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Advancing Timber for the Future Built Environment

SYSTEMATIC REVIEW ON THE ENVIRONMENTAL IMPACT AND COST COMPETITIVENESS OF MASS TIMBER CONSTRUCTION

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ABSTRACT: In recent decades, mass timber has emerged as a sustainable building technology, drawing increased attention to assess the potential advantages and challenges of mass timber construction (MTC), aiming to facilitate its broader market penetration. The majority of these studies focus on high-rise commercial timber structures, leveraging the relatively lighter weight of timber compared to steel and concrete. This review article systematically examined relevant literature and categorized them into two key domains: (1) environmental impact, and (2) cost competitiveness. Publications from 2013 to 2023 were found via Google Scholar. After two phases of screening, additional articles were added from references for the final analysis. Although extensive research remains imperative across the two domains, the results underscore the promising environmental impact of MTC compared to conventional materials, with notable advantages in terms of carbon footprint reduction, with Life Cycle Assessment (LCA) as the main tool to assess the environmental impact of MTC. The cost competitiveness review highlights the need for comprehensive comparisons across various design configurations. Future research should explore additional factors such as fire safety, moisture management, acoustics, and biophilia benefits to provide a more comprehensive understanding of the potential applications of mass timber technology.

KEYWORDS: Mass Timber Construction, Cross Laminated Timber, Life Cycle Assessment, Cost Competitiveness, Sustainability

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1 – INTRODUCTION

Expressing concern over the direct impact of greenhouse gas (GHG) emissions on climate change [1], industries are actively working to reduce their carbon footprint through the adoption of sustainable strategies. With the Architecture, Engineering, and Construction (AEC) industry being responsible for almost 40% of CO2 emissions [2], and 30%-40% of solid waste generation [3] efforts are being made to diminish its adverse environmental impacts by exploring emerging alternatives to conventional building technologies [4]. These sustainable alternatives necessitate an integrated approach from various disciplines and stakeholders, encompassing designers, engineers, suppliers, manufacturers, general contractors, the forest industry, and policymakers. The goal is to ensure environmental sustainability and cost competitiveness [5]. One noteworthy example among these emerging technologies is mass timber, a group of engineered wood products such as Cross Laminated Timber (CLT), which comprises multiple layers of lumber boards arranged crosswise, and typically bonded together on their broad faces by adhesive bonding, nails or wooden dowels [6] that have garnered significant attention over the past decades, particularly originating from Europe, specifically Austria and Germany, holding 60% of the global mass timber market in 2018 [7]. This trend has extended into the North American construction market [6], experiencing rapid growth, the number of mass timber buildings in the U.S. has surged from fewer than ten projects in 2016 to surpassing 800 projects by 2023 [8].

This review research addresses the rapid advancement of mass timber construction, the benefits, and the challenges in making it the primary structural material by gathering and categorizing information on MTC and its potential relevance for further market penetration. Additionally, it aims to investigate the application of mass timber as an alternative to conventional building technologies. This inquiry raises the following questions: What are the potential advantages and challenges associated with MTC implementation? Additionally, what are the existing knowledge base, limitations, and research gaps concerning MTC?

2 – BACKGROUND

2.1 MASS TIMBER RESEARCH

The promising outlook on building science related to mass timber products is gaining traction with an increasing number of projects being designed and constructed. The urgency of addressing climate change and the imperative for sustainability necessitates a comprehensive examination of various aspects of Mass Timber Construction (MTC). Primary among these considerations is a reassessment of our perspectives on sustainable forestry, particularly with the growing demand for mass timber products [9]. Also, this shift is steering the AEC industry towards a more holistic approach that integrates life cycle thinking [10], moisture management [11], fire safety [12], and considerations of cost and scheduling [4]. These interconnected factors are driving the formulation of policies, codes, and standards governing buildings and the emergence of new building typologies [5].

Mass timber, with its appealing aesthetics, structural benefits, and environmental advantages, holds the potential to play a crucial role in reshaping cities into carbon-neutral environments and claiming a substantial portion of the structural materials market in the U.S. However, its integration into various building typologies remains a challenge [5].

2.2 LITERATURE REVIEWS ON MTC

Researchers have extensively explored various facets of MTC, encompassing its environmental impacts [10] and contributions to sustainable forestry [13]. Additionally, investigations have delved into construction management, broader societal and economic implications, as well as technical and engineering considerations like structural and acoustical performance [14], fire safety [12], and moisture management [11].

Many studies systematically analyze specific aspects of mass timber construction (MTC). For instance, a review by Mitchell [12] focused on mass timber fire experiments, examining methods for modeling timber compartment fire behavior supported by experimental data. It categorizes models and inputs into three groups: fire conditions affecting timber, timber's thermal response, and structural response to charring. These experiments explore factors like compartment size, construction, ventilation, movable fuel load, and quantity of exposed mass timber. The review aims to identify limitations and inform future fire-safe mass timber design. The findings showed that the location of mass timber within a compartment affects charring behavior. Exposed timber ceilings had a 16% lower charring rate than walls. The charring rate is driven by ventilation and fuel load density, decreasing as timber surface area relative to openings increases. A different review study by Abed [4], concentrated on evaluating the sustainability advantages of MTC compared to conventional structures. The approach encompassed a thorough examination of existing literature on mass timber, assessing critical factors like structural integrity, environmental impact, seismic resilience, fire safety, economic aspects, and health performance. This study synthesized insights from experimental research and analyses of ongoing mass timber projects. Additionally, it conducted a comparative evaluation between mass timber and reinforced concrete construction across multiple performance metrics. It recommended transitioning to mass timber as the future's low-carbon, high-performance building material when suitable.

3 – PROJECT DESCRIPTION

This section outlines the methodology employed for the systematic search and examination of existing literature. Systematic literature reviews are recognized for their thorough, comprehensive, transparent, and reproducible approach to identifying, selecting, and critically appraising relevant research. They are also effective in gathering and analyzing data from the studies included in the review [10]. The review procedure is depicted in Fig. 1. Related publications published between 2013 and 2023 were identified through Google Scholar's database. Initially, 825 publications, comprising books, journal articles, conference papers, and non-peer-reviewed articles, were retrieved using two sets of keywords. After the initial screening phases, which involved selecting only peer-reviewed articles, eliminating duplicates, and screening titles and abstracts, the number was reduced to 86. Subsequently, during the full-text screening phase and through the addition of articles from referenced citations, 31 articles were ultimately included in the final analysis. Design theme, this section will give an overview of the project.

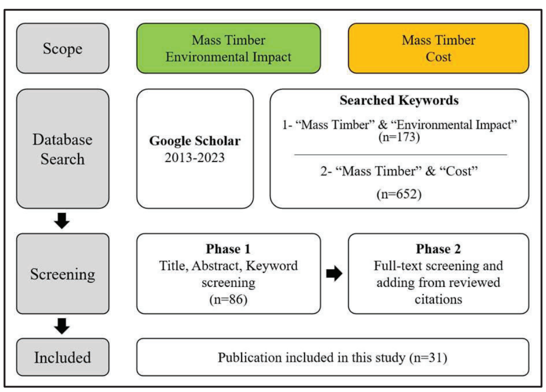

Figure 1 Systematic Literature Review Procedure

4 – LITERATURE REVIEW

This systematic review highlights discussions on the challenges and benefits of MTC into two key domains: (1) environmental impact, and (2) cost competitiveness. This section delves into these domains summarizes the current body of knowledge and examines their potential for further market penetration.

4.1 ENVIRONMENTAL IMPACT

The fundamental advantage of MTC lies in its comparatively lower carbon footprint [15], offering an opportunity for sustainable building practices and contributing to the growth of the forestry sector in the United States by creating value-added products [16]. The increasing demand for mass timber as a wood product in the United States and the broader North American wood industry, driven by the desire to diversify end-use markets, raises concerns about sustainable forestry practices [13]. While design professionals are intrigued by its potential for reduced environmental impact compared to steel and concrete, a debate persists on whether forests are more effective in reducing carbon emissions when left untouched or when managed for sustainable harvesting and wood product production [13]. In the United States alone, institutions including the U.S. Department of Agriculture (USDA) and the American Wood Council (AWC), are keen to capitalize on mass timber as an emerging value-added forestry product. Comnick [9] projected a need for increased softwood timber harvests by 2035 to meet the growing demand for mass timber and dimensional lumber, advocating for responsible expansion while emphasizing adherence to sustainable forestry practices. This approach not only addresses the rising demand for mass timber but also contributes to a reduction in GHG emissions and embodied carbon in the built environment.

Apart from the harvesting stage, the life cycle of mass timber buildings differs from that of steel and concrete, impacting both their carbon footprint and total energy consumption [17]. The life cycle assessment (LCA) method includes defining the goals and scope of the assessment, conducting a life cycle inventory analysis to quantify resource use and emissions at each stage, performing an impact assessment to assess the significance of these environmental impacts, and interpreting the results. In the context of building construction, the life cycle stages typically include product and construction, operational, end-of-life, and supplementary information beyond the building life cycle stages [10], which stands out as a reliable means to evaluate environmental impacts in the AEC industry. Over two decades of literature review indicates a growing interest in analyzing buildings of various scales and scopes through LCA, with related publications increasing from two in 2000 to over 120 [18].

A notable study by Puettmann [17], conducted a Whole-Building Life Cycle Assessment (WBLCA) comparing Mass Timber buildings with conventional concrete structures in three U.S. regions with significant potential for mass timber adoption. Their simulation-based analysis covered three building heights, from mid-rise to high-rise, and employed Life cycle inventory (LCI) data for building materials sourced from primary data and public databases, adhering to international LCA standards. The findings revealed that Mass Timber buildings demonstrated a reduction in embodied carbon ranging from 22%-50% compared to functionally equivalent concrete buildings, irrespective of height or region. However, it was observed that all Mass Timber buildings used more energy in production than their

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equivalent concrete counterparts. Conducting a regional case study, Gu [19] performed 18 WBLCAs for designed buildings across three U.S. regions. LCIs for building materials were sourced from the US LCI database, Athena database, and US-Ecoinvent database, with the SimaPro LCA software facilitating a robust, transparent, and flexible analysis. The results underscore the significance of design, supply chain, manufacturing emissions, carbon storage, and climate impact. The study emphasizes supporting the favorable environmental performance of wood. It advocates for extending the service life of building materials through reuse and recyclability, with a particular focus on future studies regarding the reuse of mass timber products.

Furthermore, recent research emphasizes that replacing steel and concrete with mass timber in mid-rise buildings has the potential to reduce emissions related to the manufacturing, transportation, and installation of building materials by 13%-26.5% [17], [20]. To ensure sustainable practices in the increasing use of mass timber in construction, key strategies include promoting enhanced tree growth, adopting sustainable forest management, utilizing local wood sources to minimize transportation impacts, creating durable wood products, designing buildings for potential reuse and recycling, and utilizing wood residues for energy generation to offset fossil carbon emissions [17].

4.2 COST COMPETITIVENESS

Among the obstacles hindering the widespread adoption of mass timber in new markets, there exists fear and a perception that MTC could lead to increased costs [21]. Building officials, consultants, and contractors may not be as well-versed in the design considerations and scheduling associated with mass timber [22]. Additionally, the material cost of mass timber could be as much as 43% higher than its conventional alternatives [23], [24]. Estimating the costs of mass timber systems necessitates a comprehensive approach to compare expenses and identify potential savings [8]. Given the relatively slow pace of change and adaptation to new technologies in the AEC industry [4], with approximately 1% in construction compared to a 3.6% annual productivity growth in manufacturing [25], addressing these cost-related issues becomes pivotal for the broader integration of mass timber in the building market.

Factors such as material costs [26], labor expenses [27], scheduling considerations [28], and the broader macroeconomic implications of MTC [29] contribute to positioning MTC as an appealing investment opportunity for various stakeholders. Material cost, as one of the main drivers of initial cost, is influenced by factors such as the supply chain of mass timber products and the manufacturing process [30]. It is important to note that economies of scale can potentially reduce manufacturing costs with increased supply and demand for these products [16]. Conversely, the lightweight nature of mass timber, with glulam weighing only 1/6th of concrete for pieces of similar size, leads to reduced foundation requirements, translating into lower foundation costs for buildings [14], [31].

Scheduling stands out as a key advantage in terms of cost efficiency, primarily attributed to the manufacturing process and off-site prefabrication inherent in MTC [12] which makes the construction site primarily reserved for the assembly of mass timber elements. Generally, mass timber demonstrates potential construction time savings compared to conventional systems. Recent experiences, however, suggest that mass timber may not yield substantial schedule savings when compared to structural steel [5]. Despite varying findings in different studies, there are noteworthy opportunities for schedule savings, possibly up to 25%. These include reduced soil remediation and smaller foundations for sites with challenging soils, faster erection of the structure and building envelope using CLT, and fewer finishes with exposed mass timber material. Such strategies aim to minimize the lag time typical in conventional building projects, where ground improvements precede the construction of the structural frame [32]. However, conflicting findings emerge in certain studies. For instance, research by Espinoza [33] suggests up to 50% schedule savings when utilizing mass timber in mid-rise residential projects compared to cast-in-place concrete alternatives. One comparative case study involving seven projects indicated that MTC can reduce construction schedules by an average of 20%, with mass timber projects averaging a duration of 12.7 months compared to 15.4 months for typical concrete construction. Moreover, there is evidence suggesting further potential for optimizing productivity improvements and achieving additional schedule savings [28].

The on-site labor costs associated with mass timber are influenced by two conflicting factors. Firstly, as mentioned earlier, the potential for significant schedule savings, particularly when compared to cast-in-place concrete, impacts labor costs [27]. However, on the flip side, given that mass timber is an emerging technology, there is a learning curve associated with it, necessitating skilled workers, and requiring an investment in human resources [8], [28], [34]. It is important to highlight that the use of mass timber may necessitate different heavy construction equipment and tools compared to those typically used by contractors, initiating new construction processes, and requiring additional investment in transportation and lifting equipment [6].

Several studies aim to assess the total LCC of timber construction and compare it to equivalent concrete and steel construction [26], [30]. This life cycle approach provides a comprehensive understanding of the current

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cost-effectiveness of MTC and highlights opportunities for optimizing design and the overall process chain [35]. The goal is to enhance cost competitiveness, bringing attention to unsustainable and inefficient building methods. This underscores the importance of an integrated process involving various stakeholders to develop a suitable design and construction approach [5]. Life Cycle Costing in Value Engineering (VE), a systematic approach that enhances decision-making, ensures value and competitiveness with existing alternatives, involves an economic evaluation of competing design alternatives using the concept of equivalent costs, emphasizing the consideration of total costs, including both initial and follow-on costs [36].

Life Cycle Costing has long been employed in construction projects to assess design feasibility. There have been feasibility studies comparing the life cycle costs of high-rise mass timber buildings with conventional structures like steel and concrete. One study, focusing on cost and construction change orders, discovered a 6.43% higher construction cost for mass timber buildings compared to modeled concrete structures. Mass timber costs, high installation expenses related to crane usage, project staffing, and certain material costs contribute to this increase. The study suggested qualitative and quantitative approaches to reduce MTC costs, including optimizing equipment operation, developing a qualified timber construction workforce, and increasing the number of mass timber manufacturing factories in the U.S. [37]. Another study assessed the life cycle cost of a 12-story, mass timber building in Portland, Oregon, compared to a functionally equivalent reinforced concrete alternative by gathering front-end construction cost data from the RSMeans database. The study explores the sensitivity of LCC results with various study periods and discount rates. While front-end costs for the mass timber building were 26% higher, the LCC over a 60-year study period showed a 2.4% cost advantage due to its estimated longer lifespan and higher end-of-life salvage value [15], [19]. Current studies indicate mass timber buildings typically come at a premium of 5%-10% compared to conventional building types. This cost difference mainly arises from the necessity to follow a distinct code compliance path for most mass timber projects. Consulting fees contribute to increased costs, driven by the time and complexity involved in documenting and peer-reviewing alternative solutions necessary to obtain approval under the building code [5].

In addition to comparing the costs of MTC with conventional alternatives, it is crucial to evaluate economic growth opportunities associated with MTC and its distinct supply chain, which can activate various industries. A study conducted a PESTEL (Political, Economic, Social, Technological, Environmental, and Legal) analysis on MTC in the Australian building industry, found that the local forestry industry and building supply chain could benefit from opportunities to develop products for MTC, utilizing lower-grade material and recycling timber for CLT production. The study also discussed the potential for government assistance, aligning with carbon reduction commitments [27]. While the reduced need for skilled laborers on mass timber projects may lead to hesitancy among state-level policymakers due to potential employment losses and opposition from construction unions, MTC, especially in high-rise construction, has the potential to reshape the building industry and stimulate local job growth [38]. In the U.S., if mass timber gained a 5% market share in the construction industry, it could generate approximately 2000 manufacturing jobs. Moreover, with a 15% market share, this number could increase to 6100 direct jobs, indicating job displacement in the construction sector but growth in the forestry industry and a renewed demand for harvesting and manufacturing jobs [28].

5 – RESULTS

In summary, the potential adoption of MTC can be reviewed in two domains: (1) environmental impact which can be broken into the impact of MTC on US sustainable forestry and life cycle assessment of the building and (2) Cost competitiveness can be broken into life cycle cost comparison of MTC with conventional structures and the larger scale impact of MTC on the economy.

It can be said that MTC is emerging rapidly and the adoption of it in new markets is worth investigating. Different studies indicate that MTC has a lower carbon footprint and the projected growth and increasing demand for mass timber products is manageable with a steady and sustainable growth of forest in North America. In cost competitiveness, material cost poses a primary challenge for mass timber. However, depending on the building category and construction type, MTC could gain a significant advantage through its time-saving potential. With a growing demand for sustainable building technologies, there is considerable potential for enhancing mass timber properties and manufacturing processes, ultimately contributing to increased cost competitiveness.

5.1 OVERVIEW

Figure 2 reveals the exponential growth in mass timber research from 2013 to 2023, in two domains of environmental impact and cost competitiveness. Initially, as shown in Figure 2. a, it appears that there has been a disproportionately higher emphasis on cost competitiveness, with over 650 publications compared to approximately 170 publications on the environmental impact of MTC. However, upon the initial screening phase, shown in Figure 2. b, where peer-reviewed articles were filtered and titles and abstracts were screened, the total number of publications dropped

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significantly to 85. Interestingly, there has been substantial growth across the two areas starting in 2018. Following full-text screening, as shown in Figure 2. c, and the inclusion of cited sources from the reviewed articles, the final tally of peer-reviewed articles decreases to 31, with articles focused on cost competitiveness dropping to half the publications in the other two domains. This decline may be attributed to the broad keyword "cost," which encompasses a wide array of publications related to mass timber, while those specifically addressing the cost competitiveness of mass timber are comparatively scarce.

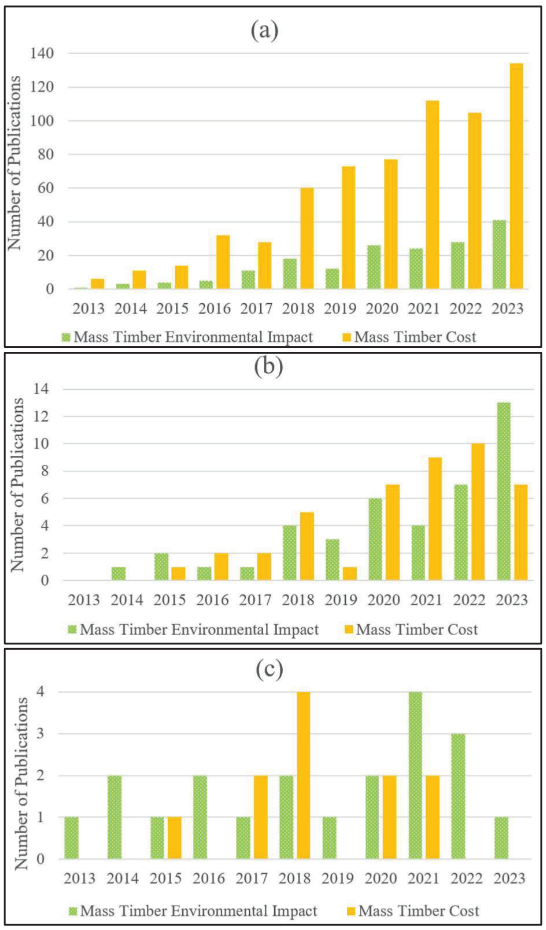

Figure 2 - Number of mass timber-related publications by year

5.2 METHODOLOGY

for the environmental impact domain of MTC, LCAmemerges as the predominant research method, as evidenced by studies conducted by multiple studies [39], [40], [41]. Additionally, there have been efforts to develop and propose frameworks aimed at enhancing the assessment of MTC [42], [43].

Regarding cost competitiveness, as shown in Figure 3, comparative studies through built case studies or simulated models [21], [44] are prevalent. Comparative LCC analyses comparing MTC with conventional materials across different scales [19], [27], [45] provide valuable insights into the cost benefits and challenges associated with MTC. Furthermore, efforts to evaluate the broader economic impact of MTC through literature reviews [46] and expert interviews [47] have been undertaken and for a more comprehensive evaluation of MTC, PESTEL strategic analyses [27] can be conducted.

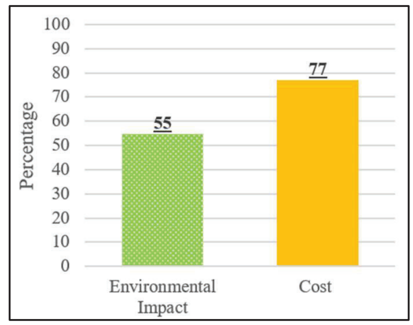

Figure 3 - Percentage of comparative studies to included studies

In comparative studies, as shown in Figure 4, research on high-rise mass timber buildings surpasses the combined total of low-rise and mid-rise investigations. This could be attributed to the greater potential for market penetration of MTC for this building type, owing to mass timber's lighter weight and quicker assembly compared to conventional alternatives [21], [31]. When comparing mass timber with other materials, the focus predominantly lies on reinforced concrete due to its larger carbon footprint and longer curing time [17], while steel occupies the second position with less than half the number of studies dedicated to comparison with concrete structures.

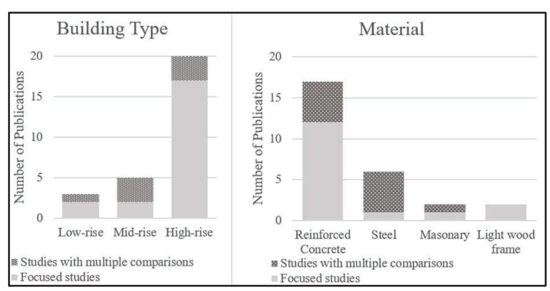

Figure 4 - Building types and material comparison of included comparative studies

5.3 GAPS AND RECOMMENDATIONS

The potential of MTC to transform the U.S. construction industry is evident. An illustration of the U.S. commitment to developing MTC is the announcement by the U.S. Department of Agriculture's Forest Service to allocate $41 million for expanding the wood market, promoting innovation, and advancing renewable wood energy [48]. However, despite this potential, mass timber buildings currently constitute only a small fraction of the overall U.S. building economy. As of March 2023, there were 1,753 mass timber projects either under construction or in the design phase in the United States, compared to the staggering construction of 5.9 million commercial buildings in 2019 alone [29].

As extensively discussed in the literature review section, the outlook for mass timber in the North American market appears promising. Environmentally, it demonstrates a favorable life cycle impact compared to conventional materials while upholding sustainable forestry practices. Regarding cost competitiveness, findings fluctuate depending on the specific case characteristics, types of mass timber products, wood species, and the database sourcing cost information. However, for high-rise projects or projects prioritizing time constraints, mass timber emerges as a viable alternative.

Recent studies on the viability of MTC predominantly are from regions such as North America [38], [40], [46], [49], Australia [27], [50], and China [42]. These studies assess both the environmental [9], [43] and economic [27] implications of MTC on a large scale.

From a methodological perspective, variations in outcomes for LCA can arise due to the utilization of different software platforms, including Commercial software IESTM [41] or SimaPro LCA software [19], each with distinct databases. Hence, the development of an LCA database containing updated information on MTC and conducting more context-based analyses becomes imperative. As the number of built mass timber projects rises, cost estimation for initial cost, total project cost (TPC), and life cycle cost are expected to become more accurate. However, maintenance costs over extended periods, especially for newer types of mass timber products like CLT, currently rely heavily on speculation.

As highlighted in previous sections, the majority of studies have concentrated on the application of MTC in mid-rise to high-rise commercial buildings [23], [38], [51]. Conversely, only a limited number have specifically addressed low-rise MTC. For instance, Allan and Phillips conducted an LCA of low to mid-rise MTC using the TRACI methodology [39], indicating its potential suitability for larger-scale low-to-mid-rise projects such as big box retail stores. This area presents a promising avenue for new research opportunities within the realm of MTC.

Selecting the appropriate structural system for a specific project entails a multi-criteria decision-making process [52], [53]. Mass timber, as an alternative to conventional structural materials, demands a comprehensive and integrated approach to devise sustainable and economically viable design and construction solutions [5]. Hence, there is a growing need for interdisciplinary research on MTC. These studies should encompass various aspects, from examining the environmental impact of mass timber buildings and their broader implications for the construction sector and forestry industry to evaluating construction management strategies and the feasibility of MTC, as well as exploring technological advancements for enhanced durability and resistance.

6 – CONCLUSION

Mass timber, a sustainable and emerging building technology, has gained considerable attention in recent years. However, effectively optimizing its application across diverse urban landscapes remains an ongoing challenge, with researchers in North America, Australia, and China actively exploring the benefits and challenges of MTC to facilitate its wider adoption in the market. While numerous scholars explore the feasibility of incorporating mass timber in high rises, leveraging its prefabricated attributes and impressive strength-to-weight ratio, there is a scarcity of research examining its potential impact in different building sectors including commercial retail architecture and large-scale, prototypical big-box stores.

Reviewing the existing literature suggests that adopting mass timber technology shows promise due to its favorable environmental impact and cost competitiveness. This potential is influenced by ongoing advancements in policies, codes, and supply chain development. Examined publications reveal common themes in methodologies. Given the complex nature of MTC, interdisciplinary research with a holistic approach can enrich current knowledge, as various factors like fire and moisture management can affect structural considerations and project life cycle costs. Therefore, utilizing integrated tools like Building Information Modeling (BIM) could prove advantageous.

LCA stands out as the primary tool for evaluating the environmental impact of MTC. Additionally, for assessing cost competitiveness, comparing LCC with alternative materials like concrete or steel is standard practice. Further refinement of databases for life cycle environmental impact and cost is essential for enhanced accuracy. Generally, findings indicate that the carbon footprint of MTC is significantly lower compared to reinforced concrete and steel buildings. However, uncertainties persist regarding the embodied energy benefits of MTC in comparison to conventional materials. Regarding cost competitiveness, conducting more comprehensive comparisons at various levels of detail (LoD) with steel and concrete buildings, across different architectural and structural configurations,

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could provide valuable insights for the analysis and design of mass timber projects.

Acknowledging limitations, other factors such as fire safety, moisture management, and acoustics were not thoroughly investigated. Moreover, exploring the health effects, the biophilia benefits of wooden components in retail spaces, and the branding advantages of utilizing mass timber in large, franchised stores warrant further examination.

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