Assessing the current knowledge and future prospect of mass timber

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ABSTRACT

Mass timber is a building wood system that is slowly growing in use in various parts of the world. The most common mass timber product in use today is cross-laminated timber (CLT) consisting of layers of glue-adhered lumber to create a component used for ceilings, floors, walls, and support beams. Most research on mass timber thus far has focused on engineering aspects of mass timber, although some sporadic studies have also investigated social and economic aspects. Since isolated knowledge does not cumulate, it establishes a need for a review of the current research surrounding the environmental, economic, social, and policy implications of mass timber. This thesis includes two studies in order to identify research gaps in promoting mass timber within the forest industry. The first study conducted a thorough and systematic review of literature on mass timber with a focus on the synthesis of current knowledge and establishing future research needs. To better fill these gaps in knowledge this thesis combines a second study connected by the topic of mass timber but narrowed in focus and purpose. The second study employed a qualitative social science method to investigate the viability of hardwood CLT manufacturing by implementing key informant interviews of knowledgeable professionals in wood sciences, engineering and architecture, and mill ownership. These studies will help better inform industry professionals, landowners, policy-makers, and the public on both the current state of mass timber in the United States in general and understanding the potential opportunities and barriers for a hardwood CLT market.

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CHAPTER 1
INTRODUCTION

Mass timber is a system that encompasses several construction products made primarily or entirely of large wood components. These components are used in varying situations, often to supplement or replace a traditional building component. Mass timber products can replace traditional constructed steel and or concrete walls, beams, columns, floors, and ceiling (Atkins et al. 2023, Oval 2024). The mass timber component used to replace traditional components can vary but the most common is cross-laminated timber (CLT). Other components include dowel laminated timber (DLT), glue laminated timber (GLT or glulam), nail laminated timber (NLT), laminated veneer lumber (LVL), mass plywood panel (MPP), laminated strand lumber (LSL), and parallel strand lumber (PSL) (Cai et al. 2021, Yadav and Kumar 2021, Atkins et al. 2023, Anderson et al. 2024). These panels and components have been used in numerous construction projects in recent years. WoodWorks, one of the wood industries leading promoters of mass timber, states that 2,205 commercial, institutional, and multi-family mass timber buildings have either started or finished construction as of June 2024 (WoodWorks 2024). Comparing this to the estimated 5.9 million non-mass timber commercial buildings constructed in 2019 alone shows how new mass timber is to the larger construction market (Riddle, 2023).

The increase in the number of these mass timber buildings is likely due to the positive climate change impact of these building components as well as prefabrication and labor benefits. These products have lower green-house gas emissions compared to traditional building materials as well as the intrinsically sustainable nature of wood (Greene et al. 2023, Kumar et al. 2024, Liang et al. 2021). Likely a major contributor to why adoption is increasing for these products (Tellnes et al. 2020). The components can be prefabricated off-site before being transported and assembled. These lowers build times and requires a lower amount of man-power to assemble (Harte et al. 2017, Scouse et al. 2020, Anderson et al. 2024). Add to these factors that in May 2020 the Biden administration increased funding for climate-smart wood products, new wood products are continuing to gain support and funding (USDA 2022).

The current research surrounding mass timber has focused on architectural, engineering, and construction. This creates a gap in knowledge surrounding many aspects of mass timber. Once these gaps are established it creates a need to synthesize the knowledge into a usable form. This synthesis is vital to direct research efforts to the areas of most impact regarding the future of the mass timber industry. To achieve these goals this thesis had two main objectives listed below:

1. To conduct a review of literature on mass timber in order to identify gaps in knowledge and establish future research needs for mass timber
2. To evaluate the feasibility of hardwood CLT through key informant interviews to establish opportunities and barriers for a hardwood CLT industry

To achieve the above-mentioned objectives, this thesis includes two separate studies both of which focus on different aspects of the mass timber industry. The first study, described in chapter three, includes a comprehensive and critical review of literature in the social, economic, and policy aspects of mass timber. After this review was conducted it allowed the establishment of gaps and areas of research need. The second study, described in chapter four, focuses on the prospect of hardwood CLT in particular and identifies potential opportunities and barriers for this new mass timber product. Given that mass timber products in the U.S. are mostly constructed with softwood species (e.g., Douglas fir, pine, spruce) the consideration of hardwood brings new opportunities as well as potential barriers. Historically, softwood species have been chosen due to their abundant supply, structural properties, and lower price compared to hardwood (Adhikari et al. 2020). Research into the mechanical effectiveness of hardwood species in CLT panel construction has been sparse with only a handful of studies being conducted (Ehrhart & Brandner 2018, Crovella et al. 2019, Abdoli et al. 2022, Palacio-Betancur et al. 2023). Due to the new nature of hardwood CLT it creates a need to establish current wood industry perspectives and opinions. To achieve this a key informant interview methodology was chosen. These interviews were conducted among wood industry professionals in the areas of wood science, engineering and architecture, as well as owners of sawmills and lumber yards. The data from these interviews will help guide efforts to promote and establish a hardwood CLT industry.

CHAPTER 2
LITERATURE REVIEW

2.1 Mass Timber

The research surrounding mass timber has been sporadic, especially in the areas of economic, policy, and social research. Gathering and synthesizing what knowledge is presently available will be valuable for the industry moving forward. What is currently known on the economic, policy, and social aspects of mass timber is listed in the appendix (Table 2.1). The following section discusses these aspects in depth and can be used as a general resource for the current state of mass timber research and knowledge.

2.1.1 Economics

Cost consideration heavily impacts whether an industry is willing to adapt to a newer technology. A study by Gu et al. (2020) found that although a 12-story mass timber building's front-end costs would be 26% higher, the mass timber building would provide a cost saving of 2.4 % over its life cycle, especially when the end-of-life salvage values of mass timber was factored in (Gu et al. 2020). Another study by Ahn et al. (2022) established similar opinions to Gu et al. (2020) with mass timber building costs likely higher than steel and concrete. The study did state that adding carbon offsets likely shifts this value consideration in favor of mass timber. The same study also found that limited research on the economic cost of mass timber was a factor affecting their ability to establish a definitive answer (Ahn et al. 2022). Another recent study by González-Retamal et al. (2022) concluded that mass timber buildings showed competitive costs when compared to multi-story buildings constructed of conventional materials like concrete and steel (González-Retamal et al. 2022). A study calculating the manufacturing cost of CLT in the northwestern U.S. by Brandt et al. (2019) stated that a hypothetical CLT plant could produce panels at an average cost of \$536/ m^3 of finished product. The price range was calculated at between \$518/m^3 and \$652 m^3 depending on facility size and location. The economic analysis in this study was conducted on a cost base year of 2015 (Brandt et al. 2019). The lack of a widespread market and availability of CLT in many regions of the U.S. likely plays a large role in the current high cost of these mass timber systems (Rajagopalan & Kelley 2017, Ahmed & Arocho 2021). A study from 2022 looking at the potential for increasing mass timber use in Malaysia found that the life-cycle-cost of dowel-laminated timber and nail-laminated timber wall assemblies were lower when compared to CLT (Balasbaneh & Sher 2022). These cost and market availability considerations will play a major role in the adoption and utilization of mass timber going forward. Continued research on the economic and life cycle cost of mass timber buildings will need to be conducted to alleviate concerns from investors, engineers, and architects on the economic viability of mass timber construction.

Small-diameter timber or lower-quality lumber in CLT panel construction may be a way to lower cost and increase timber availability. Small-diameter timber is often a bioproduct of timber harvest operations and is frequently used in pulp, biofuel, or particle board. A study by Wu et al. (2021) tested small-diameter timber as structural members and found that these components performed sufficiently for several light frame construction purposes (Wu et al. 2021). An earlier study by Fredriksson et al. (2015) tested small-diameter lumber in CLT construction utilizing a novel trapeze edging method. Fredriksson et al. (2015) concluded that this method was feasible and increased small-diameter lumber yield. A drawback to this method is that it would require changes to sawmill operations, edging machinery, and specialized CLT production equipment to fully utilize small-diameter lumber (Fredriksson et al. 2015). Vaagen Timbers, a mass timber producer in Washington, has successfully specialized in small-diameter lumber in their production process. Currently, their website lists the use of logs smaller than 8 inches in diameter in their CLT and glulam panels (Vaagen Timbers 2024). Researchers at Washington State University are working on a project funded by a USDA Forest Service wood innovations grant to model the characteristics, press loads, and performance of small-diameter timber feedstock for use in CLT panels (U.S. Forest Service 2022). Testing into utilizing low-quality lumber in CLT panels has been optimistic surrounding its mechanical effectiveness. Crovella et al. (2019) found that low-grade red maple and white ash met PRG 320 guidelines, but low-grade white pine did not meet the requirements (Crovella et al. 2019). A more recent study by Azambuja et al. (2022) tested yellow poplar No. 2 common boards in CLT panel construction. They concluded that a large portion of these low-quality yellow poplar boards can be effectively utilized in CLT panel construction under PRG 320 guidelines (Azambuja et al. 2022). Utilizing small-diameter or low-quality timber stock in mass timber systems shows potential to lower cost and increase lumber availability; however, further research and testing is needed to form conclusive results.

A consumer's willingness to adopt plays a key role in the acceptance of a new or novel product. Mass timber products are still relatively new, especially compared to other traditional construction methods and materials. For a new construction material like CLT to be accepted and utilized by architects and engineers, there needs to be both demand for the product as well as sufficient manufacturing capacity to supply the product (Evison et al. 2018). Successful adoption of new products like mass timber requires awareness, interest, evaluation, trial, repeat purchase, and finally full adoption by consumers (Laguarda Mallo & Espinoza 2015, Nepal et al. 2021). Laguarda Mallo & Espinoza (2015) found that a majority (58%) of U.S. architecture firms surveyed in their study were still unfamiliar with CLT as of 2015. A follow-up study that surveyed U.S.-based engineering firms found a similar observation with 59% of the firms not being familiar with CLT (Laguarda-Mallo & Espinoza 2018). More recent studies suggest that overall awareness about mass timber among architects has improved over time (Ahmed & Arocho 2021, Penfield et al. 2022). For example, Ahmed & Arocho (2021) found that 70% of U.S. architects surveyed as of 2021 had participated in some capacity with mass timber but that 45% of those surveyed architects had less than 1 years of experience. When the researchers asked about design difficulties, lack of stakeholder awareness was listed as one of the most frequent answers given by architects surveyed (Ahmed & Arocho 2021). Positive environmental impacts have been shown to increase a consumer's willingness to utilize or adopt a new wood-based product. Although this plays a key role in the positive perception of these products, cost is still the primary factor when indicating whether a consumer will purchase or utilize a wood-based product (Strobel et al. 2017). Another aspect influencing adoption is the perceived susceptibility of mass timber to fire. Current research is favorable toward mass timber fire performance with many studies concluding mass timber has adequate fire resistance for use in construction. Fire remains one of the key concerns surrounding mass timber use, likely impacting adoption (Abed et al. 2022). This will require a continued effort on the side of researchers to communicate the fire safety of mass timber.

Supply of and projected demand for mass timber is important for establishing the economic viability of these products. A study by Brandt et al. (2021) calculated that by the year 2030 market penetration of CLT would be estimated at 24% and the demand will be higher in some states (California, Washington, and Arizona) than in others. Their results showed that given the current CLT production capacity, manufacturing supply would not exceed demand until 2026 or 2028 depending on the scale of operations. Maximizing production to match capacity tends to generate the best economic viability given the large, fixed cost of mass timber manufacturing facilities. The economic viability of mass timber also depends on the supply of its raw material – lumber, processed using roundwood timber as input. Looking at lumber supply and assuming current production capacity, the researchers concluded that the total lumber supply required to feed these CLT manufacturers was modest, between 1.6% and 1.8% of the total U.S. lumber supply (Brandt et al. 2021). A similar study by Comnick et al. (2021) examined the potential impacts on sustainable timber supply given an increasing mass timber demand. The researchers split the U.S. into North, South, and Western and estimated impacts on demand up until 2035. The only region that under conservative estimates might see demand exceeding timber supply is that of the Western U.S. with the North and Southern U.S. able to supply projected demand under all scenarios (Comnick et al. 2021). Nepal et al. (2021) evaluated the impacts on global wood products markets of projected mass timber demand in multiple countries, which also suggested smaller impacts on global timber supply (harvests), with varying impacts on individual countries. However, they found that higher global lumber demand for mass timber production would lead to a diversion of lumber consumption away from the traditional construction industry (e.g., light-frame construction), suggesting a likely strong market competition for lumber between mass timber and traditional construction use. Depending on the demand scenarios, they projected that increased demand for mass timber globally could drive up lumber prices by 2% to 23% by 2060, suggesting likely increased costs of both mass timber and traditional constructions (Nepal et al. 2021). Although the current literature surrounding timber supply is limited, a few studies that have been published on this topic are optimistic. It seems unlikely that an expanding mass timber or CLT market would run into timber supply limitations any time soon.

Stored carbon in mass timber components is a major factor when considering the positive environmental impact and economic potential of increasing mass timber use in construction (Lehmann 2012, Ahmed & Arocho 2021, Chaggaris et al. 2021, Pasternack et al. 2022). A U.S.-based survey of architects and building contractors showed that the low-carbon emission aspects of mass timber were a primary factor when architects and builders were considering these components for construction projects (Ahmed & Arocho 2021). Positive carbon impacts and potential for carbon storage as well as lower greenhouse gas emission potential have been discussed extensively in much of the recent scientific literature (Kremer & Symmons 2015, Ahmed & Arocho 2021, Liang et al. 2021, Kumar et al. 2024). The creation of economic incentives for the stored carbon and emission reductions in mass timber products creates a potential for carbon credit systems to be established. A recent study by Taylor et al. (2023) concluded that the potential economic and monetary compensation for stored carbon in mass timber products could be significant, depending on carbon prices. These credits could be provided based on mass timbers' intrinsic storage of carbon as well as an alternative for other high GHG emitting construction materials, thus avoiding carbon emissions in two ways (Taylor et al. 2023). Carbon credits for mass timber use have the potential to address some of the cost concerns discussed in the previous section. An established mass timber carbon credits system would offset some of the operating costs associated with a mass timber building by providing a potential source of continued financial compensation over the building's lifespan.

To date, lumber in U.S. CLT manufacturing has come from softwood species (Comnick et al. 2021). Studies surrounding the performance of hardwood use in CLT have shown positive results in mechanical and performance tests. Mechanical rolling shear strength has been tested using European hardwoods with positive results (Ehrhart & Brandner 2018). A similar study using American red maple, ash, and Eastern white pine in the U.S. reached similar conclusions with both hardwood species meeting strength requirements for CLT construction (Crovella et al. 2019). Scientific literature surrounding hardwood CLT fire resistance has been optimistic about these CLT panels meeting fire and safety construction requirements (Abed et al. 2022). Scientific testing surrounding hardwood CLT mechanical performance seems to be hopeful about the future of hardwood use in mass timber products. The literature is still limited, and future testing will be required to confidently establish performance parameters and standards.

Utilization of hardwood timber stock for mass timber components such as CLT shows potential to recover declining hardwood markets. For 2023, Hardwood Market Report (2024) reported the lowest annual eastern U.S. hardwood sawmill production of 5.54 billion board feet since at least 1960, a huge decline from years pre-pandemic (Hardwood Market Report 2024). In addition, pulpwood, paper, and paperboard industries in the U.S. have shown a general decline in consumption and production since the 1990s (Brandeis et al. 2021). A survey study of current CLT manufacturers in the U.S. by Adhikari et al. (2020) stated that quality, quantity, and grading standards were the main concerns of these manufacturers. They further state that CLT manufacturers are hesitantly optimistic about hardwood use in mass timber products such as CLT (Adhikari et al. 2020). Hardwood utilization in mass timber products such as CLT shows potential to remediate some of these lost economic sectors and support rural community timber markets. The mechanical testing surrounding hardwood use in CLT is optimistic; however, the economic and logistics of utilizing hardwood species on a large scale is still up for debate.

A potential barrier to utilizing hardwood in mass timber or CLT is the cost differences between hardwood and softwood lumber. Hardwood lumber in the U.S. is on average two to three times that of comparable softwood lumber (Timber Update 2023). A potential solution is the utilization of low-grade and/or small-diameter hardwood species. Several studies have evaluated low-grade or small-diameter hardwood lumber from species such as poplar, ash, oak, and maple and concluded the CLT panels met strength requirements (Crovella et al. 2019, Azambuja et al. 2022, Norris et al. 2024, Hassler et al. 2024). Low-density yellow poplar has also been tested; however, the CLT panel did not meet structural requirements. The researchers did note that when the low-density yellow poplar was combined with traditional softwood species the panels exceeded strength requirements (Kramer et al. 2014). This was an early study from 2014 with the potential for replicating the study with modern adhesives and techniques. Small-diameter Chinese and European eucalyptus has been tested in CLT panel construction with positive mechanical results (Liao et al. 2017, Ettelaei et al. 2022). However, it is not clear how applicable these tests are to American hardwoods given the unique fast-growth characteristics of eucalyptus.

2.1.2 Policy

Government policies and regulations play a key role in the production and use of all products including mass timber. Brandner et al. (2016) found that the first policies surrounding mass timber and CLT were enacted by Germany, Austria, and Switzerland in 1998 with policies for the rest of Europe following in 2006. After this initial wave of policy introduction in European countries including Canada, China, Japan, New Zealand, Norway, and the United States started to research and enact policies and construction standards surrounding mass timber (Brandner et al. 2016, Su 2018, Nakano et al. 2020, Wahlstrøm 2020). A study in 2016 looking at the state of CLT research in North America found that building code acceptance and standardization of design methods were the most pressing research needs at the time (Pei et al. 2016). In 2010, the Japanese government enacted policies to greatly support the production and implementation of wood in building construction, where CLT has become a major push with direct government incentives and subsidies offered to companies that either produce or use CLT in construction projects. These policies led to an increase in the number of structures in Japan utilizing CLT from 26 in 2015 to 300 in 2018 (Nakano et al. 2020). President Biden recently declared the United States would rejoin the Paris Agreement (Pompeo 2019, Blinken A. 2021), which aims to curb climate change by limiting global warming from anthropogenic greenhouse gas emissions (UNFCCC 2023). Mass timber is considered to have the capacity to play a critical role in this agreement by lowering CO_2 emissions related to construction and thereby limiting global warming (Pasternack et al. 2022).

In the United States, policy formation surrounding tall mass timber buildings gained traction in 2012 with organizations such as the American Wood Council (AWC) establishing a five-year plan with support from the Softwood Lumber Board and U.S. Endowment for Forestry and Communities to expand the International Building Codes (IBC) current guidelines on tall timber building construction (Stegner & Fotheringham 2022). The IBC is a code and guideline standard created by the International Code Council (ICC) for building construction in the United States, Puerto Rico, and the U.S. Virgin Islands. These codes include building codes for all buildings, excluding townhouses up to three stories as well as one- or two-family homes. These codes are released on a three-year cycle with individual states and municipalities choosing whether to adopt the current IBC guidelines or remain under a previous version (International Code Council 2024). In 2012 the AWC proposed changes to the 2015 IBC that aided in the establishment of guidelines specifying CLT use as a heavy timber building (type IV-HT) element in the IBC 2015 guidelines (Stegner & Fotheringham 2022). It was under the IBC 2015 guidelines that the first design plans were developed such as the Framework building proposed by Lever Architecture in Portland Oregon and the John W. Olver Design Building proposed by Leers Weinzapfel Associates in Amherst Massachusetts (Kouarti 2017, Gu and Bergman 2018, University of Massachusetts Amherst 2023). These changes were proposed and spearheaded by the AWC in collaboration with the Softwood Lumber Board and the U.S. Endowment for Forestry and Communities as well as an Ad Hoc Committee on Tall Wood Buildings approved by the ICC Board of Directors in 2015. The Committee established research and testing needs and tests were conducted to support new safety and performance guidelines for CLT construction. Fourteen mass timber code changes were approved for the 2021 version of the IBC guidelines (International Code Council 2020). These changes established three types of mass timber building construction categories: Type IV-A classified as wood buildings up to 18 stories with noncombustible protection over mass timber, Type IV-B classified as wood buildings up to 12 stories with limited exposure of mass timber ceiling panels, and Type IV-C classified as wood buildings up to 9 stories with completed exposed mass timber with 2-hour fire ratings. The AWC and ICC Committee on Tall

Wood Buildings put forward changes again during the 2021 IBC development phase which were later approved and have now appeared in the 2024 version of the IBC guidelines (International Code Council 2023). The major changes in this 2024 version included new fire safety guidelines allowing for Type IV-B mass timber buildings to have all interior floors and ceiling areas constructed of exposed CLT (International Code Council 2023, Stegner & Fotheringham 2022).

One of the main factors for local governments' hesitancy or barriers to adopting mass timber building policy is the lack of knowledge on cost. A 2019 study found that governments and councils might find mass timber use more economically feasible than previous assumptions and recommended local cost-benefit analysis (Milestone & Kremer 2019). New mass timber facility costs and costs associated with upgrading current facilities have been a general concern limiting mass timber adoption. In 2018 the U.S. Farm Bill introduced the Community Wood Energy and Wood Innovation program to facilitate wood-utilizing industries. One of these applications is the Innovative Wood Product Facilities grant, which provides cost share for innovative wood facilities, which include mass timber facilities (e.g., sawmills, mass timber manufacturing). These grants can cover up to 30% ($1 million cap) of a facility's cost. However, few mass timber-related projects have been funded under this program (Riddle 2023). WoodWorks provides education for the AEC community through its outreach activities on non-residential construction, primarily mass timber systems (WoodWorks 2024).

2.1.3 Social

The most recent study directly examining public opinion on mass timber use in building construction was published in 2021 by Montague et al. (2021). The study looked at the opinions on CLT of millennials and showed participants had a positive but limited knowledge. Montague et al. (2021) concluded that information campaigns will be vital to communicate the properties and potential benefits of CLT to this younger demographic (Montague et al. 2021). An indirect recent study by Debnath et al. (2022) looked at public perception on social media. However, this study took a meta-analysis approach and did not ask direct questions about mass timber (Debnath et al. 2022). The most recent concrete research on public opinion and mass timber was conducted by Larasatie et al (2018). In this study, the researchers found that limited familiarity was common among those surveyed. Those surveyed provided neutral answers leading the researchers to state education as a positive strength concerning future steps. Participants stated mass timber construction was seen as having better environmental performance while also stating concerns surrounding deforestation, fire risk, and uncertainty surrounding earthquake (seismic) risk. This study was pivotal in establishing many of the currently held perceptions of what the public thinks about mass timber (Larasatie et al. 2018). However, the questionnaire for Larasatie et al. (2018) study was administered throughout 2017, making the information and conclusions gathered, over half a decade old. Social pressures surrounding building-oriented climate action are prominent on social media platforms and online discussions. These pressures influence the perception and discourse around recent international climate agreements and climate mitigation policies such as the 2015 Paris Agreement, EU Green Deal, and the 2017 UN Climate Change Conference (Debnath et al. 2022). Further research into the social implications including public awareness, knowledge, attitudes, acceptability, and preference of mass timber is limited. Recent research by Montague et al. (2021) and Debnath et al. (2022) has shown the importance of acquiring these perspectives as well as establishing the link between social perception and environmental policy support surrounding mass timber systems and CLT use. The dated nature of available information creates a need for up-to-date research and surveys on public opinion surrounding mass timber. Given how far the policy and construction guidelines have come in the last five years (Stegner & Fotheringham 2022), it is reasonable to assume that the public's opinion on mass timber has likely shifted since the last in-depth surveys were administered.

The connection between the natural environment and human well-being in constructed spaces has been well-established in the physiological and psychological scientific literature (Sakuragawa et al. 2005, Nyrud & Bringslimark 2010, Burnard et al. 2015, Strobel et al. 2017, Jo et al. 2019). Some early studies of note are Sakuragawa et al. (2005) which concluded that interior wood wall panels decrease depression and lower blood pressure. Similarly, Nyrud & Bringslimark (2010) showed that participants perceived interior wood panels as “natural” and “healthy” as well as quantifying physiological benefits similar to Sakuragawa et al. (2005) in their earlier study (Sakuragawa et al. 2005, Bringslimark 2010). Traditionally constructed non-wood-utilizing indoor environments have been shown to lessen a person's ability to recover emotionally and are linked to psychological drain (Burnard et al. 2015). The use of natural building components, such as wood, has been shown to improve people’s emotional and physical well-being in these constructed environments (Sakuragawa et al. 2005, Yin et al. 2018). People show decreased levels of stress, improved memory, and improved emotional state when natural biophilic components are incorporated into building construction (Yin et al. 2018). The wood used in interior spaces can influence a person’s perception of ambiance and elicit feelings of positivity and connectedness to nature (Strobel et al. 2017). These psychological and physiological considerations are important when establishing potential benefits to increased use and adoption of mass timber systems using CLT panels and glulam beams and columns.

An early study considering mass timber production and market acceptance found that economic risk and uncertainty were driving factors in AEC firms’ willingness to adopt mass timber (Laguarda-Mallo & Espinoza 2015). A survey of industry professionals at a 2018 North American Mass Timber Research Needs |Assessment Workshop found that the top concerns about mass timber adoption included the need for studies related to cost-effectiveness, comparability to other materials, environmental and carbon implications, and establishment of codes and construction standards (Zelinka et al. 2021). A recent study resulting from the 2022 North American mass timber research needs assessment workshop found that many questions related to fire performance, building durability, architectural considerations, structural performance, sustainability, and infrastructure applications require extensive future investment and research. Each section of the workshop proposed questions to participants with results broken down into a matrix examining the research and investment effort compared to the perceived or expected impact. These topics varied greatly in perceived effort and impact, but few proposed future steps fell into the low effort and high impact category (Ricco et al. 2023). Another survey of building contractors, architects, and mass timber manufacturers found that awareness and hesitancy were still primary factors driving whether a construction practitioner was willing to use mass timber products as of 2021 (Ahmed & Arocho 2021). There has likely been a shift in architect and building engineer awareness of mass timber systems as a more recent survey conducted in 2022 by Penfield et al. (2022) showed that 100% of architects and engineers were familiar with CLT. Both architects and engineers agreed that CLT shows advantages in environmental aspects but only architects stated CLT is more effective when compared to traditional building materials. Compatibility with traditional building materials was not seen as an issue for either architects or engineers. Disseminating information on the current state of mass timber construction codes, safety testing, and economic potential to building contractors, architects, engineers, and manufacturers has the potential to alleviate the current hesitancy toward mass timber products (Penfield et al. 2022).

2.2 Hardwood Cross-Laminated Timber

Hardwood lumber markets have seen a great decline in both production and number of facilities. Annual eastern U.S. hardwood sawmill production is reported to be at the low point of 5.54 billion board feet of lumber, a decline not seen since at least 1960 (Hardwood Market Report 2024). Add to this that paper, pulpwood, and paperboard industries in the U.S. have declined since the 1990s in both consumption and production rates (Brandeis 2021). Current CLT manufacturers seem to be optimistic about the potential of hardwood CLT manufacturing but have concerns and hesitancy around quality, quantity, and grading standards of hardwood lumber (Adhikari et al. 2020). Given this potential and the need for novel hardwood use cases to support struggling wood industries literature is beginning to emerge discussing the potential of hardwood CLT. Much of the studies surrounding hardwood CLT have emerged in recent years and many questions and aspects still remain unexplored.

Performance is a major factor when considering the use of hardwood lumber in CLT panel construction. The industry standard in the U.S. for CLT components falls under the ANSI/APA PRG 320 guidelines. These guidelines stipulate allowed species as well as general panel construction and use guidelines (APA 2020). CLT panels constructed of European poplar, birch, beech, and ash tested rolling shear strength greater than CLT constructed from Norway spruce (Ehrhart and Brandner 2018). Ash and beech were of special note showing exceptional shear strength compared to other species tested. Crovella et al. (2019) tested shear strength for the softwood species Eastern white pine as well as hardwood species red maple and ash and found that both hardwood species met the requirements for CLT construction, while the Eastern white pine did not meet the requirements. Nail and screw withdrawal performance in a CLT panel constructed of poplar have been found satisfactory and up to construction standards (Abdoli et al. 2022). CLT performance study on the underutilized hardwood species sycamore, red maple, and sweetgum showed the most promise in the latter two as far as structural use is concerned (Palacio-Betancur et al. 2023). The same study also noted the potential for utilizing hardwood as a veneer over a structural softwood core in a hybrid panel construction.

These studies show that certain hardwood species have potential to meet or in some cases exceed structural design requirements for use in CLT panel construction.

The cost of lumber is another factor often faced in CLT production. Hardwood lumber price is on average two to three times that of comparable softwood lumber (Timber Update 2023). Some studies have been done to find new or novel ways of lowering this cost component (Crovella et al. 2019, Azambuja et al. 2022). Consideration of lower-cost hardwood species and lumber grades may be pivotal to ease cost-related hesitation toward hardwood production. Two potential areas to lower the cost of hardwood in CLT are the use of low-grade and/or small diameter lumber. Lower grade lumber is cheaper and can lower the overall cost of the finished CLT panel. Several studies have evaluated low-grade hardwood lumber from species such as poplar, ash, and maple (Crovella et al. 2019, Azambuja et al. 2022). The early study by Kramer et al. 2014 found that yellow-poplar in CLT panel construction did not meet structural requirements alone but did exceed them when combining yellow poplar with other softwoods (Kramer et al. 2014). A more recent study on yellow-poplar found that a significant portion of low-grade boards meet the minimum requirements under ANSI/APA PRG 320 standards (Azambuja et al. 2022). Another study tested red maple and white ash and concluded that both species met the ANSI/APA PRG 320 standards for stiffness and shear strength (Crovella et al. 2019). When looking at small-diameter hardwoods lumber, European and Chinese eucalyptus was found to meet structural standards for CLT panel construction (Liao et al. 2017, Ettelaei et al. 2022). The use of smaller-diameter and/or low-grade hardwood lumber can significantly lower the cost of CLT panel manufacturing, lessening potential financial hesitancy.

Hybrid utilization of hardwood and softwood lumber in CLT panel construction has potential both in terms of saving cost and adding aesthetic value. For example, a hybrid CLT panel made of European beech hardwood and spruce softwood showed 2-3.5 times the rolling shear strength of spruce alone (Aicher et al. 2016). Similar observations were made on CLT panel constructed of beech and pine compared to its pure beech counterpart (Sciomenta et al. 2021). Brunetti et al. (2020) discussed the limitations of hardwood CLT panel construction when considering bonding parameters and concluded that none of the adhesives tested in hybrid European beech and spruce panel met European standards for CLT manufacturing (Brunetti et al. 2020). Given the lower cost of softwood lumber as well as studies showing potential structural improvements, hybrid utilization of hardwood lumber in CLT construction shows potential.

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Appendix

Table 2.1 Summary of current knowledge on economic, policy, and social aspects of mass timber.

Knowledge area	**General findings**	**References**
Economic		
Cost Consideration	The current upfront cost of mass timber construction may be higher, but the long-term life-cycle cost is low	Rajagopalan & Kelley 2017, Brandt et al. 2019, Gu et al. 2020, Ahmed & Arocho 2021, Ahn et al. 2022, Balasbaneh & Sher 2022, González-Retamal et al. 2022
Small-Diameter and Low-Quality Lumber	Limited research and utilization of small-diameter lumber in mass timber components has shown potential with projects and research continuing to develop	Fredriksson et al. 2015, Crovella et al. 2019, Wu et al. 2021, Azambuja et al. 2022, Vaagen Timber 2024
Willingness to Adopt	The U.S is likely between the evaluation and trial stage of a successful adoption with architects familiar if tentative toward full adoption of CLT	Laguarda-Mallo & Espinoza 2015, Strobel et al. 2017, Evison et al. 2018, Nepal et al. 2021, Ahmed & Arocho 2021, Penfield et al. 2022,
Supply and Demand	The likely impact on the forest resource base is minimal given the higher growth-to-drain ratio	Brandt et al. 2021, Comnick et al. 2021, Nepal et al. 2021
Stored Carbon	Stored carbon in mass timber has positive environmental and economic potential through reduced greenhouse gas emissions and carbon credit incentives	Lehmann 2012, Kremer & Symmons 2015, Ahmed & Arocho 2021, Chaggaris et al. 2021, Liang et al. 2021, Pasternack et al. 2022, Taylor et al. 2023, Kumar et al. 2024

Table 2.1 Continued

Hardwood Mass Timber	Hardwood CLT shows potential in mechanical testing and to alleviate struggling hardwood markets but will likely remain a niche product with higher cost and limited supply compared to traditional CLT products	Liao et al. 2017, Ehrhart & Brandner 2018, Crovella et al. 2019, Adhikari et al. 2020, Brandeis et al. 2021, Comnick et al. 2021, Abed et al. 2022, Ettelaei et al. 2022, Azambuja et al. 2022, Norris et al. 2024, Hassler et al. 2024
Policy		
Non-U.S Policies	Policy surrounding mass timber started in the late 90's with many countries enacting new programs to push mass timber adoption and utilization	Brandner et al. 2016, Su 2018, Nakano et al. 2020, Wahlstrøm 2020, Pei et al. 2016, Nakano et al. 2020, Pasternack et al. 2022
U.S Policies	U.S policy formation surrounding mass timber started in 2012 with the ICC continuing to evolve the International Building Codes with expanded fire safety and exposed CLT guidelines	Kouarti 2017, Gu & Bergman 2018, International Code Council 2020, Stegner & Fotheringham 2022, International Code Council 2023, University of Massachusetts Amherst 2023, International Code Council 2024
Policy Adoption and Cost	New and upgraded mass timber facility costs are likely more economically feasible than many local governments have found leading to positive potential for incentive policy programs	Milestone & Kremer 2019, Riddle 2023, WoodWorks 2024

Table 2.1 Continued

Social		
Public Opinion	The most recent studies looking at public opinion on mass timber showed limited familiarity with public opinion being generally positive about environmental aspects and safety concerns.	Larasatie et al. 2018, Montague et al. 2021, Debnath et al. 2022, Stegner & Fotheringham 2022
Psychological and Physiological Well-Being	Studies surrounding exposed wood use in building construction are extensive with long-term support for the positive psychological and physiological aspects of wood	Sakuragawa et al. 2005, Nyrud A. & Bringslimark T. 2010, Burnard et al. 2015, Strobel et al. 2017, Yin et al. 2018, Jo et al. 2019,
Willingness to Adopt	Economic risk, awareness, cost, comparability to other materials, sustainability, code standards, performance, fire safety, and durability are the primary factors affecting engineers, architects, and contractors' willingness to adopt mass timber	Laguarda-Mallo & Espinoza 2015, Zelinka et al. 2021, Ahmed & Arocho 2021, Abed et al. 2022, Penfield et al. 2022, Ricco et al. 2023

CHAPTER 3
A REVIEW AND SYNTHESIS OF CURRENT LITERATURE AND GAPS ON SOCIAL, ECONOMIC, AND POLICY ASPECTS OF MASS TIMBER RESEARCH

This article was written and revised by the primary author Alexander Bremner and his primary advisor Neelam C. Poudyal in collaboration with Prakash Nepal, Consuelo Brandeis, Adam Taylor, and Richard Bergman. All researchers provided vital feedback and guidance during the writing of this manuscript.

3.1 Abstract

Production of mass timber systems for use in large-scale building construction has been increasing as an alternative to traditional building materials. While knowledge on the environmental and engineering aspects of mass timber has been well documented in wood science and engineering literature, little is established regarding the social, economic, and policy aspects. Research on social, economic, and policy aspects of mass timber systems are emerging but remain isolated and sporadic, leading to the need for a synthesis of knowledge to identify research needs in these areas. Fifty-four peer-reviewed publications were examined to establish current knowledge and future research gaps for the social, economic, and policy aspects of mass timber systems. Remaining gaps include product and lifecycle cost, regional impacts, recyclability, carbon credit potential, small diameter timber and hardwood lumber utilization, policy and incentive programs, and current public perception, especially on the aesthetic and psychological, aspects of mass timber. Findings from this study will benefit researchers and other stakeholders in the wood industry and offer guidance on future research opportunities.

3.2 Introduction

Mass Timber is a family of engineered wood products that are manufactured by gluing, nailing, or doweling wood products in various layers resulting into large panels, post, and beams with improved strength and structural performance (Oval 2024, Atkins et al. 2023). Mass timber wood construction system has seen traction in the building, architecture, and engineering sectors in recent decades (Brandner et al. 2016, Harte 2017, Ahmed et al. 2021, WoodWorks 2024). With climate change, interest in using sustainable building materials such as mass timber in place of traditional materials (e.g., steel and concrete) has been growing. Sustainable building materials offer a potential way to mitigate greenhouse gas (GHG) emissions from the built environment, which is responsible for about one third of the global GHG emissions (United Nations Environment Program 2022). The most common mass timber product in use today is cross-laminated timber (CLT) with other products such as glued laminated timber (a.k.a. glulam or GLT), nail-laminated timber (NLT), dowel-laminated timber (DLT), and mass plywood panels (MPP) also gaining market acceptance (Atkins et al. 2023). These mass timber components are used in construction for ceilings, floors, walls, and support beams of buildings and in other large-scale applications such as crane mats or in bridge construction. These mass timber components can be prefabricated and constructed off-site, lowering potential transport cost and associated climate impacts compared to traditional construction materials (Ahmed et al. 2021, Abed et al. 2022 Taylor et al. 2023, Kumar et al. 2024). This prefabrication also lowers the amount of manpower needed for installation, as the panels only need to be raised and secured into place (Harte et al. 2017). Recent studies have shown that construction companies, engineers, and architects are becoming more familiar with mass timber (Vlosky et al. 2019, Ahmed & Arocho 2021, Penfield et al. 2022). With this increased familiarity many large-scale mass timber projects have already been completed and hundreds more are in the design and planning stages across the United States (WoodWorks 2024).

With agreements such as the United Nations Sustainable Development Goals or SDGs, increasing consideration for environmental implications is heavily influencing global politics and international relations (United Nations Environmental Program 2022). Human-caused climate change has seen global atmospheric CO_2 [carbon dioxide] levels rise almost 40% since the 18th century (Lindsey 2022). The production of steel and concrete is one of the primary contributors to the rise in global CO_2 levels, equating to 13.5% of all annual human emissions (Fennell et al. 2022). Mass timber shows potential in lowering CO_2 levels by acting as a substitute to high emission steel and concrete, releasing less CO_2 during manufacture, and as a source of stored carbon (Nakano et al. 2020, Tellnes et al. 2020, Chen et al. 2022, Greene et al. 2023, Kumar et al. 2024). Growing adoption of mass timber systems is likely to positively contribute to the climate change mitigation efforts in the construction industry (Tellnes et al. 2020). Traditional building components that use steel and concrete negatively impact climate through the release of CO_2, and increases in ocean acidification, city smog, waterway eutrophication, and heavy metal leachate in soils (Junnila & Horvath 2003). More recent studies suggest that mass timber products, such as CLT and glulam, have the potential to lower GHG emissions by almost up to 100% when they are used in place of traditional reinforced concrete or structural steel construction systems, especially when reuse/recycling of mass timber materials after the end of their first service lives is considered (Greene et al. 2023, Kumar et al. 2024).

In May 2022, the Biden administration announced allocating $44 million towards improving research and development of climate-smart wood products and to help establish future wood-based markets (USDA 2022). This investment signifies the current policy priority and focus placed on promotion of mass timber products. Job creation and market opportunities play a key role when considering the economic benefits of mass timber. With the decline in market for traditional forest products such as paper and pulp across the United States, many jobs have been lost. Mass timber shows potential for job creation particularly in these struggling wood product sectors (Scouse et al. 2020, Brandeis et al. 2021). A specific example is the closure of pulp and paper-based industries in Tennessee and surrounding states leading to a negative impact on rural communities by limiting the avenues for landowners to sell their stumpage (Brandeis & Guo 2016, University of Kentucky Forestry Extension 2015). This shows a need for the establishment and development of new industries that can create a market for the timber stock of these landowners and revitalize rural economies impacted by the decline of these traditional wood product markets (Poudyal et al. 2017, Adhikari et al. 2023). Potential hesitancy toward a larger mass timber industry harming traditional tradesperson jobs has been addressed by a recent study which concluded that a larger mass timber industry would instead add jobs to the market and raise household incomes in the economically impacted areas without harming traditional tradesperson jobs (Abed et al. 2022).

Most research on mass timber, thus far, has focused on engineering and life-cycle environmental impact aspects, although some sporadic studies have also investigated social, policy, and economic aspects. Much of the research in these areas has remained sporadic and discipline specific with no clear consolidation of findings or information. For instance, research into economic implications surrounding mass timber systems has grown greatly in recent years but, findings have not been synthesized into a concise format. Studies examining societal and policy implications are also limited and what has been done has not been synthesized (Scouse et al. 2020, Ahn et al. 2022, Liu et al. 2023). The need exists to integrate findings from various disciplines including engineering, environment, economic, social, and forestry sciences to better understand the current state of mass timber knowledge. Summarizing available knowledge as well as identifying future research needs is vital for promoting increased use of mass timber. Such knowledge will help better inform individuals and institutions associated with the forests and the wood products sector such as forestry professionals, researchers, forest landowners, wood products manufacturers, builders, architects, environmental groups, local and federal government agencies, and policymakers.

This study had three objectives. The first objective was to establish a review and synthesis of current research surrounding the economic, social, and policy implications of mass timber. The second objective was to identify gaps in knowledge and establish potential future research questions to advance the domestic mass timber sector. Findings from those two objectives led to our third objective, which was to assess the opportunities and barriers for utilizing small diameter timber and hardwood lumber in manufacturing mass timber products. Most of the current manufacturing of mass timber utilize higher grade softwood lumber as raw material. The potential for utilizing small diameter timber and/or hardwood lumber has been less explored.

3.3 Methodology

A non-systematic narrative review methodology was used to assemble and synthesize the current state of knowledge surrounding the social, economic, and policy aspects of mass timber. Relevant journal articles, technical reports, conference papers, news reports, and other scientific articles were gathered using various search databases. Primary search databases included Scopus, Web of Science, CABI Digital Library, and the U.S. Forest Service TreeSearch. Due to the majority of mass timber research emerging in the past decade, all relevant articles and publications were considered independent of article age. A total of fifty-four articles were examined: thirty-four economic articles, ten policy articles, and ten social articles. Thirty-six articles were from 2020 to 2024 with twenty-three articles published between 2015 and 2019 (figure 3.1). Search terms were broken up by social, economic, and policy, and each term was searched in each of the databases listed above. Common search criteria included primary terms such as "mass timber" and "cross-laminated timber" combined with secondary terms. Due to an overabundance of engineering-related results showing up exclusions were made for engineering-related criteria such as mechanical engineering, civil engineering, industrial engineering, etc. Search databases and excluded and included search terms are in the appendix (table 3.1). Scientific articles and publications were analyzed and selected based on the research team's assessment of quality and how closely the resources fit the above-mentioned social, economic, and policy categories.

Research gaps were established based on the reviews of the information presented in the collected literature. Areas or topics with few or no articles were noted and researched further. The designation of these missing or limited topics was established through the examination of existing literature to gain insight into what is lacking in research on mass timber systems. These research needs and gaps have been expounded upon in the discussion section.

3.4 Discussion

Mass timber research has made considerable progress in recent years, but many aspects and areas of knowledge are yet to be explored. These knowledge gaps are listed in the appendix (table 3.2). Specifically, questions related to economic viability, policy and regulation needs, and social acceptance aspects of mass timber are yet to be answered. Establishing and discussing these knowledge gaps will better guide future research and help to add to the continued knowledge around mass timber systems.

3.4.1 Economics

Regional Economic Impacts

Although several publications discuss the cost of mass timber use in building construction there is limited literature on how a mass timber industry would impact local and state economies. A recent study by Scouse et al. (2020) looked at the regional and economic impacts of mass timber in the state of Oregon. This study used a regional economic analysis of a potential 12-story mass timber building constructed with locally sourced wood would produce a net positive $4.8 million in economic benefit, dropped down to $1.09 million if the wood resource was not localized, compared to a traditional 12-story concrete frame building (Scouse et al. 2020). The forest-based economic markets in the U.S. have declined in recent years, leading to a need to replace lost economic potential (Brandeis & Guo 2016, University of Kentucky Forestry Extension 2015, Brandeis et al. 2021). Many hardwood states such as Tennessee have seen closures of pulp and paper mills removing these markets that local landowners relied upon to sell their timber (Brandeis & Guo 2016, Poudyal et al. 2017). Mass timber products such as CLT show the potential to alleviate some of these economic losses. Research into specifics of these market implications such as the investment needed to establish mass timber plants, and the expected regional economic impacts (i.e., multipliers of jobs, GDP, tax implications) will be vital to justify new investment for mass timber production and secure support from stakeholders in the forest products industry. This economic potential will likely dictate regional acceptance of mass timber with struggling markets more likely to adapt to novel products such as mass timber. Continued research into which regions will likely benefit most from an expanded mass timber market will help to achieve a clearer picture of the total economic potential of mass timber.

Cost and Availability

Studies have examined the direct cost of mass timber in large-scale building construction and as an individual finished product (Brandt et al. 2019, Gu et al. 2020, Ahn et al. 2022, González-Retamal et al. 2022). However, these studies have been limited in scope and lacked definitive supporting economic research to confidently state conclusions. Ahn et al. (2022) stated limited research is a negative factor in definitively establishing the economic competitiveness of mass timber when compared to traditional building materials such as steel and concrete (Ahn et al. 2022). A 2020 study in Japan found that CLT slabs utilized in bridge construction would be significantly more expensive than currently used reinforced concrete methods. Greenhouse gas emissions could be lower than reinforced concrete but only if CLT without waterproofing was used (Iwase et al. 2020). Future research into regional economic impacts, financial feasibility over time, increasing product availability and cost, and utilization of more cost-effective lumber resources will likely have varied but major impacts on the economic feasibility of future projects utilizing mass timber. Research into other applications such as in large-scale residential, commercial, and parking garages, or more research into utilization in bridge construction has the potential to create new avenues for mass timber that may be more suited to overcome the economic hurdles currently in place.

Recyclability

Recyclability and salvageability of mass timber components at the end of a building's life cycle have been discussed in several scientific publications about mass timber (Robertson et al. 2012, Vamza et al. 2021, Hassegawa et al. 2022, Greene et al. 2023). Studies specifically looking at the economic impacts of recyclability are limited (Liang et al. 2021). A study by Vamza et al. (2021) states that recycling CLT into a mycelium insulation material shows the most potential followed by wood pellet production (Vamza et al. 2021). Even though this study covered the environmental and feasibility implications of recycling CLT well, it did not get into the economic benefits. Further research into ways to recycle CLT and other mass timber components will be vital if economic circularity and environmental factors are to be positively addressed. Research into the economic benefits of recycling CLT has the potential to shift the economic feasibility. Additionally, recycled CLT could be used for new structural applications, further showing the economic feasibility of these components. If possible, this could lower the demand for new CLT components as recycled components would continue to be utilized well beyond the original structural application. New and novel ways of utilizing CLT and mass timber at the end of a building life-cycle will need to be researched to establish a clearer picture of the true lifetime cost of CLT building construction.

Small-diameter/Low-Quality timber

Low-quality softwood and hardwood lumber is not currently being utilized in structural applications. These lumbers often come from young or low value timber stands. Some studies have been conducted on the use of low-quality and small-diameter hardwood lumber for CLT construction (Crovella et al. 2019, Azambuja et al. 2022). Some studies have been done and shown that small-diameter lumber has potential both in terms of strength and production (Fredriksson et al. 2015, Wu et al. 2021). Although these studies show positive results, Azambuja et al. (2022) and Crovella et al. (2019) assessed limited species and Fredriksson et al. (2015) stated several potential barriers in implementing small-diameter lumber in mass timber components (Fredriksson et al. 2015, Crovella et al. 2019, Azambuja et al. 2022). Some companies such as Vaagen Timber have even adopted manufacturing models to make use of these low cost small-diameter lumber stocks showing a successful economic model can be achieved (Vaagen Timber 2024). A deeper investigation is needed to determine if other low-quality softwood or hardwood lumber is financially viable for use in CLT products. The U.S. Forest Service has continued to support advancements in new and novel wood products through their wood innovation grants (U.S. Forest Service 2022). Further utilizing these programs to promote and expand the knowledge surrounding small-diameter and low-quality lumber feedstock in CLT will likely be pivotal to successfully implementing these products. The use of under-utilized timber has the potential to revitalize struggling economies as well as bring down the potential cost of CLT or other mass timber products. New and novel ways of manufacturing mass timber products may be specifically developed to make use of these types of low-grade lumber.

Carbon Credit Potential

Since mass timber structures store carbon in their wood biomass while simultaneously acting as alternatives to other high GHG-intensive materials, there is a potential for carbon credit generation (Chaggaris et al. 2021, Taylor et al. 2023, Georgia Forestry Commission 2024). However, our current understanding of the effectiveness and logistics of carbon credits for mass timber use in construction is limited. Further economic analysis is needed to quantify the value of such carbon credits, demonstrate that they meet all eligibility criteria (e.g., additionality, permeance), and propose feasible market protocols (e.g., commitment, payment vehicles, beneficiaries, monitoring, and verification) and models for their trade in the market. Perhaps, existing models of trade in other commodities (e.g., biochar, agriculture soil carbon) may be evaluated for their replicability in the context of mass timber. Overall carbon credits show great potential to both promote and further highlight the economic feasibility of mass timber.

Impact on Wood Markets

Although research has shown that the current timber supply can adequately support the continued growth of mass timber manufacturing (Comnick et al. 2021, Nepal et al. 2021, Atkins et al. 2023), this does not mean that there will be no impact on wood markets. The potential for increasing mass timber manufacturing to raise demand in timber markets the has potential to raise prices and create supply scarcity. These increased prices and scarcity have the potential to negatively affect traditional wood-utilizing markets (Nepal et al. 2021). However, given the current size of the mass timber industry as well as its projected growth it is unlikely that traditional wood markets will be significantly impacted. National forest growth has exceeded harvest since the 1940's. Even under high estimates of mass timber utilizing total harvestable forest demand would only equate to 82% of national forest supply. This does not take into regionality with areas such as the Western U.S. likely more susceptible to demand exceeding forest growth. (Comnick et al. 2021). Research into these impacts will likely need to be done on a local and regional scale and replicated across a variety of different models before a clear picture of mass timbers' impact on forest resources can be understood.

Aesthetics and Perception

Positive aesthetics play a key role in how people perceive wood products through increased attractiveness as well as positive emotional, physical, and psychological well-being (Sakuragawa et al. 2005, Burnard et al. 2015, Yin et al. 2018). A review by Harju et al. (2022) states that environmental impacts, health implications, perceived naturalness, and symbolism all influence whether a consumer is willing to make an economic decision based on wood characteristics (Harju et al. 2022). However, no studies have directly examined if mass timber in particular shares the same emotional, physical, and psychologically positive attributes as the previous studies have suggested. It is possible that a structure made entirely of a mass timber such as CLT could have diminished, neutral, or expounded effects on people's willingness to adopt mass timber. It is likely that perceptions surrounding the positive aesthetic aspects of mass timber and CLT will be a large driving factor for the promotion of these products moving forward. New and novel mass timber products will likely develop with visual and exposed components being the largest draw for prospective buyers.

Incentives and Cost Share

Incentives and cost-sharing policies are another avenue for future research to consider. A policy establishing incentives similar to those discussed by Nakano et al. (2020) in Japan could be implemented in the U.S. to help promote and spur mass timber adoption. In 2014 Japan initiated a program to expand CLT production as an expansion of a previous 2010 plan to promote wood use in public buildings. This plan involved the subsidizing of CLT production facilities and has seen the expansion from 26 facilities in 2015 to 300 by 2018 (Nakano et al. 2020). These policies could be nationwide efforts or enacted by state, county, or city governments to promote adoption in specific regions. Cost share programs could influence whether a person, company, or organization would utilize mass timber in building construction. Future studies to examine the potential impacts of different levels of incentives, regionality of implementation, length of incentive programs, and mode of payment (e.g., direct payment, tax break, cost-share) could help derive a predicted future demand under different scenarios. These studies could be quantitative economic analyses or implemented under qualitative methodologies such as gathering stakeholder opinions and perceptions under differing scenarios.

Hardwood Mass Timber

Hardwood mass timber has gained attention in recent years as a potential way to address struggling hardwood lumber markets. These markets have declined in recent years with sawmill production levels at the lowest point since 1960 (Hardwood Market Report 2024). Add to this the general decline of paper, pulpwood, and paperboard and this decline becomes even more prevalent (Brandeis et al. 2021). A new product such as hardwood CLT could create a new avenue for hardwood lumber and alleviate some of the burden on these struggling industries. Hesitancy toward the use of hardwood in mass timber often forms when discussing the cost increase between hardwood and the more available softwood options. It is true that hardwood lumber is on average two to three times that of softwood lumber (Timber Update 2023). However, studies have been conducted in areas that show potential to lower this cost and make hardwood mass timber more competitive (Crovella et al. 2019, Azambuja et al. 2022, Norris et al. 2024, Hassler et al. 2024). These studies show that hardwood mass timber may show potential to be economically competitive under specific scenarios. More studies into these aspects of hardwood mass timber will be vital to establish a clearer picture of the true potential of this novel product. Although hardwood mass timber will likely not be a one product solution to these struggling hardwood markets, any increased demand for hardwood lumber can be seen as a positive.

3.4.2 Policy

New Policy Programs

In the U.S., current incentive programs directed toward mass timber have been limited with no direct mass timber-specific policies in place. Riddle (2023) suggests several measures for increasing the adoption of mass timber including expanding research grants and programs, specifying requirements for government buildings to utilize mass timber wholly or partially in new construction, and monetary incentives for utilizing mass timber in construction projects (e.g., tax incentives, access to credit), and direct federal timber harvest to support mass timber manufacturing facilities lumber requirements. Expansion of current programs to incorporate more mass timber would likely be the simplest solution as several programs in the Wood Innovation Grant Program have already supported mass timber projects (Riddle 2023). Requirements for new construction to utilize mass timber either partially or wholly have been successful in other countries such as Japan (Nakano et al. 2020). Monetary incentives (e.g., tax incentives, access to credit) have been successful in other similar industries and may show positive results if applied to the mass timber industry. California's Buy Clean California Act in 2017 and the U.S. Department of Agriculture's Partnership for Climate-Smart Commodities Program are examples of U.S.-based policies pushing for cleaner manufacturing and material use (Taylor et al. 2023). The potential for mass timber manufacturers to utilize federal timber stock could address some of the cost and lumber availability concerns surrounding current mass timber systems. Research into the viability and potential of these measures would better inform policymakers when considering options for increasing mass timber adoption.

Synthesis of non-U.S. Policy

The United States and other countries interested in promoting the mass timber industry should assess the feasibility of some of the successfully implanted mass timber policy incentives elsewhere (e.g., Japan) (Nakano et al. 2020). It is not guaranteed that success will translate to other countries, but future research could examine the factors that contributed to the success and adapt similar or reasonably modified models that fit the local conditions. Although this paper examines and discusses research in other countries its primary focus is on policy implications in the United States. Regulations and construction standards such as the U.S.-specific IBC guidelines have been discussed. Testing for mass timber component properties must take place in the U.S. to be considered as evidence for updating the IBC guidelines (Stegner & Fotheringham 2022). Although non-U.S. studies may not be directly applicable to the specific manufacturing and construction parameters in the U.S., the synthesis of quality scientific testing in other countries can better shape and direct U.S.-based efforts.

3.4.3 Social

Public Attitudes and Preferences

How the public and potential consumers of mass timber products view mass timber is largely unknown. Support for public policies and demand for and adoption of mass timber products will largely depend on public attitudes towards the product and its availability. Limited social research thus far (Larasatie et al. 2018, Montague et al. 2021) has not considered consumer willingness to pay for mass timber products. These types of studies are vital when evaluating wood products and a consumer's likelihood and willingness to adopt new or novel wood product solutions. Environmentally certified timber products are similar to mass timber concerning the environmental considerations and potential for consumers to value the eco-friendly aspects. A recent study found that consumers are willing to pay a premium price for environmentally certified timber products due to the environmentally conscious management behind them (Poratelli et al. 2023). A study looking at consumers' willingness to pay for modern wood buildings in China and Japan showed differences between the two markets and helped to establish a lack of consumer knowledge as a factor impacting willingness to pay for modern wood buildings (Luo et al. 2018). Establishing willingness to pay for mass timber products from architects and engineers as well as building owners or project funding agencies will be vital if the adoption of mass timber systems is to increase. Future research needs to be done to fill this knowledge gap as well as gain further perspective on consumers' willingness to adopt mass timber systems and products.

Environmental Opinion

Environmental concerns and considerations have been shown to impact the perception of and support from the public on the use of mass timber systems and products (Larasatie et al. 2018, Montague et al. 2021, Debnath et al. 2022). This public concern aligns well with the current scientific literature on mass timber, particularly when examining environmental impacts. Improved sustainability and environmental benefits over traditional construction materials such as steel are some of the driving factors behind the scientific communities' positive stances toward the increased adoption of mass timber products (Abed et al. 2022). This support will be vital particularly when considering the establishment of governmental policies that have the potential to subsidize and promote the use of mass timber products. Further research is needed on the connection between the current public and consumer perception of the environmental aspects of mass timber and how these aspects will impact willingness to pay and willingness to adapt.

Exposed Wood

The current research on the psychological and physiological benefits of wood exposure in the built environment has been stated in a substantial amount of scientific literature (Sakuragawa et al. 2005, Nyrud & Bringslimark 2010, Burnard et al. 2015, Strobel et al. 2017, Jo et al. 2019). However, none of these publications examined the direct psychological and physiological impacts of mass timber products on experiment participants. As such, only indirect conclusions can be made on the potential positive end-user experience-based benefits of mass timber products. This creates a need for research on the direct psychological and physiological impacts of mass timber use in large-scale building construction. It is likely exposed wood will become a major selling point for mass timber moving forward. However, it is difficult to state certainties when no studies have been done on these psychological and physiological aspects of mass timber.

3.5 Conclusion

Most mass timber products are still a novel wood product system and many questions about its economic, policy, and social aspects are yet to be answered. Discipline-specific research thus far has resulted in sporadic and isolated knowledge lacking coalescence between disciplines. This study synthesized the current knowledge and research surrounding the economic, policy, and social aspects of mass timber. Informed by this rigorous review, it also established the need for several potential directions for future research, which will benefit researchers, policymakers, and stakeholders in the wood products industry interested in promoting mass timber adoption.

Mass timber systems show promise both as a financially sensible product and with added potential for future incentives such as carbon credits to further incentivize adoption. Governmental assistance and incentive programs (e.g., innovation grants, tax incentives, research grants) have seen positive results for other wood product industries but limited programs have been directly applied to mass timber. The social aspects surrounding mass timber show that stakeholders are becoming more aware of mass timber as well as supporting the continued expansion and utilization of mass timber in projects and designs. Policy, regulation, and guidelines in the U.S. have expanded greatly in the past decade and continued efforts are still underway to develop new policies toward expanding mass timber adoption. Because mass timber building systems are still relatively novel, it will take continued development over many years before they can reach a point of mainstream acceptance and adoption.

Research into the economic aspects surrounding mass timber has been the most explored to date, with policy and social aspects fairly limited in the current literature. However, economic research gaps are still extensive and include regional availability and cost, recyclability and end-of-life solutions, utilization of low-grade or low-cost lumber, and carbon credit potential. Policy research gaps include expanding current cost-share and incentive programs, development of new policy programs and their impacts, and synthesis of non-US-based policy programs as a means to inform U.S.-based policy formation efforts. Social gaps include research into current public opinion on mass timber, public perception of environmental and sustainability considerations, and specific research on the physiological and psychological impacts of different mass timber systems. Mass timber shows great potential, but the growth of this industry will likely be slow given the competitive hurdles when compared to long-supported traditional building materials.

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Appendix

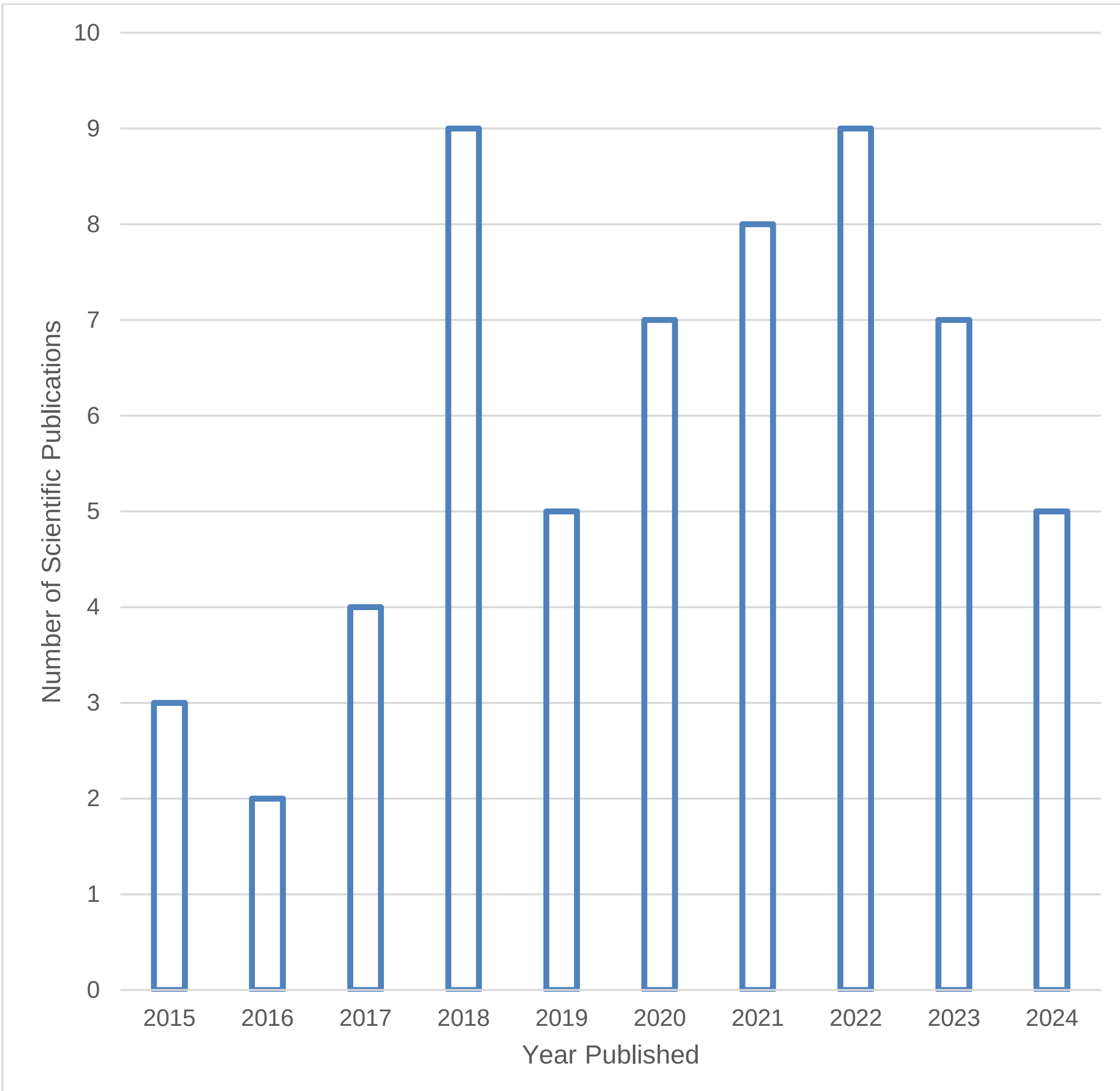

Figure 3.1 Frequency of publications by year on social, economic and policy aspects of mass timber and mass timber systems research. Publications were gathered from Scopus, Web of Science, CABI Digital Library, and the U.S. Forest Service TreeSearch.

Table 3.1 Databases and terms used during the literature review process.

Search Database	Excluded Terms	Included Terms
Web of Science	"Engineering Civil", "Engineering Mechanical", "Engineering Geological", "Engineering Multidisciplinary", Engineering", "Electrical", "Electronic", "Engineering Industrial", "Engineering Manufacturing", "Metallurgy", "Metallurgical", "Engineering"	"econom*", "job creation", "investment cost", "production cost", "supply", "building cost", "market demand", "production standard", "building code", "market assurance", "subsid*", "grant", "acceptance", "mental well-being", "physical well-being", "aesthetic", "safety", "eco-friendly", "perception"
Scopus	"Engineering", "Chemical Engineering"	
CABI Digital Library	None	
Forest Service Tree Search	None	

Table 3.2 Summary of knowledge gaps for economic, policy, and social aspects of mass timber.

Knowledge area	General findings	References
Economic		
Regional Economic Impact	There has been a decline in forest-based markets in the U.S. However, research into the direct economic impacts of mass timber has been limited, showing potential for research into new ways to support and revitalize declining markets.	Brandeis & Guo 2016, University of Kentucky Forestry Extension 2015, Poudyal et al. 2017, Scouse et al. 2020, Brandeis et al. 2021
Cost and Availability	Current literature lacks definitive answers on mass timber cost and availability, likely due to regional complexities in resources and infrastructure. Studies have stated this uncertainty as a primary factor in the inability to establish mass timbers' economic competitiveness.	Brandt et al. 2019, Iwase et al. 2020, Gu et al. 2020, Ahn et al. 2022, González-Retamal et al. 2022
Recyclability	Most studies into the recyclability of mass timber are newer and continued efforts into novel end-of-life uses need to be pursued.	Robertson et al. 2012, Liang et al. 2021, Vamza et al. 2021, Hassegawa et al. 2022, Greene et al. 2023
Small-Diameter/Low-Quality Timber	Two studies have shown positive results when looking into small-diameter timber use in CLT. Utilization of small-diameter lumber could aid declining industries, but more research is needed to support the current findings and research new timber species viability.	Fredriksson et al. 2015, Crovella et al. 2019, Azambuja et al. 2022, U.S. Forest Service 2022, Vaagen Timber 2024

Table 3.2 Continued

Carbon Credit Potential	Carbon credits for mass timber show the potential to shift the economic feasibility of large-scale mass timber use and increase stored carbon. However, carbon credits for mass timber is a new concept that will require further research into the benefits, drawbacks, and consequences if implemented.	Chaggaris et al. 2021, Taylor et al. 2023, Georgia Forestry Commission 2024
Impact on Wood Markets	The current research is confident that current timber markets can supply a mass timber industry. However, research into the specifics of supply and demand and impacts on product prices has been limited.	Comnick et al. 2021, Nepal et al. 2021, Atkins et al. 2023
Aesthetics and Perceptions	The positive impact of wood aesthetics and human perception in literature is well supported. However, no studies have directly examined if mass timber shows the same positive impacts as other wood products.	Sakuragawa et al. 2005, Burnard et al. 2015, Yin et al. 2018, Harju et al. 2022
Incentives and Cost Share	Incentives and cost-share programs, such as the successful ones implemented in Japan, show the potential to support U.S. industries in an emerging mass timber market. Studies into the economic impacts of these programs will be vital to establish if U.S. markets will benefit from new or expanded mass timber incentive programs.	Nakano et al. 2020, Riddle 2023

Table 3.2 Continued

Hardwood Mass Timber	Hardwood mass timber is a novel product gaining traction in the wood products field. Uses of low-quality and small-diameter feedstock may increase the economic viability of these products. There is potential for these products to alleviate some of the economic struggles felt by declining hardwood markets.	Crovella et al. 2019, Brandeis et al. 2021, Azambuja et al. 2022, Norris et al. 2024, Hassler et al. 2024
Policy		
New Policy Programs	The research into mass timber policy formation and implementation has been limited. The few U.S. policy programs that are in place have likely not been sufficiently utilized. New research into expanding current programs and creating new policies will be vital to support an expanding mass timber sector.	Nakano et al. 2020, Riddle 2023, Taylor et al. 2023
Synthesis of non-U.S. Policy	Testing to establish U.S. construction standards and regulations must take place in the U.S. However, further research and examination of programs, such as those in Japan, could bring insight and help guide U.S.-based policy efforts.	Nakano et al. 2020, Stegner & Fotheringham 2022

Table 3.2 Continued

Social		
Public Attitudes and Preferences	Research into what the public thinks of mass timber products such as CLT has been limited. Research has shown that the public is generally unaware of mass timber. Further research into current perception and education and outreach programs will be vital to gain a clearer picture of the social acceptance and public attitude toward mass timber.	Larasatie et al. 2018, Luo et al. 2018, Montague et al. 2021, Poratelli et al. 2023,
Environmental Opinion	Positive environmental impacts of a product are often a leading driver toward public support. What studies have been done show positive public opinions toward mass timber. Further studies and research will need to be done as the mass timber industry grows to establish current public perceptions and opinions.	Larasatie et al. 2018, Montague et al. 2021, Abed et al. 2022, Debnath et al. 2022,
Exposed Wood	The benefits of exposed wood are heavily supported in the literature. However, no studies have been done directly examining the impacts of exposed mass timber on study participants. Further studies will be needed to establish the psychological and physiological impacts of exposed mass timber on building inhabitants.	Sakuragawa et al. 2005, Nyrud & Bringslimark 2010, Burnard et al. 2015, Strobel et al. 2017, Jo et al. 2019

CHAPTER 4
ASSESSING THE VIABILITY OF CROSS-LAMINATED TIMBER SOURCED FROM HARDWOOD LUMBER: A KEY INFORMANT APPROACH

This article was written and revised by the primary author Alexander Bremner and his primary advisor Neelam C. Poudyal in collaboration with Prakash Nepal, Consuelo Brandeis, and Adam Taylor. All researchers provided vital feedback and guidance during the writing of this manuscript.

4.1 Abstract

With the expanding market for mass timber products, there is growing interest in understanding the technological, economic, social and environmental viability of mass timber products such as cross-laminated timber (CLT) manufactured from hardwood lumber. The most commonly used lumber in CLT construction in the United States has come from softwood species but the emerging evidence have shown potential to utilize hardwood species as well. Many states across the Southeastern United States possess a vast amount of hardwood lumber which has lost considerable share of its market in recent years. Traditional industries (e.g., pulp and paper) that historically relied on hardwood tree resources have recently declined or ceased to exist, and have impacted rural communities, thereby creating a need for new industries to utilize the hardwood resources and revitalize rural economy. For the hardwood CLT industry to succeed, key information on barriers and opportunities will be vital. This study uses key informant interviews of 21 wood industry professionals as well as related studies and scientific literature to shed light on the opportunities and barriers related to vitality of hardwood CLT production. The findings of this study show promise for hardwood CLT in the areas of mechanical effectiveness, lumber supply, and aesthetic appeal. Potential barriers for hardwood CLT include limited awareness, higher cost, liability, decay, longevity as well as lack of established lumber grading, technical skills, and supporting infrastructure. These barriers will need to be addressed and overcome if widespread adoption of hardwood CLT is to occur.

4.2 Introduction

Mass timber products are gaining traction as a potential way for the construction sector to utilize sustainable materials. Currently, the most commonly used construction materials are steel and concrete, both of which produce extensive amounts of greenhouse gas (GHG) emissions (Junnila & Horvath 2003, Brashaw & Bergman 2021, Abed et al. 2022, Kumar et al. 2024). Wood is an inherently sustainable product and if managed, harvested, transported, and utilized in environmentally conscious ways, can mitigate much of the GHG emissions in construction (Brashaw & Bergman 2021, Yadav & Kumar 2021, Abed et al. 2022, Kumar et al. 2024).

Currently, the number of mass timber projects in the U.S. is small, compared to traditional construction, but is growing. WoodWorks, a leading non-profit in the wood product and mass timber sector, states that 2,205 mass timber projects have been completed as of June 2024 (WoodWorks 2024). Typically, harvested logs processed by sawmills are then used to construct a variety of mass timber products including cross-laminated timber (CLT), dowel-laminated timber (DLT), nail laminated timber (NLT, glue laminated timber (GLT or glulam), and mass plywood panels (MPP) (Cai, et al. 2021, Comnick et al. 2021, Anderson et al. 2024). Of these products, CLT is one of the oldest and most widely used mass timber products (Walch & Watts 1923, Harpole et al. 1979, Bergman et al. 2010, Parajuli & Laleicke 2018), and therefore is the focus of this study. CLT consists of 3 to 5 layers of lumber that are placed with the wood grain perpendicular to the layer above and below and secured with a wood glue adhesive. These layers can be shaped to form columns, floors, ceilings, or beams and are used in mid to high-rise building construction (Abdoli et al. 2022).

Thus far, softwood lumber has been primarily used in CLT manufacturing because of its structural properties appropriate for construction purpose, price competitiveness, and abundant supply (Adhikari et al. 2020). Consideration into hardwood lumber utilization in CLT panel construction has recently gained traction in novel wood products research. This is likely due to the abundance of hardwood lumber in many regions of the Eastern U.S. as well as the potential for utilizing and supporting underutilized and struggling hardwood markets (Brandeis et al. 2021). Hardwood CLT may serve as a new product to make use of this underutilized hardwood lumber resource.

In the U.S. the ANSI/APA PRG 320 is the standard construction guideline for mass timber components such as CLT. The PRG 320 specifies the tests a CLT component must pass relating to performance to be used in building construction (APA 2020). It is under these guidelines that the current softwood species (e.g., pine, spruce, Douglas fir) that are commonly used in CLT have been certified. Currently, the only hardwood species that is being considered for approval under the PRG 320 is yellow poplar. As of the completion of this project yellow poplar has been accepted under the PRG 320 guidelines and can now be used for use in CLT panel construction according to a key informant involved in the process. As yellow poplar CLT becomes available there will likely be more interest in testing for other commercially available hardwood species to be added to the PRG 320. Nonetheless, it is reasonable to note that hardwood is yet to become a significant source of lumber used in CLT panel construction.

Research on wood science continue to examine the mechanical effectiveness of hardwood CLT and shown some promises (Aicher et al. 2016, Espinoza & Buehlmann 2018, Adhikari et al. 2020, Palacio-Betancur et al. 2023) but the limited studies are not conclusive, and more research and testing will be needed moving forward. From societal perspective, the promise of hardwood CLT bears a tremendous potential to revitalize struggling rural economy in many regions of the United States. This is because hardwood markets in the U.S. have been declining since the 1990's due to a decrease in demand for traditional forest products such as paper, pulpwood, and paperboard manufacturing (Ince and Nepal 2012, Brandeis et al. 2021). Additionally, there has been a decline in U.S. hardwood sawmill production, which is at the lowest point since 1960 at 5.54 billion board feet (Hardwood Market Report 2024). These factors show a need for new hardwood markets and products to revitalize this sector and bring hardwood production and manufacturing back to previous levels. While the emerging research in hardwood CLT shows promising results on its structural and other suitability, the technological and economic feasibility of producing hardwood CLT and sustaining this industry is currently unknown. While a few recent studies have assessed the perspectives of CLT manufacturers and other stakeholders (Vlosky et al. 2019, Adhikari, et al. 2020, Schenk et al. 2022), focus of these studies have been limited to softwood CLT. This leaves a gap in our understanding and knowledge around hardwood CLT production and their adoption in construction. To address this gap in knowledge, this study adopted a qualitative social science inquiry method and examined the technological economic, social and environmental viability of hardwood CLT production. In particular, the study conducted in-depth interview of 21 key informants from the wood industry to identify the potential opportunities and barriers in promoting hardwood CLT in the United States.

4.3 Methodology

4.3.1 Key Informants Interviews

Given the novelty of the subject and limited familiarity of the mass timber products within the wood industry, a qualitative research method called key informant interview (KII) was adopted for this study. A KII is an in-depth qualitative interview methodology that gathers perspectives from knowledgeable stakeholders, industry professionals, researchers, community leaders, or any other person or persons that have insight into a research topic. This method typically makes use of fewer interview participants when compared to other social science methods (e.g., survey) relying instead on gathering in depth and quality information. This method is commonly used in policy analysis or aiding other industry decision-making (Crabtree et al. 1999) and has been used in previous studies to gain perspectives of stakeholders in the forestry sector (Elmendorf & Luloff 2006, Twongyirwe et al. 2018, Maraseni et al. 2022).

Key informants were identified for this study representing three groups in the wood industry: sawmill and lumber yard owners, engineers and architects, and wood scientists. Sawmill and lumber yard owners were selected for potential feasibility aspects of production and supply implications. Sawmill and lumber yards were chosen in collaboration with the National Hardwood Lumber Association with participation and involvement in previous novel wood product research as a primary selection criterion. Engineers and architects can offer insights on feasibility for construction and potential barriers to policies, local ordinance governing development or building codes. Engineers and architects were selected based on previous CLT project experience or involvement in research around novel wood use in construction. Wood scientists were selected to gain a scientific perspective and insight into the technical feasibility of manufacturing hardwood CLT, potential markets and economic impacts. Wood scientists all had previous experience in either softwood mass timber and CLT or hardwood CLT specifically. The aim of this study was to interview six to eight informants per group. The number of interviews was chosen with the goal of achieving information saturation. This number can vary depending on the type of study and data being collected. However, it is typically recommended that 15-35 interviews be conducted in a thorough KII (Crabtree et al. 1999). Saturation is defined in a qualitative survey methodology as the point at which further interviews are not providing any new or relevant perspectives or information (Saunders et al. 2018). The final number of informants after conducting the interviews was 21 (6 sawmill/lumber yard owners, 7 engineers and architects, and 7 wood scientists.

Interviews were conducted over four months between May 2023 and August 2023. Informed consent was gathered from participants and interviews were conducted over zoom or by phone, depending upon the preference of the respondents. Recorded interview audio files were transcribed for analysis purposes. The interviews ranged from 45 minutes to one hour and consisted of 10 questions.

4.3.2 Key Informants Checklist

The KII Checklist consisted of nine main interview questions with the final question left open-ended for comments or concerns. A SWOB (strengths, weaknesses, opportunities, and barriers) framework was followed to develop the checklist. This framework considered both positive and negative aspects of hardwood CLT viability to better guide question generation. The list of key informant interview questions used for the interviews is listed in (Table 4.1). The checklist and interview protocols were reviewed and approved by the University of Tennessee Institutional Review Board for human subject research (UTK IRB-22-07110-XM). The KII checklist was used as a guideline and template for consistency across key informant interviews. However, interviews were not held to a rigid interview structure to allow key informants to voluntarily offer additional information according to their expertise and interest. This was done in an attempt to enrich the conversation and lead to topics and aspects that may have been overlooked by the research team. An example is that several key informants discussed liability and insurance concerns, something that was not included in the list of questions for the KII.

4.3.3 Data Analysis

Interviews were transcribed, assigned unique identifiers, and transferred into Dedoose, program (Dedoose 2024). The program allows coding and analysis of data in qualitative studies. Transcripts were organized into three respondent groups: wood scientists (WS), sawmill/lumber yard owners (SL), and engineer/architect (EA). Each interview was given a numerical identifier (e.g., WS1, SL2, EA6) to distinguish quotes and excerpts further on in the analysis process. Answers were coded based on subject (e.g., lumber supply, aesthetic potential, supporting infrastructure) and further coded as positive, neutral, or negative in respect to positionality on the given subject. Answer positionality was used for organization and to ensure differing stances on each given subject were properly represented. A code co-occurrence analysis (Table 4.2) was used to establish connections between KII answers. This was to show potential connections between given subjects and participant stances. Patterns, similarities, and comparisons between key informant groups are discussed but no further qualitative analysis methodologies, other than the co-occurrence analysis, were performed.

4.4 Results

4.4.1 Key Informant Characteristics

Sawmill and lumber yard owners were primarily from Tennessee with one key informant from Pennsylvania. The National Hardwood Lumber Association's (NHLA) lumber & products members directory was used in connection with contacts at the NHLA to choose sawmills/lumber yards to contact for interview (NHLA 2023). Criteria for chosen sawmills/lumber yards included size and operational capacity, familiarity with mass timber and CLT, and participation as suppliers in previous mass timber or CLT research projects. Most sawmill and lumber yard owners had previous knowledge of mass timber or CLT with several participating in supplying hardwood for CLT research projects. Engineers and architects were located across the U.S. with emphasis on varied expertise, field of work, and affiliations (e.g., academic vs corporate). Familiarity, knowledge, or prior work using CLT was a requirement, and these informants possessed a high degree of knowledge in the area of mass timber or CLT. Wood scientists were similar to the engineers and architects with key informants located across the U.S. and possessing varied expertise, field of work, and affiliations (e.g., academic vs corporate). Familiarity, knowledge, or prior work with mass timber systems or CLT was similarly required for wood scientists as with the engineers and architects to qualify as KII participant for this study.

4.4.2 Code Co-occurrences

Examining key informant co-occurring excerpts on each given topic shows insight into potentially connected topics. These interview analysis codes by number of co-occurring responses for each interview (Table 3.2). Six code co-occurrences were the highest between all key informants. Positive economic impact x positive environmental impact and positive hybrid potential x positive aesthetic impact were the codes that occurred the most often together. For example, this means that positive economic impact and positive environmental impact were shown in six overlapping codes during the analysis. When asked about the economic impact of hardwood CLT a wood scientist connected economic potential to forest and environmental health. They shared their views on how a positive economic impact from hardwood CLT may lead to better management of natural hardwood forest resources and in turn a positive environmental impact.

> *WS3: I think it would have a positive impact… You say a tree does not last forever... Our forest health needs to be constantly being rejuvenated… we need to continually work in our forest to ensure their health. Hardwoods in particular are much more sustainably managed forests because we don't clear cut.*

Another co-occurring pair was positive hybrid potential and positive aesthetic impact. A wood scientist discussed how hardwood could be used as a veneer to improve the aesthetics of a hybrid CLT panel with a pine core.

WS2: There could be a approach where the structure comes from the SYP (southern yellow-pine)… If that ends up being something that can convert CLT into a more palatable aesthetic approach for a wider audience… Then maybe we have a shot at saying that these (hardwood veneer) additional layers are valuable because of that aesthetic approach.

These code co-occurrences can shed light on what aspects of hardwood CLT key informants felt were interconnected. These interconnected aspects may share the same or similar solutions and show potential that addressing one barrier may solve or mitigate another.

4.4.3 Key Informant Interview Discussions

Current Knowledge and Interest

Each key informant was asked their opinion on the current interest and conversation surrounding hardwood CLT. This question was designed to gain insight into how many people in the wood products and construction industry are discussing hardwood CLT. A common sentiment shared by key informants was that industry professionals or the public lacked knowledge and interest in hardwood CLT. One key informant described hardwood CLT as a niche product both currently and in terms of hardwood CLT as a future product.

EA3: Hardwood CLT is almost always talked about as a very niche product. Good in certain cases for its aesthetics, structural performance, thinness tied to structural performance… there's some happening, but it's still really niche.

A wood scientist talked about the lack of public knowledge on mass timber in general and how this might impact climate change mitigation efforts.

WS1: the general public is very disconnected. They do not even know this is a product... And they probably don't even know about mass timber in general. Which is tragic because it has such huge potential for carbon storage.

Another wood scientist discussed how low knowledge and interest will likely be a barrier for yellow-poplar CLT specifically.

WS4: The biggest will be the architects or specifiers being aware of using yellow poplar for CLT panels. And then the mills… that will be another barrier. But if they see a business opportunity, if they are struggling, certainly they're going to try.

Mechanical Effectiveness

Hardwood CLT is still in the starting stages when compared to already used softwood CLT products. This led to many key informants discussing potential novel use cases and aspects where hardwood CLT may gain market acceptance. One of these areas is looking at the mechanical effectiveness of hardwood CLT. An engineer/architect discussed how hardwood CLT shows potential for use in longer spans compared to softwood CLT.

EA3: For commercial use of hardwood CLT the structural properties are important as you can achieve longer spans for the same thickness. It's stronger and that's really important in cities... The greater we can span with the less thickness the better hardwood CLT is than softwood CLT.

When comparing the anatomical differences between hardwoods and softwoods one wood scientist emphasized that the additional strength properties of these species may show benefits when used in CLT panels.

EA1: Hardwoods have an advantage because of their unique anatomy and structure... You can make thinner laminates with yellow poplar and get the same strength (compared to softwood). That's probably due to the fact that yellow poplar has a lower microfibril angle. The microfibril angle of young pine is around 40-45 degrees, and so that it drops the stiffness considerably. While yellow poplar has a high stiffness and low density.

A wood scientist who had previously been involved with testing hardwood component strength properties for construction applications stated that hardwoods could be up to three times stronger than pine in CLT.

WS1: Our results for the three hardwood species in compression, all three of those species were three times stronger than southern yellow pine… And when you look at the stiffness of the panel going from a three-ply panel to a five-ply panel, it's like three-hundred percent stronger… the hardwoods are just exponentially stronger than the pine is.

Positive mechanical potential was not only discussed by architects, engineers, and wood scientists but also by sawmill owners. For example, one sawmill owner discussed the versatility of yellow poplar as follows:

> *SL4: I've got a friend that used it (yellow pine) for construction beams... Poplar is a very versatile, good wood that I know will stand up against southern yellow pine.*

Not all of the statements from key informants were positive with several informants stating some concerns surrounding mechanical effectiveness of hardwood CLT. An engineer/architect discussed how hardwoods stiffness and rigidity have potential to cause structural issues during seismic events, something softwood CLT had to overcome.

> *EA6: Hardwood lumber would perform more rigid than a softwood lumber, meaning if there's an earthquake, you don't want to have a brittle break. Softwood CLT had to overcome that because a CLT panel is very rigid.*

None of the key informants had directly negative opinions surrounding the mechanical effectiveness of hardwood CLT. Several key informants, such as the above engineer/architect, had concerns and questions but none were especially negative.

Cost Considerations

Concerns around the final cost of a hardwood CLT panel compared to other mass timber products were pointed out by several key informants. A sawmill/lumber yard owner discussed how low-grade lumber may create competitiveness for hardwoods.

> *SL2: Softwood is always cheaper… I see hardwood CLT being a player when you're talking about visible wood… You're going to have to figure out a way to use low grade hardwood… Your low-grade yellow poplar products are more in line (price wise) with the pine product than oak… prices even for those lower grade poplar products are still double.*

An engineer/architect discussed this price difference between hardwood and softwood CLT and brought up potential positive value adding aspects in the form of sustainability. These aspects could come in the form of carbon storage and subsequent carbon credits as well as any other potential mechanical differences between hardwood and softwood CLT.

> *EA6: Hardwood lumber is more costly than softwood… the bottom line on why a developer or owner will go with hardwood mass timber is they have tangibles about*

sustainability and speed of construction... If the lumber for hardwood is more expensive than softwood, they're going to go with the softwood unless there's some other benefit.

The potential for hardwood to mechanically outcompete softwood in a CLT panel was discussed by several key informants. This could bring costs down by requiring less material to achieve the same structural capabilities when compared to softwood CLT.

WS4: You can achieve the same mechanical properties with less volume. So that's another appealing factor of using hardwoods compared to softwoods. You can technically say that you will compensate because it costs more, but you are using less material.

Hybrid Potential

Utilizing both hardwood and softwood in a single CLT panel was another topic that was not directly asked in the KII checklist but was brought up by many key informants. A sawmill/lumber yard owner brought up the potential of utilizing higher appearance grade hardwoods, such as oak, as a veneer to increase the aesthetic appeal of a hybrid CLT panel.

SL5: You could have a combination of the two where you have a pine core, or a poplar core, but a red oak or white oak face… so that you could use it as a structural component that's actually exposed… the oaks would lend themselves better appearance wise.

There has been some discussion surrounding the appearance of softwood CLT. Generally, softwood CLT is not being marketed as an exposed product and appearance has not played a large role in its promotion. A wood scientist discussed some of these aspects and how a hardwood veneer could be a solution to promoting the visual aspects of softwood CLT.

WS3: Consumers are going to want a higher value appearance, which is what hardwood CLT would offer. But that could possibly be offered in a softwood CLT with a hardwood CLT veneer on it… CLT appearance will continue to be an issue where people want a better appearance.

An engineer/architect that had done some work with hardwood CLT discussed some of the challenges they saw when researching previous projects that had utilized hybrid CLT panel construction.

EA3: (referring to the Columbus project) Not all of them were hybrid, but some of them were hybrid and they performed very poorly. The pavilion had to be taken down well before it was due to be taken down because of delamination problems. But that was a really early-stage experiment into hybrid CLT.

The same engineer/architect then went on to discuss the positive aspects while working with hardwood CLT such as its structural effectiveness.

EA3: What our team discovered in many different types of hardwood/softwood layups was that they performed very well structurally. It was about the process, the glues used, and the science of it which wasn't done properly in the Columbus project.

Economic Impact

Key informants were positive when considering the potential economic and development opportunities in establishing a hardwood CLT manufacturing facility. An engineer/architect was very optimistic when discussing the potential of a hardwood CLT facility to benefit rural economies. These facilities would add manufacturing jobs and create a new avenue for landowners to sell hardwood timber.

EA3: We can utilize rural facilities that may have been abandoned or underused to house new equipment and train a new workforce to generate a new economic base... It's something of high value that rural economies in particular can market.

The current economic investment going toward hardwood CLT plants in North America is far behind that of Europe. When asked about the potential economic impact of a new hardwood CLT facility an engineer/architect was very optimistic.

EA7: It's huge. I'm already witnessing big interest in the one facility that's being developed right now… It's right in the middle of the Appalachians... It's a prime location for servicing a lot of the big markets… There's nowhere near as many CLT plants in North America as there are in Europe... We still have a long way to go to catch up to Europe.

There is a value in a local wood utilizing industry to lower potential shipping and logistic costs for sawmills and lumber yards. A sawmill/lumber yard owner discussed the positives of a local hardwood CLT facility both for their community and as a local customer for their products.

SL3: I think it would be good. Lots of our communities are pretty distressed. It could add to, improve, and give some jobs in the community and help things out there. We're always looking for another supplier for our product… we'd rather ship it locally and make a product domestically.

Timber Supply

Timber supply is an important aspect of any industry that relies on wood as its primary component. A sawmill/lumber yard owner discussed their perspective on how the lumber supplying industry keeping up with demand shouldn't be a concern. Instead, they were worried about the feasibility of a manufacturing facility to get up and running.

SL1: I would line up to sell my poplar domestically right now. There shouldn't be any concern from CLT manufacturers about getting supply… But I think the concern should be placed more on how fast you can build a plan, how fast you can get up and going. That's a bigger hurdle.

An engineer/architect discussed how we are growing a large amount of hardwood lumber without a market or avenue for that wood resource.

EA1: In Virginia I see a huge amount of hardwoods that are being grown, and nobody's utilizing them. Because there's not a market for them.

The decline of hardwood lumber utilizing industries and how this creates lumber resource availability was discussed by a wood scientist.

WS6: There's definitely a resource available for hardwoods… What's happening with hardwoods, particularly in the US, is that there's less being used. So, there's more availability of hardwoods for other purposes.

Another sawmill/lumber yard owner was less optimistic about whether hardwood suppliers can keep up with demand for hardwood CLT. Hardwood is managed differently than pine, bringing questions of long-term lumber supply into question.

SL2: We don't produce as much hardwood as we produce pine… We produce 18 million board feet a year. They (softwood producers) could be producing that weekly. The forest management of our pine is a crop… where hardwoods are the forestry model.

An engineer/architect who is involved in producing softwood CLT took a less optimistic view of hardwood lumber supply. They brought into question the logistical and feasibility aspects of supplying a hardwood CLT manufacturing facility of the same size as currently producing softwood CLT facilities.

> *EA2: We (softwood CLT producer) use about 4 to 5 trucks a day... Would that be available in hardwoods? I just don't think the infrastructure exists in the industry (hardwood producers). I'm telling you that everybody's (softwood producers) got 200 million, 300 million board foot a year capacity. Multiple continuous drying and they run 24 hours day, 5 days a week. I don't think it's out there on that scale at all with the hardwoods.*

Liability and Insurance

The question of liability and insurance was not a specific question asked during the key informant interview process. However, it came up several times in multiple interviews, often linked with discussions around economic feasibility and supporting infrastructure. A sawmill/lumber yard owner discussed their concerns around the liability of supplying structural grade hardwood for use in CLT panel construction.

> *SL2: We do not carry any type of builder's risk or any type of product liability insurance currently… building failure, what type of liability does that create for us.... Who would be liable if that CLT failed?*

A wood scientist also brought up insurance and liability and discussed the difficulties a hardwood CLT industry may face due to high insurance costs.

> *WS5: Another issue is insurance. The insurance companies are charging outrageous amounts for construction insurance on a mass timber building… So, I'm not negative, it's still really early.*

Lumber Grading

Addressing concerns surrounding lumber grading of hardwood for structural applications will be an important hurdle for the industry to overcome. An engineer/architect discussed the lack of graders who are trained to structurally grade hardwood lumber and how this is a likely hurdle moving forward.

> *EA1: Softwood lumber graders grade for strength, while hardwood lumber graders grade for visual grade… there aren't any graders out there that can actually grade (hardwood). If you did have it in the code your next hurdle would be having people that could actually*

separate it and grade it… there would have to be some training from extension and workshops… I could see that being a hidden hurdle.

Key informants discussed the challenge for hardwood lumber suppliers to adjust their grading practice to new structural grading standards. This would require new investment in technology in order to supply yellow poplar to hardwood CLT manufacturing facilities.

WS4: They'll have to make some investments in technology. And they'll have to make huge investments in grading because the grading is different, but it can be done. I think once that is approved (yellow poplar into the PRG 320 guidelines), whoever gets into that market, I think it's going to be very successful.

A respondent with expertise in wood science argued that the specifics required for facilities to adjust to supply a hardwood CLT market, technical skills in particular, is a significant barrier.

WS1: A lot of these facilities do not have personnel or equipment that can actually scan or visually grade that lumber to a structural standard. So, there are barriers there, one in technology and equipment and then human personnel.

Supporting Infrastructure

Supporting infrastructure will be vital if a hardwood CLT industry or facility is to succeed. This aspect was discussed at length by many of the key informants and answers ranged from optimistic to pessimistic. One engineer/architect discussed the small size of hardwood sawmills and how this might bring into question the ability of a facility to get certified under the ANSI/APA PRG 320 standards.

EA7: If you're going to buy hardwoods for your CLT factory you might be dealing with many small mills as opposed to larger ones. That will be a topic of certification because when the APA certifies a mill like a CLT factory that's a question they ask is what your resource is and how consistent will the material be coming from that resource. So…that would be a question, not a concern.

A wood scientist respondent, based on their conversion with sawmill owners, brought up the hesitancy of those businesses in upgrading systems and infrastructure. This hesitancy for sawmills and lumber providers to upgrade facilities would greatly limit the possibility of a new CLT facility succeeding.

WS7: I have a great chance to visit many of the sawmills… They are lamenting that the big guys are coming here... And if we (sawmills) cannot compete then we need to shut down… Another way of saying that is they haven't upgraded their system, their practice, and everything that is making them non-competitive in the business.

Technical Skills

Development of new technical skills plays a key role in the successful growth of the hardwood CLT market. Even if lumber supply, infrastructure, and demand needs are met, if the workers at sawmills or CLT manufacturing facilities do not possess the technical skills, a market can't succeed. Sawmill/lumber yard owners were positive about their willingness and ability to adapt to new markets, especially if it shows the potential of being profitable.

SL3: It's all about what the price points are, we're willing to change... That's a new market (hardwood CLT) for us and may improve our margins on our products.

However, whether lumber producers will be willing to change to new market demands of dimensional and grade requirement was a matter of concern to engineers and architects. They called into question if loggers and sawmills will be willing to change to new ways of cutting and processing dimensional lumber.

EA5: My question is, are they going to? They have to change something in their process. To make the input meet specs to make CLT out of it. That's like cutting trees at different cross section dimensions to make lumber structural grade. There might be other nuances in the grade requirement for processing that has to be sorted out.

Building Codes

Respondents pointed out a number of concerns and potential regarding the building codes as they relate to the use of hardwood CLT. An engineer/architect shared some optimistic thoughts while also reflecting upon some complications surrounding building codes, insurance, and performance standards. They worked around these issues by showing structural capabilities first in order to get code and subsequent insurance approval.

EA3: The first one was the building code, because there's no code approved. The second issue we ran up against was insurance. Who's going to ensure a project from a new material product like hardwood CLT that hasn't been certified and isn't code approved? The way we got around the first issue with the building code is our engineer showed his research on the structural capabilities of our tulip poplar CLT to the code official… he said, "look this is performing better than the softwood CLT that's code approved". So, they approved the material for use in our project.

An engineer/architect discussed how yellow poplar was recently added to the ANSI PRG 320 guidelines. This had already led to one company (TimberKraft) to propose a new facility in Virginia.

EA7: The PRG 320, which is the industry standard for CLT, has recently added yellow poplar… It's right now in voting… That's where the industry is at as far as having a standard. And now you have a company, TimberKraft, looking to set up the first hardwood CLT plant.

The same engineer/architect as above continued to discuss the potential of other species to be added to the standard. Commercial availability of a species will likely play a large role in efforts to push that species through testing to get ANSI/APA PRG 320 approved.

EA7 : Red maple is another candidate; I don't know about red oak… there's a little more processing challenges when you start getting into those high densities. I think red maple will probably be next. All of this is about commercial availability… what are the most commercially available hardwoods? Yellow poplars up there…. it will pave the way for other hardwoods… what hardwoods? The answer is always commercial availability.

Decay and Longevity

Several key informants brought up longevity aspects during the interview process discussing things like fire, moisture, and pest resistance. A wood scientist summarized the potential struggles hardwood CLT may face as far as decay and longevity are concerned.

WS3: You're going to have to figure out how to make it fire resistant, mold resistant, and also get that high appearance out of it… I hope as a hardwood industry that we go for durability protection. You look at the cross-laminated timber manual... there's not a single chapter on wood durability, and that's an issue… You're building a hardwood CLT *building in Tennessee, you've got termites around here… they can do a lot of damage. It's important that we continually monitor and ensure the structural integrity of these hardwood CLT buildings.*

Another wood scientist went in depth on some potential products and solutions for increasing hardwood CLT's longevity and decay resistance. They brought up thermally modified wood as a potential solution to wood longevity in hardwood CLT panels.

WS1: Any kind of water allows for insects and fungus to infiltrate. One of the big ones is thermally modified wood…You're exposing this wood to high temperatures in a kiln chamber, and you modify the cellular structure... it loses its ability to regain moisture. In an exterior environment, it really becomes much more durable. And there are folks that are working on gluing together thermally modified wood in CLT panels… Borates can be put into that wood to reduce fungal and insect activity. If you combine those together, you end up with very durable exterior potential for these panels.

Fire Safety

A wood scientist who had done testing on wood element burn rates was extremely positive about hardwood CLTs fire resistance. They argued that a hardwood structure likely has a more predictable fire resistance to that of concrete due to wood's innate and predictable fire resistance.

WS5: I am pretty optimistic. Why? Because concrete fails quickly in high heat... If I put a mass timber product, and there is a fire burning, it will take a long time to burn. And it will burn at a predictable rate... I can design a two-hour fire-resistant building, connection, floor, wall and within two hours, I can get a person out of a building.

Another wood scientist brought up the question of hardwood CLT fire resistance when compared to softwood CLT. He questioned whether testing of hardwood CLT has been conclusive as far as code standards for fire resistance are concerned.

WS6: One of the big issues and challenges is fire… That's one of the key elements when getting it into the building code. When it catches on fire, there's a charring that slows down the progress of the fire. A lot of testing had to be done to show that (softwood) CLT could create a char layer to resist fire. I don't know if hardwood performs better in fire or not.

Aesthetics

No key informants shared negative outlooks on the aesthetics of hardwood CLT. Overall hardwood was viewed as an aesthetically pleasing material. The degree to which aesthetics play into the equation of hardwood CLT acceptance and market viability were the primary focus in these discussions. A positive response from a wood scientist discussed his optimistic outlook surrounding hardwood aesthetics and human perception of built environments.

WS1: I like wood more than most people do. All the cabinets in my house are hickory and I put down the red oak floor in our home… I've seen some really interesting studies over the years with biophilic properties and how we respond to that. If you look at a hospital setting, an office setting, there's been a good bit of work on people's moods and feelings and how they respond positively in a wood environment.

An engineer/architect discussed the importance of aesthetics to architects and end users and how hardwood may play a positive role in these equations.

EA4: For architects, end users, specifiers, the aesthetics are always going to be really huge. I definitely think if there is an aesthetic sell that will be really large… I would say aesthetics is always going to be a thing with architects.

Using hardwood as a veneer over softwood species to improve aesthetics was a sentiment shared by several of the key informants. A wood scientist discussed the aesthetics of hardwood in combination with pine.

WS6: I like the appearance of hardwood, whether it's oak or maple… I guess that there may be a preference for at least the outside shell of the CLT. Which you can always add on as a veneer to make it more appealing to the customer, the end consumer.

Future Steps and Recommendations

Key informants were asked to give their opinion on the future steps or recommendations for the manufacturing and promotion of hardwood CLT. This unstructured question led many key informants to provide extensive feedback. This was often used as a summarization by key informants to restate much of what was stated in previous questions. A wood scientist stressed the potential role of subsidies and market assurances and how those may play a key role in the industry moving forward. They questioned the viability of subsidies and how they may have a negative impact as far as long-term market health is concerned.

WS7: I want them to be like, that market is mine, I can be a part of that market. Do subsidies help with that? If the subsidy will attract them and initiate, it's perfect… But how long are you going to subsidize those industries… I think that's a good thing to say as principal support there, but why you are operating your mill? To make money? … Does that cycle still remain positive for the sawmill or the lower manufacturer? That is the question.

An engineer/architect shared similar thoughts as the above wood scientist. They called into question the long-term sustainability of a hardwood CLT market after initial subsidies are taken away.

EA1: Subsidies are always helpful, but I think it's going to have to be self-sustaining… It seems to me like subsidies are very helpful in getting things started but then if subsidies are given and there's no profitability after the subsidies go away then it's not really a good strategy.

A wood scientist pointed out the value of innovation grants to encourage production but was cautious about the provision of subsidies.

WS6: Wood innovation grants are a great idea… I know that the wood innovation grants do support a lot of facility production from hardwoods… subsidies though, well I don't know how well that would fly.

When asked about next steps for the hardwood CLT industry an engineer/architect discussed the importance of education for the owners, architects, and engineers.

EA6: Education is a big deal with this new technology. Educating the owners, the architects, the engineers on utilizing wood… Education really needs to happen with the whole team embracing mass timber. We're not quite there yet as far as it being an easy thing for them to use throughout the nation.

Another engineer/architect discussed the importance of utilizing low value forest resources. They then went on to talk about what needs to be done as far as research, code development, and education to help a hardwood CLT market succeed.

EA3: It's important for our region to maximize the use of our low value forest resources… There needs to be more demonstration for one, because I think the research is there proving that structurally it works… We need to test this out in the real world to verify performance… It's crucial that it be structurally approved in the building codes *through ANSI/APA PRG 320 certification. So that architects can simply specify hardwood CLT, and it can be used without any code dilemmas… after that would be targeted marketing in certain regions and for certain project types to really get hardwood CLT into real big buildings. WoodWorks has done an amazing job with softwood CLT, that's what should happen with hardwood.*

4.5 Discussion

4.5.1 Opportunities For Hardwood CLT

Availability and supply of hardwood fiber and the potential of economic development are likely two important opportunities associated with promoting hardwood CLT manufacturing in the United States. Wood industries have declined in recent years across many of the south-eastern hardwood states. Market for traditional products such as pulpwood, paper, and paperboard have shut down manufacturing facilities leading to a loss in vital timber demand (Brandeis et al. 2021). Many of these facilities utilized hardwood fiber from several states including Tennessee, Kentucky, and North Carolina. This lower demand for hardwood lumber has forced sawmill production to shut down or operate at lower levels not seen since 1960 (Hardwood Market Report 2024). The prospect of revitalizing these communities by finding new and novel ways to utilize hardwood timber resources was a common aspect brought up across the three key informant groups. As a new product, hardwood CLT shows potential to increase lumber demand in these areas. This will likely incentivize hardwood landowners to manage and harvest their timber and allow hardwood sawmills to ramp up production of sawn lumber. Several studies have been conducted looking at the impact of a larger mass timber industry on timber supply and forests (Comnick et al. 2021, Nepal et al. 2021, Pasternack et al. 2022). These studies either focused on softwoods or combined softwoods and hardwoods together. There have been no studies directly examining timber supply and demand implications for a hardwood CLT market. However, given the decline in hardwood industries and the slowing of sawmill production, concerns about short term hardwood timber supply are likely unwarranted. There is enough hardwood lumber to supply an emerging hardwood CLT market. If hardwood CLT gains market acceptance and production increases, studies examining this increased lumber demand and forest health implications will become more necessary in the future.

Mechanical effectiveness and performance continue to be some of the more researched aspects of hardwood CLT. Current literature is optimistic about testing of these panels and most researchers have concluded that hardwood CLT performs sufficiently for structural applications (Ehrhart & Brandner 2018, Crovella et al. 2019, Abdoli et al. 2022, Palacio-Betancur et al. 2023). When looking at low-quality hardwood for use in CLT Azambuja et al. (2022) found that No. 2 common yellow poplar lumber met the mechanical requirements for CLT under the PRG 320 (Azambuja et al. 2022). Consistent with the literature on wood science, most key informants in this study were optimistic about the mechanical performance of hardwood CLT. With some key informants even stating that they saw potential for hardwood CLT to outperform softwood CLT in certain situations. Given the positivity of key informants and the emerging literature supporting the mechanical and performance aspects of hardwood CLT, the question of whether hardwood can be effectively used in structural CLT components is yes. Whether it will enter the market as a niche product or find larger market acceptance is still unknown. However, it is likely that structural grade hardwood CLT will enter the market in some capacity in the near future.

Closely connected to mechanical effectiveness and performance is the question of construction code development. New species used in CLT panels must pass mechanical and performance testing before they can be added into the code standards. Construction code for CLT falls under the ANSI/APA PRG 320 standards for mass timber products (APA 2020). Yellow poplar has already tested positively in CLT panel construction and will be qualified under the most recent iteration of the PRG 320 according to a key informant involved in the certification process. Yellow poplar is readily available in most hardwood markets in sufficient quantities, a likely reason it was the first to be tested for acceptance under the PRG 320 guidelines. Given the positive testing results for other hardwood species (Ehrhart & Brandner 2018, Crovella et al. 2019, Abdoli et al. 2022, Palacio-Betancur et al. 2023), it is likely more hardwood species can pass the PRG 320 testing process. However, questions of specific lumber species abundance market availability, and price indicate that each species will need to be evaluated for more than mechanical effectiveness. These secondary questions will likely be the driving decider around whether a specific species will gain a market foothold in CLT manufacturing. Testing and code development is still in the early stages, and it will likely take years of continued research before a clear picture of which species have the most potential for CLT manufacturing.

Aesthetics and hybrid potential are often interconnected aspects associated with hardwood CLT. This is not surprising considering that the aesthetics and visual appearance of wood in the constructed environment has been studied extensively in scientific literature (Sakuragawa et al. 2005, Burnard et al. 2015, Yin et al. 2018, Jo et al. 2019). Finding by researchers on these aspects as well as the perspective of key informants in this study indicate beauty and appearance of hardwoods in CLT will be an important aspect. This aesthetic value shows potential to be one of hardwood CLTs strongest market drivers and selling points. In addition, the discussion around the potential of hybrid CLT panel construction implied that utilizing both softwood and hardwood lumber may achieve these aesthetic values while keeping costs low. This would involve either applying a hardwood veneer to a softwood CLT core or by replacing the top or outer layer of a softwood CLT panel with hardwood. Scientific testing into hybrid CLT panel construction has been optimistic with some researchers finding greater mechanical effectiveness when compared to softwood CLT panels (Aicher et al. 2016, Brunetti et al. 2020, Sciomenta et al. 2021). This is likely a valuable area for new research to be conducted as the financial and aesthetic value-adding components are promising. If wholly hardwood CLT does not succeed in the larger mass timber and CLT market these hybrid aspects may still succeed. It is possible that hybrid panel construction could even become the standard for exposed interior CLT given the positive findings of this study.

4.5.2 Barriers For Hardwood CLT

Lumber grading, technical skills, and supporting infrastructure are barriers that will likely hinder the hardwood CLT industry. These aspects were often discussed at length by key informants. These barriers focus primarily on hardwood lumber producers as well as the infrastructure to transport sawn lumber from the sawmill to a CLT manufacturing facility. Structural grading is currently not done at hardwood sawmills as hardwood lumber is graded for visual appearance and non-structural purposes (Cassens 2001). Once a hardwood species (e.g., yellow poplar) is added to structural guidelines, sawmills will then need to train and/or hire new personnel that possess the expertise to structurally grade hardwood lumber. It is likely that these barriers can be overcome given the appropriate financial input and time.

The cost of lumber will likely remain one of the larger barriers for hardwood CLT. Given that hardwood lumber is on average two to three times that of softwood (Timber Update 2023), creative solutions must be discovered to offset this increased cost. Several studies into utilizing lower cost hardwood lumber have shown positive results. These studies used small-diameter or low-value hardwood lumber, feedstock that is often much cheaper (Crovella et al. 2019, Azambuja et al. 2022, Norris et al. 2024, Hassler et al. 2024). Although several studies have been positive about the use of small-diameter or low-value hardwood lumber, further testing is needed. Testing will need to continue, and more positive results will need to be shown before these methods can be certified under PRG 320 guidelines. Another potential to lower the cost while keeping the aesthetics of hardwood is in the manufacture of hybrid hardwood and softwood CLT panels. Several studies have been done on hybrid panel construction and have shown positive results (Kramer et al. 2014, Aicher et al. 2016, Brunetti et al. 2020, Sciomenta et al. 2021). Creating a CLT panel where the outside layer is made of an aesthetic hardwood and the inner a structurally applicable softwood has potential to achieve cost effectiveness while retaining the visual component of hardwood.

Technical skills refer to all other aspects of processing lumber, other than grading, and include the ability to cut, dry, process, and ultimately produce lumber that can pass structural grading requirements. Common methods for drying hardwood lumber include air-drying and solar kiln drying and can take weeks to months to dry (Stelzer 2017, Hiziroglu & Mitch 2017). Hardwood lumber is also cut into random lengths and random widths, leading to loss of valuable lumber when trimmed for CLT manufacturing (Espinoza & Buehlmann 2018, Adhikari et al. 2020). These aspects have been discussed in much of the literature, but no definitive solutions have been established. Technical skills will likely remain

Supporting infrastructure includes the size and number of lumber processing facilities required to support a hardwood CLT manufacturing facility as well as the roads and transport needed to support them. Hardwood sawmills across the South-Eastern U.S. tend to be smaller and more spread out when compared to Western softwood operations. This causes potential logistical complications and may lead to challenges for a hardwood CLT manufacturing facility to receive adequate lumber quantities and qualities when dealing with a larger number of lumber suppliers. Add to this the smaller batch sizes hardwood mills dry, and the hardwood industry takes significantly longer to dry lumber than the more established softwood industry (Espinoza & Buehlmann 2018, Adhikari et al. 2020). It is likely these barriers are solvable given enough resources and time. Most key informants were positive that these aspects can and will be addressed while several others remained pessimistic. Further studies on these infrastructure aspects will likely shed much needed light on one of the more complicated aspects of hardwood CLT manufacturing.

Other barriers such as liability and insurance, decay and longevity, and fire safety were aspects brought up by key informants. No studies have been done thus far on liability, insurance, decay, or longevity concern of hardwood CLT panels. A handful of studies have performed fire performance on softwood CLT and found positive results (Harte 2017, Abed et al. 2022). Although these studies were optimistic about softwood CLT's fire resistance, more studies will be needed to establish if hardwood CLT shows the same fire resistance as softwood CLT. Many questions surrounding softwood CLT decay and longevity are still unanswered and further research is needed (Cappellazzi et al. 2020, Udele et al. 2021). The research for hardwood CLT longevity and decay is even further behind that of softwood CLT. Studies into the biological durability of hardwood

CLT will be pivotal for long term market success. This lack of consideration for durability will likely remain a large barrier for hardwood CLT. When examining liability and insurance concerns correlations can be made by looking at the softwood CLT industry. WoodWorks states that the two insurance challenges facing mass timber are builder's risk insurance and fixed property insurance. These insurances cover risks for builders and property owners (WoodWorks 2024). WoodWorks does not state the need for liability or insurance to be held by the lumber suppliers, a common concern stated by several sawmill and lumber yard owners during the key informant interview process. The lack of studies examining the decay and longevity aspects of hardwood CLT will remain a large barrier moving forward that will need to be overcome. It is likely that hardwood CLT will pass the testing for decay and longevity. However, until further studies are completed these aspects remain uncertain.

4.6 Conclusion

This study shows that key informants in the wood products industry are generally positive about hardwood CLT. Findings from this study corroborate several recent studies on hardwood CLT while also bringing up other potential barriers and areas of research needs. Key informants brought up many aspects that will be important for hardwood CLT moving forward. Some of the more promising areas for hardwood CLT are its mechanical effectiveness, potential to alleviate struggling markets, and positive aesthetic attributes. Mechanically hardwood CLT has been shown to work with promising mechanical results providing evidence for potential building code-based changes moving forward. Utilizing the abundance of hardwood and in turn aiding struggling hardwood markets was a common sentiment among key informants and will likely be a major reason for continuing to advocate for more hardwood CLT. Aesthetics have always been a selling point for wood products, and this is even more so for hardwoods. How well the industry leverages the aesthetics of hardwood to promote and push hardwood CLT will likely be a major factor in its success or failure. This could be done through a wholly hardwood CLT panel or by applying a hardwood veneer layer to a softwood CLT panel.

A number of potential barriers including limited awareness, high cost of raw lumber material, lack of hardwood structural grading, limited technical skills, distribution of supporting infrastructure, liability and insurance, decay and longevity, fire safety, and mechanical effectiveness were discussed in depth by key informants. Limited awareness is expected given the novel emergence of hardwood CLT and will likely fade away with time through education and outreach efforts. Agencies interested in promoting a hardwood CLT market may benefit from implementing extension programs to educate and train industry professionals on the specifics of the product. Educating the public about the potential benefits (e.g., aesthetic, durability) of hardwood CLT products over traditional products will further enhance hardwood CLT's marketability and perception. The high cost of raw lumber material may be mitigated by the addition of low-grade materials or hybrid panel construction. However, as the cost will likely persist as a primary detractor for hardwood CLT, it also may imply that some level of subsidy or grant may be needed for this product to penetrate the market. However, given the political controversy surrounding any product with subsidy or tax instrument, a strong justification to demonstrate the societal benefit may be needed. Key informants were generally hesitant when discussing subsidies as a general solution.

Lack of hardwood structural grading as well as the need for expansion of facility size and adjustment in cutting, drying, and processing this new structurally graded lumber will require extensive upgrades to current sawmill and lumber production facilities. Key informants felt that these upgrades were possible and would likely benefit the sawmills but were still unsure if the historically hesitant market would adjust. Other barriers include questions surrounding liability and insurance, decay and longevity, fire safety, and mechanical effectiveness. It is likely that hardwood CLT will equal or outperform testing seen on softwood CLT for these aspects, but without further research this statement cannot be asserted. Some of these aspects have been addressed or are still being addressed in respect to softwood CLT. Studies following the same framework and design as previously successful softwood CLT testing can likely be adopted to a hardwood CLT model. It is likely that some new and novel testing methodologies will need to be researched to address the hardwood specific attributes. While these can be considered barriers in the short-term, this study indicated that these may be overcome in the long-term given adequate attention, funding, research, and time.

Though utilizing hardwood lumber has not received much attention in the broad scale of CLT production, the recent addition of yellow poplar to the ANSI/APA PRG 320 guidelines, has marked a pivotal first step for hardwood CLT. New research shows potential to expand the interest in new hardwood species as well as continue to support the efforts surrounding yellow poplar. Hardwood CLT shows potential to revitalize struggling hardwood markets and add a novel use for currently underutilized hardwood timber. However, it is likely that hardwood CLT will remain a niche part of the greater mass timber and CLT market. Admittedly, it will take time for other hardwoods to follow in the footsteps of the yellow poplar testing and success is not guaranteed. Whether hardwood CLT can help struggling hardwood lumber markets is still largely unknown. This will likely be a question of both scale and time, considerations that have not been conclusively defined let alone studied. It is likely that this market will slowly develop over the coming decades if support continues from the forest products industry and forest researchers. It is not reasonable to assume that hardwood CLT will be a one-product solution for currently declining hardwood markets. However, any product that increases the demand for hardwood lumber can be viewed as part of the larger solution toward continued market and industry success.

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Appendix

Table 4.1 Questionnaire used while conducting Key Informant Interviews.

Question #	Key Informant Interview Questionnaire
1	What is your current familiarity with Cross Laminated Timber (CLT)?
2	What are your general thoughts on how CLT may impacts the environment, climate, or forests?
3	How would you describe the scope of hardwood CLT production, utilization, or interest currently?
4	How do you think (e.g., aesthetic, structural, adding value) hardwood CLT would compare to softwood CLT?
5	What are ways that consumers may value hardwood CLT (e.g., aesthetic, structural, adding value) compared to softwood CLT?
6	How do you think a hardwood CLT manufacturing facility would impact (e.g., economic, societal, environmental) local and state economies?
7	In what ways could legal and structural constraints (e.g., supply of lumber, code standards) effect the establishment of a CLT mill?
8	In what ways could technical and logistical constraints (e.g., lack of structural grading skills, drying kiln, dimension lumber) effect the establishment of a hardwood CLT mill?
9	(question a. if participant is positive/question b. if participant is negative) a. What needs to be done (e.g., market assurance, capacity building, subsidy, innovation grant, outreach, and promotion) to make hardwood CLT more successful? b. Why might hardwood CLT not be successful (e.g., lack of market assurance, capacity building, subsidy, innovation grant, outreach, and promotion)?
10	Are there any other comments, concerns, or information that you would like to provide that haven't been asked in the previous questions?

Table 4.2 Key informant codes by number of times a position on a given topic was shared with other topics in a single excerpt.

Key Informant Interview Analysis Codes			Number of Co-Occurrences
Economic Impact (+)	x	Environmental Impact (+)	6
Hybrid Potential (+)	x	Aesthetic Impact (+)	6
Timber Supply (+)	x	Economic Impact (+)	5
Timber Supply (+)	x	Environmental Impact (+)	3
Technical Skills (±)	x	Lumber Grading (±)	3
Technical Skills (-)	x	Supporting Infrastructure (-)	3
Lumber Grading (+)	x	Mechanical Effectiveness (+)	2
Lumber Grading (-)	x	Technical Skills (-)	2
Timber Supply (+)	x	Supporting Infrastructure (+)	2
Timber Supply (+)	x	Price (+)	2
Technical Skills (-)	x	Price (-)	2
Aesthetic Impact (+)	x	Mechanical Effectiveness (+)	2

Note: (+) = a positive positionality, (-) = a negative positionality, (±) = a neutral positionality.

CHAPTER 5
CONCLUSION

Mass timber products have many inherently positive attributes that make them a solid choice for the ever-evolving landscape of building construction. From positive environmental and sustainability aspects to ease of installation it is likely that mass timber will continue to grow in the U.S. and globally. However, mass timber is still new compared to traditional construction materials such as steel and concrete. Due to this there are many areas of mass timber that have yet to be established or researched. The economics of mass timber products have been the most researched with policy and social research the sparsest. It is in these areas of social and policy that the majority of research efforts should focus on moving forward. Aspects such as spreading general awareness, increasing marketability and aesthetics, continuing to expand construction codes and guidelines, and developing new and novel manufacturing methods will be vital for the continued success of this industry. Mass timber has a lot of potential moving forward and will likely continue to grow in the larger market over the coming years.

Hardwood CLT has many opportunities that include availability of hardwood lumber, positive economic potential, mechanical effectiveness, construction code development, positive aesthetics, and hybrid potential. However, barriers such as high price of raw hardwood lumber, limited awareness, lack of lumber grading standards, technical skills, supporting infrastructure, liability and insurance, decay and longevity, and fire safety will need to be addressed if hardwood CLT is to succeed. These aspects of hardwood CLT show many similarities to the larger mass timber market with a couple caveats. The first being that hardwood CLT is newer compared to the much larger and more established softwood CLT market. The second being that although yellow poplar has been accepted into the ANSI/APA PRG 320 guidelines, this does not guarantee that other hardwood species will follow. Continued research and testing will need to be done if other species are to be added to the PRG 320 guidelines. Hardwood likely has a place in the larger mass timber market due to its unique aesthetics and potential to aid struggling hardwood markets. Overall key informants were optimistic that the barriers surrounding hardwood CLT can and will be overcome given time and adequate industry efforts. Even if hardwood CLT does not gain mainstream adoption it is possible to remain a niche and valuable product in the larger mass timber market.

VITA

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