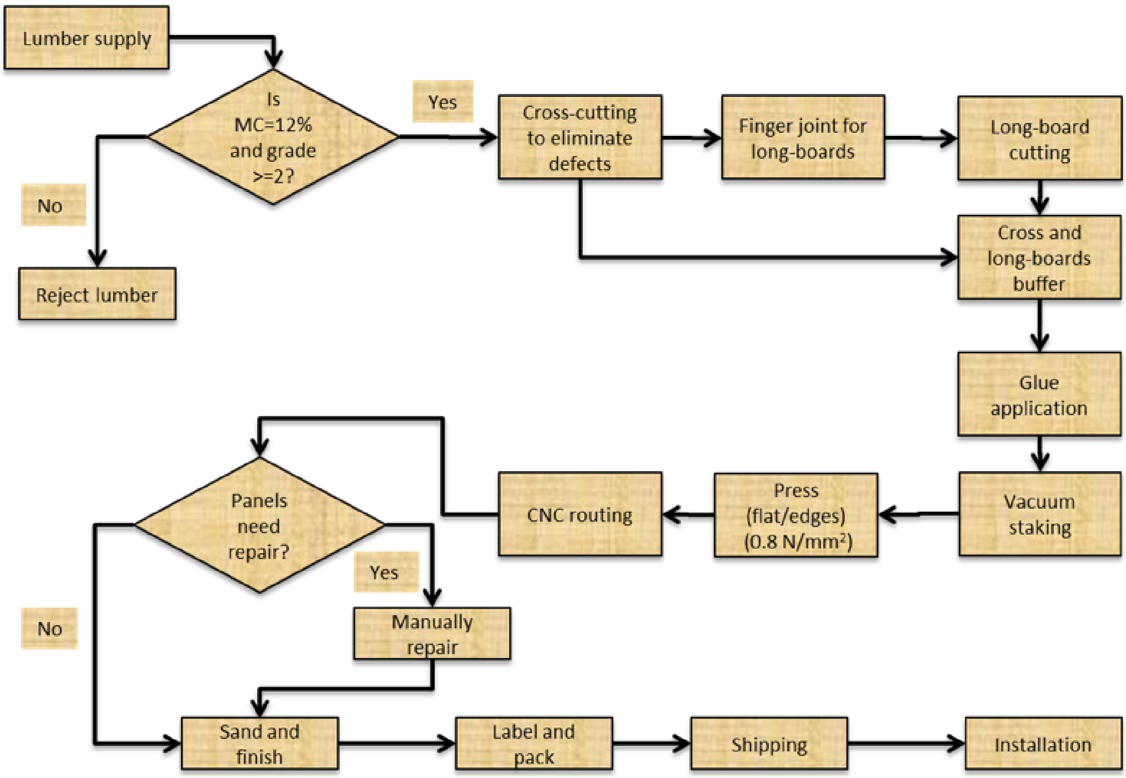

Figure 1: Typical CLT production line. (Source: Ledinek, 2018)

use the case study as the research method for obtaining the detailed information required to answer the research questions. To get accurate answers regarding the research questions, the authors required both qualitative and quantitative data on current CLT manufacturing practices. Additionally, hardwood CLT production is not currently common practice; thus, we were required to make numerous assumptions and predictions to answer the research questions. The use of case study methodology allows researchers to observe information beyond the quantitative statistical results and helps researchers see the circumstances from the subject's perspective Zainal (2007). Tellis (1997) and Yin (2013) argued that the case study approach helps to clarify the process and outcome through comprehensive observation and analysis together with both quantitative and qualitative data from the subject under study. This case study was designed according to the theoretical framework proposed by Yin (2013), which includes five main components: research questions, research purpose, unit of analysis, linking data to the research purpose, and criteria for interpreting a case study's findings.

The research questions for this case study were defined as 1) what are the current practices and capacities of CLT manufacturers in North America, and 2) what are the manufacturers' perspectives on the potential as well as the limitations of using hardwood lumber in the existing manufacturing set-up? The primary data collection methods were face-to-face interviews (FTFI) and facility visits. This research satisfied the minimum conditions mentioned by Mathers et al. (2007) to choose FTFI as the data collection method. The use of hardwood lumber in CLT manufacturing is a new concept, and the language used in production is not well defined, so the survey questions needed to be worded carefully. Therefore, most of the questions in this case study required further clarification to get a quality response.

The scope of this case study was limited to North America. At the time of the survey, there were only six CLT manufacturers - four in the US and two in Canada. The research team contacted all six CLT manufacturers. Both CLT manufacturers located in Canada did not agree to be interviewed, and only three of the four CLT manufacturers in the US agreed to participate.

A set of twenty-seven questions was prepared to address the research questions. Specific questions were developed on production capabilities, current practices of raw material acquisition and preparation, supply chain practice, manufacturing process, maintenance, and quality control to document the current practices of CLT manufacturers. Also, questions were designed to understand the opportunity of using hardwood lumber as raw materials, especially lower grade lumber that was graded as NHLA 2 Common and lower, in CLT manufacturing. Additionally, questions were developed to receive information from manufacturers regarding the scale and level of the modification required, after knowing their existing technology was not adequate to process hardwood lumber. Finally, questions were also designed to help understand the opportunities for continuous collaboration between hardwood sawmills and CLT manufacturers to manufacture lower-grade lumber as ready to use raw material.

With the FTFI method of data collection, validating the answers to the questions asked of participants was the most critical factor. In qualitative research, findings must reflect the existing situation and be supported by definitive evidence. The most widely used approach for validating qualitative research is data triangulation (Barbour, 2001). The interview tool developed asked the same questions of all participants. Additionally, while interviewing the participants, the same question was asked multiple times to the participants in similar contexts, with various follow-up questions, to cross-check the answers. Most of the information collected was verified with secondary sources available in the literature.

Two members of the research team visited all three facilities. One manufacturer allowed the visit before the interview process, and the other two scheduled our visit following the completion of the interview. The research team had the opportunity to ask follow-up questions to understand the current practice of the manufacturers. The information collected during the plant tours was used to supplement the interview process or clarify the information collected if the visit was after the interview process.

Results

The research team visited three of the four US CLT manufacturers currently in operation, and the results are discussed in the following three sections.

Status and practice of CLT manufacturing

The demographic information and current practices of the companies are summarized in Tables 1, 2, and 3. Table 1 highlights the introductory information. The production efficiency and inventory capacity are presented in Table 2. Table 3 summarizes the existing supply chain practice of the manufacturers, company policy for dealing with non-conformity, the company's practice of using a combination of the species, and level of collaboration with lumber producers. One company does not produce any structural grade CLTs, so it is not clear what will be the bottleneck when these companies begin production of structural grade CLT in full scale. Those companies with experience using hardwood lumber stated that this required higher press capacity and slightly longer pressing time, in comparison to when using softwood lumber. All companies have a press with the ability to press up to 9 plies (five layers in one direction alternating with four layers in the perpendicular direction). Two of the manufacturers were built to manufacture 60-foot-long panels. One can produce 52-foot-long panels, but the current production of CLTs is limited to the maximum length of 40 feet due to limitations in transportation for larger panels.

Hardwood lumber to produce CLT

Two manufacturers had used hardwood lumber in CLT panels in the past. The customers' demand guided the practice of using hardwood, and both CLT manufacturers produced the panels as a customized product. All the hardwood CLT produced by the manufacturers was non-structural grade CLT for use as crane mats. When the research team visited the manufacturing facilities, both manufacturers were using only softwood lumber to fabricate CLT panels. Both companies would manufacture hardwood CLT if, and only if, there was a significant and constant demand for the product. During our visits, neither company had a demand for hardwood CLT, and the only demand for hardwood CLT was for matts used in the oil and gas industry. Company A produced seven-ply CLT panels that had five layers of softwood lumber in the middle and a layer of hardwood lumber on the top and bottom. This company used mixed hardwood species that included beech, hickory, and other species provided by the customer. The company manufactured multiple batches of CLTs using mixed species of hardwood lumber.

Table 1: Introductory information on CLT manufacturers interviewed for this study.

Particular/Company	A	B	C
Number of Mills	1	1	1
Wood Species Used	SPF No. 1/No. 2	SYP/Douglas-fir/ SPF	SYP No. 1/No. 2
Maximum Press Capacity(p-si)	1000	1000	1000
Maximum Format (m X m)	2.4 x 12	3.5 x 12	3.5 x 12.2
APA- Certified	Yes	No	Yes
Production Capacity (m3)	75,000	350,000	188,000
Automation in Production Lines	Semi-automated	Highly automated	Semi-automated
Number of Presses	1	3	1
Dimensional Grade CLT (%)	38	0	40

Table 2: Production efficiency and inventory capacity of participating companies.

Company	A	B	C
Efficiency Based on Lumber Consumption	70%	98%	88%
Effectiveness Based on Machine Utilization	45%	85%	50%
Bottleneck of Production Line	Press	Press	Press
Lumber Inventory (MMBF)	500	90000	One-week consumption volume
Finish Goods Inventory	One-week production volume	600,000 panels	One-week production volume

The productivity of each company is dependent upon the efficiency of the equipment and technology adopted. The equipment or process that has the potential to limit the production capacity is identified as the bottleneck equipment or process for the production line. At present, the press is the bottleneck at most of the CLT production lines because the process is time sensitive as well as a comparatively higher time-consuming process. The production volume of the CLTs for structural applications is less than 50% for the two companies.

Table 3: CLT manufacturers' policies of the raw material supply chain and non-conformity.

Particular/Company	A	B	C
Dedicated lumber suppliers	No, receive raw materials from various suppliers within a 200-mile radius	Limited, but receive raw materials within a 100-mile radius	Three suppliers in a 50-mile radius and working for more
Receiving ready to use lumber	Most of the time	Yes, if not return to suppliers at their cost	Most of the time
Major non-conformity	High moisture content	High moisture content	High moisture content
Handling non-conformity	Re-work to match the minimum requirement	Return to suppliers for major non-conformity	Return to suppliers for major non-conformity
Additional value-added work	Surfacing, air drying, trimming, regrading	Air drying (if required), surfacing, trimming	Air drying, surfacing, trimming, regrading
Dedicated line to work on non- conformity	Yes	No	No
Used combination of lumber species	Yes	Used to but now stick with single species	No
Collaborates with lumber producers	No, but with some suppliers to supply limited volume of lumber	Yes, for softwood, but not enough to meet the capacity	In the process and has a policy to receive the raw material from limited suppliers
Current collaboration	Drying	Supplying ready to use lumber	None

Based on these experiences, the company identified the following problems when using hardwood lumber in CLT panels:

1. The inventory of various dimensions (length, width, and thickness) of the lumber significantly decreased productivity.
2. Most of the lumber was not dried to below 15% moisture content. This company received the lumber from the end-use customer, so they had to dry the lumber to meet the minimum moisture content before using it for CLT manufacturing. Hardwood dries at a slow pace, so it was challenging to produce the CLT panels in the scheduled time-frame because the company had to rely on air drying the lumber. Since it required extra work at the manufacturing facility, the cost of manufacturing was higher than regular production.
3. Using multiple species of lumber in the same layer in CLT production impacted material handling efficiency since it required additional sorting of lumber by species to avoid applying excessive pressure on low-density lumber during the bonding process.
4. Some hardwood lumber was significantly harder on cutting tools, and the production process had to be halted numerous times due to the dulling of tools.
5. Some of the hardwood dust was caustic to employees, causing respiratory issues.
6. The press time for hardwood CLTs was longer than for softwood CLTs.

The second company had used both hardwoods only and a combination of hardwood and softwood lumber in making CLT panels. This company collected lumber from different hardwood species from the region, including red oak and white oak, with various thicknesses, lengths, and random widths. However, that caused multiple problems during the production process. The company reported the following problems using hardwood lumber:

1. Manual pre-sorting of the lumber based on length, thickness, and width was the biggest problem for the highly automated production line.
2. The company did not have finger joint capacity, so it was difficult to collect similar length lumber. The company trimmed each piece of lumber to a specific length. Lack of finger-joint technology increased wood loss and reduced productivity.
3. Surfacing the lumber on all four sides was the most complicated process, due to various widths and thicknesses of the lumber.
4. Almost all the lumber had higher moisture content and needed to be dried to below 15%.
5. Due to the variation in the dimensions of the raw material, the company had to build supplemental production lines, as a bypass to the main production line, where lumber of different thicknesses and widths were sorted. This lumber was pulled into the process by the operator if he/she found non-conformity layers. This practice caused multiple interruptions in the production process, which reduced productivity and required two additional employees on the production line.
6. The CLT press time for hardwood CLTs was longer than softwood CLTs.

Company B used polyurethane as the adhesive, and in their experience, it performed well on hardwood lumber and a hybrid CLT made of hardwood and softwood lumber. The company worked together with the glue manufacturing company to test polyurethane on lumber with different moisture contents and found that polyurethane worked well on hardwood lumber with a moisture range of 7% to 25% and produced a significantly strong bond.

The company mentioned that a hardwood-softwood combination in the CLT panels yielded a considerably higher bond strength. The observed shear strength for the softwood-hardwood hybrid CLT panel was, on average, 1000 psi, and, for all tests carried out, there was a 100% wood failure. However, using a similar manufacturing process and shear strength test for softwood CLT panels, the shear strength was observed in the range of between 600 psi to 800 psi, and for all the tests carried out, there was an 85% to 100% wood failure. These results suggest that hardwood-softwood CLT bonds were more robust and performed better when compared to softwood CLTs.

Company B also reported transportation problems for hardwood CLT panels for delivery on the construction site. Because hardwood species suitable for CLT application have a higher density than softwood species, the cost of transportation increased for the same numbers of the CLT panels, ultimately impacting the overall cost of the project. For a large project, it would be necessary to consider transportation costs, given the additional weight. The company estimated that the hardwood CLT panels they produced required 40% more trucking cost than softwood for the same volume of panels.

Both companies were optimistic about markets for hardwood CLTs, and Company A believed that there would be demand for hardwood CLT on an industrial scale in the next ten years. Company A strongly believed that the CLT market would flourish in the coming days and that there would be the opportunity to use hardwood lumber as raw material to provide variation in CLT for structural application. Both companies believed that adequate supplies of the dimensional grade hardwood lumber would be the primary driver of the market in the future. Company A saw the opportunity for hardwood lumber in producing hybrid CLT with softwood, and gradually moving toward hardwood only CLT, if the market were to see significant demand. Additionally, both Both manufacturers suggested that there was minimal or no communication with hardwood sawmills, meaning that there was a lack of sharing of information on specific requirements of the raw material between hardwood lumber producers and CLT manufacturers. One of the common reasons for both CLT mills to avoid contacting hardwood sawmills to produce ready to use lumber for CLT application was the minimal demand for the lumber. Both manufacturers required a limited volume of lumber for a project and were not sure about future demand. On the other hand, hardwood sawmills were unaware of this potential market. None of the CLT manufacturers had requested hardwood sawmills produce ready to use hardwood lumber for CLT application. Company B had suggested that it was cheaper for them to prepare the lower grade lumber available on the market for CLT application, compared to buying ready to use lumber from a sawmill. As a result, low grade lumber from hardwood sawmills was being produced to meet the requirements of industrial-grade lumber that could be sold as pallets and for other industrial applications. None of the hardwood sawmills produced low value hardwood lumber specifically for CLT application, so these mills were not meeting the raw material specification in PRG 320. There was not much information on their capabilities of producing lumber for the CLT application.

Table 4: Challenges and drivers of using hardwood in CLT

Particular/Company	A		B		C	
	Challenges	Driver	Challenges	Driver	Challenges	Driver
Raw materials	▲		▲			
Technology	▲		▲			
Suppliers	▲		▲			
Partnerships		▲		▲	No Experience	
Education	▲		▲			
Markets		▲		▲		
Financing		▲		▲		
Labor	▲			▲		
Regulations	▲		▲			
n = 2						

companies suggested that to promote hardwood lumber as CLT raw material in combination with softwood. It would be necessary to document performance tests of hardwood – softwood CLTs and provide the results to the concerned stakeholders.

Drivers and challenges of CLT manufacturing

The responses obtained from the manufacturers to identify the drivers and challenges for hardwood CLT manufacturing are presented in Table 4. The availability of the raw material was identified as a challenge in using hardwood lumber. Both manufacturers reported low value hardwood lumber that was graded as 2 common, and below was potential raw material, due to the higher price of superior grade lumber. Both manufacturers also agreed that within the acceptable radius to obtain raw materials, the available volume of the low value hardwood lumber was high. However, this lumber was mixed species and needed significant value-added work to prepare it for for use in CLT applications.

Education was identified as a limiting factor for CLT manufacturers in two respects. The first was the lack of formal training and workshops for the CLT mill operators, which was the reason that it was challenging for CLT manufacturers to find qualified technicians and other employees. The second was a lack of education, which would increase awareness about the capabilities and advantages of using the CLT system. All three participants agreed that many potential consumers were not educated about the additional advantages of CLT construction compared to existing construction material. Lack of awareness by the public and potential customers was identified as a challenge for CLT construction. The existing technologies to manufacture softwood CLTs were recognized as inadequate to process various hardwood species for CLT panels by both manufacturers, as some of them are caustic and hard on tools, causing multiple breakdowns in production.

The cost of the CLT manufacturing system was not identified as a challenge by the manufacturers because most of the projects completed or in the construction phase using structural grade CLTs were supported by federal or local governments to promote CLT construction systems in the region. The manufacturers were confident that, when people became more aware of the advantages of constructing with CLT systems, the expansion of the CLT market would not be limited by the associated cost.

Additionally, if the production of CLTs were to move to an industrial level, manufacturers were confident that the production cost would lower, making CLT panels more competitive. Existing regulations in the US construction industry were identified as another challenge to market adoption of hardwood CLT because the standard code excludes hardwood lumber for dimensional applications. All three manufacturers agreed that current market opportunities and possible collaboration with other CLT manufacturers, lumber producers, and suppliers were primary drivers for promoting hardwood CLTs for structural construction use in the US.

Discussion

The present study indicates that the efficiency of CLT manufacturers is decreased because of the additional value-added work that needs to be performed on lumber transported to CLT mills. At present, using softwood lumber still requires additional work that includes drying to the proper moisture content, trimming, and surfacing before applying glue. For example, one company reported that for 100 lumber deliveries of softwood lumber, less than 90 deliveries passed the required moisture content test. The other ten deliveries required additional drying at the facility or were removed for alternative use. If CLT manufacturers could receive ready-to-use softwood lumber, productivity would increase significantly. Collaboration with lumber producers was discussed as a possible solution to avoid additional value-added work. At present, there are few collaborations between CLT mills and lumber suppliers in the US.

All participants in this study indicated that using hardwood lumber as raw material required some modification in their current production process. The two manufacturers that had used hardwood lumber as raw material did not see problems in finger jointing, adhesion, pressing, and CNC machining when using hardwood lumber. However, the CLT mills reported that using certain species of hardwood lumber would require the replacement of cutting tools with higher strength tools, due to the increased density of hardwoods. Also, the CLT mills agreed that using currently available hardwood lumber in CLT manufacturing could negatively impact the productivity of the industry. The overall efficiency of the CLT mill when using softwood lumber is approximately 70%. Using non-dimensional grade lumber as a raw material in the existing system would require additional value-added and material removal work. Additional value-added work would require more resources that would reduce the productivity of the mill. Thus, with the current manufacturing system, non-dimensional grade hardwood lumber does not exhibit additional raw material opportunities.

The primary concern expressed by the CLT manufacturing companies was the availability of hardwood lumber in the required quality and quantity within the supply chain radius. The companies believe that many hardwood sawmills would have to work together to meet the lumber demand. For example, the mill producing CLT mats required 150 MMBF of lumber on average for a single project, which is beyond the capacity of any single hardwood lumber producer, unless the company decided to produce only dimensional grade hardwood lumber. Producing only dimensional grade hardwood lumber would not be an economical choice for the hardwood sawmills, as higher-grade lumber has a significantly higher price. In addition to the volume, hardwood lumber should be of dimensional grade-standard, uniform dimension, surfaced in all four sides, and dried to below 12% moisture content- to avoid extra work and cost at the CLT mill. The randomness in width and various thicknesses of the lumber is a significant problem for CLT manufacturers. In preparing lumber with random widths, there is a significant wood loss, which consequently increases the production cost. Also, for a CLT manufacturer that includes finger jointing of lamellas, various length of the lumber increases the cost as well. Worst case, for a CLT mill that does not do finger jointing, it would be difficult to find the uniform hardwood lumber length needed to produce CLTs.

All participants interviewed for this case study agreed that for the successful implementation of hardwood CLT at the commercial level, the production of dimensional grade hardwood lumber is essential. At the same time, some agencies have developed rules for grading hardwood lumber for dimensional applications. Northeastern Lumber Manufacturers Association (NELMA), Northern Softwood Lumber Bureau (NSLB), and Western Wood Products Association (WWPA) are some agencies that had developed dimensional grading rules for hardwood lumber. None of the hardwood sawmills are currently producing lumber using these rules. Hardwood sawmills would have to adopt these rules and produce lumber according to these rules if they were interested in producing dimensional grade lumber to meet the CLT manufacturers' needs.

Even with all the challenges of using hardwood lumber in CLT panels, manufacturers are optimistic about using more hardwood as a raw material. First, CLT mills are looking for a sustainable supply of ready to use raw material. There is a surplus of hardwood lumber, given the contraction of the hardwood lumber market. Second, as CLT use in construction continues to grow, there will be rising competition for softwood lumber between the traditional market and the CLT market. This competition can provide opportunities to use hardwood lumber for dimensional applications. For successful hardwood lumber implementation in the CLT market, the first step will be informing hardwood lumber producers about the opportunity. It is necessary to encourage the hardwood industry to change their practices to manufacture dimensional grade lumber that meets the APA/ANSI PRG 320 standard. There is even more potential if hardwood sawmills focus on producing dimensional material from low value logs.

Finally, a collaboration between hardwood sawmills and CLT manufacturers is an essential factor in solving potential problems. Some specific hardwood log species have similar mechanical and physical properties as softwood lumber, and hardwood sawmills and CLT manufacturers could collaborate to explore the performance of lumber from these species in CLT application. The results from such collaborations will be significant for the future use of hardwood lumber in CLT manufacturing.

Summary

The research team visited all three CLT manufacturers between June and September 2019. Since then, there have been several changes in CLT manufacturing. Based on the observations of the research team, the study can be summarized in the following points.

- Structural grade CLT and CLT mats are the standard product for CLT manufacturers in the US, and, at present, CLT mats comprise approximately 74% of the total production volume.
- The production efficiencies of CLT manufacturers are, on average, 84% based on lumber consumption for the manufacturers considered in this study, where efficiency

was based on machine utilization averages below 70%.

- The lumber species most often used to produce CLTs is southern yellow pine (SYP). However, the manufacturer has considered using other softwood species and groups like Douglas-fir, Larch, the Spruce-Pine-Fir (SPFs) group, and the Hem-Fir group.
- Two of the CLT manufacturers have considered using hardwood lumber in CLT for specific projects. They have had positive experiences with the performance. The hybrid CLT, a combination of softwood and hardwood lumber tested for performance, yielded higher strength when compared to softwood CLT.
- The significant problems for the manufacturers in using hardwood lumber in making CLTs include are the various dimensions of the lumber available on the market, limited suppliers, and insufficient volume of lumber for a species or group of species. Additionally, some of the hardwood lumber is hard on tools as well as caustic to breathe, causing health problems for employees.
- In comparison to softwood CLTs, hardwood CLTs of similar dimensions and layers have higher transportation costs, due to the increased weight of hardwood and its impact on trucking weight limits, which can be the primary variable cost in larger projects.
- From manufacturers' perspectives, there is a increased potential to use hardwood in CLTs. However, it is more dependent on the volume of lumber that matches the minimum specifications of the CLT standards.
- Some manufacturers are interested in collaborating with hardwood lumber producers to promote increased hardwood lumber use in CLTs. However, they are looking for a guarantee to supply the minimum volume of lumber.

Recommendations

Producing hardwood CLT mats and hybrid CLTs with hardwood lumber should be the first step to structural grade hardwood CLT production. Performance tests and specification development of the new product should be appraised before using CLTs for structural application. CLT companies may choose to work together with research institutions to support performance test as well as specification development. For commercial use of hardwood in CLT, collaboration with a hardwood sawmill will be vital. The company can choose to collaborate in multiple aspects.

1. Sharing production information between sawmill and CLT companies. This practice can help to understand the need for each other. Sawmill can produce ready to use lumber so that lumber waste and cost due to raw material preparation can be avoided.
2. Collaboration with a broker, lumber supplier, and lumber distributor. For a CLT company to get ready to use lumber at their inventory, collaboration with broker, suppliers, or distributor is the best choice to avoid wood waste and increase productivity. If the company needs a large volume of the lumber from multiple species, this can be much beneficial as compared to relying on one to one collaboration with sawmills.
3. Sharing investment to adopt new technology to produce ready to use lumber. CLT companies can exercise collaboration with sawmills to acquired new technology to manufacture dimensional grade hardwood lumber. Currently, dimensional grade hardwood lumber is not produced for the commercial market. CLT mill and sawmill can invest in required technology, which will minimize the investment risk as well as address the need of both companies.

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