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Filling the Knowledge Gaps in Mass Timber Construction: Where are the Missing Pieces, What are the Research Needs?

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As mass timber construction evolves from a niche product to a mainstream, there is an urgent need for focused research activities to support the industry and avoid duplication or overlap of work being done internationally. To identify and prioritise the future of mass timber research agenda, this article pursues responses to the following questions: What is the current state of knowledge and where are the remaining research needs in mass timber construction? For example, newcomers to mass timber often believe it is imperative to research fire performance, fire resistance, or sound transmission when these areas have been extensively explored and are now widely seen as resolved. Consequently, the focus has shifted, towards answering new research questions, including explorations of carbon storage, and life cycle analysis durability. There is already a growing research activity in mass timber, involving several research centres worldwide, that would benefit from some guidance on research needs. Thus, defining new trends and research gaps that help avoid replicating research. A more nuanced discussion on knowledge gaps and industry research needs is also timely, to truly capture and disseminate information on the full potential of engineered-wood products as an innovative construction material, which helps reduce the use of carbon-intensive conventional building materials. To answer the above-mentioned research questions, this study has consulted experts at an international conference, and seven key research areas have been identified and presented as the results.

Keywords: *Mass timber performance, knowledge gaps, research needs, impact, multistorey application, embodied carbon.*

1 Introduction

Design and construction professionals are increasingly turning to mass timber as a construction method, due to being a strong, lightweight, and low-carbon alternative to concrete and steel (Ahn et al., 2022; Kremer and Symmons, 2015). However, as buildings with engineered mass timber (layers of wood bonded together) products are gaining popularity worldwide, misconceptions about the characteristics and potential of this construction material are also growing.

Low-embodied carbon prefabricated modular construction systems (see Figure 1), using engineered solid wood panel construction, and “design for disassembly” principles will offer significant opportunities for greenhouse-gas emission reduction and waste avoidance, among other benefits (Lehmann, 2013, 57). With the rapid adoption of mass timber, associated research and development is further advancing wood construction in commercial markets. In 2007, when the European trend of building with mass timber, such as cross-laminated timber (CLT), first sparked interest in the Canadian and Australian construction sectors. At this timber, there were few experts in the field. Most contractors underwent a phase of learning-by-doing on early projects and gained their knowledge from mistakes or the experiences of others. Today, developers and industry stakeholders continue to hold tentative opinions about the risks and rewards of mass timber adoption that deserve a closer examination (Kremer et al., 2019).of the lamellae. Some panel layup configurations also include edge-gluing where adhesive is applied between the boards in a single layer. Once these steps are completed, CLT panels are ready to undergo quality control and finally customization and shipping.

Figure 1: A lightweight CLT panel is hoisted into position: a mass timber construction project in the US, using CLT panels and glulam beams (courtesy of Lever Architecture, 2023).

There is no doubt modular mass timber construction can offer distinct advantages, and it is increasingly attractive to designers, engineers, developers, and builders, for numerous reasons. With built examples of over 1,600 mass timber projects in the last

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decade in the US alone (WoodWorks, 2023); analysts estimate that mass timber's share of the global construction industry in 2027 to be at US$2.5 billion with a growing community of experienced designers, engineers, members of academia, developers and builders who have completed multiple projects, and new pressing questions. So, it appears to be an appropriate time to ask: What are the remaining research and knowledge gaps that will need to be filled in the coming years? What is the current state of affairs and what are the biggest issues facing the mass timber industry? If one wants to understand where the challenges are, one has to speak with the industry leaders and experts closely involved in the next generation of mass timber projects. What do the industry leaders think are the most important issues facing the industry today?

There is a need to find answers to these questions and examine the policies and initiatives in place to encourage the uptake of mass timber construction, efforts to source it sustainably, and the recent advances in engineering to suit a diversity of building typologies and locations. A recent international mass timber conference provided the opportunity to find answers. From the conversations, it became clear that there is a real need for more focus and coordination of research activity, to avoid unnecessary duplication of research efforts and much overlap of work being done internationally. For example, it is widely believed there is a need for research into fire performance, fire resistance, seismic performance, or sound transmission, whereas most experts within the mass timber sector agree that these areas have been extensively explored and widely resolved. For example, most questions have been answered concerning seismic performance research and earthquake testing, where even full-scale tests have been conducted. A 10-story mass timber "rocking" frame, designed to be resilient enough to withstand powerful earthquakes with little or no structural damage, proved its worth in May 2023 during seismic simulations at the largest high-performance outdoor shake table. Through these tests at the University of California San Diego, ways have been identified to build tall wood structures in seismically vulnerable areas that are earthquake-proof (See Figure 2).

Figure 2: Extensive research in seismic performance has been conducted. The image shows the 34 metres tall (122 ft) test structure with mass timber rocking walls on a shake table at UC San Diego simulating earthquakes of magnitude 7.7 (Image: courtesy UC San Diego, 2023)

Early tests of the structure conducted in 2023 have been successful, receiving positive feedback from experts, indicating promising prospects for the future of mass timber buildings. In a simulation carried out in early May 2023, researchers replicated two significant earthquakes from recent history. These included the 6.7 magnitude Northridge earthquake, which occurred in California in 1994, as well as the 7.7 Chi-Chi earthquake which struck Taiwan in 1999. Whilst the testing results have not been released at the time of writing, the ultimate goal of the TallWood project is to showcase the capability of large wooden buildings to withstand earthquakes and outperform structures made of concrete, brick, or steel (Shiling, 2023).

A growing number of very informative and practical manuals and design guides have recently been published and are available online (Softwood Lumber Board, 2018; Green and Taggart, 2020; Think Wood, 2022; Forest Business Network, 2023; WoodWorks, 2023; Lever Architecture and Atelier Ten, 2023). Consequently, the focus has shifted towards new research questions, including in the areas of carbon storage, durability, supply chain, and other pressing themes. The carbon sequestration and storage benefits of wood have been widely researched and documented (Duan et al., 2022). If a tree naturally falls and disintegrates back into the earth, it releases the carbon back into the atmosphere, which it absorbed through its growing life. However, if the wood is sustainably harvested, the carbon remains captured in its structure forever. One cubic meter of timber stores one ton of carbon. One ton of carbon is the equivalent of carbon produced by 4.5 cars with normal driving for a year. The carbon embodied in the structure represents the same amount of carbon from cars driving for a year.

There are now several research centres worldwide working on focussed areas of mass timber research, and the authors feel that offering them some guidance on the research needs will be useful. Finding and describing the most critical gaps is also likely to help in directing future research funding, increasing the impact of the research globally, and improving project outcomes.

2. Growing in Popularity while Knowledge Lagging Behind

The introduction of mass timber construction technology over the last 30 years is a story of successful industry transformation, with Cross-laminated Timber (CLT) being the industry's preferred product. The mass timber movement started in the early 1990s in Europe (mostly in the Vorarlberg region of Austria, and in Southern Germany) and was soon picked up in countries with a sustainable forestry system and high-quality architectural profession, including Austria, Germany, Switzerland, Sweden, Norway, Finland, Italy, France, the UK, Australia, New Zealand, Japan, and Canada. The authors have been involved in mass timber research for over twenty years. Mass timber is now rapidly conquering the United States; where currently at the time of writing (May 2023) over 1,700 projects using mass timber have been built or are now in the pipeline of delivery. The list includes timber buildings up to 18 stories tall.

Up to 2007, most of the research focus was on the processes and challenges of design and delivery of timber construction, which was then in its early stages. Julius Natterer (1938-2021) in Lausanne, Hermann Kaufmann (1955-) in Munich, and Andrew Waugh (1957-) in London were the first to design and build large-scale timber projects as urban infill for inner-city sites; this changed the way we thought about wooden buildings. They are the pioneers of modern timber construction, establishing wooden buildings as an alternative for contemporary urban applications. Some of the earliest research papers were by Lattke and Lehmann in 2007 (who focussed on technical aspects of timber usage for multistorey residential buildings in Europe), and Lehmann's 2012 paper, which examined the viability of mass timber buildings in Australia through eight case studies from a technical and regulatory framework perspective; and more recently Kurinski et al. (2022) examined the global approaches to standards development across regions of the world to ensure harmonisation in standards in design and fabrication to accelerate the uptake for adoption of mass timber.

During the last decade, an avalanche of articles and papers on mass timber construction has been published, and there is now a good understanding of the many benefits mass timber construction can offer. Such recent research has concentrated on panel manufacturing, fire performance, structural performance, connections and system assembly, acoustics, vibrations, seismic performance, and the environmental benefits of using mass timber (Gagnon and Pirvu, 2011; Green, 2012; Bernheimer, 2015; Mayo, 2015; Kolb, 2018; Kaufmann et al., 2018; Wilson, 2018).

The regulatory frameworks and building codes in numerous countries have been updated to allow for multistorey wooden structures. However, there is still much Research and Development (R&D) that needs to be done to create the relevant new knowledge, positive impact, and scientific evidence that is required to improve the application of mass timber. To be useful, research should aim to deliver real impact, transforming practice and improving the application and performance of existing technologies. To move the mass timber industry in North America (and elsewhere) forward, it is essential to fill the remaining knowledge gaps and concentrate work on the most pressing research needs.

Numerous research centres and research groups have been established worldwide (often in partnership between industry, government, and universities) to further explore mass timber technology, and it is now important to focus on the research that is truly needed and will make a real difference. In March 2023, the authors met with 20 industry leaders at the 7th International Mass Timber Conference in Portland, Oregon (USA), to hear their thoughts and views about the most urgent research that is still required (see Figure 3). They were able to speak with a diverse group of people and industry leaders with expertise in mass timber and an overview of the state of research – particularly in the application of Glued-laminated Timber (GLT) and Cross-laminated Timber hybrid systems (please refer to the list of discussants in Acknowledgments).

3. A Rapidly Growing Body of Knowledge

Given the rapid uptake of mass timber, despite its relative newness, we need to consider what questions to ask and which areas to prioritise. Over the last five years, there has been a rapidly growing body of knowledge and refinement of the evidence on mass timber buildings' additional potential. From the building owner's perspective, the most obvious benefits include capturing higher lease rates, with lower tenant turnover, and demonstrating further advantages for the owner's return that result from shortened schedules. A 25% reduction in the overall construction schedule is now the norm. As carbon credits have emerged as a relevant theme, much work is dedicated to further quantifying the cost-benefits and confirming the value proposition – including cost comparisons with other structural systems, as well as carbon storage capabilities and whole building-lifecycle evaluations – to evaluate the benefits of mass timber over a longer period. When we build with timber, it locks up carbon that is stored in the wood until the building is demolished and the timber burns or decomposes.

Calculating embodied carbon must include several factors, such as the carbon footprint of other materials used to construct wooden buildings and the interior finishes. Indeed, major global city centres, such as New York City, have recently implemented strategies which go beyond the building codes and standards to accommodate a "climate resiliency" overlay for projects to include carbon accounting measures (see The Climate Resiliency Design Guidelines, 2020). Calculating embodied carbon, carbon storage and biogenic carbon sequestration are still relatively new research areas for building projects, and this field is rapidly evolving (Kremer et al., 2019).

In the last ten years, building codes have changed in numerous countries, allowing in some for up to 18-storey wood buildings. In France, for example, public buildings are now mandated to use bio-based materials, as well as lifecycle embodied-carbon analysis for new residential buildings, schools, and selected commercial building types, with limits set to tighten in stages by 2027 (Assemblée Nationale in March 2022; Bill Number 5166). In Sweden, lifecycle embodied-carbon calculations are now a precondition for planning permission for new buildings. Some of the most pressing knowledge gaps mentioned repeatedly by the experts include durability, specifically moisture control, building moisture monitoring and treatment of feedstock, and questions about forestry's ability to support the progression of mass timber (Franklin et al., 2018). Cost is always a key consideration when embarking on a new project or technology, and mass timber's popularity is not helped by the fact that it can still be more expensive than conventional building materials. Besides the question, almost everyone outside the design and engineering sector asks when considering mass timber, "How much does it cost?", one issue that arose repeatedly is related to the construction labour force: the industry's labour shortages and the need for training, knowledge, and skills development. For future growth of the mass timber market share, a larger and more skilled labour force is paramount. Training existing employees can overcome this shortage of skilled workers in the sector or recruit workers from outside – and these solutions are linked to economic factors.

In Europe, training specific to mass timber has been incorporated into apprenticeship programs, mostly through on-the-job experience (for example, the University of Applied Sciences in Rosenheim, Germany; and Bern University in

Switzerland provide such training), and new specialist skills in interdisciplinary teamwork. A broad network of experts is the foundation for careers in fabrication, construction, and design. There are currently around 70 CLT-panel manufacturers worldwide (despite the excitement around mass timber, modular construction and the investment in CLT panel manufacturing is not without risk, as recent closures of manufacturing plants show: Katerra in North America in 2021, followed by Legal & General in the UK and Structurlam in Canada in 2023, had to halt panel production at their loss-making modular prefab-housing factories, casting financial doubts over the sector's prospects if modular can deliver at scale).

In the US, Germany, Canada, and Australia, an increasing number of dedicated research institutes are supporting the mass timber industry, such as the Oregon-based Tall Wood Design Institute (TDI). Iain MacDonald, director at TDI, is cautiously optimistic about future research in mass timber: "Looking five years down the road, I see a lot of opportunities for mass timber construction. However, the degree and speed of adoption of mass timber from its current niche status to the mainstream are yet to be determined. The sector will grow much faster if we can address the two big issues – fibre supply and workforce skills and numbers" (2023).

Efforts to enhance training in several countries, outside of the European Union, have focused on the delivery of mass timber projects, such as in Australia the Box Hill Institute, which offers a course in Prefabricated Timber Installation and Project Management that began in 2017; and more recently the WoodWorks Mass Timber Installation Curriculum for those in the United States. These programs are positioned at the vocational level, and the higher education sector has yet to see a significant uptake in mainstream programs. The training of a higher-skilled workforce will be an important predictor of the success of mass timber in locations outside of seeded locations and countries, like the EU, Australia/New Zealand, and parts of Asia (Singapore, for example).

4. Zero Waste Construction

A major criticism of the global construction sector is that it does not engage enough with waste minimisation, waste avoidance, and recycling. The issue of construction and demolition (C&D) waste is a serious one, as over 35% of all waste in the U.S. and European countries is generated by C&D activities. The building sector is the greatest consumer of raw materials, and only a very small amount of it is ever being reused. Most of the C&D waste ends up in landfill or is being burnt. Furthermore, around 20% of all building materials and products are never used on-site, but discarded (Lehmann, 2011).

Finding new strategies to reduce the wasteful practice has become essential, and panelised forms, kit of parts, and full modular volumetric construction allow for flexibility in design ultimately aiming for disassembly (a concept known as cradle-to-cradle in Life Cycle Analysis) as a helpful concept to minimise construction material use and waste. Therefore, a priority should be on advocating for reduced consumption and minimising the use of construction materials, as well as adaptive reusability of existing structures and components, rather than focusing on recycling. This is not because recycling is less valuable, but merely because recycling systems and sustainable waste management tend to legitimise and sometimes even justify our continuous over-consumption. Making sure our structures are highly efficient and reusable, reducing waste, and using salvaged materials must be part of the solution. The key philosophy that should be adhered to here is to use the right material, in the right quantity, for the right purpose in the building. The over-consumption of material, even mass timber, for the sake of its use extends beyond responsible use, into misuse, and contributes to the waste problem, not solving it.

The growing trend in adaptive reuse of existing structures offers a real field of application for mass timber. Lightweight timber construction often allows adding a couple of floors on top of existing structures, making adaptive reuse more profitable for the developers. It is also a way to meaningful way to tackle the embodied carbon problem when considering "retrofit first" in all new proposals as a first step and including a whole-of-life carbon assessment as a key decision-making metric when assessing proposals for adaptive reuse.

5. State of the Research and Identified Knowledge Gaps

The following part of the article is the outcome of a series of recent expert conversations; its purpose is to deliver an assessment of research needs and provide guidance for architects and engineers working with mass timber construction. Prioritising research needs and R&D is important because it ensures that the industry can continue to evolve. Most experts we spoke to share the opinion that some research areas have been well covered and are now less of a focus area, such as fire performance or acoustics. They believed optimised solutions in these areas are known and available. However, knowledge gaps appear to exist in various other interconnected areas, and the most frequently mentioned research topics are included in the following list of research needs in seven areas.

Based on the conversations of the industry peers, we can see the following trends when assessing the current state of knowledge, the following gaps were identified. These are suggested to further the development of 'mass timber systems' performance in specified areas. The comments made can be separated into the following categories (see Table 1; the categories are in no particular order).

In particular, the Research Areas (RA) listed above, with their missing "research pieces", can be described in more detail, based on the expert's opinions:

Research Area 1.1 Forest management and transparency in the supply chain. It makes sense to start the research in the forest and examine whole-lifecycle carbon; carbon storage; there is too much greenwashing; opportunities for a circular economy; understanding the value chain optimisation; increasing productivity through forest investment; carbon impacts. Wood products are only as sustainable as the forestry practices associated with those products; thus, it is important to consider material sourcing and transportation carbon impacts (see Figure 4).

Forestry restoration can drive environmental stewardship.

Table 1: A list of the seven research areas that were mentioned most frequently in 20 conversations about future research requirements and questions to be further investigated (2023).

Categories of future research areas required to fill the most pressing knowledge gaps	The frequency of this topic was mentioned in 20 discussions
1.1 Forest Management and Transparency in the Supply Chain	Frequently n = <10
1.2 Collaboration; Education and Awareness; Workforce Skills	Very frequently n = >10
1.3 Technical Innovation and New Products	Frequently n = <10
1.4 Building Physics Improving the Durability (moisture), Dimensional Stability, and Longevity of Wooden Structures	Very frequently n = >10
1.5 Architectural and Structural System Design for Disassembly and Modularity	Frequently n = <10
1.6 Quantifying Biophilia and Health Benefits	Frequently n = <10
1.7 Analysis of Case Studies and Built Examples with Real Data; Post-Occupancy Evaluation; Whole-lifecycle Carbon and its Economic Implications	Very frequently n = >10

Sustainable forest practices and resource management are highly relevant for the future of mass timber and will determine the industry's success in the long run (Richards, 2023). Wood is a limited resource, and the carbon footprint of any mass timber construction is impacted by how and from where the wood was sourced and transported. If the industry can increase the volume of mass timber projects and scale up panel production will largely depend on the successful management of forests and the supply chain, balancing the supply and demand of mature trees and suitable timber resources, all responsibly harvested (preferably from close by to avoid long transport). With better-managed forest resources and the planting of the most suitable species (using more selective harvesting), the timber yield could be greatly increased. Waugh (2023) points out that we need to get better at using timber by burning less and being more efficient. For example, in Europe, around half of the trees that are cut down are turned into wood pellets to be burned as so-called 'renewable bioenergy'. This is an immense waste of a precious, finite resource and it is unsustainable. Mass timber has the advantage that it can use small and lower-quality trees than traditional wood construction (which depends on more mature trees); this creates a commercial incentive for harvesting and utilising smaller trees (FBN, 2023).

Research Area 1.2 Collaboration; education and awareness. Ways to improve the collaboration between all stakeholders. Currently, training programs that deliver a skilled workforce are missing. Thus, the timber construction industry is held back by "a lack of skilled craftsmen and technical knowledge, which can have a detrimental effect on building quality", according to Hermann Kaufmann (after Hahn, 2023). Early engagement between the architect and the timber panel fabricator is crucial to streamline and optimise the design process and to secure the fabrication time window to meet the project construction schedule.

Research Area 1.3 Technical innovation and new products. Next-generation manufacturing: improved short or long-term performance and functionality, adhesive technology, developing improved or new products (such as composite products), refining existing technologies. More in-depth research is needed on the possibilities and limitations of timber construction. Expanding and opening new markets for wood products. An important part of this research category includes the exploration of bio-based alternative materials, such as wood-based composites; building with fewer resources; using more bio-based materials. Coordination of the research that is being conducted globally is required. The notion of development for an international hub could be proposed to ensure resources are aligned to projects and thus reduce the considerable overlap. However, to also ensure the portability of resources to "activate" markets that are yet to engage with mass timber are ready and available. Increases in building height and scale call for higher capacity connections, new products, and better construction details. There is always a need for research and innovation in connections and subsequent testing to validate their performance and the development of design guidelines. Hybrid structural systems can pose a challenge in terms of accuracy: the interface tolerances between different materials (timber – steel – concrete) must be considered in the design and specifications.

Research Area 1.4 Building physics to improve the durability and longevity of wooden structures. The durability of mass timber construction is often questioned by the public as wood is traditionally viewed to be less resistant to environmental deterioration compared to steel and concrete. A better understanding of construction science and building physics is needed, to improve the durability and longevity of wooden buildings, especially moisture content management and avoidance of decay. Biological threats include beetles, fungi, termites, mildew, and moisture impact. Using the naturally most durable species of wood. Wooden buildings designed for the tropical climate or other extreme climate zones, climatic suitability. Design for longevity and durability, such as weather protection, treatments, reducing the dangers of water ingress, and avoiding trapped moisture through ventilated wood structures. Using timber only where it makes sense as a material. The increased complexity and precision required for timber construction pose a challenge for the industry. If a mass-timber building is not properly waterproofed, it can cause the build-up of moisture inside walls, which can quickly result in the structure deteriorating. The research should include an investigation into the longer-term efficacy of moisture monitoring devices as a network of sensors installed on the waterproof membrane to monitor moisture content trends and schedule repairs. Targeted structural monitoring uses sensors at critical locations for long-term structural health monitoring. This can be achieved in concert with the treatment of lamella feedstock used in the production of mass timber products for designated wet-area locations. Extending the lifespan of our buildings, repurposing existing structures, and improving durability are essential components of future mass timber. Making buildings out of wood rather than concrete requires architects to take a fundamentally different approach to design that includes structural thinking and moisture management from the beginning (Waugh, 2023).

Research Area 1.5 Architectural and structural system design for disassembly and modularity. This includes research on modular system thinking and the circular economy, concerning design versus structural and spanning capabilities, and decision-making on structural grids. Grid optimisation through structural analysis to improve decision-making on column spacing and span distance can lead to a significant reduction (up to 30%) in material use (e.g., using CLT panels with fewer plies), shallower beams and weight reduction, which leads to lighter building mass and smaller foundations. Zero-waste construction (minimising waste, reuse, and recycling); hybrid construction to increase spans; comparative case studies of retrofits (including economic calculation tools for better decision-making and cost-benefit analysis). Connections and penetrations. Volumetric modules. Retrofitting; reuse of components; replacement and repair. End-of-life treatments and deconstruction, including the cradle-to-cradle concept of building repurposing. This research domain is less about increasing building heights, but about finding other ways of measuring the success of a timber building, such as its carbon storage, aesthetic qualities, and speed of construction. It is also about finding smarter and more material-efficient ways to build. This means embracing the hybrid nature of mass timber construction as a complex system and "assemblage" that can combine different structural methods. Research shows that mass timber is most efficient in mid-rise construction with three to seven stories; this is the housing segment that is frequently referred to as the "missing middle" (Softwood Lumber Board & Forestry Innovation Investment, 2018). Despite the material's many advantages, the affordability of mass timber housing is still a challenge. To deliver more affordable multistorey, multifamily housing projects in mass timber requires that the industry develop standardised, repeatable, and rapidly installable solutions. This requires a focus on repeatable, adaptable, and up-scalable multifamily housing prototypes for middle-income demographics.

Research Area 1.6 Quantifying biophilia and health benefits. Long-term effects of biophilia on human health. Quantifying biophilia and its health benefits examining the physiological and psychological responses of people exposed to biophilic elements including natural mass timber surfaces. What is less known is the longer-term effects of biophilia on human health and the sustained benefits that individuals experience from biophilic environments over extended periods. Research into the incorporation of biophilic elements into workplaces, apartments, schools, and homes can have lasting positive effects on occupant well-being, leading to improved health outcomes and increased productivity. Quantifying occupants' health (especially after the COVID pandemic of 2020–22) includes research on well-being, and how to measure the impact through research on post-occupancy evaluation (POE) behaviour. Indoor air quality and the impact of adhesives on the indoor environment especially in conjunction with passivhaus treatments or the natural airtight qualities of mass timber buildings (due to the precise way in which elements are manufactured and assembled). There is still a lack of financial incentives for making the switch from concrete and steel to mass timber construction, and this research could help remove the barriers.

Research Area 1.7 Analysis of case studies and built examples with real data. Post-occupancy evaluation; whole-lifecycle carbon and its economic implications; lifecycle assessments; embodied carbon. Lessons must be learned from failures. The mass timber sector will need a diverse range of project types that can serve as reference points for developers and contractors, including overbuild/vertical extensions, kit of part solutions, panelised and volumetric/exoskeletal solutions. Research in analysing and comparing new developments, designs, and projects will always need to accompany this innovative industry. An ongoing analysis of the performance of mass timber precedents. This will involve sharing best practices, so that all stakeholders can better understand the benefits and challenges, and the optimised systems can become mainstream.

Mass timber construction can be an important pathway toward carbon-neutral buildings, but there are always other critical factors that need to be considered. As mentioned in the final area listed above, new comparative analysis of case studies, post-occupancy evaluation, and ongoing monitoring will continue to add much-needed new insights to the constantly growing body of knowledge on mass timber construction. For example, the recently published "Mass Timber Performance Index" (2022) aims to provide the latest information on mass timber capacity, production, and cost factors from around the world and is now recognised as an important resource (Anderson and the Beck Group, 2022).

One of the findings of this article is that embedding C&D waste avoidance and waste reduction concepts requires strong industry leadership, new policies, and effective education curricula, as well as raising awareness (through research and education) and refocusing research agendas to bring about attitudinal change and the reduction of wasteful consumption. The whole-lifecycle carbon approach will become increasingly relevant in the coming years; however, it requires more research. It breaks down the lifecycle of a building into stages, including the pre-construction and design stage, construction stage, in-use phase, and the end-of-life, reuse, and recovery stage. This approach also evaluates the upfront-embodied carbon associated with sourcing the wood, manufacturing, and transporting mass timber products (See Figure 3).

Design for disassembly and building circularity has emerged as a new field where all materials and components can be reused. A good case study for this is Matrix ONE, 2023 completed office building by MVRDV, Amsterdam, the Netherlands (See a short video on YouTube: https://www.youtube.com/watch?v=kADrLd34Oh8). The Matrix ONE building has been designed to be demounted at its end-of-life, and all 120.000 parts of the building are demountable and registered in the Dutch material database Madaster (See Figure 5).

Figure 3: The International Mass Timber Conference in Portland (Oregon, USA) has emerged as the prime annual venue for mass timber experts to meet (Photo by the authors, 2023).

6. Conclusion

The present article aims to provide helpful information on the current needs of mass timber research and what the industry professionals think about the knowledge gaps. To identify the most pressing research question, experts at the conference were consulted, and seven key research areas have been identified and presented (see Table 1).

The mass timber industry has continuously evolved and matured over the last 30 years and now appears to be at a crossroads, with big questions that need to be answered to move the industry forward. The authors urge a coordinated deep dive into the identified knowledge gaps, to assure sustained success for the mass timber industry. Therefore, the article provides seven priority research areas that focus on long-term application, including sustainable forest management, circular economy principles, and supply chain; interdisciplinary collaboration and workforce skills training; technical innovation to enable new products; durability through appropriate building physics; recognising mass timber as evolving, with new modular systems for disassembly; measuring and quantifying biophilia and health benefits; and the ongoing performance analysis of built mass timber projects. The identified questions and research areas are all intertwined and need a coordinated R&D approach, rather than seeing them as separate challenges. Part of it relates to scalability, clarifying the limits of supply and demand, and strengthening mass timber's value proposition by making it more affordable.

Throughout the last two decades, the mass timber-building sector has experienced steady growth in terms of multistorey construction volume, and research in specific areas is now needed to ensure future advances. An increasing amount of literature, in the form of research papers, scientific articles, books, and design-related comparative case studies, has been

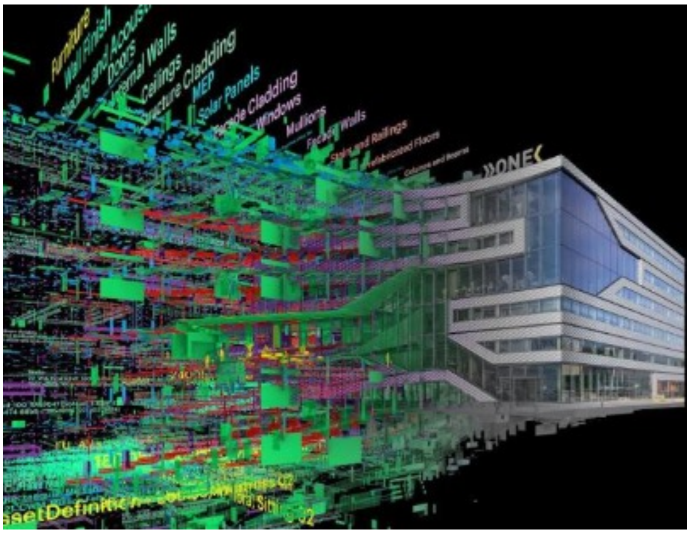

Figure 5: Office building 'Matrix ONE' in Amsterdam, The Netherlands, is the first large building designed for disassembly. (Courtesy MVRDV Architects, 2023)

published on the benefits, strengths, trends, challenges, opportunities, and disadvantages of timber construction, from various technical perspectives. However, the research seems to lack overall coordination, and knowledge gaps are becoming barriers to widespread adoption. Despite major advances and a growing number of publications, until recently, very few comprehensive, comparative design studies have been conducted (Svatoš-Ražnjević et al., 2022).

As the mass timber construction and modular industries are maturing, innovative projects have been realised; and as more mass timber panel manufacturers join the market, the research and knowledge base will continue to grow. While steel and concrete have their place in the construction sector, architects, engineers, developers, and builders will likely have much to gain by increasing the application of mass timber in the built environment. The research challenges that remain unaddressed, could potentially hinder the future adoption of mass timber.

The article provides a "pulse check", reports on and summarise the feedback received, and identifies seven critical areas of pressing research needs where an intensification of research should occur, to advance and deliver the required knowledge. As an agreement seems to be emerging on the most critical knowledge gaps, this list should inform the research programs of existing research centres and guide the future allocation of limited research funding. The study has shown that better overall coordination of research efforts in these seven domains is required to avoid duplication, as well as a more nuanced discussion on the research needs of the industry in general, to truly capture

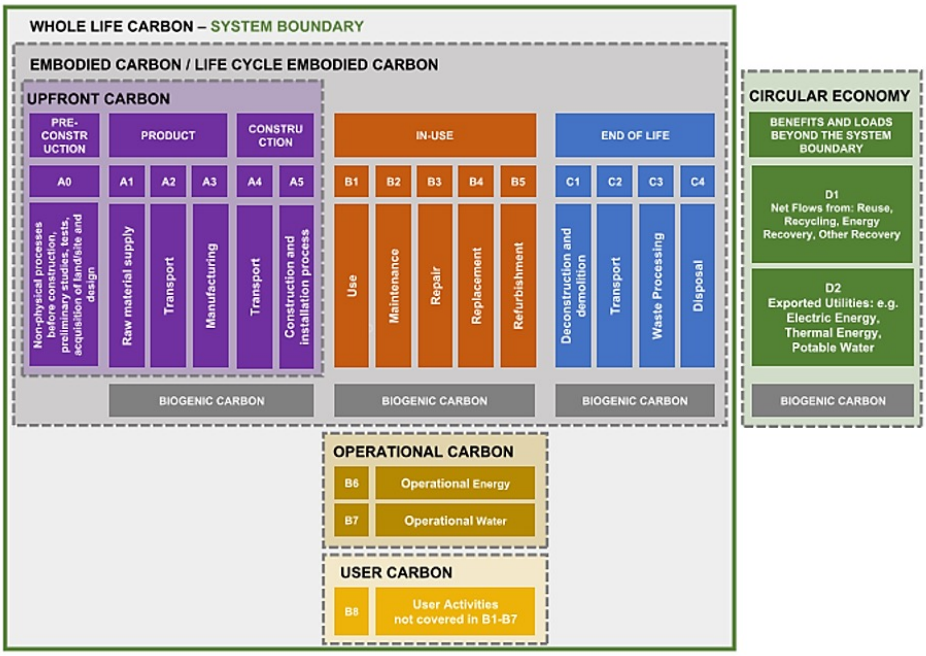

Figure 4: The established Whole-Life Carbon lifecycle schema (Courtesy: RICS, UK, 2023).

the full potential of wood as an innovative construction material. Industry and academia have already started on the right path with research that is useful, practical, and creates a real positive impact. Facilitating the broad adoption of mass timber will require more application-focused research with government decision-makers, investors, and industry practitioners to join forces to remove the cost, code, and policy obstacles currently standing in its path.

It is recommended that future mapping of mass timber research inventory would help policymakers, engineers, and architects to prioritise specific systems and technologies based on their effectiveness in mitigating climate change, enabling flexibility for future repurposing of buildings, and supporting research to fill critical gaps for informed decision-making.

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Conflicts of Interest

The authors declare no conflict of interest.

Some Useful Websites of Timber Organisations

dataholz.eu
proholz.at
swedishwood.com
softwoodlumberboard.org
thinkwood.com
timberarchitecture.com
woodsolutions.com.au
woodworks.org
www.iamtc.org

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