

UNIVERSIDADE DE LISBOA
INSTITUTO SUPERIOR TÉCNICO

**Sustainable Construction: The role of high-rise timber buildings
requirements during the life cycle of a building**

Elżbieta Jadwiga Hamadyk

Supervisor: Doctor Miguel José das Neves Pires Amado
Co-Supervisors: Doctor Jorge Manuel Calião Lopes de Brito
Doctor Alfredo Manuel Pereira Geraldês Dias

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Abstract

The construction industry faces increasing pressure to reduce its environmental impacts in response to global urbanization, climate change and finite natural resources. This thesis investigates the potential of tall and high-rise mass timber buildings as a sustainable alternative to conventional steel and concrete systems. Through a holistic and life cycle-based approach, the research explores mass timber's environmental, technical, regulatory and societal dimensions, from forest management and material selection to design, construction, use and end-of-service stages.

The adopted methodology combines a systematic literature review, comparative analysis of contemporary case studies and synthesis of performance data across critical domains, including structural, fire, thermal, acoustic and seismic behaviour. The research identifies key benefits of mass engineered timber, such as carbon sequestration, low embodied energy, material renewability and prefabrication efficiency, alongside persistent challenges, including fire safety, moisture control, sound insulation and lateral stability in seismic zones.

A core contribution of the thesis is the development of a structured framework of guidelines for the sustainable design and construction of high-rise timber buildings. These guidelines are organized into five sequential life cycle stages (strategy, product, design, construction and use/end-of-service) and are explicitly linked to relevant stakeholders involved in the building process. This framework directly addresses the central research question: "What are the requirements for the sustainable design and construction of high-rise timber buildings?".

By translating complex interdisciplinary knowledge into actionable strategies, the guidelines intend to support architects, engineers, contractors, developers and policymakers in implementing high-performance timber solutions. The thesis emphasizes that the transition to mass timber must be accompanied by code development, educational investment and industry-wide collaboration.

Ultimately, this research contributes to a growing body of knowledge advocating for mass timber as a cornerstone of sustainable urban development, promoting a low-carbon, resilient and circular built environment.

Key words: high-rise timber buildings; engineered timber; sustainable construction; life cycle design, guidelines.

Resumo

A indústria da construção enfrenta uma pressão crescente para reduzir os seus impactos ambientais, em resposta à urbanização global, às alterações climáticas e à escassez de recursos naturais. Esta dissertação investiga o potencial dos edifícios em altura em madeira como alternativa sustentável aos sistemas convencionais em betão e aço. Através de uma abordagem holística e baseada no ciclo de vida, a investigação explora as dimensões ambientais, técnicas, regulamentares e sociais da construção em madeira, desde a gestão florestal e seleção de materiais até às fases de projeto, construção, utilização e fim de vida útil.

A metodologia adotada combina uma revisão sistemática da literatura, análise comparativa de casos de estudo contemporâneos e síntese de dados de desempenho em domínios críticos, incluindo comportamento estrutural, resistência ao fogo, desempenho térmico, acústico e sísmico. A investigação identifica as principais vantagens da utilização da madeira projetada, como a capacidade de captura de carbono, baixa energia incorporada, renovabilidade do material e eficiência na pré-fabricação, a par de desafios persistentes, incluindo a segurança contra incêndios, o controlo da humidade, o isolamento acústico e a estabilidade lateral em zonas sísmicas.

Uma contribuição central desta dissertação é o desenvolvimento de um quadro estruturado de diretrizes para o projeto e construção sustentáveis de edifícios em altura em madeira. Estas diretrizes estão organizadas em cinco fases sequenciais do ciclo de vida (estratégia, produto, projeto, construção e uso / fim de vida) e estão explicitamente associadas aos intervenientes relevantes no processo construtivo. Este quadro responde diretamente à questão de investigação central: “Quais são os requisitos para o projeto e construção sustentável de edifícios em altura em madeira?”.

Ao traduzir conhecimento interdisciplinar complexo em estratégias aplicáveis, estas diretrizes visam apoiar arquitetos, engenheiros, empreiteiros, promotores e decisores políticos na implementação de soluções em madeira de alto desempenho. A dissertação sublinha que a transição para a construção em madeira deve ser acompanhada por uma atualização dos códigos normativos, investimento em formação e colaboração transversal no setor.

Em síntese, esta investigação constitui um contributo relevante para o avanço do conhecimento na área da construção sustentável, consolidando o papel da madeira estrutural maciça como pilar essencial para o desenvolvimento urbano sustentável, promovendo um ambiente construído mais resiliente, a circularidade e com baixas emissões de carbono.

Palavras-chave: edifícios em altura em madeira; madeira estrutural maciça; construção sustentável; design ciclo de vida; diretrizes.

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List of abbreviations, acronyms and symbols

AI	Artificial Intelligence
ASCE	American Society of Civil Engineers
ASTC	Apparent Sound Transmission Class
BIM	Building Information Modelling
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Method
BRI	Building Research Institute
C-CLT	Circular Cross-Laminated Timber
CE	Circular Economy
CEN	European Committee for Standardization
CFRP	Carbon Fibre-Reinforced Polymer
CLST	Cross-Laminated Secondary Timber
CLT	Cross Laminated Timber
CLTE	Coefficient Of Linear Thermal Expansion
CNC	Computer Numerical Control
CO ₂	Carbon Dioxide
CO ₂ e	Carbon Dioxide Equivalent
CORRIM	Consortium for Research in Industrial Renewable Materials
CPR	Construction Products Regulation
DfA	Design for Adaptability
DfD	Design for Disassembly
DfR	Design for Reuse
DLT	Dowel-Laminated Timber
D _{nTW}	Weighted Standardised Level Difference
EEA	European Economic Area
EPD	Environmental Product Declaration
EPDM	Ethylene Propylene Diene Monomer
ETA	European Technical Assessment
EUTR	European Union Timber Regulation
FBD	Force-Based Design
FIIC	Field Impact Insulation Class
FPL	Forest Products Laboratory
FRT	Fire Retardant Treatments
FSC	The Forest Stewardship Council
FSR	Flame Spread Rating
GCWood	Green Construction through Wood
GDP	Gross Domestic Product
GEM	Global Earthquake Model

GHG	Greenhouse Gases
Glulam	Glued Laminated Timber
GlulamST	Glued Laminated Secondary Timber
GWP	Global Warming Potential
HDF	High Density Fibreboard
IBC	International Building Code
ICC	International Code Council
IDP	Integrated Design Process
IIC	Impact Insulation Class
ISO	International Organization for Standardization
ITTO	International Tropical Timber Organization
JIT	Just-In-Time
L'_{nTW}	Weighted Standardised Level Difference of Impact Noise
L'_{nW}	Weighted Normalized Impact Sound Pressure Level
LCA	Life Cycle Assessment
LDF	Low Density Fibreboard
LEED	Leadership in Energy and Environmental Design
LSL	Laminated Strand Lumber
LVL	Laminated Veneer Lumber
MCE	Maximum Considered Earthquake
MCPFE	Ministerial Conference on the Protection of Forest in Europe
MDF	Medium Density Fibreboard
MET	Mass Engineered Timber
MPs	Material Passports
MTB	Mass Timber Building
MTC	Mass Timber Components
NBCC	National Building Code of Canada
NFPA	National Fire Protection Association
NIED	National Research Institute for Earth Science and Disaster Resilience
NISR	Normalized Impact Sound Rating
NLT	Nail-Laminated Timber
OSB	Oriented Strand Board
OSL	Oriented Strand Lumber
PBD	Performance-Based Design
PBD	Performance-Based Design
PDCA	Plan, Do, Check, Act
PEFC	Programme for the Endorsement of Forest Certification
PGA	Peak Ground Acceleration
PSHA	Probabilistic Seismic Hazard Analysis
PSL	Parallel Strand Lumber

R' _w	Weighted Apparent Sound Reduction Index
RCSM	Reduced Cross-Section Method
R _w	Weighted Sound Reduction Index
SC	Self-Centring
SCL	Structural Composite Lumber
SDC	Smoke Development Class
SDGs	Sustainable Development Goals
SLT	Stress-Laminated Timber
SOG's	Standard Operating Guidelines
STC	Sound Transmission Class
STC	Steel-Timber Composite
STL	Sound Transmission Loss
TCC	Timber-Concrete Composite
TiC	Timber in Construction
WEP	Wood Encouragement Policies

1. Introduction

In face of accelerating climate change, urbanization and resource scarcity, the construction sector is undergoing a profound transformation. Traditional building practices, rooted in the widespread use of carbon-intensive materials such as steel and concrete, are increasingly being scrutinized for their environmental impact. As cities continue to expand and the pressure for high-density urban development intensifies, there is a growing urgency to adopt more sustainable construction methods that align with climate goals and resource efficiency.

Among emerging solutions, mass engineered timber (MET) has gained significant attention as a renewable, low-carbon building material capable of meeting both environmental and performance requirements. Its application in tall and high-rise structures represents a promising yet complex evolution in sustainable architecture, offering the potential to substantially reduce embodied carbon, support circular economy principles and enable modular, prefabricated construction systems.

However, the integration of timber into high-rise construction is still constrained by regulatory, technical and cultural barriers. These include challenges related to fire resistance, moisture durability, acoustic and thermal performance, and seismic stability. Moreover, the industry lacks a unified, life cycle-based framework to guide practitioners through the sustainable implementation of timber in high-rise applications, from forest management and material production to design, construction, use and end-of-service phases.

This chapter introduces the context, motivation and structure of the research. It begins by defining the broader problem—how sustainability intersects with urban growth, climate policy and the construction industry. It then identifies the research gap concerning high-rise timber buildings and sets forth the objectives, research questions and methodological approach adopted in the study. The chapter concludes with a description of the thesis structure, outlining how the investigation progresses from foundational concepts to practical guidelines for sustainable timber construction.

By addressing these issues, this research seeks to contribute a structured, stakeholder-oriented framework, that not only advances academic discourse on sustainable construction but also supports real-world application of timber in the next generation of urban development.

1.1. Background and motivation

The 21st century presents humanity with urgent global challenges like rapid urbanization, escalating climate change and the unsustainable depletion of natural resources (Buhaug & Urdal, 2013; Stocchero et al., 2017; United Nations, 2017, 2018; Zhang et al., 2019). These interconnected pressures are placing unprecedented demands on urban centres and the construction industry, prompting a fundamental rethinking of how mankind designs, forms and maintains the built environment. At the heart of this transformation lies the urgent need for sustainable construction solutions capable of addressing environmental concerns while supporting the demands of a growing global population.

Cities have always been central to human development. From primitive shelters to complex urban infrastructures, the evolution of the built environment reflects mankind's continuous pursuit of safety, comfort and progress. Technological advancements in medicine, energy and transportation have significantly increased life expectancy and quality, accelerating demographic growth and the pace of

urbanization (ARUP, 2019). According to the United Nations, the global population is projected to reach 9.7 billion people by 2050, with nearly 70% residing in urban areas (Buhaug & Urdal, 2013; United Nations, 2017, 2018). This urban shift intensifies the strain on housing, infrastructure and natural ecosystems, underscoring the urgency of sustainable urban development strategies that are both climate-conscious and resource-efficient (Hamadyk et al., 2020; Huang et al., 2018).

The construction industry lies at the intersection of these environmental and urban challenges. It is one of the largest consumers of natural resources and a major contributor to greenhouse gas emissions, responsible for nearly 40% of global emissions over the full lifecycle of buildings (Dias et al., 2020; FAO & UNEP, 2020). In Europe alone, construction accounts for half of all raw material extraction (FAO & UNEP, 2020). Simultaneously, the sector plays an important role by supporting the economic stability, contributing around 9% of the European Union's Gross Domestic Product (GDP) and employing millions across its supply chains (European Commission, 2021). However, the traditional reliance on energy-intensive materials such as concrete, steel and aluminium, continues to exacerbate environmental degradation. These materials demand vast quantities of energy to produce, emitting significant levels of carbon dioxide (CO₂) and accelerating global warming (Pérez-Lombard et al., 2008).

In response to these mounting concerns, the concept of sustainable construction has gained prominence. First formally articulated by Charles Kibert in 1994, sustainable construction promotes the preservation of natural resources, the elimination of harmful materials and the creation of healthy, efficient and resilient built environments (Lucas & Amado, 2012). Kibert's five foundational principles—reduce, reuse, recycle, protect and eliminate—remain highly relevant today. They serve as the foundation for an expanded framework that now incorporates life cycle assessment (LCA), circular economy (CE) thinking and performance-based design (PBD). The evolution of these concepts reflects a broader shift toward integrating sustainability into all phases of the construction process, from resource extraction and material production to design, construction, operation and end-of-life management.

This change is further driven by global policy frameworks such as the United Nations Sustainable Development Goals (SDGs), the Paris Agreement and the European Green Deal, which collectively call for urgent reductions in emissions and a transition toward low-carbon, circular economies (United Nations, 2015, 2018; European Commission, 2019). These initiatives intend to create resilient and inclusive cities, promote renewable energy and decouple economic growth from environmental harm. Within this context, the building sector is increasingly recognized not only as a source of environmental impact but also as a critical vehicle for climate action and sustainable transformation.

Among the most promising innovations in sustainable construction is the emergence of MET. Timber has historically played a foundational role in architecture, but advancements in engineered wood products, such as cross laminated timber (CLT), glued laminated timber (glulam) and laminated veneer lumber (LVL), among others, have transformed it into a viable alternative to steel and concrete in mid- and high-rise construction (Crawford & Cadorel, 2017; Kaufmann et al., 2018). These technologies provide the necessary structural strength while capitalizing on the renewable and carbon-sequestering properties of wood (Kaufmann et al., 2018; Pryce, 2016).

Timber's environmental advantages are considerable. Unlike conventional materials, the production of structural timber requires relatively little energy, resulting in lower embodied carbon

(Forest Products Laboratory, 2010; Sabnis et al., 2015). Furthermore, forests act as natural carbon sinks. When timber is harvested from sustainably managed forests and used in construction, it stores carbon throughout the building's lifecycle, effectively delaying its release into the atmosphere and contributing to long-term carbon reduction strategies. These characteristics position timber not only as a low-emission material but also as an active agent in climate mitigation.

Moreover, timber's lightweight nature facilitates faster and more efficient construction through prefabricated and modular techniques, which reduce on-site waste, limit disturbance to surrounding environments and shorten construction timelines. In urban contexts where speed, space constraints and emissions control are critical, timber offers transformative potential. It enables vertical expansion through lightweight additions and supports densification without the environmental costs associated with heavier construction systems.

There is growing consensus that timber can play a vital role in sustainable construction. International strategies promoting timber align closely with climate action, CE principles and sustainable forest management. Certification systems such as the Forest Stewardship Council (FSC) and Programme for the Endorsement of Forest Certification (PEFC) ensure the ecological integrity of sourcing practices, while green building certifications like Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Method (BREEAM) increasingly reward biogenic materials for their low carbon footprints.

In addition to its environmental performance, timber construction also supports the social and economic pillars of sustainability. It fosters rural development through forest-based economies, promotes healthier indoor environments and reflects biophilic design principles that enhance occupant well-being. As the construction industry seeks to balance affordability, efficiency and sustainability, MET provides a compelling path forward.

Despite these benefits, the widespread adoption of high-rise timber construction remains limited. Barriers include fire safety concerns, acoustic and thermal performance optimization, moisture durability and resistance to seismic events. In many countries, building codes have yet to adapt fully to accommodate mass timber innovations. Additionally, knowledge gaps persist among stakeholders, particularly regarding life cycle impacts, maintenance strategies and integration of timber into circular economic models (Wong et al., 2024; O'Ceallaigh et al., 2021).

In this context, present research is motivated by the urgent need to bridge the gap between the potential of high-rise timber construction and its practical implementation. Ultimately, timber's integration into high-rise architecture is not merely a material substitution—it represents a fundamental reimagining of how humankind builds in harmony with the planet. By leveraging the natural advantages of wood and aligning them with scientific rigor and policy ambition, timber can emerge as a cornerstone of sustainable urban development.

1.2. Problem statement and research gap

As mentioned previously, the construction industry is both a critical enabler of economic development and one of the largest contributors to global environmental degradation. The sector faces the urgent challenge of transforming its practices to align with international climate goals and

sustainability targets. Conventional reliance on high-embodied-carbon materials perpetuates environmental impacts, while growing urban populations and housing demands increase the pressure on infrastructure and resources.

MET offers a promising pathway toward more sustainable construction, combining structural performance with environmental benefits; however, the transition from potential to mainstream adoption remains slow and fragmented. Despite growing interest, several critical barriers hinder the widespread use of timber in high-rise applications:

- Technical challenges including fire performance, seismic resilience, acoustic insulation and moisture durability;
- Regulatory limitations due to restrictive building codes and lack of harmonized standards for taller timber construction;
- Knowledge gaps in life cycle performance, long-term maintenance strategies and integration into circular construction models;
- General lack of knowledge and experience to work with timber among building industry practitioners;
- Stakeholder misalignment, where architects, engineers, developers and policymakers often operate with differing priorities and levels of familiarity with MET technologies.

Existing studies address aspects of timber construction, such as structural performance, environmental benefits, or market trends, but research remains shuttered. There is limited work that integrates all dimensions of high-rise timber construction into a comprehensive, life cycle-based framework that accounts for environmental, technical, economic and social factors. Furthermore, current guidelines are often project-specific or region-specific, lacking the universality required to inform global best practices. This fragmentation limits the ability of practitioners to adopt MET confidently and consistently in high-rise applications.

While there is a growing body of literature on sustainable construction and timber engineering, the following gaps persist:

- Lack of integrated life cycle frameworks that connect sustainable forestry practices, engineered timber product performance and building life cycle management in the context of high-rise construction;
- Insufficient cross-disciplinary synthesis of technical, regulatory and economic remarks into actionable guidelines for practitioners;
- Limited documentation of best practices from existing high-rise timber projects, especially in terms of lessons learned, stakeholder roles and scalability to different urban contexts;
- Underrepresentation of policy and market mechanisms that could accelerate the mainstreaming of high-rise timber construction.

This thesis addresses these gaps by developing a comprehensive, stakeholder-oriented set of guidelines for the sustainable design and construction of tall and high-rise mass timber buildings. By combining literature review, case study analysis and performance assessment across the full building life cycle, the study intends to bridge the divide between the environmental potential of timber construction and its real-world adoption.

1.3. Research aim and questions

To address the identified challenges, this thesis intends to develop a structured framework of guidelines for the sustainable design and construction of tall and high-rise mass timber buildings, grounded in life-cycle thinking and tailored to stakeholder roles.

By synthesizing current knowledge, identifying technical and regulatory challenges and evaluating best practices and emerging trends, the research seeks to provide a structured and interdisciplinary reference tool for professionals engaged in mass timber projects. The guidelines intend to support more effective collaboration between stakeholders, facilitate performance-driven and climate-resilient timber architecture and promote the broader adoption of mass timber as a viable solution for low-carbon, high-density urban development.

Ultimately, the research aspires to bridge the gap between sustainable ambition and practical execution by offering actionable, evidence-based strategies that respond to the growing demand for environmentally responsible construction in the context of climate change, urbanization and the transformation of the built environment. This aligns directly with the main research question:

What are the requirements for the sustainable design and construction of high-rise timber buildings?

This is supported by sub-questions that seek to understand:

How tall timber buildings are designed and built and what critical stages and practices define their life cycle?

What barriers hinder broader adoption of MET in high-rise contexts?

Where are the current knowledge and implementation gaps, and how can these be addressed through coordinated guidelines?

By filling the identified research gaps, the study contributes both academically and practically: it consolidates fragmented knowledge, integrates sustainability with performance and regulatory issues and provides stakeholders with a tool to guide the successful delivery of high-rise timber projects.

1.4. Objectives of the research

The primary objective of this research is to develop a comprehensive, multi-stage framework of guidelines for the sustainable design and construction of tall and high-rise mass timber buildings. These guidelines intend to bridge the gap between sustainability goals and practical implementation, supporting architects, engineers, policymakers and industry professionals in addressing the complex challenges associated with high-rise mass timber construction.

This thesis sets out to respond to the growing global interest in timber as a low-embodied carbon building material and to address the barriers that currently hinder its broader adoption. The research therefore takes a holistic approach, analysing timber use across the full life cycle of a building, from forest management and material sourcing to design integration, construction processes and end-of-life strategies.

The specific objectives of the research are:

- To evaluate the role of MET in contributing to sustainable urban development, particularly in reducing the environmental impact of the construction sector through carbon sequestration, lower embodied energy and circular economy principles;
- To identify and assess key technical, regulatory, cultural and economic challenges that affect the widespread implementation of high-rise timber buildings, with a focus on fire performance, seismic behaviour, acoustic quality, thermal efficiency and moisture durability;
- To examine and synthesize best practices, requirements, barriers and knowledge gaps related to MET construction through a state-of-the-art review and analysis of case studies, material properties, stakeholder roles and lifecycle impacts;
- To structure the findings into an actionable framework of guidelines, categorized into five key project stages: strategy, product, design, construction and use/end-of-service, thus providing a tool that supports interdisciplinary collaboration and decision-making across the entire value chain;
- To map each guideline to the relevant stakeholders, clarifying responsibilities and promoting coordinated, integrated planning among forest managers, product manufacturers, designers, contractors, regulators and facility managers.

By meeting these objectives, the research intends not only to facilitate more sustainable and technically sound high-rise timber buildings but also to stimulate a broader paradigm shift in how professionals approach timber construction, grounded in scientific evidence, practical insight and long-term resilience.

1.5. Research methodology

1.5.1. Methodology

The methodologic research procedure was supported by a group of steps and adopted different tools to deal with data and procedures. The research design is characterized by a systematic, comprehensive and phased approach to investigate the sustainability of high-rise timber buildings and develop practical guidelines. The methodology proceeds through the following sequential steps, often involving iterative processes. The procedure is represented in Figure 1.

This thesis employs a qualitative and integrative research methodology aimed at developing comprehensive, practical and scientifically grounded guidelines. The research is structured in two major parts, each supported by a multistage analytical framework that synthesizes existing knowledge, evaluates case-based evidence and develops actionable insights.

The methodology is visualized in a sequential workflow that integrates five main components: (1) state-of-the-art review, (2) technical analysis of design and construction processes, (3) formulation of guidelines, (4) stakeholder mapping and (5) synthesis into a life cycle-based framework. Each step contributes incrementally to the final objective: a structured set of guidelines that align with sustainability goals and practical realities of high-rise timber architecture.

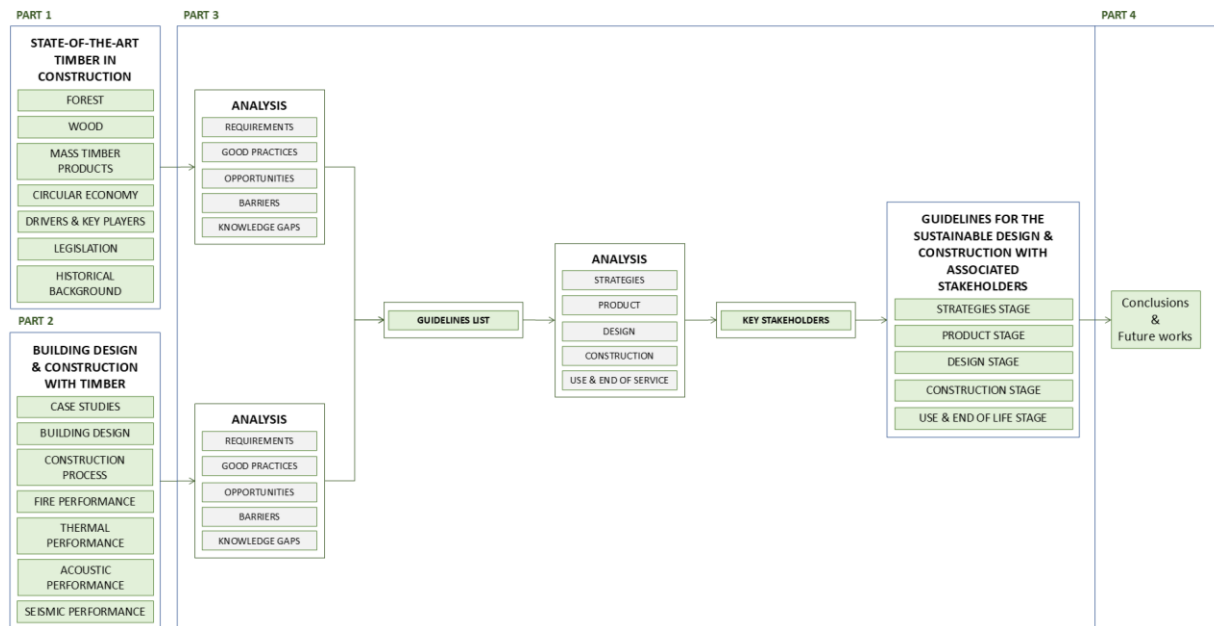


Figure 1. Methodologic research procedure

Part 1 - State-of-the-art review

The first phase of the research compiles and synthesizes existing knowledge on timber as a construction material. This includes:

- Forest and wood resources;
- Mass timber products;
- Circular economy;
- Drivers and stakeholders;
- Normative framework and historical background.

Each thematic area is analysed to extract requirements, good practices, market opportunities, implementation barriers and existing knowledge gaps, forming a foundational basis for further guidelines development.

Part 2 - Technical analysis of building design and construction

The second phase focuses on the application of mass timber in building design and construction. It includes:

- Case study analysis;
- Building design and construction process;
- Performance dimensions: In-depth analysis of architectural, structural, fire, thermal, acoustic and seismic performance aspects of high-rise timber buildings.

This part adopts a multi-perspective approach that integrates scientific literature, professional reports and technical documentation, again categorized through the analytical lenses of requirements, best practices, opportunities, barriers and knowledge gaps.

Part 3 - Development of guidelines

Based on the consolidated findings from both parts, a comprehensive Guidelines list was developed and structured across five critical life cycle stages:

- Strategies stage - focusing on sourcing, forest management and early project decisions;
- Product stage - addressing material selection, classification and treatment;
- Design stage - covering architectural, structural and environmental integration;
- Construction stage - involving on-site processes, assembly and quality control;
- Use & end-of-service stage - related to building performance monitoring, maintenance, disassembly and reuse.

Each guideline was accompanied by an analysis of specific implementation needs and mapped to the key stakeholders responsible for its execution, ranging from forest managers and manufacturers to architects, engineers, contractors and regulatory authorities.

Part 4 - Synthesis and evaluation

The guidelines were then consolidated into a final framework titled: "Guidelines for the sustainable design and construction of tall and high-rise timber buildings with associated stakeholders." This structure supports practical implementation by linking lifecycle phases with responsible actors and the technical, environmental and procedural challenges addressed. The used methodology directly answers the main research question "What are the requirements for the sustainable design and construction of high-rise timber buildings?" by systematically identifying, categorizing and analysing these requirements across the full building life cycle. The integration of literature review, case-based evidence, performance evaluation and stakeholder roles ensure that the guidelines respond not only to theoretical sustainability objectives but also to practical and context-specific conditions. Therefore, the methodology provides a comprehensive, structured and actionable response to the central inquiry of the thesis.

The final chapters of the thesis include a detailed discussion of findings, identified knowledge gaps, critical reflections and recommendations for future research. The methodology, therefore, not only produces a functional tool for industry stakeholders but also contributes to the academic discourse on mass timber architecture, policy and construction sustainability.

1.5.2. Data sources

The data sources for this study were selected to comprehensively cover the technical, regulatory and practical dimensions of high-rise mass timber construction. They encompass both academic and industry-based materials to ensure a balanced perspective between theoretical research and real-world application.

First, academic literature was gathered from relevant books and peer-reviewed articles focusing on mass timber buildings, sustainable construction and life cycle assessment. Searches were conducted in major scientific databases, targeting both review papers and recent case studies relevant to the research topic. Search terms were designed to capture publications that address the environmental, structural and regulatory aspects of engineered timber buildings.

Second, institutional and regulatory sources were consulted, including the websites of governmental organizations and both national and international bodies responsible for standards, building codes, regulations and industry guidelines. This included official reports, statistical datasets and policy documents, as well as outputs from national and international projects in the field of timber construction.

Third, a variety of professional and industry publications were reviewed, including architectural and engineering websites, trade magazines and project documentation available from architects, construction companies, real estate developers and engineering consultancies. These sources provided detailed insights into built case studies, including project descriptions, design rationales, construction techniques and material specifications.

Fourth, industry-specific resources from the timber sector were analysed. This involved consulting websites, product manuals and catalogues from companies directly involved in engineered timber manufacturing, construction systems and related services. These materials offered practical information on available technologies, performance data and market trends.

The literature review was conducted using a non-systematic (narrative) approach, chosen to allow flexibility in incorporating diverse types of sources and formats. Relevant articles were screened for quality, scientific validity and alignment with the study objectives. A snowballing strategy was applied, whereby additional publications were identified through the reference lists of initially selected sources, enabling the capture of influential works that might not have appeared in initial database searches.

This multi-source, narrative review approach ensured that the study's foundation was both broad in scope, covering environmental, technical, regulatory and market perspectives, and targeted in depth, focusing on materials most relevant to high-rise mass timber construction.

1.5.3. Use of generative AI-tools

In the preparation of this doctoral thesis, selected generative Artificial Intelligence (AI) tools, such as *ChatGPT* and *Copilot* were purposefully used to support various stages of the research and writing process. These tools assisted with grammar and spelling correction, refinement of writing style and text analysis. Additionally, *Scopus AI* was employed to enhance the search and discovery of scientific literature, while *Notebook* was used to improve information localization and organization within large and complex documents. All AI-generated outputs were critically evaluated, with interpretation, validation and final editing conducted exclusively by the author, ensuring the integrity, accuracy and originality of the final thesis

1.6. Structure of the document

This thesis is organized into eight main chapters, structured to provide a comprehensive and logical progression from the contextual background of sustainable construction to the technical, methodological and practical implications of tall and high-rise MET architecture. The document is divided into four principal parts: Part 1 focuses on foundational knowledge and material background, while Part 2 addresses applied aspects of design, construction, performance and finally Part 3 with the guidelines development, and Part 4 with synthesis and the evaluation of the results. The structure is described as follows:

Chapter 1 - Introduction establishes the context and relevance of the study. It outlines the problem definition in the light of sustainability, climate change and the environmental impact of construction. It then articulates the research objectives and questions, and the adopted methodology. A brief summary of the thesis structure is also provided.

Part 1 - State-of-the-art of timber material in construction - forms the foundational body of knowledge on which the study is built.

Chapter 2 examines timber as a renewable building material. It discusses forest ecosystems, certification systems (e.g. FSC, PEFC), timber's physical and mechanical properties, durability, carbon footprint and its comparative performance against conventional materials. The chapter also provides a detailed overview of engineered wood products and the mass timber market.

Chapter 3 presents the historical evolution of timber construction, from its early use to the emergence of high-rise timber buildings in the 20th and 21st centuries, highlighting key milestones and global developments.

Chapter 4 offers a concise summary of the first part, consolidating key insights related to material properties, sustainability potential and market readiness of mass timber.

Part 2 - Building design and construction with timber - transitions from theoretical exploration to the applied aspects of MET in contemporary construction.

Chapter 5 introduces selected case studies of high-rise mass timber buildings. These examples are analysed to identify best practices, challenges encountered and lessons learned across various global contexts.

Chapter 6 addresses the multidisciplinary dimensions of timber building design and construction. It includes architectural and structural design strategies, the construction process (planning, prefabrication, logistics) and detailed assessments of specific performance areas such as fire safety, thermal and acoustic performance and seismic behaviour. Each subsection concludes with a project team handout summarizing key remarks for practitioners.

Part 3 - Development of guidelines – synthesis and life cycle staging.

Chapter 7 synthesizes the findings of previous chapters into a structured set of Guidelines for the sustainable design and construction of tall and high-rise timber buildings. The guidelines are organized across five stages of the building lifecycle: strategy, product, design, construction and use/end-of-service. Each guideline is supported by a mapping of responsible stakeholders, reinforcing the interdisciplinary nature of MET projects.

Part 4 – Synthesis and evaluation

Chapter 8 presents the discussion and conclusions. It interprets the research results in light of global trends, identifies performance and implementation challenges and reflects on the broader implications of the study. This chapter includes a detailed assessment of knowledge gaps, critical remarks and proposes directions for future research. It underscores the importance of the developed guidelines and their potential to inform policy, education and professional practice.

The thesis concludes with a comprehensive Bibliography, reflecting the depth and interdisciplinary scope of the research. Supporting lists of figures, tables, abbreviations and acronyms are provided at the beginning of the document for reference clarity.

This structure intends to guide the reader through a coherent narrative that progresses from the underlying environmental and material context to practical, technical and strategic remarks essential for the widespread adoption of high-rise mass timber construction.

Part 1. State-of-the-art of timber material in construction

2. Timber as a building resource

The increasing interest in high-rise timber buildings reflects a broader movement toward sustainable construction and innovative engineering. This chapter delves into the complex role of timber as a building resource, providing a comprehensive understanding necessary for its optimal use in the construction of tall and high-rise structures.

Beginning with a global overview of forests, this chapter examines the extensive forested areas that cover the planet, emphasizing their ecological importance and the resources they provide. By promoting practices such as sustainable managing, harvesting, reforestation and biodiversity conservation, the management programs ensure that forests continue to thrive and contribute not only for their ecological benefits, but also for the global carbon cycle. Forests act as significant carbon sinks, they are invaluable habitats for wildlife and play a critical role in combating climate change. They contribute to air purification, reduce the incidence of droughts and floods, and prevent soil erosion (United Nations Department of Economic and Social Affairs, 2015). This chapter explores the mechanisms through which forests capture and store carbon, highlighting the importance of preserving and responsibly managing forest resources to sustain this essential ecological service.

The chapter then transitions to the natural properties of wood, focusing on its unique characteristics and how they affect its performance as a construction material. Wood's anisotropic nature and hygroscopic properties can impact its dimensional stability and longevity. Understanding these properties, among the others, is crucial for architects and engineers to effectively utilize wood in high-rise buildings. Further on, the chapter discusses how timber presents itself in comparison with traditional construction materials and, subsequently, investigates the current state of the mass timber market, highlighting the rapid growth and increasing acceptance of timber as a viable material for large-scale construction. It reviews the range of available mass timber products, including laminated solid timber, glued veneer timber and glued strand timber composites. The market's expansion is driven by several key players and influenced by factors such as technological advancements, regulatory support and growing environmental awareness. The contributions of leading companies and the innovations that have propelled the market forward are examined in detail.

In the context of sustainability, the chapter explores the principles of the circular economy, recycling, repurposing and wood cascading, and how these approaches can contribute to mitigation of climate change impacts, promoting a more sustainable and responsible use of timber.

Throughout the chapter, the importance of understanding timber's unique properties and its broader environmental context is emphasized. Such knowledge is essential for leveraging timber's full potential in tall and high-rise buildings, ensuring both structural efficiency and environmental sustainability. By appreciating the intricacies of forest management, the natural behaviour of wood and the dynamics of the timber market, stakeholders can make informed decisions that support the growing trend of using timber in urban construction. This holistic perspective is vital for advancing the adoption of high-rise timber buildings and fostering a sustainable future in architecture and construction.

2.1. Forest

Forests play an essential role in maintaining the balance of our planet's environment. They provide

a multitude of ecological, economic and social benefits. This following section provides a comprehensive overview of forests on a global scale, highlighting the importance of sustainable management and certification programs and elucidating the carbon cycle's role in climate regulation, sustainability and the timber building industry.

2.1.1. Global overview

Forests are vital ecosystems that produce oxygen and provide numerous ecological, economic and social benefits. They serve as habitats for diverse species, regulate climate, protect watersheds and offer recreational opportunities. Forest constitutes most of Earth's terrestrial biodiversity. Nearly all living organisms benefit from forest biodiversity in the form of carbon, water and nutrient cycles. It has been the source of raw materials for hundreds of years. It is essential in the fight with climate change due to its ability to store the carbon and it is a key subject to guarantee sustainable supply of wooden products (FAO & UNEP, 2020; UNECE & FAO, 2023). Additionally, the studies of Barnes et al. (2024) have shown that the reforestation in eastern United States has a consistent cooling effect on both surface and air temperatures, with the near-surface air temperature reduced by up to 1 degree Celsius.

There are 4.06 billion hectares of forest, that correspond to almost 31% of the total land area. With very uneven distribution, the majority, comprising 54%, is concentrated in just five countries: the Russian Federation, Brazil, Canada, the United States of America, and China, in decreasing order (FAO, 2020). The values for these five nations in millions of ha are represented in Figure 2.

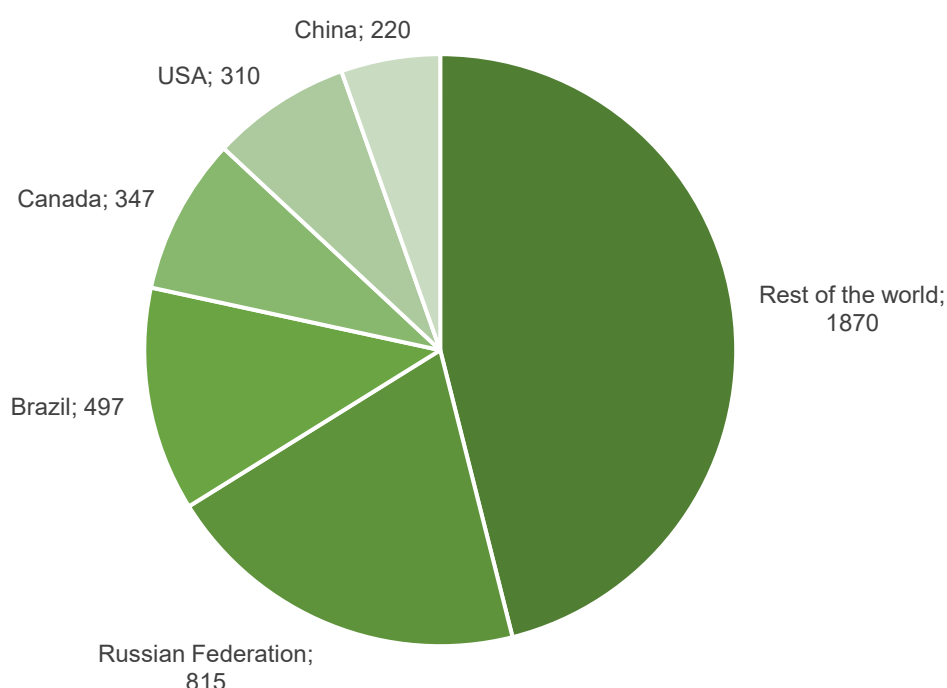


Figure 2. Forest area in top five countries in 2020 (million ha) (FAO, 2020)

There are still significant parts of native forest worldwide. The tropical region holds the largest share of the world's forests, accounting for 45 percent, followed by the boreal, temperate and subtropical regions (FAO, 2020).

Various threats, including climate change, heightened wildfire occurrences, insect infestations, diseases and deforestation stemming from urban development, extend beyond the scope of the forest industry. The world has lost a net area of 178 million ha of forest since 1990. Between 1990 and 2020, there was a significant reduction in the rate of net forest loss. This decline can be attributed to a decrease in deforestation in certain countries, as well as the expansion of forested areas through afforestation and natural forest growth in others (FAO, 2020; FAO & UNEP, 2020). However, deforestation and forest degradation continue to threaten many forested regions, particularly in tropical areas. Deforestation, primarily driven by agricultural expansion, logging, infrastructure development and urbanization, leads to permanent loss of biodiversity, disruption of ecosystem services and contributes to climate change through the release of carbon stored in trees (Woodard & Milner, 2016). These challenges call for societal-level responses and comprehensive strategies to mitigate their impacts and ensure the resilience of both forests and human communities.

Efforts to restore degraded forests and establish new forests through reforestation and afforestation are gaining momentum worldwide. Sustainable harvesting involves the careful removal of trees, coupled with long-term replanting and species diversification integrated into the planning process, ensuring that the forest continues to thrive. Sustainably managed forests are essential for supporting both economic viability and carbon sequestration benefits associated with mass wood building systems. Achieving widespread acceptance of increased wood utilization and the construction of tall wood buildings in the market hinges on unwavering commitment to the principles of a sustainably managed forestry sector (Green & Eric Karsh, 2012). Furthermore, renewal is an inherent trait of forest ecosystems, where generations of forests succeed one another over centuries. More than 90 percent of world's forest area is naturally regenerating (FAO & UNEP, 2020).

2.1.2. Management and certification

Today, sustainable forest management is a critical necessity, especially when paired with Forest and Chain of Custody Certification programs. The sustainable forest management and certification rely on forestry and harvesting methods that safeguard its long-term health and diversity and lead to increased use of wood (Green & Eric Karsh, 2012; Woodard & Milner, 2016). The definition of sustainable management was presented on the Ministerial Conference on the Protection of Forests in Europe, 16-17 June 1993 in Helsinki and it defines sustainable forest management as “stewardship and use of forests and forest lands in such a way, and at a rate, that maintain their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfil, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems” (European Environment Agency, n.d.). Forest management refers to the practice of planning, implementing and monitoring activities aimed at the sustainable use and conservation of forest resources. It involves a range of activities, including timber harvesting, wildlife habitat conservation, watershed protection, fire management and recreation planning, through selective logging, reforestation, habitat restoration, and community engagement (Diez & Martín-García, 2012; European Environment Agency, n.d.; PEFC Council, 2018).

Sustainable forest management is typically achieved through the application of criteria and indicators. Criteria represent the fundamental categories of conditions or processes used to evaluate sustainable forest management. Quantitative indicators are then selected to offer measurable aspects of these criteria, allowing for periodic monitoring to identify trends. Qualitative indicators, on the other hand, are crafted to outline the overall policies, institutions and instruments relevant to sustainable forest management. There is significant group of countries that have implemented their own sets of criteria and indicators within the framework of the nine international or regional processes: African Timber Organization [ATO], Dry Forest in Asia, Dry Zone Africa, International Tropical Timber Organization (ITTO), Lepaterique of Central America, Montreal Process, Near East, Pan-European Forest (also known as the Ministerial Conference on the Protection of Forest in Europe, MCPFE) and Tarapoto of the Amazon Forest. ITTO, MCPFE and Montreal processes are the most widely used, covering more than 90% of the world's temperate and boreal forests, and 80% of the world's tropical forests (Diez & Martín-García, 2012). Because of variations in indicator sets and challenges in interpreting certain indicators, there is an ongoing pursuit within scientific communities to continually seek new and better-suited indicators for sustainable forest management.

In the past two decades, alongside the efforts of various states to establish criteria and indicators for sustainable forest management, another initiative has emerged: forest certification. This voluntary system is supervised by an impartial third party with expertise, ensuring that forest management complies with predetermined standards and labels products accordingly. These standards are rooted in the criteria and indicators framework, and the consumer-visible label distinguishes certified products. Forest certification operates across the entire forest supply chain, advocating responsible practices and ensuring that both wood and non-wood forest products are produced in accordance with the highest ecological, social, and ethical standards (Diez & Martín-García, 2012; PEFC Council, 2018; PEFC UK Ltd, 2020). In another word, certified timber is a proof that the harvesting processes have taken environmental remarks. This fosters consumer confidence and enables businesses to access markets that prioritize sustainability.

The certified forest area experienced rapid growth during the 1990s and has since expanded more gradually. By May 2011, it had reached 375 million hectares, accounting for nearly 10% of the global forest area (UNECE & FAO, 2011). Recently however, the percentage of certified forest area has dropped by 18.5 percentage to the lowest level in over a decade. It is mainly due to the suspension of the certification practices in Belarus and Russian Federation, countries with significant forest cover areas (UNECE & FAO, 2023). While numerous forest certification systems were created during the 1990s, the majority of the world's certified forests are currently covered by only two schemes: Programme for the Endorsement of Forest Certification (PEFC) and Forest Stewardship Council (FSC). By September 2018, PEFC was the largest forest certification system in the world, with 300 million hectares of certified forest (PEFC Council, 2018). Most of the certified forests are located on the territory of Europe and North America. European forests (excluding Russian Federation) are certified in more than 50%. The situation looks drastically different in the Africa, Asia and South and Central America, where only small part, less than 2%, is represented by certified forests (Diez & Martín-García, 2012).

Apart from certification programs exist also Environmental Product Declarations (EPDs). EPDs are a standardized, third-party-verified labels, designed to transparently communicate information about a product's life cycle and provide quantified data regarding its environmental impacts. These documents are crucial for assessing the environmental footprint of products and seeking constructive solutions to improve their environmental performance (Dias et al., 2020). They include data on various environmental aspects such as carbon emissions, energy consumption, water usage and waste generation, and serve as valuable tools for consumers, businesses and policymakers to make informed decisions regarding product selection, procurement and environmental management strategies. When it comes to wood products, sustainable forest management certification enhances the insights provided by an EPD, offering a comprehensive perspective that includes aspects not addressed in LCA. The format of EPDs enables the aggregation of environmental impacts across a product's supply chain, a capability that significantly amplifies the utility of information derived from LCA. The wood industry has been a leader in the development of EPDs.

2.1.3. Carbon cycle

The carbon cycle plays a crucial role in regulating Earth's climate and maintaining the balance of CO₂ in the atmosphere. This cycle is the natural mechanism by which carbon atoms transition among living organisms, the atmosphere, oceans, soil and rocks. It is an intricate activity that comprises a series of interconnected biological, geological and chemical processes that perpetually circulate carbon across various bodies. Human activities, particularly the burning of fossil fuels and deforestation, have significantly altered the carbon cycle, leading to increased atmospheric CO₂ levels and contributing to global warming and climate change. Fossil fuels originate from organic matter but have remained underground for millions of years, making them distinct from the current carbon cycle. When CO₂ is released from burning fossil fuels, it disrupts the natural balance of the carbon cycle (Forest Europe, 2017). In case of the trees on the other hand, carbon dioxide existing in the atmosphere is absorbed by plants during photosynthesis, where it is converted into organic compounds such as carbohydrates.

During this process, sunlight supplies energy, carbon dioxide is absorbed from the air and water is drawn from the soil. Given the current context of climate change and widespread concern for environmental and human well-being, the role of CO₂ sequestration is paramount. This process fixes carbon into plant tissues in the form of biomass, while simultaneously releasing a significant amount of oxygen into the atmosphere. Forests' trees and soil serve as reservoirs storing significant amounts of carbon. When plants and animals die, their organic matter can be incorporated into soil or become fossilized, storing carbon for long periods. When wood is employed as a material, the carbon remains stored within it and it does not emit CO₂ until it is burned or decomposed.

The amount of carbon sequestered varies depending on the age of the forest and how the intervals between planting and harvesting are managed. It also depends on the species, but it is consistently directly proportional to the trees growth rate. Saplings and young trees exhibit rapid growth, leading to higher rates of CO₂ absorption. However, as trees mature, their growth rate slows, resulting in a decrease in CO₂ absorption rate (Green & Taggart, 2017). Research conducted by the Consortium for Research in Industrial Renewable Materials (CORRIM) suggests that shorter intervals between

harvests result in increased carbon sequestration (Forest Products Laboratory, 2010). Continual monitoring through Sustainable Forest Management protocols is essential. Each climate, region and type of forest has an ideal rate of harvest determined by the annual growth rate. This increase in volume of wood fibre annually is referred to as the stem wood increment. By aligning the harvesting rates with the stem wood increment, there is an opportunity to contribute to climate change mitigation, as by harvesting wood fibre from forests at a rate that optimizes volume, the carbon sequestration can be maximized (Green & Taggart, 2017).

2.2. Wood properties

The use of timber in construction is gaining renewed interest due to its sustainable properties and environmental benefits. As the building industry seeks more eco-friendly alternatives to traditional materials like steel and concrete, understanding the unique properties and characteristics of wood becomes crucial. This chapter provides a comprehensive examination of wood properties and their implications for construction. It highlights the importance of understanding timber's natural characteristics, managing moisture content, assessing strength and load duration effects, and ensuring proper grading and durability. Additionally, it underscores the environmental advantages of timber, emphasizing its lower carbon footprint and potential for sustainable construction. Also, there is a subsection of this chapter that compares timber with traditional construction materials. While steel and concrete have long been favoured for their strength and durability, they come with higher environmental costs. Timber, with advancements in engineering and construction techniques, now offers comparable strength and durability, while also providing aesthetic and environmental benefits. Understanding these comparisons helps in making informed choices about material selection in sustainable building practices.

2.2.1. Natural characteristics

Over the centuries, the forest has thrived, renewing itself and adapting to the unique conditions of local climates. Each habitat hosts a diverse array of species and unique composition, shaping timber's structure and properties across the globe. Consequently, numerous tree varieties lend themselves to mass timber construction, each possessing its own unique traits, strengths and weaknesses. Wood exhibits significant variability, particularly among species, where each tree type boasts distinct characteristics and properties crucial for informed material selection. Given the high heterogeneity and marked anisotropy inherent in wood, it's essential to categorize different species and understand their key characteristics and properties concerning their suitability as construction materials.

Wood is an intricate organic material characterized by a cellular structure. It consists of elongated tubular compartments with cellulose walls, typically measuring between 0.5-6 mm in length, enclosed by lignin, hemicelluloses and some materials in cellular structure. The process of photosynthesis imbues it with a natural capacity for water retention within its biological structure. Variations in the dimensions of these components and differences in structure significantly impact the properties of timber, determining whether it is lightweight or heavy, flexible, or rigid, soft or hard and influencing its anisotropic and hygroscopic behaviours. The strength and stability of wood fluctuate according to the grain orientation and

moisture levels. Mastering control over these two factors is crucial for creating precise, dimensionally stable, robust components and structures, leading to enhanced durability (Green & Taggart, 2017).

Consequently, trees can be categorized into two classes known as hardwoods and softwoods. Typically, hardwoods are plants characterized by broad leaves, while softwoods are usually cone-bearing plants with needle- or scale-like evergreen leaves. The classification of the two primary wood categories relies on significant disparities in the anatomical structure found among different species within each group. Hardwoods, classified as angiosperms, bear seeds within the ovaries of flowers and possess a porous structure characterized by wood cells with open ends arranged in a continuous tube called a vessel. Softwoods, on the other hand, belong to the gymnosperm category, with seeds not enclosed within flower ovaries. These conifers exhibit a nonporous structure. Both hardwood and softwood trunks comprise two distinct zones: sapwood, responsible for sap conduction, storage and biochemical synthesis, and heartwood, composed of dead cells for long-term storage of extractives (Coulson, 2021; Forest Products Laboratory, 2010; Ramage et al., 2017). The macroscopic properties of wood are derived from the cells and wood polymer composition, but there are other attributes that depend on the chemical and anatomical features of wood's structure, such as extractives, that provide coloration and contribute to its inherent durability (Forest Products Laboratory, 2010).

2.2.2. Influence of moisture

As a natural material, wood exhibits hygroscopic properties, meaning it absorbs moisture from the air. Therefore, it is sensitive to fluctuations in relative humidity and temperature in its surroundings, directly influencing its moisture content and, by extension, its mechanical properties (Wójcik, 2019). This moisture correlation and inherent water content within the wood impacts its strength and stiffness, presenting numerous challenges. High moisture content can weaken wood, reducing its load-bearing capacity and structural integrity (Forest Products Laboratory, 2010).

Moisture content is quantified as the ratio between the mass of water present in the wood and the mass of oven-dried wood, typically expressed as a percentage. Green wood, freshly cut from trees, typically exhibits a moisture content ranging from 30% to 200% (Forest Products Laboratory, 2010). This high moisture content is attributed to the saturation of cell walls with water and the presence of free water within the cell lumina. The initial moisture content varies based on factors such as species, whether it is softwood or hardwood, and whether it is sapwood or heartwood. The point at which the mechanical properties of wood remain unchanged regardless of moisture content is called the fibre saturation point. At this stage, only the cell walls are fully saturated, with no free water present in the cell lumina. Typically, the fibre saturation point of wood is around 30%. Beyond this threshold, wood maintains dimensional stability. However, below this saturation level, the mechanical properties of wood undergo significant changes as it either swells or shrinks, potentially leading to reduced functionality and distorted shapes, like warping, twisting, or cracking (Coulson, 2021). Importantly, lower moisture content corresponds to higher strength and modulus of elasticity values, particularly when comparing values between 12% and 25% moisture content (Yamasaki et al., 2017). To achieve a target moisture content of 12% (engineering reference value for structural elements), harvested trees undergo kiln drying, also called seasoning. This process reduces the material's volume while enhancing its strength (Forest

Products Laboratory, 2010). In environments with higher humidity, the moisture content of wood in service must be carefully managed. Design codes typically adjust strength values for timber in environments prone to high moisture content to account for its influence. Eurocode 5 specifies three service classes corresponding to specific annual average moisture content levels, as outlined in Table 1 (CEN, 2004a; Coulson, 2021).

Table 1. Service classes of wood according to Eurocode 5 (CEN, 2004a)

Service class	Relative humidity of the surrounding air	Average moisture content	Description
1	Exceeding 65% for a few weeks/year	< 12%	Structural members that are used in a protected indoor environment
2	Exceeding 85% for a few weeks/year	< 20%	Structural members that are used in a protected outdoor environment
3	Exceeding 85% more than a few weeks/year	> 20%	Structural members that are used in an exposed outdoor environment

As previously noted, moisture content plays a significant role in determining wood's vulnerability to decay, fungal growth and insect infestation. Elevated moisture levels create favourable conditions for biological deterioration, whereas drier conditions can delay microbial growth and help maintain the integrity of the wood. Additionally, moisture presence can increase the electrical and thermal conductivity of wood, making it more prone to corrosion in contact with metals, especially in outdoor applications and impacting its suitability for insulation purposes, as wet wood conducts heat more effectively than dry wood.

Wood's moisture content directly impacts its workability and finishing processes. Wet wood tends to be more malleable and easier to manipulate, facilitating machining and shaping tasks. Conversely, excessively dry wood can become brittle, posing challenges during manipulation. Alterations in moisture content can also affect the visual characteristics of wood, including its colour, texture and grain pattern. Swelling or shrinking of wood fibres due to moisture absorption or loss may lead to surface irregularities or blemishes.

Overall, managing moisture levels is essential for preserving the structural integrity, longevity and visual attractiveness of wood products. Utilizing appropriate seasoning, storage and treatment methods is key to mitigating the adverse impacts of moisture on wood. Additionally, decisions regarding materials must be made at every scale, ranging from the initial building concept and the selection of wood type to building logistics, and especially at the 1:1 detail level. A primary consideration in architectural detailing for wooden elements involves devising solutions to prevent water from infiltrating the exposed fibres at the cut surface. To avert harm, it's crucial to address humidity and condensation control measures and implement waterproofing strategies, further addressed in Chapter 6.

2.2.3. Strength and influence of load duration

Wood consists of elongated tubular cells with cellulose walls, held together by lignin. These cells are predominantly oriented in the direction of the tree trunk, defining wood's anisotropic behaviour.

Sawn timber, as larger specimens, encompass not only wood fibres but also natural characteristics like knots, pitch pockets, fissures, or grain deviations irregularities. These natural features significantly influence timber's properties. Clear, straight-grained wood is utilized for establishing fundamental mechanical properties, but knots, formed from embedded branches within the tree, are the most significant defects affecting timber's structural performance.

The strength of a building material reflects its capacity to endure a given load without failing. Structural components may encounter various types of loads, including compression, tension, bending, shear and torsion. Timbers with comparable strength characteristics are categorized into strength classes, as specified in EN 338:2016 (CEN, 2016a). For hardwoods, there are six strength classes ranging from D18 to D80 and there are twelve strength classes designated for softwoods (C14 to C50). The differences of characteristic values of strength and stiffness of popular hardwood and softwood species according to the strength classes is presented in Table 2 and Table 3 (CEN, 2016).

Table 2. Characteristic values of strength classes for softwoods to EN 338:2016 (CEN, 2016a)

	Softwood species											
	C14	C16	C18	C20	C22	C24	C27	C30	C35	C40	C45	C50
Strength properties (N/mm ²)												
Bending $f_{m,k}$	14	16	18	20	22	24	27	30	35	40	45	50
Tension parallel $f_{t,0,k}$	7.2	8.5	10	11.5	13	14.5	16.5	19	22.5	26	30	33.5
Tension perpendicular $f_{t,90,k}$	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Compression parallel $f_{c,0,k}$	16	17	18	19	20	21	22	24	25	27	29	30
Compression perpendicular $f_{c,90,k}$	2.0	2.2	2.2	2.3	2.4	2.5	2.5	2.7	2.7	2.8	2.9	3.0
Shear $f_{v,k}$	3.0	3.2	3.4	3.6	3.8	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Stiffness properties (kN/mm ²)												
Mean modulus of elasticity parallel $E_{0,mean}$	7.0	8.0	9.0	9.5	10.0	11.0	11.5	12.0	13.0	14.0	15.0	16.0
5% modulus of elasticity parallel $E_{0,05}$	4.7	5.4	6.0	6.4	6.7	7.4	7.7	8.0	8.7	9.4	10.1	10.7
Mean modulus of elasticity perpendicular $E_{90,mean}$	0.23	0.27	0.30	0.32	0.33	0.37	0.38	0.40	0.43	0.47	0.50	0.53
Mean shear modulus G_{mean}	0.44	0.50	0.56	0.59	0.63	0.69	0.72	0.75	0.81	0.88	0.94	1.00

Table 3. Characteristic values of strength classes for hardwoods according to EN 338:2016 (CEN, 2016a)

	Hardwood species													
	D18	D24	D27	D30	D35	D40	D45	D50	D55	D60	D65	D70	D75	D80
Strength properties (N/mm ²)														
Bending $f_{m,k}$	18	24	27	30	35	40	45	50	55	60	65	70	75	80
Tension parallel $f_{t,0,k}$	11	14	16	18	21	24	27	30	33	36	39	42	45	48
Tension perpendicular $f_{t,90,k}$	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Compression parallel $f_{c,0,k}$	18	21	22	24	25	27	29	30	32	33	35	36	37	38
Compression perpendicular $f_{c,90,k}$	4.8	4.9	5.1	5.3	5.4	5.5	5.8	6.2	6.6	10.5	11.3	12.0	12.8	13.5
Shear $f_{v,k}$	3.5	3.7	3.8	3.9	4.1	4.2	4.4	4.5	4.7	4.8	5.0	5.0	5.0	5.0
Stiffness properties (kN/mm ²)														
Mean modulus of elasticity parallel $E_{0,mean}$	9.5	10.0	10.5	11.0	12.0	13.0	13.5	14.0	15.5	17.0	18.5	20.0	22.0	24.0
5% modulus of elasticity parallel $E_{0,05}$	8.0	8.4	8.8	9.2	10.1	10.9	11.3	11.8	13.0	14.3	15.5	16.8	18.5	20.2
Mean modulus of elasticity perpendicular $E_{90,mean}$	0.63	0.67	0.70	0.73	0.80	0.87	0.90	0.93	1.03	1.13	1.23	1.33	1.47	1.60
Mean shear modulus G_{mean}	0.59	0.63	0.66	0.69	0.75	0.81	0.84	0.88	0.97	1.06	1.16	1.25	1.38	1.50

Strength class information ensures that timber products meet the necessary standards for structural performance and safety, a crucial aspect for obtaining regulatory approval for construction projects. These classes offer numerous benefits to both designers and suppliers by providing standardized data. This includes crucial information about the load-bearing capacity of different timber species, aiding in the selection of appropriate timber members capable of supporting applied loads adequately. Furthermore, strength classes assist architects, engineers and builders in choosing the most suitable timber species for specific applications, reducing the risk of structural failure by matching the strength class of timber with the required structural demands. Optimizing material usage and minimizing costs is also achievable through the selection of timber with an appropriate strength class. Over-engineering and increased material expenses can be avoided by choosing a timber species with a strength class that matches the project requirements. By categorizing timber based on their strength properties, it becomes easier for suppliers and manufacturers to communicate the value of their products to customers and to ensure consistency and quality control in timber production and supply chains.

There are various types of loads that buildings may encounter, including:

- Dead load: The weight of the structure itself, including the weight of the walls, floors, roofs, and other permanent components;
- Live load: Temporary or movable loads imposed on the building, such as occupants, furniture, equipment, and substances accumulation;
- Wind load: The force exerted by wind on the building's surfaces, including walls, roofs, and windows;
- Rain or snow load: The weight of rainwater or snow collected on the roof or other horizontal surfaces;
- Seismic Load: The force generated by earthquakes, which can cause lateral movement and deformation of the structure (Coulson, 2021).

To withstand applied forces of varying directions and magnitudes, structural components of a building must be carefully considered during the design process. They need to be adequately calculated to transfer these loads from their origin, through the structure, to the foundations and ultimately into the ground. This ensures the stability and safety of the building.

The capacity of structural timber members to withstand loads is significantly influenced by the duration for which the load is applied. Consequently, timber can withstand larger loads for shorter durations compared to permanent loads. Over time, timber experiences a notable decline in strength due to factors such as load duration effect, climate conditions and deteriorating agents. Therefore, when designing timber structures, it's crucial to consider the range of potential loadings and the duration for which each load is expected to be applied (Cavalli et al., 2016; Coulson, 2021; Forest Products Laboratory, 2010). The impact of load duration of wood is incorporated into the analysis and classified into various load duration classes as outlined in Eurocode 5 and summarized in Table 4 (CEN, 2004a). According to the load duration, the strength reduction or increase is possible. When referring to United States and Canada, the Forest Products Laboratory (Forest Products Laboratory, 2010) states that there are also some differences in short-term duration design stresses between treated and untreated lumber. American and Canadian design standards define preserved wood load duration factor as much lower than of the unprocessed one when considering instantaneous, impact-type load (Forest Products Laboratory, 2010).

Table 4. Load duration classes of wood according to Eurocode 5 (CEN, 2004a)

Load duration class	Order of accumulated duration of characteristic load	Examples of loading
Permanent	more than 10 years	Self-weight
Long-term	6 months 10 years	Storage
Medium-term	1 week - 6 months	Imposed floor load, snow
Short-term	less than one week	Snow, wind
Instantaneous		Wind, accidental load

2.2.4. Grading of timber

As previously noted, growing trees exhibit variability, including within samples of the same species, in terms of specific gravity, number of imperfections and anomalies. The impact of a knot on the mechanical characteristics of a wooden member arises from the disruption of continuity and alteration in the direction of wood fibres linked with the knot. The effect of anomalies varies depending on factors such as their size, position, shape and quality, as well as the local grain slope and the type of stress applied to the wooden member (Forest Products Laboratory, 2010).

Through thorough inspection of each piece of timber, identification and quantification of size and frequency of defects present, it becomes feasible to classify the elements into different grades, mentioned formerly. The fundamental mechanical and physical properties of structural timber (strength, stiffness and density) can be determined by visual or mechanical strength grading and the actual performance of timber products and their relative quality for construction can be evaluated (Ridley-Ellis et al., 2016).

The criteria for accepting the defect sizes within each grade are proportional to the dimensions of the timber piece under consideration. Consequently, a large plank with significant defects may be categorized in the same grade as a smaller plank with fewer defects. However, if a large plank is divided into two or more smaller planks by the longitudinal cut, the timber must be reassessed and potentially regraded.

In summary, timber grading assists consumers in making informed decisions regarding the quality and suitability of timber products for their specific requirements, while simultaneously ensuring adherence to building codes and standards.

Timber grading systems differ depending on the region and may be developed by industry associations, governmental bodies, or standardization organizations. The grading of structural timber in Europe is governed by the harmonized standard EN 14081-1:2016+A1:2019 (CEN, 2019), while in United States the American Hardwood Export Council and The American Lumber Standard Committee serve as the bodies that act on behalf of the grading control.

The inherent irregularity and variability within the same tree species pose challenges in precisely defining performance criteria. To address this, engineered wood products have undergone extensive development and study in recent decades. They intend to reduce variations and enhance the strength and utility of timber in construction. Innovative construction techniques, such as cross-laminated timber and laminated veneer lumber, help to mitigate wood's anisotropic effects, allowing building elements'

dimensions and shapes to be primarily dictated by manufacturing capabilities and transportation constraints (Kaufmann et al., 2018).

2.2.5. Durability

The durability of a timber structure defines its lifespan. It is influenced by the species of timber, its natural properties, treatment methods, environmental exposure and maintenance practices. Some wooden buildings have endured for centuries across various climates, while others have been demolished within a few years. Identifying potential causes of issues and defects that compromise construction quality and building functionality aids in highlighting essential durability requirements.

Wood as a natural material is vulnerable to biodegradation process and several factors contribute to reducing its durability, including:

- Thermal degradation (fire);
- Load (stress, fatigue);
- Weathering (moisture, UV radiation);
- Chemical degradation;
- Biological attack (fungi, insects, marine borers).

As mentioned previously, certain tree species exhibit inherent durability, which is largely attributed to the presence of extractive compounds that impart colour and display biocidal activity against fungi and insects. Woods such as cedar and teak are well known for their high durability due to their elevated extractive content (Forest Products Laboratory, 2010). Therefore, each wood species possesses distinct characteristics that define its natural durability, encompassing resistance to biological degradation agents and its ability to absorb liquid water. These characteristics allow for the classification of wood species into specific classes, as outlined in EN 350:2016 (CEN, 2016):

1. Very durable,
2. Durable,
3. Moderately durable,
4. Slightly durable,
5. Not durable.

As outlined in Eurocode 5: Design of timber structures, EN 1995-1-1 (CEN, 2004a), specifically *Design of timber structures - Part 1-1: General - Common rules and rules for buildings*, precise standards are provided to ensure accurate assessment of the durability of wood types when exposed to adverse conditions. Other standards regarding the durability of wood and its derivatives, are listed below:

- EN 335:2013 Durability of wood and wood-based products - Definitions of use classes;
- EN 350:2016 Durability of wood and wood-based products - Testing and classification of the durability to biological agents of wood and wood-based materials;
- EN 351-1:2023 Durability of wood and wood-based products - Preservative treated solid wood. Part 1: Classification of preservative penetration and retention;
- EN 351-2:2023 Durability of wood and wood-based products - Preservative treated solid wood. Part 2: Guidance on sampling for the analysis of preservative-treated wood;
- EN 460:2023 Durability of wood and wood-based products - Guidance on performance.

As noted earlier, wood, particularly hardwoods, exhibits notable durability. However, even species with high natural durability may succumb to adverse conditions such as excessive moisture content and exposure to certain biological agents over time. Today, with the presence of standards and certifications, it is necessary for construction materials to surpass the minimum durability requirements set forth.

The likelihood of degradation is intricately tied to the positioning of wood-based products and their susceptibility to moisture. Detailed descriptions of use classes, their associated moisture conditions, and vulnerability to biological attack can be found in the Standard EN 335:2013 (CEN, 2013), summarized in Table 5.

Table 5. Summary of use classes according to EN 335:2013 (CEN, 2013)

Use class	Service condition	Exposure to moisture	Fungi, bacteria	Insects
1	No contact with the ground, covered, dry	None	Insignificant, accidental	Possible, depends on the geographical region
2	No contact with the ground, covered, risk of wetting	Occasional	Possible	Possible, depends on the geographical region
3	No contact with the ground, covered or uncovered, risk of wetting	Frequent	Possible; decay risk	Possible, depends on the geographical region
4	In contact with the ground or freshwater	Permanent	Possible; if fully saturated-bacterial decay	Possible, depends on the geographical region
5	Submerged in saltwater	Permanent	Possible; high risk of the attack by invertebrate marine organisms	Possible above water

Although numerous factors impact wood durability, the most significant are water exposure (moisture content) and subsequent biodegradation by biological agents. While all construction materials are susceptible to degradation triggered by water or water vapour, stemming from condensation, roof leaks, breaches in the building envelope, or damp foundations, timber's propensity to absorb moisture more readily than it evaporates makes it a crucial focal point for achieving durable construction. Moreover, owing to wood's anisotropic nature, any fluctuation in moisture content affects its dimensional stability, leading to shrinkage or swelling. Additionally, extreme oscillations in moisture content can result in undesired dimensional variations, nail protrusions, drywall damage and cracking. Under certain environmental conditions, such as a moisture content exceeding 20%, ample oxygen availability and temperatures ranging between 10°C and 35°C, wood becomes vulnerable to fungal infestation (Forest Products Laboratory, 2010). Mould or staining may occur when the wood remains wet, even for brief periods. The ramifications can impact air quality, lead to discomfort and cause aesthetic concerns. In more severe cases, moisture can compromise the structural integrity and weaken the wood-resin bonding strength in composites, leading to substantial expenses for renovations (Wang et al., 2019). Therefore, safeguarding timber buildings from moisture exposure is essential to prevent durability issues during both construction and operation stages. It is crucial to maintain timber in a dry state, ensuring a constant water content of $u \leq 20\%$, without surpassing the fibre saturation point (28-35%) so that it can remain in service for hundreds of years. Moreover, physical and chemical treatments can be employed to enhance timber performance in terms of durability (Forest Products Laboratory, 2010; Wang, 2016).

Despite the availability of treatment methods for mass timber, the need for appropriate design remains undeniable. The solutions should aim at preventing moisture entrapment between connections, exposure of wood ends, contact with the ground during transport, storage and construction, as well as the use of unsuitable materials (such as membranes and barriers that cause water condensation). Instead, designs should promote features that facilitate ventilation, water drainage and drying, while judiciously incorporating water-shedding barriers and insulation, further explored in Chapter 6 (Coulson, 2021; Wang, 2016; Wang et al., 2019). Untreated wood exposed to ground moisture is susceptible to rapid decay. While treated wood and decay-resistant wood offer greater durability, they will eventually deteriorate after many decades. Moisture control imposes collaboration among manufacturers, architects, engineers and construction personnel to prevent the risk of moisture interference and degradation during later stages of building operation. This approach encompasses proper production environments, protection during transport and storage, as well as meticulous design and execution. Thus, particular attention to moisture management is essential at every stage of the project. A dedicated specialist responsible for overall control, along with experts designated for specific areas, including moisture management, should be employed. It is imperative to establish comprehensive operation and maintenance guidelines for moisture safety and to provide thorough instruction to all parties involved regarding this issue, as well as the hierarchy and control protocols.

2.2.6. Carbon footprint

The carbon footprint concept is utilized to quantify the total greenhouse gas emissions generated throughout the production, operation and end-of-life stages of a human activity, organization, or a product. It serves as a tool to assess the environmental impact of various processes and actions in terms of their contribution to climate change. The carbon footprint encompasses all stages of a product's or activity's life cycle, including raw material extraction, production, transportation, use and disposal. It considers all greenhouse gases emissions, such as carbon dioxide, methane, nitrous oxide and fluorinated gases, but it is most commonly linked to CO₂, as the gas that is most emitted by human activities.

Carbon footprint can be calculated by quantifying emissions from direct sources (e.g. fuel combustion) as well as indirect sources (e.g. electricity consumption) by using standardized methodologies such as LCA and greenhouse gas accounting protocols. LCAs take into account all stages of the product life cycle and provide a comprehensive analysis of their environmental impacts, including carbon emissions. The result is usually expressed by climate metrics (e.g. Global Warming Potential (GWP) and carbon dioxide equivalent (CO₂e)) which aggregates all greenhouse gas emissions based on their global warming potential relative to CO₂ over a specified time horizon and facilitate to compare or combine emissions of pollutants based on their influence on the global climate. By understanding the concept of carbon footprint, consumers, businesses and policymakers can make informed decisions in terms of material, product, or activity selection.

Despite timber's significant advantage in comparison with concrete and steel in carbon sequestration capacity (Green & Eric Karsh, 2012), its carbon footprint can vary depending on several factors. These include the type of forestry practices used, transportation distances, energy sources utilized in processing and the end-use of the timber product. At the last stage of the building's life, wood

can be recovered for recycling or re-use in another structure or product, integrated into cascading scheme, chipped for fuel or mulch, or sent to a landfill, altering significantly its carbon footprint.

Furthermore, sustainable forestry practices play a crucial role in minimizing carbon emissions and enhancing carbon sequestration by maintaining healthy forests and fostering the growth of new trees. The method of timber harvesting also affects its carbon footprint. Selective logging, which targets specific trees while leaving others intact, generally has a lower footprint than clear-cutting, that harvests all trees in selected area. The transportation distance between forest and processing factories and markets significantly influences the carbon release. Consequently, shorter timber products travel tends to result in lower emissions compared to long-distance transport.

The energy sources and efficiency of processing facilities are crucial in influencing the carbon footprint of timber products. Much energy from wood processing has been significantly reduced in recent years. The most energy-consuming process in wood making is kiln drying (Forest Products Laboratory, 2010). Utilizing renewable energy sources and implementing energy-efficient technologies can help reduce emissions, though reliance on non-green energy sources during processing can outweigh the carbon sequestration benefits of timber.

Furthermore, the durability of timber products and their intended end use can also impact their carbon footprint. Products with longer lifespans, such as those used in construction or furniture, can store carbon for extended periods, potentially reducing total emissions.

Overall, carbon foot printing serves as a vital tool for deciding on climate action, guiding decision-making processes, shaping consumer choices and informing policy development aimed at achieving greenhouse gas emission reduction targets and addressing the impacts of climate change on a global scale.

2.2.7. Comparison with other constructive materials

Timber, being a renewable resource, is frequently linked with sustainability (Henry, 2018; Silva et al., 2013). Its suitability for construction has been demonstrated across various climates and over many centuries. Over the past few decades, it has gained significance and emerged as a competitive alternative to concrete and steel in the construction of high-rise buildings (Crawford & Cadorel, 2017; Kaufmann et al., 2018).

As previously discussed, the primary material utilized in structural timber products originates from solar energy and the absorption of carbon dioxide from the air, retaining it within the carbon cycle and effectively contributing to CO₂ reduction (Gauzin-Muller, 2002; Kaufmann et al., 2018; Pryce, 2016). It is possible to quantify the amount of CO₂ absorbed by wood used in construction and compare it with emissions throughout its lifecycle. For instance, trees utilize CO₂ (0.9 tons), water (0.5 tons) and solar energy to produce one cubic meter of biomass through photosynthesis, with carbon accounting for half of its composition (225 kg). As production and processing of other construction materials generate significant quantities of CO₂, the carbon neutrality of wood works in its favour. The values of embodied carbon for different construction materials are presented in Table 6.

From environmental point of view, when planned sustainably, timber buildings can significantly reduce their total embodied energy compared to structures made from other materials (Forest Products Laboratory, 2010; Tucker & Ambrose, 1997). For instance, as can be seen in Table 6, producing timber

material requires only 8.5 MJ/kg, whereas steel demands 24.4 MJ/kg and aluminium as much as 155 MJ/kg. Although plain concrete has the lowest embodied energy per kilogram at only 0.95 MJ/kg, the sheer volume of concrete needed for a building, results in a higher total embodied energy value (Sabnis et al., 2015). This low embodied energy translates to less fossil fuel usage and subsequently fewer CO₂ emissions into the atmosphere. This highlights the environmentally friendly aspect of timber construction and underscores its potential to mitigate climate change.

Table 6. Embodied carbon and energy coefficients of selected materials (Sabnis et al., 2015)

Material	Embodied Energy MJ/kg	Embodied Carbon kgCO₂/kg*
Aluminium (Gen)	155	8.24
Aggregate (Gen)	0.1	0.005
Bricks	3	0.22
Cement (Portland)	4.6	0.73
Cement mortar (1:4)	1.21	0.177
Concrete (Plain)	0.95	0.13
Concrete (Reinforced)	1.21	0.148
Concrete (Precast)	2	0.215
Glass (Gen)	15	0.85
Steel (Gen)	24.4	1.77
Stone	1	0.056
Timber	8.5	0.46
Plywood	15	0.81
Marble tiles	3.3	0.187

On another hand, timber presents an impressive strength-to-weight ratio (Asdrubali et al., 2017; Cuadrado et al., 2015; Kaufmann et al., 2018). When compared to other materials, a steel structure of equivalent size can weigh up to 20% more than timber, while a concrete structure may weigh up to 600% more (New Zealand Pine Manufacturers Association, 2008). Furthermore, research conducted by Hermann Kaufmann (2018) reveals that timber buildings can weigh 35-50% less than conventional structures. For instance, where one concrete slab is used, the equivalent weight of two timber slabs could be accommodated. This weight advantage enables reduction in the size of foundations, thus in the overall cost, the construction of taller structures atop existing buildings or the entirely new constructions, particularly in areas where soil conditions are unsuitable for heavier materials (UK Construction, 2017). The example of such extension build with timber is presented in Figure 3.

Whereas timber can match reinforced concrete in terms of strength, it falls short in compression resistance. Additionally, timber exhibits less stiffness compared to concrete and steel. Nevertheless, its lower density makes it efficient for long-span or tall structures (Ramage et al., 2017). The inherent anisotropic nature of wood can be mitigated through innovative construction methods, such as CLT and LVL, allowing for flexibility in shaping and sizing building elements, where the limitations depend only on the manufacturing capability and transport restrictions (Kaufmann et al., 2018).

The lightweight nature of wood also enhances its seismic performance, as evidenced by numerous studies (Ceccotti et al., 2006; Ramage et al., 2017). Timber buildings tend to exhibit greater flexibility compared to their concrete or steel counterparts, which can help dissipate seismic energy and reduce structural damage. Furthermore, wood's natural damping properties can help mitigate the effects of seismic vibrations. The combination of timber elements and steel connections enables the creation of

dissipative structural systems with ductile response (Asdrubali et al., 2017; Popovski & Karacabeyli, 2012). In tall and high-rise timber buildings, where the structural components are inherently rigid, the connections play a crucial role in this regard. Employing innovative engineering techniques, advanced computer modelling and simulations allow engineers to optimize their design for maximum seismic performance and make timber buildings safe to erect even in regions prone to earthquake activity. Mass timber hybrid structures exemplify this pioneering approach. They not only meet but sometimes surpass the seismic performance of equivalent steel and concrete buildings, possessing all the necessary characteristics to withstand intense winds and earthquakes (WoodWorks & Think Wood, 2021). The seismic performance of MET and hybrid assemblies in tall and high-rise structures are further explored in the section 6.7.



Figure 3. Example of the extension of the existing building with a timber structure (Dietrich Untertfaller Architekten, 2007)

Timber possesses unique acoustic properties. Also, due to its light weight, sound waves and impact stress affect it much easier than the heavy mass of concrete. This characteristic makes it ideal for creating desirable acoustic environments in spaces such as theatres and opera halls (Caniato et al., 2017; Kaufmann et al., 2018). On the other hand, additional soundproofing measures are often required to minimize sound impact and reverberations in other scenarios, particularly in residential buildings where acoustic performance significantly impacts occupants' comfort (Smith et al., 2018). For more information, see Chapter 6.6.

Timber also features advantageous thermal properties. Its thermal conductivity (λ -value) typically ranges from 0.12 to 0.19 W/mK (The Engineering ToolBox, 2003), which is lower when compared to concrete, steel-frame and masonry construction methods (WoodWorks & Think Wood, 2021) as presented in Table 7. This can be readily illustrated by touching a wooden surface and a metallic or concrete one at the same temperature. Because wood does not conduct heat as effectively, it imparts a

sense of warmth upon contact (Kaufmann et al., 2018). Its limited heat conductivity, combined with insulation materials, naturally promote excellent thermal comfort and energy efficiency (see Chapter 6.5).

Therefore, incorporating timber in construction contributes to balancing energy consumption throughout the building's lifespan (Dodoo et al., 2014; Forest Products Laboratory, 2010; Pryce, 2016). Moreover, the inherent aesthetic and texture of timber can enhance the perception of warmth and cosiness compared to colder or more industrial-looking materials. Its hygroscopic capabilities contribute to regulating the indoor environment and some studies have shown its potential as a material with a healthy calming effect (Amado et al., 2015; Kaufmann et al., 2018).

However, due to their hygroscopic properties, timber elements have the ability to absorb and retain both liquid and vapour forms of water. This characteristic gives rise to distinct thermal behaviour that requires a more meticulous understanding compared to concrete or steel. Moisture significantly influences the density and thermal properties of timber, highlighting the need for careful consideration in design and construction processes. It is especially important when designing the building envelope to deliberate the adequate placement of insulation, air barrier and vapour control layers, aiming at avoiding condensation at all costs.

In addition, despite common misconceptions, it is indeed feasible to construct high-rise buildings using timber while meeting stringent fire safety standards. Concerns about timber buildings posing a heightened fire risk largely stem from past fire incidents. However, modern timber constructions utilizing mass timber elements differ significantly from traditional timber frame or truss structures.

Table 7. Range of values of density, thermal conductivity and thermal diffusivity for different construction materials (Glass & Zelinka, 2010; Santos & Matias, 2007; Oktay et al., 2016; Cengel, n/d)

Material	Density, ρ (kg/m³)	Thermal conductivity, λ (Wm⁻¹K⁻¹)	Thermal diffusivity, α (m²s⁻¹) x 10⁻⁷
Wood (12% mc)	450-800	0,10 - 0,22	1,6 - 2,6
Brick	1500-2000	0,55 - 0,85	3 - 5,2
Concrete	2400	1,5 - 2,0	7 - 8
Steel	7800	50	100 - 140
Aluminum	2700	230	
Glass	2500	0,8 - 1,0	
Mineral wool	20-100	0,036 - 0,045	10 - 12
Extruded polystyrene, XPS	22-40	0,034 - 0,038	32

Fire codes in many countries have historically focused on pre-existing constructions, which typically excluded combustible materials in load-bearing structures. Extensive examining has demonstrated that mass timber is inherently fire-safe and provides natural resistance to fire (WoodWorks & Think Wood, 2021). The recent fire testing conducted in Europe and Canada have shown that solid wood structural elements can be engineered to meet the stringent 2-hour fire-resistance rating required for tall buildings (Green & Eric Karsh, 2012). Additionally, it is possible nowadays to find parts of the building codes around the world dedicated to timber fire design and reaction. The Eurocode 5 (CEN, 2004a) contains the general rules concerning structural fire design, including the charring rates for softwoods and hardwoods (0.8mm per minute and 0.55mm per minute accordingly) (Coulson, 2021) and the EN 13501-1 (CEN, 2018) classifies all materials into six fire

reaction Euroclasses, where untreated timber can be classified as D or E and with fire retardant even C or B, facilitating a process of choosing the materials for the right context. The EN 13501-1 classification system, it is a European tool for assessing the reaction to fire of construction materials, however, it has gained widespread adoption beyond the EU member countries. The six fire reaction Euroclasses are presented in Table 8.

Table 8. Euroclass ‘reaction to fire’ classifications. Adapted from EN 13501-1, Reaction to Fire Classification (Coulson, 2021)

Euroclass	For all construction products excluding flooring
Class A	As B for single burning item (SBI) reaction plus no significant contribution to the fire load and growth. A1 defined as non-combustible A2 defined as: limited combustibility or no contribution in any stage of the fire.
Class B	As C but satisfying more stringent requirements and showing very limited lateral spread of flame under thermal attack by a SBI
Class C	As D but satisfying more stringent requirements and showing limited lateral spread of flame under thermal attack by a SBI
Class D	Products capable of resisting, for a longer period, a small flame attack without substantial flame spread
Class E	Products capable of resisting, for a short period, a small flame attack without substantial flame spread
Class F	Products for which no reaction to fire performances are determined or which cannot be classified

NOTE: To be categorized as non-combustible or of limited combustibility, a material must attain Class A1 or A2 in testing. Any other classification related to limited spread of flame does not imply resistance to combustibility. Therefore, timber cannot achieve a Class A rating through any treatment or process (Coulson, 2021).

Although mass timber is commonly perceived as a combustible construction material, it does not inherently pose a greater fire risk compared to other materials. Its fire performance can be reliably designed, based on predictable charring rates, to comply with specified by codes hourly fire resistance requirements. The detailed analysis of fire behaviour of MET systems are presented in Chapter 6.4.

Timber construction has seen a surge in popularity due to its highly prefabricated manufacturing process, offering numerous advantages over conventional construction methods. This approach is particularly beneficial for projects with tight schedules, such as schools or rental buildings, where speed and efficiency are paramount. The prefabricated nature of timber construction allows for pre-assembly and faster assembly on-site, significantly reducing construction time (Crawford & Cadorel, 2017; Kaufmann et al., 2018; Smith et al., 2018). With components manufactured in a controlled factory environment, precision is enhanced, leading to fewer errors and less material waste during the construction process (Smith et al., 2018). Additionally, the use of prefabricated timber elements increases on-site safety by minimizing the need for complex assembly tasks and reducing the risk of accidents. Moreover, timber construction requires less labour compared to traditional methods, further contributing to cost savings and improved project efficiency. As presented by R. E. Smith (2018) the average cost savings compared to the traditionally built comparative projects is 4.2% and 20% in the schedule reduction. The streamlined production process also facilitates better control over costs and energy usage, resulting in more sustainable and environmentally friendly construction practices. Prefabrication enables easier planning and optimization of the entire production, transportation and construction process, leading to reduced CO₂ emissions and a smaller ecological footprint (Barber & Gerard, 2014; Kaufmann et al., 2018). This approach allows for greater flexibility in design and adaptability for future uses, as prefabricated timber elements can be customized to meet specific project

requirements and architectural visions. Moreover, once the first story is erected, subcontractors can be brought in to work on installations and infrastructure, even as construction progresses on the higher floors (Smith et al., 2018). Overall, the advantages of prefabricated timber construction, including speed, precision, safety and cost efficiency, make it a highly competitive alternative to conventional construction methods for a wide range of projects.

Additionally, growing environmental concerns have prompted European Directives to advocate for increased re-use and recycling of materials wherever feasible. Embracing the principles of circular economy and wood cascading, efforts are directed towards reusing timber elements and extending their lifespan, thereby enhancing carbon sequestration. These initiatives collectively contribute to reducing overall construction waste and promoting a more environmentally conscious approach to resource utilization and are further discussed in Chapter 2.4 (Kaufmann et al., 2018).

Timber buildings offer a rapid solution that effectively addresses the three primary sustainability objectives: environmental, financial, and social (Silva et al., 2013). Besides its renewable nature, it also boasts an appealing, visually pleasing appearance, a natural aroma and an enjoyable texture.

While the mass timber industry offers numerous benefits, there are also some downsides to consider. Unfortunately, due to the relatively small number of completed projects compared to other construction systems, many general contractors, designers and engineers are not familiar with MET construction methods. This lack of experience creates a learning curve for professionals in the industry, requiring additional studies and comprehension, ultimately leading to lower popularity (Wong et al., 2024). Compared to conventional construction materials, engineered timber requires additional and more careful design at the initial stage of the project and supplementary attention throughout the construction process. Additionally, logistical organization for transport and erection, including documentation, engineering and permit acquisition, is often more complex and time-consuming. Advanced planning and prefabrication mean that on-site changes and adaptations are almost impossible, requiring precise execution from the outset (Smith et al., 2018). Moreover, timber structures are more susceptible to weather conditions, particularly in regions with higher precipitation levels. Extra precautions may be necessary to protect timber structures and elements and ensure their longevity and structural integrity. Overall, while mass timber offers many advantages, it's essential to consider these potential challenges when embarking on a mass timber construction project.

2.3. Mass timber market

The rise of mass timber as a viable and sustainable construction material marks a significant shift in the building industry. This chapter explores the increasing mass timber market, focusing on the products, drivers and key players that are shaping its expansion. It delves into the various engineered timber products available, the factors triggering market growth and the roles of designers, contractors and manufacturers in advancing this innovative construction method.

2.3.1. Mass timber products

Given the inherent variability of natural wood, predicting its performance becomes challenging. Consequently, researchers in the wood industry globally have dedicated decades to developing engineered wood products. The primary objective is to enhance wood strength through the reduction in the variability in its behaviour while used as construction material. The emergence of innovative building systems is expanding the structural use of wood across various building types, increasing the array of low-carbon options accessible to building designers.

The ever-evolving group of new solutions, especially when combined with other construction materials, makes it challenging to categorize all available innovations. The following selection of products represents common solutions used globally, regardless of local regulations, expected performance and technical standards. These products can be categorized into three main groups, as depicted in Figure 4, based on the type of lumber elements comprising the product: laminated solid timber, veneer lumber and timber strands.

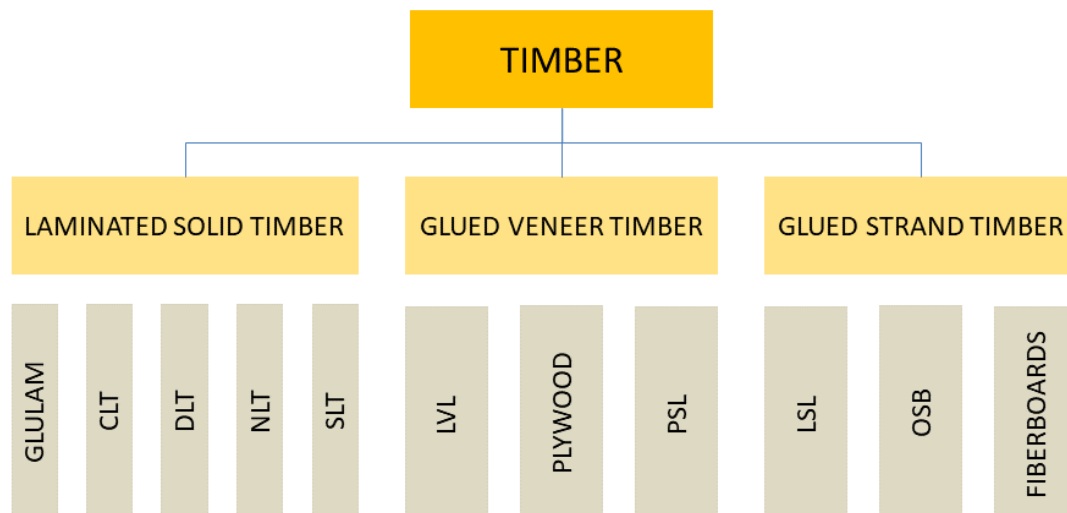


Figure 4. Timber products and derivatives

Laminated solid timber, glued veneer lumber and glued strand timber are all types of engineered wood products, but they differ in the composition of the wood elements used in their construction:

- Laminated solid timber is made by bonding together solid lumber pieces, typically of the same species, with adhesives, dowels, nails, or steel rods. The resulting product retains the natural appearance and characteristics of wood while offering improved strength and dimensional stability. Glued solid timber is often used for structural applications where the aesthetic appeal of wood is desired and in heavy duty structures. Examples of laminated solid timber include Glulam, CLT, dowel laminated timber (DLT), nail-laminated timber (NLT) and stress-laminated timber (SLT);
- Glued veneer lumber is made by bonding thin veneer sheets together with adhesives under heat and pressure. These veneer sheets are typically oriented with their grain direction alternating, which enhances the strength and stiffness of the final product. Glued veneer lumber is commonly used in structural applications where long spans and high load-bearing capacities are required. Examples of glued veneer lumber are LVL, Plywood and parallel strand lumber (PSL);

- Glued strand timber is made by bonding strands or particles of wood together with adhesives and compressing them into panels. The strands are typically oriented in specific directions to optimize the mechanical properties of the product. Glued strand timber is valued for its high strength-to-weight ratio and is often used in structural applications such as beams, joists, and columns (Forest Products Laboratory, 2010). Laminated strand lumber (LSL), oriented strand lumber (OSB) and different fibreboards are the examples of glued strand timber products.

In summary, while all three types of products are manufactured using wood and bonding component, they vary in the form and arrangement of the wood elements, which results in differences in their mechanical properties and applications.

2.3.1.1. Glued laminated timber (Glulam)

Glued laminated timber, often referred to as glulam, is a versatile engineered wood product crafted from dry and finely polished solid wood. Its roots trace back to the late 19th century in Europe, signifying its long-standing presence in construction (Gong, 2019). It is composed of at least three layers, or lamellae, of softwood, each ranging from 6 to 45 mm in thickness, bonded together using moisture-resistant adhesives under pressure, aligning in the direction of the grain. The layers can be of the same strength class (homogenous) or combined strength class (with external lamellae of distinct strength class). During the manufacturing process, defects and irregularities in the wood are largely dispersed, while major defects such as large knots are removed, resulting in greater uniformity in the final product. The longitudinal joining of lamellae creates larger and longer elements, making glulam an ideal choice for structural components bearing high stresses. These components include frames with long spans, columns, beams, cantilevers and rafters, as well as elements of complex straight or curved structural assemblies in wood. Beyond buildings, glulam finds applications in bridges and pavilions, showcasing its versatility in various architectural contexts. The wood species commonly used in glulam production include spruce, fir, pine, hemlock and larch. Glulam's mechanical strength surpasses that of solid wood, enhancing its suitability for demanding construction applications. To ensure quality and compliance with industry standards, the production of glulam should adhere to norms like EN 14080. These standards provide clear specifications and characterization of glulam's parameters, ensuring its integrity and performance in construction projects. As the demand for sustainable and resilient building materials grows, glulam continues to emerge, offering a blend of strength, durability and environmental consciousness (Coulson, 2021; Forest Products Laboratory, 2010; Gong, 2019; Green & Taggart, 2017; Swedish Forest Industries Federation, 2022; WoodWorks & Think Wood, 2021).

2.3.1.2. Cross laminated timber (CLT)

Cross-laminated timber (CLT), akin to glulam, stands as a solid wood softwood lamellae system. Used in form of the panels that can consist of three, five, seven or nine layers. CLT was used for the first time in Austria and Germany in the 1990s and it represents a modern innovation in timber construction. Unlike glulam, CLT panels feature adjacent boards glued with structural adhesive crosswise at 90-degree angles, enhancing their structural integrity and load-bearing capacity. This unique arrangement enables CLT to efficiently withstand the loads applied to its plane and out-of-plane (one or two-dimensional bending), compression, tension and shear forces, making it an ideal choice for

various structural applications. Similar to glulam, these panels can be tailored to custom dimensions, with transportation constraints being the only limiting factor on their overall size. As a result, CLT panels find widespread use in floors, walls, roofing, as well as in shafts and staircases (Asdrubali et al., 2017; Bowyer et al., 2015; Green & Eric Karsh, 2012; Kurzinski et al., 2022).

In the field of construction, CLT emerges as a cost-effective alternative for multi-storey buildings. Using Computer Numerical Control (CNC), the panels can be precisely trimmed to their exact form, significantly reducing material waste and enhancing manufacturing efficiency. Its versatility and structural aptitude make it a preferred choice for architects and engineers seeking sustainable and resilient building solutions. However, it's worth noting that CLT use is not yet explicitly specified in Eurocode 5. The ongoing development of the second generation of Eurocode 5 includes initiatives to incorporate the design specifications for cross-laminated timber. Nevertheless, various organizations rely on design methods informed by common knowledge from Eurocodes or guidance provided by the European Committee for Standardization (CEN) and national standards (Schickhofer et al., 2016; Swedish Wood, 2019). In 2015, CEN issued a dedicated standard for CLT "Timber structures - Cross laminated timber - Requirements", establishing technical criteria for the product (Swedish Wood, 2019; Kurzinski et al., 2022). The latest iteration of this standard for CLT products in Europe is EN 16351-2021 (CEN, 2021). As CLT continues to gain traction in the construction industry, further standardization efforts may be warranted to ensure its seamless integration into regulatory frameworks.

2.3.1.3. Nail-laminated timber (NLT)

Nail laminated timber (NLT), also known as nail-lam, is a traditional, a century-old form of mass timber construction and it is experiencing a resurgence in popularity due to its sustainability, cost-effectiveness and aesthetic appeal, offering structural performance and modern design elegance (Binational Softwood Lumber Council, 2017). NLT panels are composed by stacking individual boards or planks on edge and fastening them together with nails or screws, driven through the faces of the boards into adjacent layers. This creates a strong, rigid panel suitable for various structural and architectural applications, including floors, walls, roofs and ceilings (Gong, 2019; WoodWorks & Think Wood, 2021). Similar to other mass timber products like glulam and DLT, NLT can also be bent to achieve curved structures. Versatility is a key advantage of NLT, as it can be made from a wide range of lumber species and sizes to meet specific design requirements. It can be custom manufactured using locally sourced dimensional lumber without the need for dedicated production facilities (Green & Taggart, 2017). NLT panels can be easily prefabricated on-site or in the factory and assembled quickly, reducing construction time and labour costs. NLT is more prone to mould and water-related damage compared to engineered wood alternatives (Green & Taggart, 2017). It's essential to take significant precautions, especially to safeguard the end grain from prolonged moisture exposure.

While there are no European standards specifically for NLT, it is recognized as code-compliant by the International Building Code (IBC) for buildings of varying heights, areas and occupancies (Type III, IV and V) (International Code Council & American Wood Council, 2020), and in Canada, a NLT design and construction guide provides guidance on quality control and design (Binational Softwood Lumber

Council, 2017). Overall, nail laminated timber offers a compelling combination of strength, sustainability, and versatility, making it an attractive option for a wide range of construction projects.

2.3.1.4. Dowel-laminated timber (DLT)

Dowel-laminated timber (DLT), a member of the laminated timber family, is manufactured using solid softwood lumber boards. Developed in the early 1990s in Switzerland, DLT represents another innovative step in the dominion of one-dimensional additive processes (Gong, 2019). Often known as Brettstapelholz or Dübelholz. DLT utilizes hardwood dowels to connect the boards stacked on end, differing from NLT's use of nail (WoodWorks & Think Wood, 2021). Also, in contrary to NLT, finger-joined lumber is typically employed in DLT production. The varying moisture content of softwood boards and hardwood dowels ensures tight interlocking of panels, obviating the need for metal fasteners, nails, or adhesives. As both materials equilibrate post-fabrication, dowels swell and lumber shrinks, creating a robust friction-fit joint that renders glue or nails unnecessary. Typically, dowels penetrate through 7-10 laminations, streamlining DLT manufacturing compared to NLT. DLT can incorporate various dowel connections, including diagonal dowel wood, where dowels are inserted at an angle of around 15 degrees (Gong, 2019). Structurally DLT performs similarly to Glulam and NLT, as its grains run in one direction. Panels made with DLT serve diverse structural roles such as walls, floors, roofs and stairs, and can be adapted even to curved architectural designs (WoodWorks & Think Wood, 2021). DLT can be easily manufactured using CNC machinery, with panel size and design constrained only by transportation limitations. Offering various joint options, DLT stand out in acoustic, thermal and structural performance. With its nearly 100% wood composition, except for finger-joined laminations containing minimal adhesive, DLT gains interest in Europe and North America.

Validated by the International Code Council (ICC) in North America, DLT meets Building Code requirements (International Code Council & American Wood Council, 2020). DLT may feature different dowel connections. However, there is a scarcity of manufacturers offering published design values for their respective DLT products. Consequently, the utilization of DLT necessitates approval from the building authority on a case-by-case basis (Gong, 2019).

2.3.1.5. Stress-laminated timber (SLT)

Stress-laminated timber is a popular structural system used in bridge decks. Developed in North America in 1970s, rapidly started to gain popularity worldwide, especially in Nordic countries and Australia. It consists of solid timber beams stacked together, usually by their longer side, with the direction of the grain parallel to the length of the bridge. The stacking in this case is done by pre-stressed steel rods inserted perpendicularly to the fibres into pre-drilled holes. Due to compressive stress and friction between lamellae, SLT decks are stable and gaps-free (Massaro & Malo, 2020).

2.3.1.6. Laminated veneer lumber (LVL)

Laminated Veneer Lumber (LVL) is an engineered wood product known for its high strength. It falls under the category of Structural Composite Lumber (SCL) and is predominantly used for structural purposes. LVL can be tailored to specific climatic conditions and can be protected from biological

attacks through pressure treatment. It is effectively free from warping and splitting due to the dispersion or elimination of knots, slope of grain and splits throughout the material (Green & Taggart, 2017). This homogeneous and dimensionally stable material can be used in a wide array of applications, from beams and headers to floors, walls and roofs. It can also serve as a panel or a beam, wall, door, window, or truss, competing with Glulam in the same range of applications.

The production process involves the bonding of wood veneers under the application of heat and pressure. Logs are initially peeled into thin slices, typically 3mm thick, referred to as veneers, which are subsequently dried and graded based on their strength and stiffness. The wood for the production of LVL can be sourced from a variety of tree species, including pine, spruce, Douglas fir, and larch, as well as the fast-growing species that are otherwise unsuitable for solid-sawn timber products (Green & Taggart, 2017).

Subsequently, the veneers are coated with a waterproof adhesive, such as phenol formaldehyde or phenol-resorcinol formaldehyde and are oriented in the same direction as the grain (Asdrubali et al., 2017). Then they are assembled into a large billet and subjected to heat and pressure. This process cures the adhesive and bonds the veneers together. The dried and compressed billet is then cut into boards or sheets (Green & Eric Karsh, 2012). LVL is available in a range of sizes, with sheets typically produced in widths of 0.6 to 1.2 meters and a thickness of 38 mm. Thanks to scarfed or lapped jointed veneers, LVL can be produced in lengths that far exceed those of conventional lumber. Continuous presses can be employed to create a potentially infinite sheet, which is then cut to the desired length and form. Lumber of various widths can also be produced at the manufacture facility (Forest Products Laboratory, 2010). LVL can also be manufactured with approximately 20% of the veneers oriented so their grain is perpendicular to that of the other veneers in the billet. This results in a partially cross-laminated panel with greater crushing strength than conventional LVL panels (Green & Taggart, 2017).

For construction design, the Eurocode 5 provides basic values for LVL, with more detailed information available in EN 14374 and EN 14279 (CEN, 2004a). In conclusion, LVL is a versatile and high-performance material that offers a sustainable and cost-effective alternative among other MET products. Its uniform appearance and predictable performance make it a popular choice in modern construction.

2.3.1.7. Plywood

Plywood, an engineered wood product, shares similarities with LVL but differs in its manufacturing process. It's primarily composed of veneer sheets, or plies, that are bonded together. The grain direction of each layer is perpendicular to its adjacent layers, enabling the creation of long structural panels. These panels typically measure 1 200 × 2 400 mm or 1 220 × 2 440 mm and have a thickness ranging from 12 – 24 mm. The panels may consist of an odd or even number of plies, but the number of layers (either a single ply or multiple plies with parallel grain directions) is always odd. The grain direction of the outer layers and all odd-numbered layers runs parallel to the panel's long dimension (Forest Products Laboratory, 2010; Swedish Forest Industries Federation, 2022).

Plywood finds widespread use in various areas such as bracing elements, floors, ceilings, furniture and construction sheathing. It can also serve as a component in other engineered wood products and systems like prefabricated I-joists, box beams, stressed-skin panels and panelised roofs.

The structural characteristics of plywood depend on the number and thickness of the veneers and the load direction. Factors such as the quality of the veneer plies, the layer arrangement, the type of adhesive and the control of bonding conditions during production all contribute to the properties of plywood. The panel grade is determined by the quality of the used veneers, especially the face and back. Plywood panels display considerable bending strength in both longitudinal and transverse directions. The differences in strength and stiffness along the panel length versus across the panel are significantly less than those in solid wood. Plywood offers excellent dimensional stability lengthwise and widthwise and experiences minimal irreversible thickness swelling when wet. Its resistance to splitting enables the placement of fasteners close to the panel edges (Forest Products Laboratory, 2010; Swedish Forest Industries Federation, 2022).

Eurocode 5 provides basic values for plywood construction design, with EN 636 offering more detailed information (CEN, 2004a). Depending on its intended use, plywood can have a higher defect count, making it more affordable. For applications where internal knotholes and voids could be problematic, plywood can be ordered with a solid core and face veneers. In summary, plywood is a versatile, high-performance material that presents a sustainable and cost-effective alternative to traditional building materials.

2.3.1.8. Parallel strand lumber (PSL)

Parallel Strand Lumber (PSL) is a type of composite made up of wood strand elements, with the wood fibres primarily aligned along the length of the component. This material was first introduced in Canada during the 1980s by a company called MacMillan Bloedel, which is now known as Weyerhaeuser Company Ltd. It is sold under the brand name Parallam® (Forest Products Laboratory, 2010; Green & Taggart, 2017).

The process of manufacturing PSL is quite similar to that of LVL, with the main difference being the size of the veneers. In PSL, the veneer strips are approximately 3 mm thick, 15-19 mm wide and typically at least 0.6 m long (Forest Products Laboratory, 2010). These elongated strands are arranged lengthwise, parallel to the major axis of the beam and bonded together with adhesives. The strands are covered with a waterproof structural bonding agent, often phenol-resorcinol formaldehyde and positioned in a press using specialized equipment to ensure proper alignment and distribution. The pressing process results in the densification of the material and the adhesive is cured using microwave technology.

The most commonly used species in the production of PSL are Douglas fir, southern pines, western hemlock and yellow-poplar, but other species can also be used (Forest Products Laboratory, 2010). The manufacturing process was optimised to utilize the material from the roundup of the logs in the veneer cutting operation, as well as other less than full-width veneer, allowing to make use of waste material from a plywood or LVL fabrication.

PSL easily can accept preservative treatment, which provides protection from moisture damage. This results in a product that is dimensionally stable and appropriate for interior and exterior applications. Moreover, since the growth imperfections have been removed from the wood strands before fabrication, PSL products have consistent properties and a high load-carrying capacity. This

uniform timber construction material offers high resistance to bending and compression, making it an ideal solution for long free span beams and columns, as a substitute for solid-sawn lumber or glulam.

In terms of aesthetics, PSL can exhibit a rich timber texture and a high-quality looking surface, making it suitable for exposed elements.

2.3.1.9. Laminated strand lumber (LSL)

Laminated Strand Lumber (LSL) is a product in the family of dried and graded wood veneers. Unlike LVL and plywood, which use layers of veneers, LSL is made from flaked wood strands approximately 300 mm long and 0.8 mm - 1.3 mm thick (Forest Products Laboratory, 2010). The strands are oriented parallel to the panel's longitudinal axis, providing one-directional spanning capability and are usually manufactured from fast-growing tree species (Green & Eric Karsh, 2012).

During fabrication, veneer flakes of differing sizes are blended, covered with waterproof bonding agent and steam-pressed to form a solid board that can be cut to various sizes, with a maximum width of 2.4 meters and a variable thickness adaptable to the applications requirements (Green & Taggart, 2017).

Like other veneer engineered products, LSL presents predictable strength, significant moisture resistance and dimensional stability, with reduced problems with twisting or shrinkage. Although it has lower strength and stiffness compared to LVL or PSL, LSL is more affordable and remains as a common material for structural framing for headers, beams and design features, and in taller wood buildings, for floors, walls, and roof panelling (Green & Taggart, 2017). It is also used in I-joist flanges and other applications similar to LVL (Asdrubali et al., 2017).

2.3.1.10. Oriented strand lumber (OSB)

Oriented Strand Lumber (OSL), or more commonly Oriented Strand Board (OSB) is a broadly used engineered wood product consisting of thin, rectangular-shaped wood chips. OSB shares many similarities with LSL, but the primary difference is that the wood strands in OSB are much shorter, ranging from 8 to 15 cm in length. These strands are meticulously arranged in cross-oriented layers and joined together using an adhesive in a composition of approximately 95 percent wood and 5 percent adhesive under heat and pressure (Swedish Forest Industries Federation, 2022). Due to the small size of the strands, OSB can be produced with no waste, using small-diameter logs or entire trees, even those with defects.

Modern OSB products are dimensionally stable and comparable in strength to plywood. Their lightweight and water-resistance make them a versatile solution for roofs, wall and floor sheathing. Depending the type, OSB can be used as structural elements similarly to CLT panels and in I-joist webs (Asdrubali et al., 2017). OSB panels typically measure 1,200 × 2,400 mm with thicknesses between 6 and 25 mm, but they can also be manufactured in sizes up to 3 meters in width, 25 meters in length and 75 mm in thickness (Swedish Forest Industries Federation, 2022).

Basic values for OSB construction design can be found in Eurocode 5 and more detailed information is available in EN 300 (CEN, 2004a).

2.3.1.11. Fibreboards and particleboards

Fibreboards and particleboards are timber products manufactured from lignocellulosic particles of various sizes and densities, combined with resin and bonded through heat and pressure to form panels. High Density Fibreboard (HDF), Medium Density Fibreboard (MDF), Low Density Fibreboard (LDF), and Particleboard (Chipboard) are the main types of the boards available on the market nowadays.

Fibreboards and particleboards primarily differ in the physical configuration of the wood elements. Chipboards are made from wood chips slightly smaller than those in OSB and on average consist of 85 percent wood chips and 15 percent bonding agent (Swedish Forest Industries Federation, 2022). Particleboards can also be composed of smaller wood particles, such as sawdust, mixed with adhesives and are primarily used in floor structures. Fibreboards, which include hardboard and cellulosic fibreboard, are typically classified by density. They take advantage of the fibrous nature of wood, utilizing its inherent strength more effectively than particleboard. The bonds between wood fibres must be break down firstly, usually through attrition milling or refining, to obtain fibres for composites. They can be produced using wood fibres and bonding agents in a process similar to particleboard fabrication or through a wet process that utilizes the lignin within the wood as a binder. This second method, developed by William H. Mason and generally known as masonite, is used for structural elements, while other types of fibreboards are used in furniture and joinery (Swedish Forest Industries Federation, 2022). HDFs and MDFs are subjected to dry processes, while wet processes are appropriate for both high-density hardboard and low-density cellulosic fibreboard manufacture (Forest Products Laboratory, 2010).

Detailed design values and specifications can be found in EN 312, EN 316 and EN 622 (CEN, 2004a; CEN, 2009).

2.3.1.12. Hybrid timber-based composites

The inherent limitations of wood as a material have led to an increase in the pursuit of hybrid composite elements. The quest for perfectly stable, economically viable, environmentally friendly and durable solutions has significantly advanced this market. Despite the wide range of mass timber products available for construction, to enhance mechanical properties, energy efficiency, acoustic performance, fire resistance and durability, timber structures are often integrated with other materials like concrete and steel. This combination results in hybrid timber-based structures, which leverage the strengths of each material to achieve superior overall performance. Innovative new products now combine various types of engineered timber and incorporate other materials, merging the best attributes of each to meet the growing demands of modern construction.

Material hybridization can be applied at two distinct levels: the building component scale and the system level. At the building component scale, different materials are combined within a single element, such as a column, beam, floor panel, or wall panel. At the system level, various materials are utilized for different building components, including the vertical structure, horizontal structure and building envelope. Hybrid components that combine timber with concrete or steel are commonly referred to as Timber-Concrete Composite (TCC) and Steel-Timber Composite (STC) components, respectively (Pastori et al., 2022). These include timber-concrete slabs and Easy-Joists® (which feature timber and metal webs) for floors, walls and roofs, as well as timber-steel beams for frame structures.

Furthermore, the composites products can be made with timber elements only. Combinations of various engineered wood products have led to innovative structural elements such as timber ribs, timber box slabs and I-beams, crafted from materials like glulam, LVL and OSB. These advanced hybrid solutions offer improved mechanical properties, durability, and efficiency, catering to the diverse demands of modern construction (Dias et al., 2016, 2018).

2.3.2. Drivers and key players

2.3.2.1. Mass timber market drivers

The mass timber market is experiencing significant growth driven by a confluence of sustainability initiatives, regulatory support and the collaborative efforts of industry players. This section focuses on the interplay between these components driving the mass timber market. It underscores the importance of continued collaboration and innovation to overcome challenges and capitalize on opportunities, ultimately paving the way for a sustainable future in construction.

Sustainability

One of the foremost advantages of the mass timber market is its potential for sustainability. As discussed in previous chapters, wood as a renewable resource offers several environmental benefits for timber buildings.

Additionally, sustainable forestry practices, including selective logging and reforestation, ensure that forest ecosystems remain healthy and productive. Certified forests follow stringent guidelines to maintain biodiversity, soil quality, water resources and air purification.

Moreover, mass timber components offer significant potential for integration into the CE through their inherent reusability and recyclability. These components can be designed for disassembly, facilitating their reuse and recycling at the end of a building's life cycle. This approach aligns with the principles of the CE, which intend to maintain materials in use for as long as possible, thus minimizing waste and resource consumption (see section 2.4). At the end of their lifecycle, mass timber elements can be processed into secondary products, such as particleboard, fibreboard, or even new engineered wood products. This recycling process retains the value of the wood and reduces the demand for new raw materials. Timber that is no longer suitable for structural use can be converted into biomass energy, offset fossil fuel use, further contributing to a sustainable resource cycle. Even when timber products reach the end of their useful life and can no longer be recycled, they possess the inherent ability to decompose naturally. This biodegradation process allows timber to return valuable nutrients to the ecosystem, thereby avoiding environmental harm. By closing the loop in the material's lifecycle, this natural decomposition contributes to the reduction of landfill waste and supports a more sustainable waste management strategy.

Mass timber construction supports several United Nations SDGs. By aligning with these global objectives, the mass timber market gains additional momentum and legitimacy. Therefore, sustainability is a key driver for the mass timber market due to its environmental benefits, economic advantages, alignment with global sustainability goals and the strategic importance. These factors collectively create

a strong and compelling case for the widespread adoption of mass timber in construction. Consequently, bound by increased awareness of climate change, there is a growing consumer and investor demand for sustainable buildings. According to Salvadori (2021), sustainability was indicated by the investors as a main motivation for using mass timber in their constructions.

Regulatory support and policy incentives

Fire safety has been one of the limiting factors in the use of timber for tall and high-rise buildings over the years. Due to significant fire events globally, building codes evolved to restrict the use of timber to meet stringent fire and life safety standards. Wood, being classified as a combustible material, was limited in application to small, low-rise and low-hazard buildings. Consequently, the construction of multi-storey timber buildings was permitted only in select jurisdictions. As a result, there are few surviving examples of such structures, as discussed in Chapter 5 (Bowyer et al., 2015; Green & Eric Karsh, 2012; Green & Taggart, 2017). However, with advancements in fire-resistant technologies and evolving regulatory frameworks, there is a growing acceptance of timber as a viable material for a wider range of structures. This changing landscape is opening new possibilities for the use of timber in modern, sustainable construction practices.

Recent building codes are progressively accommodating and promoting the use of mass timber, acknowledging its substantial environmental benefits and robust structural capabilities. The regulatory support is a pivotal factor in driving the adoption of timber-based products within the construction industry. Furthermore, in response to escalating concerns about climate change, governments are implementing policies and incentives aimed at promoting sustainable building materials. These measures, yet not very widespread, include updating building standards to facilitate mass timber construction and offering subsidies, grants and tax incentives for green building practices and the use of eco-friendly materials such as MET.

In 1941, Canadian building regulations were relatively permissive regarding the use of heavy timber, allowing constructions up to 22.5 meters. However, the post-World War II era saw significant regulatory reforms aimed at standardizing building practices across the country. With the adoption of the National Building, Plumbing and Fire Codes in 1953, these regulations were revised, reducing the permissible height of such buildings to four storeys. This regulatory shift reflected growing concerns over fire safety and structural integrity in taller timber structures (Green & Taggart, 2017). The reduction in allowed building height reflected the evolving understanding of fire dynamics and the need for enhanced safety measures. Timber, due to its combustible classification, was subject to more stringent regulations to prevent and contain fires in taller buildings. This regulatory shift not only shaped construction practices of the time but also influenced the evolution of building standards with focus on more common materials.

In line with the findings of Gosselin et al. (2017) and Milestone & Kremer (2019), the survey results highlight that rigid building codes are perceived as the most significant barrier to the wider utilisation of wood in construction, representing 40% of the reported obstacles as presented in Figure 4. National regulations often impose a range of restrictions on wood, including stringent fire safety requirements, misconceptions about its fire resistance and a general lack of knowledge regarding code provisions and

the structural calculation of timber members. The data also reveal that a shortage of expertise within the industry (18%) and the perceived cost of timber construction (16%) act as major impediments. Secondary concerns include durability (8%), technical limitations (4%), prevailing industry culture (4%), and material availability (4%), which, although less influential, further contribute to the hesitation surrounding timber adoption in building projects. Together, these findings reinforce the notion that institutional and knowledge-related barriers, rather than purely technical material properties, continue to restrict the development of timber construction in many regions.

However, recent revisions to building codes in some countries have increasingly incorporated provisions for the use of mass timber, enabling taller and more complex structures.

In Canada, current baseline regulation permits timber structures up to six storeys. However, in 2020, the Canada National Building Code introduced provisions for structures up to twelve storeys, reflecting an increasing confidence in the safety and viability of taller wood buildings. This change followed British Columbia's earlier decision to raise the height limit for newly constructed wood buildings, setting a precedent for nationwide regulatory adjustments and demonstrating the feasibility and safety of taller timber and hybrid constructions.

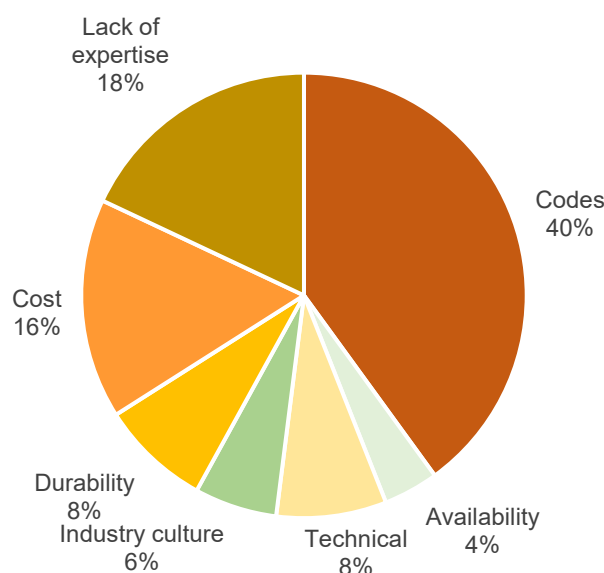


Figure 4. Barriers in wood utilisation in construction (Milestone & Kremer, 2019)

In the United States, the International Building Code (IBC) traditionally allowed timber structures up to six floors. However, significant regulatory advancements were made in July 2021 when the California Building Code was updated to permit the construction of tall mass timber buildings up to 18 floors (International Code Council & American Wood Council, 2020). This progressive change was facilitated by the introduction of three new construction types in the 2021 IBC: Type IV-A, Type IV-B, and Type IV-C. The new categories delineate specific requirements and performance criteria for different levels of fire resistance and structural integrity in mass timber construction (WoodWorks & Think Wood, 2021). Type IV-A allows for fully encapsulated mass timber with the highest fire resistance, Type IV-B permits partially exposed mass timber with moderate fire resistance and Type IV-C allows for fully exposed mass timber with the least stringent fire resistance requirements, suitable for specific design and use cases (Breneman et al., 2022; International Code Council & American Wood Council, 2020).

The regulatory advancements in Canada and the United States reflect a growing recognition of the potential for mass timber in sustainable construction. By updating building codes to accommodate taller timber structures, both countries are pioneering efforts to integrate environmentally friendly materials into the construction industry, balancing safety, performance and sustainability. These changes not only enhance the use of timber in modern architecture but also set a global example for the adoption of innovative building materials and resulted in the completion of ASCENT- the world's tallest timber building in 2023 in Milwaukee, USA (ASCENT, 2023; Barera, 2022; Carlson, 2022)

In Europe, the specific technical criteria are outlined in harmonized European standards (EN standards: EN 1990 - EN 1999), as illustrated in Figure 5. The Eurocodes, which are a set of standardized building codes for structural design, are integral to this regulatory framework, cover various aspects of structural engineering, including basis of design, actions on structures and specific rules for different materials and types of structures. Each member country is required to implement these Eurocodes and adopt them as national standards, ensuring a uniform approach to safety and performance across the EU, consistency and reliability, creating a binding legal framework that all relevant stakeholders must follow.

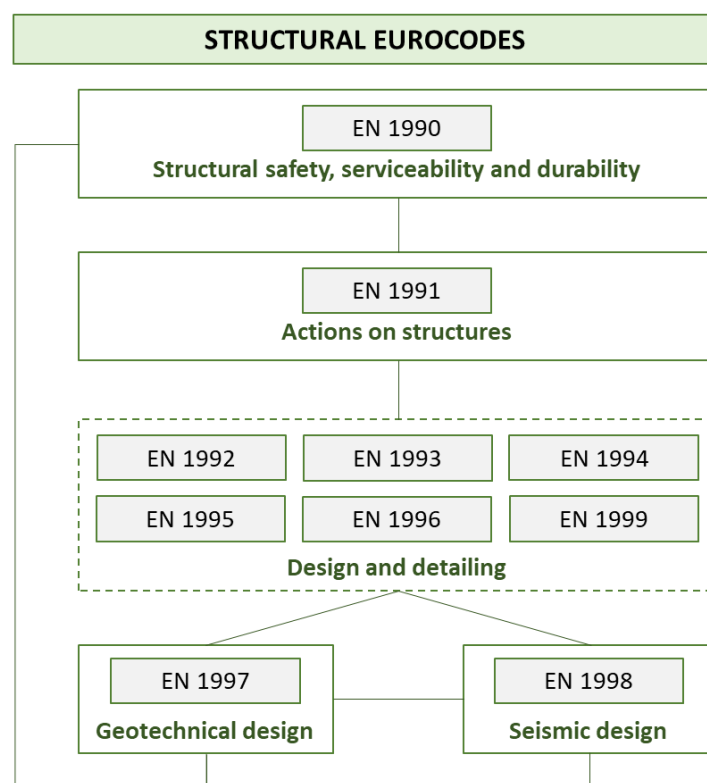


Figure 5. Structural Eurocodes

The Eurocodes are developed through a collaborative process involving industry experts, researchers and regulatory bodies, guaranteeing they reflect the latest scientific and technical knowledge.

Eurocode 5, specifically dedicated to the design of timber structures, has influenced the adaptation of national building codes across most European countries. The publication of EN 1995 Eurocode 5 – Design of Timber Structures in 2004 has significantly advanced mass timber construction, providing a

comprehensive framework that has facilitated the construction of taller wood buildings across most European countries in the subsequent years (Green & Taggart, 2017).

Given the intricate and interrelated nature of these codes, changes to accommodate the innovative possibilities offered by timber are implemented gradually yet progressively. The second generation of Eurocode 5 is currently under development, with one of the key initiatives being the inclusion of design guidelines for CLT (Kurzinski et al., 2022). New materials, products and assemblies must undergo rigorous testing and certification before they can be integrated into national and international standards. This meticulous process ensures safety and reliability but requires significant time and effort. Despite these challenges, an increasing number of countries are recognizing the potential of timber for high-rise construction. Consequently, the practical application of timber in tall buildings is gradually aligning with theoretical advancements, demonstrating a growing acceptance and implementation of timber-based solutions in modern architecture. Additionally, to assist manufacturers in preparing declarations of performance and applying CE marking for construction products not covered by harmonized standards, the European Technical Assessment (ETA) provides detailed information on the performance evaluation of these products.

Moreover, the European Union has issued directives pertaining to various wood and timber products. The EU's directives on wood and timber products, supported by harmonized European standards and the Eurocodes, establish a robust regulatory framework that ensures consistent safety and health standards across member states. This comprehensive system promotes uniformity in the quality and performance of timber products, facilitating safer and more sustainable construction practices throughout the CEN member states. These directives are mandatory and must be transposed into national laws and regulations by each member state. While the directives establish the essential binding requirements, they do not provide technical details (Arangio, 2012).

List of European standards and directives related to timber products:

Standards (EN Standards) for Timber Products:

- EN 1990: Eurocode - Basis of structural design (general principles applicable to all Eurocodes);
- EN 1995: (Eurocode 5) Design of timber structures;
- EN 300: Oriented Strand Board (OSB) Definition, classification and specifications;
- EN 301: Adhesives, phenolic and aminoplastic for load-bearing timber structures; Classification and performance requirements;
- EN 312: Particleboards – Specifications;
- EN 316: Wood fibre boards - Definition, classification and symbols;
- EN 335: Durability of wood and wood-based products - Use classes: definitions, application to solid wood and wood-based products;
- EN 338: Structural timber - Strength classes;
- EN 350: Durability of wood and wood-based products - Testing and classification of the durability to biological agents of wood and wood-based materials;
- EN 351-1: Durability of wood and wood-based products - Preservative-treated solid wood - Part 1: Classification of preservative penetration and retention;
- EN 351-2: Durability of wood and wood-based products - Preservative-treated solid wood - Part 2:

Guidance on sampling for the analysis of preservative-treated wood;

- EN 383: Timber structures Test methods Determination of embedding strength and foundation values for dowel type fasteners;
- EN 384: Structural timber - Determination of characteristic values of mechanical properties and density;
- EN 385: Finger jointed structural timber Performance requirements and minimum production requirements;
- EN 14080: Timber structures - Glued laminated timber;
- EN 16351: Timber structures - Cross laminated timber;
- EN 14081: Timber structures - Strength graded structural timber with rectangular cross section;
- EN 14374: Timber structures - Structural laminated veneer lumber;
- EN 13986: Wood-based panels for use in construction - Characteristics, evaluation of conformity, and marking;
- EN 387: Glued laminated timber - Large finger joints - Performance requirements and minimum production requirements;
- EN 408: Timber structures - Structural timber and glued laminated timber - Determination of some physical and mechanical properties;
- EN 409: Timber structures - Test methods. Determination of the yield moment of dowel type fasteners – Nails;
- EN 460: Durability of wood and wood-based products Natural durability of solid wood - Guide of the durability requirements for wood to be used in hazard classes;
- EN 594: Timber structures Test methods - Racking strength and stiffness of timber frame wall panels;
- EN 622: Fibreboards – Specifications;
- EN 636: Plywood Specifications;
- EN 912: Timber fasteners - Specifications for connectors for timber;
- EN 1075: Timber structures Test methods - Testing of joints made with punched metal plate fasteners;
- EN 13271: Timber fasteners - Characteristic load-carrying capacities and slip moduli for connector joints;
- EN 1380: Timber structures - Test methods - Load bearing nailed joints;
- EN 1381: Timber structures - Test methods - Load bearing stapled joints;
- EN 1382: Timber structures - Test methods Withdrawal capacity of timber fasteners;
- EN 1383: Timber structures - Test methods Pull through testing of timber fasteners;
- EN 13696: Timber structures - Prefabricated structural members - Performance requirements and general principles for detailing;
- EN 13986: Wood-based panels for use in construction - Characteristics, evaluation of conformity and marking;
- EN 14080: Timber structures - Glued laminated timber – Requirements;
- EN 14081-1: Timber structures - Strength graded structural timber with rectangular cross section - Part 1: General requirements;
- EN 14250: Timber structures - Production requirements for fabricated trusses using punched metal plate fasteners;
- EN 14279: Laminated veneer lumber (LVL) - Specifications, definitions, classification and requirements;

- EN 14358: Timber structures - Fasteners and wood-based products - Calculation of characteristic 5-percentile value and acceptance criteria for a sample;
- EN 14374: Timber structures Structural laminated veneer lumber – Requirements;
- EN 14545: Timber structures Connectors Requirements;
- EN 14592: Timber structures - Fasteners - Requirements;
- EN 14915: Solid wood panelling and cladding;
- EN 15497: Structural finger jointed solid timber;
- EN 16351: Timber structures - Cross laminated timber – Requirements;
- EN 26891: Timber structures - Joints made with mechanical fasteners General principles for the determination of strength and deformation characteristics;
- EN 28970: Timber structures - Testing of joints made with mechanical fasteners; Requirements for wood density (ISO 8970:1989).
- European Directives Related to Timber Products:
- Construction Products Regulation (CPR) EU 305/2011: Regulation laying down harmonized conditions for the marketing of construction products;
- Timber Regulation (European Union Timber Regulation, EUTR) EU 995/2010: Laying down the obligations of operators who place timber and timber products on the market;
- Directive 2010/31/EU: On the energy performance of buildings (recast) - Promotes the improvement of the energy performance of buildings within the European Union
- Directive 98/8/EC (Biocidal Products Directive): Concerning the placing of biocidal products on the market, including wood preservatives;
- Directive 2008/98/EC (Waste Framework Directive): Establishing measures to protect the environment and human health by preventing or reducing the adverse impacts of the generation and management of waste, including timber waste.

Additional frameworks and assessments:

- CE Marking: Indicates conformity with health, safety, and environmental protection standards for products sold within the European Economic Area (EEA);
- European Technical Assessment (ETA): Provides detailed performance assessment for construction products not covered by harmonized standards, facilitating CE marking.

These regulatory outline and directives collectively ensure that timber products used in construction across Europe meet high safety, health and environmental standards, supporting sustainable and resilient building practices.

The International Organization for Standardization (ISO), which unites a global network of national standards bodies, has recognized the expanding mass timber building sector by appointing specific ISO Technical Committees. These include ISO/TC 218 Timber and ISO/TC 165 Timber Structures, both of which intend to provide comprehensive guidelines and standards to ensure the quality, safety and sustainability of timber structures worldwide (Kurzinski et al., 2022).

Additionally, governments globally are enacting supportive policies and actions that include financial incentives to encourage sustainable construction. These include (Green & Eric Karsh, 2012; Macandrew, 2024; Milestone & Kremer, 2019):

- Subsidies and Grants: Direct financial support for projects that incorporate mass timber, helping to offset initial costs and make sustainable options more competitive;
- Tax Incentives: Tax breaks and credits for developers and builders who choose eco-friendly materials, thereby reducing the financial burden and promoting broader adoption;
- Use of information clearinghouses on how to build with mass timber, including offering low-cost or free training;
- Setting up of model building programs (demonstration initiatives) that showcase the use of mass timber systems in construction;
- Offering of government-subsidized insurance premiums or the underwriting of insurers who provide insurance to builders and owners.

Some Wood Encouragement Policies (WEPs) examples include (Macandrew, 2024; Milestone & Kremer, 2019):

- British Columbia Building Code Amendments (2019): British Columbia was one of the first regions to allow the construction of tall wood buildings up to 12 storeys. This amendment was made to encourage the use of mass timber and demonstrate its feasibility and benefits;
- Canadian Green Construction through Wood (GCWood) Program: This program promotes the use of wood as a green building material in infrastructure projects across Canada. It provides funding for projects that demonstrate innovative uses of wood in construction;
- Californian Tall Wood Building Prize Competition: Sponsored by the U.S. Department of Agriculture, this competition awards funding to projects that use mass timber in tall building construction, promoting innovative uses of wood in urban environments;
- The European Green Deal: includes policies that support sustainable construction practices, including the use of renewable materials like mass timber. The European Union intends to reduce carbon emissions and promote a CE, in which mass timber plays a crucial role (European Commission, 2019);
- Japanese Act for Promotion of Use of Wood in Public Buildings (2010): This act encourages the use of wood in the construction of public buildings. It intends to increase the demand for domestic timber and promote sustainable forestry practices;
- New Zealand Wood First Policy: Adopted by several local councils, this policy encourages the use of wood in construction projects to support the forestry industry and promote sustainable building practices;
- Finnish National Wood Building Program: This program intends to increase the use of wood in construction by promoting its benefits and supporting research and development in wood construction technologies;
- Swedish Wood Building Strategy: The strategy intends to double the use of wood in construction by 2030. It includes measures to promote wood construction, support innovation, and ensure the availability of sustainable timber resources;
- The UK Government's Timber in Construction (TiC): The roadmap intends to safely increase the use of timber in construction;
- French Timber Construction Ambition Plan 2030: The policy that encourages the use of timber in construction.

These policies and actions are part of a global effort to transition to a sustainable, circular economy and to decarbonize construction. They reflect a growing global recognition of the environmental, economic, and social benefits of using mass timber in construction, driving innovation and adoption in the industry.

The regulatory and policy measures are transforming the construction market by making sustainable practices more financially viable and attractive to developers. With improved regulatory frameworks and financial incentives, there is a notable increase in the adoption of mass timber by builders and architects seeking to meet new sustainability benchmarks and consumer demand for greener buildings.

In summary, the convergence of updated building codes, supportive government policies and financial incentives is significantly driving the adoption of mass timber in the construction industry. This regulatory and economic landscape not only facilitates the use of sustainable materials but also aligns construction practices with global climate change mitigation goals. Ongoing research into the fire performance of mass timber structures continues to provide data that supports the safe and effective use of timber in a broader range of building types and technological innovations in construction techniques have begun to shift perceptions of timber's viability in taller buildings.

2.3.2.2. Key players

Many countries, such as the UK, Austria and Norway, have developed highly interconnected networks between case studies and stakeholders in the timber construction sector (Salvadori, 2021). These collaborative frameworks facilitate the exchange of knowledge, best practices and innovations, thereby accelerating the advancement and adoption of mass timber technologies. These networks play a crucial role in bridging the gap between theoretical research and practical application, ensuring that stakeholders from academia, industry and government can effectively collaborate to promote sustainable and efficient timber construction.

Designers

According to Salvadori (2021), architects specializing in mass timber buildings (MTBs) typically design projects within their own countries. There are relatively few instances where foreign architects are involved in such case studies. Even architectural competitions for MTBs predominantly feature local architectural firms, highlighting a strong preference for domestic expertise in the design of these innovative structures. Overall, architectural offices are not highly repetitive in the design of MTBs, with only a select few accumulating significant experience in this field, what can be further seen in Table 11, in Chapter 5, while looking at the selected case studies and their references. In Europe, notable exceptions include firms such as Hermann Kaufmann, Waugh Thistleton Architects, Kaden-Lager Architekten and White Arkitekter. Michael Green is a prominent advocate for mass timber construction in Canada. He has designed several iconic projects and published numerous references about design and construction of MTBs. Perkins&Will and Lever Architecture are pioneering firms in USA, while Japanese Shigeru Ban Architects projects are characterized by their innovative use of timber and other sustainable materials, demonstrating the potential of mass timber in diverse architectural contexts, in different parts of the globe. While primarily a construction and development company, Lendlease has been instrumental in promoting and constructing mass timber buildings in Australia. These offices have established themselves as leaders in the sector, leveraging their

extensive expertise to advance the design and implementation of MTBs, as well as the share of knowledge in the form of books, manuals and publications (Green & Eric Karsh, 2012; Green & Taggart, 2017; Kaufmann et al., 2018; Waugh Thistleton Architects, 2018).

Architects and designers play a pivotal role in the popularization of mass timber buildings through a showcase of innovation and design excellence. Architects like Shigeru Ban and firms such as Waugh Thistleton Architects design landmark buildings that display the potential of mass timber (Waugh Thistleton Architects, 2018). These projects serve as proof of concept, demonstrating that mass timber can be used for large, complex and aesthetically pleasing structures. Architects innovate in design and construction techniques, pushing the boundaries of what is possible with mass timber. This includes, in collaboration with R&Ds, engineers, builders and material scientists, developing new structural systems, hybrid materials and novel construction methods, to optimize the use of mass timber in construction. They act as advocates for sustainable building practices, educating clients, stakeholders and the public about the benefits of mass timber. Through lectures, publications and participation in industry conferences, architects share knowledge and experiences, contributing to a broader understanding and acceptance of mass timber. Successful mass timber projects by renowned architects demonstrate the feasibility and advantages of this construction method, encouraging developers and investors to consider mass timber for their own projects and use mass timber to create visually appealing buildings that resonate with contemporary architectural trends.

By integrating these roles, architects and designers are essential in driving the adoption and popularization of mass timber buildings, promoting sustainable, innovative and aesthetically pleasing construction practices.

General contractors

General constructors, mostly timber engineers and engineering firms specializing in timber buildings, or in wide selection of structures including timber structures, play a critical role in expanding mass timber construction method. These experts are often more consistent in their involvement than architectural offices, contributing to a significant number of case studies and projects worldwide (Salvadori, 2021).

Several timber engineering firms have emerged as leaders in the field, demonstrating a high degree of expertise and a consistent track record of successful projects. Eurban is one of them and has been involved in numerous high-profile mass timber projects across Europe. iTRE in Italy, Woschitz Group in Austria, Merz Kley in Switzerland and Martinsons in Sweden are renowned for their precision and expertise in timber engineering. Veidekke and Sweco Norge are ones of Norway's largest construction companies that has been at the forefront of mass timber construction, contributing to the country's leadership in sustainable building practices (Salvadori, 2021) and KLH is a globally recognized leader in the field of timber engineering, particularly known for its pioneering work with cross-laminated timber.

ARUP and Lendlease are among the most prominent companies in Australia in the field of timber engineering and mass timber construction. Both firms have made significant contributions to the industry, advancing the use of sustainable materials and innovative construction techniques.

Engineers and timber engineers are crucial for the successful implementation of mass timber buildings. They ensure that the timber structures are safe, stable and capable of withstanding various

loads and environmental conditions. They play their part in developing new methods and technologies for timber construction and navigating and adhering to complex building codes and standards, including national and international regulations specific to timber construction. The general contractors are responsible for overseeing the construction process to ensure that timber buildings are completed on time, within budget and to the highest quality standards.

The consistent involvement of the leading engineering firms and construction companies has significantly advanced the mass timber market. Their expertise and dedication have helped overcome many of the challenges associated with timber construction, such as fire safety, structural integrity and building code compliance. By demonstrating the feasibility and advantages of mass timber through numerous successful projects, these firms have played a critical role in popularizing this sustainable construction method worldwide.

Suppliers

Several companies around the world are leading the charge in supplying mass timber products, particularly CLT, glulam and other MET products. Some of the main mass timber suppliers globally are presented in Table 9.

Table 9. Main mass timber suppliers around the world

No.	Name	Location	Main products
1.	KLH	Austria	CLT
2.	Mayr-Melnhof Holz	Austria	CLT, Glulam
3.	Binderholz	Austria/ Germany	CLT, Glulam
4.	Stora Enso	Finland/ Sweden	CLT, LVL, Glulam
5.	Metsä Wood	Finland	Kerto LVL, Glulam
6.	Moelven	Norway/ Sweden	Glulam, CLT, Plywood
7.	Martinsons	Sweden	CLT, GLulam
8.	Structurlam	Canada	CLT, Glulam
9.	Nordic Structures	Canada	CLT, Glulam, NLT
10.	StructureCraft	USA	CLT, Glulam, DLT, hybrid systems
11.	Carmo Wood	Portugal	Glulam, CLT, LVL

More than half of the total case studies analysed in Salvadori's research (2021) were supplied by Austrian sawmills. Notably, Austria, Canada and the Nordic countries not only primarily rely on their national timber producers for their construction needs but also actively export their high-quality timber products globally. This dual focus on domestic use and international trade highlights the robust production capabilities and the strong reputation of these countries in the timber industry. Their sawmills and timber producers are recognized for delivering sustainable and structurally sound materials, making them key players in the global mass timber market, each contributing to the advancement of sustainable construction practices through innovative products and solutions.

2.4. Circular economy, recycling and wood cascading

The prevailing model of industrial and urban development has been the linear economy, characterized by the extractive "take–make–dispose" approach. This system has led to excessive depletion of natural resources, high embodied energy and vast quantities of waste. In the construction sector, the inefficiencies of linear processes are particularly visible. Concerns about global shifts toward environmentally sustainable models of production and consumption have prompted the European Union to invest heavily in major policy programs centred around the circular economy (CE) (European Commission, 2019; 2020). This has led to a significant increase in research, both nationally and internationally, aimed at addressing global sustainability challenges and supporting governmental initiatives. The prevailing framework in this domain emphasizes four key pillars: reduce, reuse, recycle and remanufacture. Within this context, timber recycling and wood cascading play important roles in achieving sustainability in the wood industry. The relatively short history of construction technology involving prefabricated mass timber panels, in comparison to traditional building methods, has resulted in a lack of documented cases of these structures reaching their end-of-life stage. Consequently, there are no practical examples of incorporating CE concepts at the great scale in such projects to date (Ahn et al., 2022). Recognizing this challenge, the European Union has positioned CE as a cornerstone of its sustainability agenda, most notably through the European Green Deal (European Commission, 2019) and the Circular Economy Action Plan (European Commission, 2020). These frameworks intend to minimize waste, retain materials in use for as long as possible and transform supply chains towards regenerative models of production and consumption.

2.4.1. Circular economy concept

Circular economy promotes continuous cycles of resource use by applying strategies as mentioned above: reduce, reuse, recycle and remanufacture, thereby keeping materials at their highest intrinsic value for as long as possible (Iacovidou et al., 2021). In contrast to the linear model, CE incorporates biological and technical cycles, visualized in the "Butterfly diagram" (Ottenhaus et al., 2023), where the biosphere cycle involves biodegradable, renewable materials such as timber, which can safely return to nature or be cascaded through multiple applications before being used for energy recovery and the technosphere cycle, where industrial, non-biodegradable products (e.g. steel, glass, plastics) circulate through maintenance, repair, reuse and refurbishment, delaying waste and minimizing embodied impacts. The concept is represented in Figure 6. In both cycles, value retention is prioritized through strategies such as designing for durability, adaptability and modularity.

Timber is inherently aligned with CE principles due to its renewable, biodegradable and carbon-sequestering properties (Henry, 2018; Silva et al., 2013). Engineered timber products further extend its applications, making it suitable for mid- and high-rise buildings.

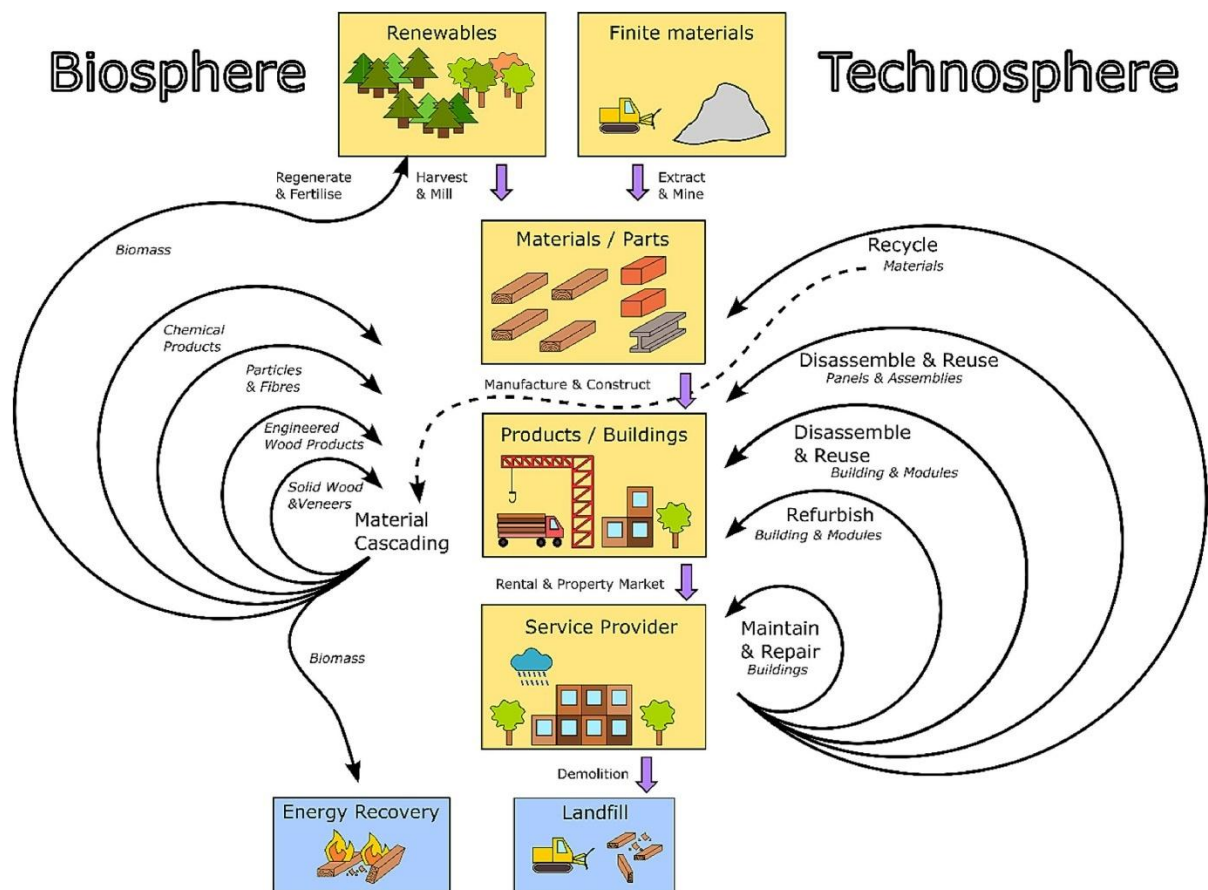


Figure 6. Butterfly diagram of circular buildings (Ottenhaus et al., 2023)

However, timber construction also faces challenges in CE integration, primarily because mass timber panels have only recently entered large-scale building practice (Ahn et al., 2022). Nevertheless, several strategies can be applied to timber:

- Recycling and repurposing: Reclaimed timber elements can be transformed into new products, particleboards, or wood-cement composites (Claußen & Lebow, 2011);
- Energy recovery: When reuse is no longer possible, timber can be combusted for energy. Treated wood must be incinerated in specialized facilities, such as regulated incinerators or boilers, in compliance with relevant regulations. This approach presents a viable alternative in the face of rising fuel costs and increasing energy demand. However, cogeneration processes must address challenges associated with the presence of heavy metals in treated wood. These metals can lead to concerns regarding emissions and the concentration of metals in the resulting ash, imposing further processing to mitigate environmental impact (Forest Products Laboratory, 2010);
- Wood cascading: A key strategy refers to the sequential use of wood across applications of maintaining or decreasing value until final energy recovery (Höglmeier et al., 2016; Jarre et al., 2020). This can occur across time (progressive repurposing), value (prioritizing high-value uses before low-value ones), or function (integrating timber into co-production systems).

In the context of timber construction, the successful integration of CE principles depends not only on the use of renewable materials but also on design approaches that enable longevity, flexibility and material recovery. As buildings represent long-term material reservoirs, strategic design is essential to maximize their adaptability, minimize waste and ensure that structural components can be effectively

reused at the end of service life. To this end, several design-oriented strategies have been identified as particularly relevant for advancing circularity in timber buildings:

- Design for Adaptability (DfA): Ensures that buildings can evolve over time, accommodating changes in use without demolition (Hasani & Riggio, 2025; Ottenhaus et al., 2023);
- Design for Disassembly (DfD): Enables easy separation of building components, facilitated by modular construction, standardized reversible connections and digital tools such as Building Information Modelling (BIM) (Ottenhaus et al., 2023);
- Design for Reuse (DfR): Extends DfD by ensuring that reclaimed materials meet safety and performance standards, supported by material passports and smart tagging systems (Silvestre, 2021).

These strategies support longer building service lives, higher reuse potential and reduced waste, making timber buildings not only low-carbon during construction but also regenerative over their full life cycle.

Over time, CE thinking has evolved from the Charles Kibert's concept and the early 3R framework (reduce, reuse, recycle) to the more comprehensive 10R hierarchy (Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover). The R-strategies and their circularity potential are presented in Figure 7. It can be observed that strategies higher in the hierarchy (R0–R3) represent deeper systemic shifts and higher circularity, such as refusing unnecessary products or rethinking design to avoid waste, while strategies in the bottom are more focus on useful applications of materials closer to linear economy (Morseletto, 2020; Potting et al., 2017).

Furthermore, a recent master thesis co-supervised by the Author provided a detailed analysis of the 10R framework of circularity and investigated how CE principles can be systematically integrated into the structural system design of high-rise timber buildings with the aim of maximizing material reuse and minimizing waste. This research addressed a critical gap in the literature: while most CE studies in the built environment focus on material sourcing, recycling, or end-of-life management, the role of structural design as an enabler of circularity remains underexplored.

Through a comprehensive literature review and case study analysis, the thesis demonstrated that CE strategies, particularly those situated at the upper tiers of the 10R framework (refuse, rethink, reduce and reuse) can be effectively applied to timber structural systems. Engineered timber products such as CLT and glulam emerged as central to this transition, due to their renewable nature, carbon sequestration potential and compatibility with modular and reversible construction systems (Vancoppenolle, 2025).

The study also highlighted the necessity of integrating DfA, DfD and DfR strategies at the earliest stages of structural design, in order to enable recovery of structural components and minimize demolition waste. Importantly, the thesis emphasized the supporting role of digital tools (including BIM, parametric design and CNC fabrication) in achieving traceability, precision and life cycle management. Material passports (MPs) and smart tagging systems were also recognized as crucial instruments for documenting origin, treatment and reuse potential of mass timber elements (Vancoppenolle, 2025).

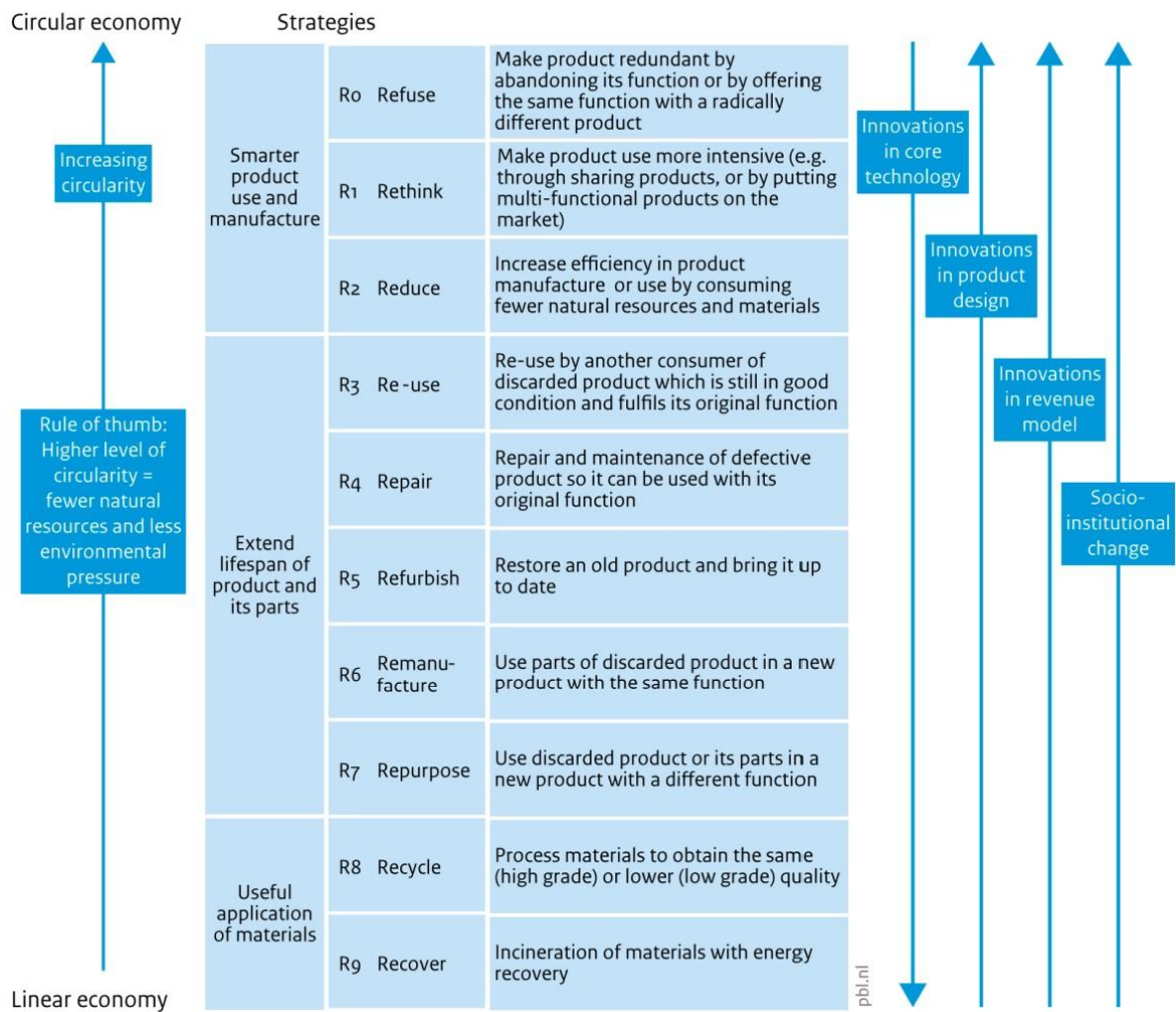


Figure 7. R-strategies and their lever of circularity (Potting et al., 2017)

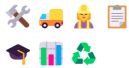
The findings were synthesized into 13 clustered guidelines presented in Table 10, designed as a practical framework for integrating CE principles into the structural design of high-rise timber buildings. These guidelines cover environmental, technical, digital, economic and regulatory dimensions of circularity, align with present study's outcomes. They serve not only as a conceptual roadmap but also as a set of actionable measures to guide industry stakeholders in applying CE strategies effectively.

Table 10. Key guidelines of CE for structural systems (Vancoppenolle, 2025) and the main stakeholders involved

Key guidelines and R-strategies	Cluster guideline	Primary stakeholders (see Table 20)
Prioritize the choice of mass timber elements CLT and Glulam in high-rise construction and limit the use of non-sustainable materials such as steel and concrete to extreme cases to minimize carbon emissions and environmental impact (R0).	Prioritize the choice and maximize the use of CLT/Glulam, emphasize prefabricated and modular timber for increased sustainability and efficiency, and limit the use of high-carbon materials such as steel and concrete.	Design stage
Leverage as much as possible the benefits of engineered timber, prefabrication and modularization ensuring precision, speed and minimal waste (R1).		
Prioritize CLT and Glulam for sustainable (including remanufactured) load-bearing systems (R6).		

Key guidelines and R-strategies	Cluster guideline	Primary stakeholders (see Table 20)
Ensure the use of FSC or PEFC labelled wood from local sources to promote ethical and sustainable harvesting, increase carbon sequestration and reduce transportation (GHG) emissions (R0).	Ensure the use of locally sourced, certified (FSC, PEFC labelled) timber to reduce greenhouse gases (GHG) emissions and support ethical forest management.	<i>Strategies and Product stages</i> 
Prioritize the use of locally sourced timber to reduce emissions from transportation and support regional supply chains, thereby lowering the environmental impact of material delivery (R2).		
Strengthen awareness and public acceptance by educating stakeholders on the long-term benefits of mass timber and taking away potential fears by showcasing success stories in high-rise timber buildings (R0).	Strengthen public engagement and acceptance of the long-term benefits of mass timber by showcasing success stories and promote stakeholder education and cross-sector collaboration and partnerships.	<i>Strategies and Use stages</i> 
Develop collaborations between industry, policymakers and researchers to overcome financial and technical barriers to further improve adoption of reuse strategies (R3).		
Establish and standardize regulations and policies with safety standards and building codes that promote the use of mass timber and support material reuse (R0).	Establish, standardize and harmonize regulatory frameworks, building codes and policies to support and promote mass timber and safe reuse, supporting circularity and waste reduction.	<i>Strategies stage</i> 
Further develop policies and regulations that promote and harmonize at national or global levels circularity and improved reuse efficiency of mass timber elements (including waste minimization principles) (R3).		
Document the source, specifications and sustainability certifications of timber components, such as FSC and PEFC labels, in a MP (R0).	Develop and implement efficient MPs, combined with BIM and smart tagging for comprehensive material documentation and traceability by life cycle tracking.	<i>Strategies, Product, Use and end of service stages</i> 
Develop and use MPs for high-rise timber buildings. Promote standardization and collaborative data exchange between all stakeholders in the value chain. Integrate digital tools including smart tags and material tracking to improve data generation of timber components and easy traceability (R1).		
Use MPs, smart tagging systems and BIM to digitalize and manage the life cycle of timber elements and to improve reuse planning across the different construction phases (R3).		
Maintain a comprehensive overview of repair events in MPs and in BIM to ensure transparent material traceability (R4).		
Ensure proper documentation of certification, compliance and structural grading of secondary timber and timber remanufacturing status through MPs (R6).		
Integrate MPs and CE principles to support tracking and documentation, ensuring that timber can be repurposed effectively over time (R7).		
Adopt a circular mindset from the conception phase by integrating DfA and DfD strategies thinking ahead and anticipating future adaptability, reuse and disassembly (R1).	Embed circular design principles from the early design phase by integrating DfA, DfD and DfR strategies to enable reuse and adaptability.	<i>Design stage</i> 
Implement DfR as a core principle of high-rise timber design and ensure that it is an integral part of DfD strategies. Prioritize demountable and standardized timber components to maximize reversibility, reuse potential and prevent unnecessary downcycling of timber elements (R3).		
Stimulate and integrate future innovations in connection systems, advanced timber protective treatments, bio-based coatings and combinations with green insulation (R1).	Promote further innovation in timber construction technologies and continue the development of	

Key guidelines and R-strategies	Cluster guideline	Primary stakeholders (see Table 20)
Implement automation, such as robotic disassembly technologies and automated metal fastener removal, to streamline timber recovery and reuse (R6).	new connectors, bio-based coatings and automated disassembly technologies.	<i>Product stage</i> 
Implement BIM, algorithm-driven mass customization and Just-In-Time (JIT) manufacturing in high-rise timber buildings to prepare materials on demand, improve coordination across disciplines and reduce construction time and waste (R2).	Incorporate digital designs and manufacturing technologies such as BIM, parametric design and CNC production for coordination, mass customization and JIT manufacturing for reduced waste.	<i>Product, Design and Construction stages</i> 
Incorporate parametric design and CNC-production in high-rise timber buildings to enable precise fabrication, optimize material usage (including avoiding over-use) and streamline the construction process (R2).		
Use modular and interchangeable prefabricated timber components that are manufactured off-site and assembled on-site. This approach minimizes material waste, speeds up construction, reduces on-site disturbance (including noise) and increases overall resource efficiency, e.g. by using lightweight CLT panels for non-load-bearing elements instead of massive panels (R2).	Prioritize the use of modular, prefabricated (CLT and Glulam), off-site construction designed with reversible connections for speed, precision and low waste.	<i>Design and Construction stages</i> 
Use prefabricated timber modules such as CLT and Glulam that are reconfigurable and demountable to facilitate easy reuse. Use bolted and dowelled joints to maintain timber integrity during disassembly (R3).		
Prioritize the use of prefabricated timber products such as CLT and Glulam and the use of reversible connections to allow an easy part replacement (R4).		
Implement preventative protection for timber elements such as moisture-resistant coating, pest-prevention treatments or fire-retardant applications (R4).		
Include accessible inspection points for non-destructive monitoring, and for maintenance and repair of structural systems and critical joints, from the start as part of the design of the building (R4).	Implement protective measures to prevent fire, pest and moisture damage and to ensure long-term durability, and develop inspection and repair protocols for efficient follow-up.	<i>Construction and Use stages</i> 
Provide Standard Operating Guidelines (SOG's) with operating guidelines and procedures for good practice repair (R4).		
Consider strengthening damaged timber elements by overlays or hybrid reinforcements while maintaining safety (R4).		
Enhance fire and thermal performance by application of intumescent coatings for fire resistance and consider integrated insulation methods like wood-fibre panels or hemp blocks to optimize energy efficiency (R5).		
Implement (hybrid) reversible connection strategies (R1).		
Prioritize structural integrity in load-bearing systems by reinforcing existing timber elements using CLT, Glulam, steel plates, fibre-reinforced polymers, or epoxy injections to enhance stability and durability (R5).	Ensure structural integrity of load-bearing structures by implementing (hybrid) reversible and flexible connections, reinforcements, joint upgrades and appropriate grading and certifications related to environmental and seismic stresses.	<i>Product and Design stages</i> 
Upgrade connection systems for high-rise stability by replacing old fasteners with bolts, metal brackets, glued-in rods, hybrid fasteners and densified wood dowels to improve joint strength and seismic resilience (R5).		
Adapt flexible joint systems for environmental changes by using engineered joints to accommodate temperature fluctuations, moisture variations and seismic activity without compromising structural integrity (R5).		

Key guidelines and R-strategies	Cluster guideline	Primary stakeholders (see Table 20)
Ensure structural integrity by applicable certification, grading, moisture control and fire/pest protection to ensure safety in high-rise applications (R7).		
Remanufacture and upcycle timber into engineered wood products such as CLST and GlulamST (R6).	Promote upcycling and structural repurposing of reclaimed timber by remanufacturing it into engineered wood products and prioritize reuse over down-cycling.	<i>Product, Use and end of service stages</i> 
Prioritize structural repurposing as the final upcycling stage instead of down-cycling to recycle and recover (R7).		
Showcase and leverage successful industry initiatives to demonstrate that repurposed timber can replace traditional materials in modular high-rise structures, showcasing innovation in sustainable construction (R7).		
Develop efficient supply chains for reliable storage, transportation and processing methods, which are essential for scaling reclaimed timber in high-rise buildings. (R7).	Develop a robust and efficient circular supply chain for reclaimed timber by implementing standardized classification, optimized logistics and prioritizing recycling over energy recovery.	<i>Product, Use and end of service stages</i> 
Prioritizing recycling over energy recovery: EU directives and national laws advocate for reuse and recycling as the primary end-of-life option, with energy recovery as a secondary alternative when other options are unfeasible (R8).		
Install classification and contaminant control: waste wood must be sorted and classified, following national (or preferably EU/global regulations) classifications, ensuring that only clean, recyclable wood is repurposed (R8).		
Install logistics and supply chain efficiency: collection, transport and storage of wood waste require a well-organized supply chain, as large-scale recycling can be resource-intensive (R8).		

2.4.2. Recycling and repurposing

Timber that is primarily harvested from forests and persistently recycled presents a unique environmental advantage. As this timber is reused, the carbon it initially sequestered remains stored within its structure. This locked-up carbon, which would otherwise be released into the atmosphere, continues to be sequestered for the duration of the timber's lifecycle, even as it transitions through various stages of reuse. This process underscores the importance of recycling and reusing timber, as it contributes to the reduction of carbon emissions over time and plays a pivotal role in efforts towards sustainable environmental practices, thereby contributing to the mitigation of the impacts of climate change.

The potential for recycling treated wood material is influenced by various factors, including its natural durability, original use, geographic location and the characteristics of its preservative treatment. Regulatory agencies determine whether treated wood removed from its original application can be repurposed for similar functions, provided it retains sufficient durability and structural integrity (Forest Products Laboratory, 2010). One of the major challenges of construction with treated wood is the lack of an efficient system for the collection and sorting of wooden components (Forest Products Laboratory, 2010). This process requires a comprehensive understanding of wood as a material, including the ability to identify specific wood species and assess whether the timber elements remain suitable for reuse. Consequently, there has been a global increase in initiatives aimed at the responsible recycling of wood and wood-based products (Coulson, 2021). However, the presence of substances such as adhesive

resins and impregnating agents used in timber product manufacture and treatment poses significant challenges (Forest Products Laboratory, 2010).

The example of the new possibilities of repurposing and upcycling timber are represented in the ongoing project “The Urban Wood”. The recent development of a ten-storey residential high-rise in Delft, the Netherlands, scheduled to open its doors in early 2026, represents a pioneering application of circular construction principles through the use of Circular Cross-Laminated Timber (C-CLT) fabricated entirely from upcycled pallet and demolition wood (The Urban Woods, 2024). This project constitutes the first large-scale demonstration of CLT produced from post-consumer timber waste, thereby advancing both material circularity and carbon reduction strategies within the built environment. Unlike conventional timber structures, the building minimizes reliance on concrete by using engineered timber even in traditionally concrete-intensive elements such as the core, balconies and elevator shaft. The production process involved the collection of low-grade wood waste by a social enterprise, its transformation into finger-jointed planks and subsequent lamination into certified structural panels, thus ensuring both mechanical reliability and long-term durability (The Urban Wood, 2024). Beyond its environmental benefits, the project demonstrates the scalability and affordability of waste-based bio-construction, highlighting its potential to address resource scarcity and reduce dependence on imported materials. The adoption of the world’s first C-CLT vacuum press further underscores the technological innovation enabling this transition, while simultaneously positioning waste wood as a viable structural resource within the framework of the circular economy and climate-neutral construction goals of the European Green Deal.

An alternative method for reclaiming wood treated with heavy metals, as demonstrated by researchers, involves processing the wood into particles and flakes to create durable panel products or wood-cement composites. Despite its potential, this solution has not yet reached commercial viability (Clausen & Lebow, 2011; Coulson, 2021).

While timber recycling is not a new concept and technology continues to advance, significant challenges remain in achieving widespread acceptance of reclaimed timber elements. Ensuring that timber products are transformed into new products rather than becoming waste after their initial use is crucial, just as important as discovering new applications for wood products. The smart and varied recycling of wood might not only significantly substitute products derived from non-renewable resources but also supply energy and other commodities. This practice would alleviate issues related to waste disposal and enhance the significance of forest-derived products as replacements for non-renewable source products (Laas et al., 2011). However, the transition towards a circular economy requires more effective life-cycle management of products, the creation of robust markets for waste-derived materials, and careful planning in design and installation to enable disassembly without damage. It also calls for a reconsideration of bioenergy demands, adapted to local contexts, while simultaneously addressing sector-specific barriers and technical challenges (Yayla et al., 2025).

2.4.3. *Wood cascading*

In contrary to the common concept of reusing or recycling, a key strategy within the circular economy for the wood industry is the concept of wood cascading. This approach seeks to maximize the

reuse of wood by employing the same piece or unit multiple times, which can be categorized by time, value, or function (Jarre et al., 2020), as illustrated in Figure 8.

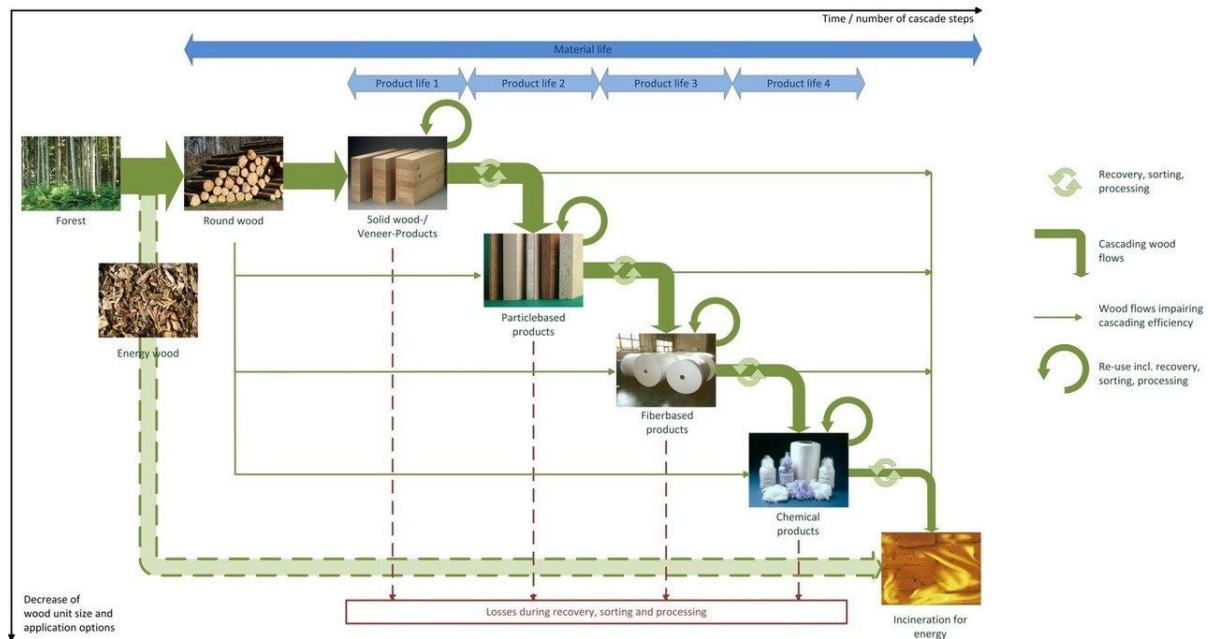


Figure 8. Biomass cascading (Höglmeier et al., 2016)

Cascading in time involves the progressive use and conversion of biomass, wherein high-quality timber is continually repurposed into various products or smaller components until it ultimately reaches a stage where it is no longer recyclable and is then utilized for energy production. It involves utilizing wood initially in its solid form before subsequently converting it into particleboard products, fibre-based products and ultimately using it as an energy source, what has been a significant focus of recent research (Höglmeier et al., 2016). This approach intends to extend the lifecycle of wood products, maximizing their utility and sustainability at each stage of use. Conventional example of this process is paper recycling, as well as the conversion of construction waste into particleboards. However, more advanced solutions are currently feasible and under active investigation. Cascading in value optimizes the stages of this process by prioritizing applications that yield the highest potential value throughout the entire life cycle of the material. Lastly, cascading in function focuses on enhancing co-production, ensuring that each stage of the material's life cycle maximizes its functional utility and integration into various products and processes (Jarre et al., 2020).

Implementing cascading is essential for advancing towards a sustainable and responsible economy and way of life. However, several critical factors influence the successful realization of this process. One of the most crucial factors is policy reform. Comprehensive and updated regulations on wood and reclaimed wood are necessary. These regulations should include detailed guidelines on how wood can be reused, the requisite standards, conditions and processes, and the parameters that determine the suitability of timber for further applications. Establishing such a regulatory framework is vital to facilitate the effective and widespread adoption of cascading practices (Höglmeier et al., 2016).

The applicability of wood cascading is also significantly influenced by technical approaches. Implementing some of these solutions requires consideration during the design phase of projects,

requiring a shift towards Design for Disassembly and Reuse (Hughes, 2019). Additionally, the production of composites and their treatments must employ innovative strategies to ensure that, at the end of a building's life, deconstruction rather than demolition can be carried out. This approach maximizes the recovery and reuse of materials (de Arana-Fernández et al., 2020; Jarre et al., 2020). To ensure that elements are fit for reuse, much more detailed and controlled documentation is necessary. Moreover, the implementation of this concept critically depends on the presence of skilled architects, engineers and a workforce educated in this field (Hughes, 2019). While there is substantial promise in cascading timber products, realizing their maximum potential requires overcoming several challenges. In addition to the scarcity of practical examples, there is currently little incentive to adopt alternative approaches to building design (Hughes, 2019). There are substantial knowledge gaps and pressing research needs in the development of holistic approaches to prepare mass timber construction for integration into the circular economy. Addressing these gaps is crucial for the advancement and sustainable implementation of mass timber construction within a circular economy framework (Ahn et al., 2022).

The integration of CE into mass timber construction presents significant opportunities: reduced carbon emissions, extended carbon storage, and more resilient building systems. Yet, substantial research gaps persist, particularly in developing holistic approaches for mass timber end-of-life management, cascading strategies and regulatory frameworks for reuse (Ahn et al., 2022). Emerging digital tools (e.g. BIM, parametric modelling, CNC production) and systemic concepts (e.g. material passports) offer promising pathways for overcoming these challenges.

Ultimately, advancing a circular timber economy will depend on cross-disciplinary collaboration among architects, engineers, policymakers and industry stakeholders, supported by clear regulatory frameworks and robust documentation of best practices.

3. History of high-rise timber buildings

Since the early Stone Age, wood has been a fundamental part of human life, valued for its multipurpose, versatile, and adaptive forms (Cuadrado et al., 2015; Pryce, 2016; Ramage et al., 2017; Woodard & Milner, 2016; Youngs & Hamza, 2016). In the Palaeolithic era, early human species relied on this renewable material as a primary fuel source, which provided warmth, protection from predators and new cooking methods. This reliance enabled the occupation of new, colder territories and the creation of complex social structures, significantly contributing to human evolution. During the Neolithic period, wood's use expanded as it was fashioned into tools and weapons, facilitating digging, foraging, hunting and the construction of simple structures that supported the nomadic lifestyle of human tribes. The advent of metal tools in the Bronze Age, followed by the increased use of copper and iron in the Iron Age, led to advancements in timber joints. As a result, wood became even more crucial, being shaped into more sophisticated shelters, temples and religious circles. Archaeological findings and structures that have endured for millennia attest to wood's exceptional, long-lasting properties (Forest Products Laboratory, 2010). Over time, masonry architecture adopted patterns and techniques characteristic of timber buildings. The material's distinct qualities, ease of processing and the availability of vast expanses of forests that existed five thousand years ago facilitated its widespread use (Pryce, 2016).

Despite the loss of more than half of the wooded area since then, wood remained a crucial construction material due to its lightweight nature, workability, capacity to perform in bending, tension and compression, and its ability to withstand earthquakes, from Central, Northern and Eastern Europe to South East Asia and Japan, and into North America, even up to the 19th century (Foliente, 2000; Pryce, 2016; R. Youngs, 2009). The Industrial Revolution, with its new possibilities for using steel and concrete, sidelined wood for tall and high-rise structures for several decades. However, the rapid development, exploitation of natural resources and carbon emissions of the 20th and 21st centuries have prompted societies to seek more sustainable alternatives, including in the construction sector. In this new "Plastic Age," attention has returned to timber. Inspired by the resilience of towering sequoias and their 26-floor height as living proof of timber's durability (Smith & Snow, 2008), recent advancements in timber technologies, the mass timber industry and engineered timber products have led to the construction of nearly two hundred buildings ranging from six to twenty-five floors, where wood is the primary structural material, heralding a new era of tall and high-rise timber buildings.

The resurgence of timber as a primary construction material marks a significant shift in the architectural and engineering landscape. This sub-chapter summarizes the history of timber in construction, tracing its use from the earliest wooden structures to the development of the first tall timber buildings, and examining its enduring presence and evolution through the 20th and 21st centuries. By exploring this historical journey, the chapter intends to demonstrate how timber has not only stood the test of time but also adapted to various conditions and technological advancements.

3.1. First timber structures

Even though in many places on Earth timber was abundant, it was subjected to the process of changes over time. During the prehistorical era, as the most important raw material, it was used for most of the supplies of day-to-day life: buildings, tools, weapons and furniture (Youngs, 2009). However,

as human forebears were equipped with simple tools for woodworking, their shelters consisted of simple, tent-like, predominantly circular forms made of thin beams supporting the earth-covered or plant-covered roofs. Throughout those times, timber as light but strong material, responded to the nomadic, simple lifestyle of ancient people (ARUP, 2019). The presence of development, the style and durability of structures depended on the quality and availability of timber and the lifestyle of the people in different areas of the world. The early Palaeolithic structures were made from poles using small trees (Youngs & Hamza, 2016). In Neolithic China, man rise their primitive shelters from timber elements (branches and thatch) creating “nest residencies” (Smith & Snow, 2008). In Neolithic Europe, timber logs were set vertically in the ground, turning to longhouses and roundhouses, reinforced over time with clay walls (ARUP, 2019; Youngs & Hamza, 2016). This started to change about 9000 BC with the evolution of the Turkish-Iranian civilization and their houses with lightweight timber frame structure. Even though the circular form continued to be a predominant one, with the development of tools and the possibility to use heavier elements for walls and roofs, new typologies have emerged (Foliente, 2000). Subsequently, two-story houses, with rectangular plan had been made in the regions of Anatolia and Cyprus dated 6500-6000 BC, using a hybrid structure of stone, mud bricks and timber (Foliente, 2000).

The advancement of even more sophisticated forms and sizes can be observed as a consequence of the development of copper tools around 5000 B.C. (Youngs, 2009) and furthermore mortised joints in the Iron Age.

The construction techniques were evolving in accordance with specific conditions and traditions. Different locations on Earth had distinct resources, starting from the concentration of forests, type of obtainable wood and the nature of corresponding trees, up to different cultures inhabiting them. Despite the distance between several places, due to parallel development paths and trades of techniques, some similarities could be observed, which were later influenced by local modifications and improvements (Foliente, 2000; Youngs, 2001).

Palisade or stave construction, which appeared already in Neolithic, was one of the first forms of complex timber creations. It was formed by placing vertically, one next to the other, the entire tree trunks (Youngs & Hamza, 2016). It was not the most durable solution. Arranging the logs in that way exposed timber to the direct contact with moisture from the ground. Due to the natural characteristics of wood and its capillary absorption in the direction of fibres, the bottom parts of such construction were consequently at highest risk of degradation. With rotting and decay appearing at a large extent, the position of the logs had changed over time from vertical to horizontal, parallel to the soil, representing the first forms of the log-cabin type of construction. Therefore, the palisade way of building persisted from the Iron Age until Norman times, influencing the architecture of the Northern and Central Europe's houses and churches. Thick wooden logs assured very good thermal insulation, turning buildings erected with this system into excellent shelters to withstand harsh Scandinavian and Russian winters for many decades, among them Viking fortresses and stave churches (Youngs & Hamza, 2016). The St. Andrews church in Greensted, Essex, England is the oldest wooden example of stave construction preserved in Europe (Tyers, 1996). From 16th century on, the stave system significantly influenced the building techniques of the northern America, where it was brought by French settlers (Foliente, 2000;

Pryce, 2016; Youngs, 2009; Youngs & Hamza, 2016).

Horizontal arrangements of the logs gave the origin to the blockwork method of construction, also called log cabin. This technique made use of peeled wooden blocks placed one on the top of another and it closely depended on size and type of available trees. Forested zones of Russia and Scandinavia offered abundant quantity of regular tree trunks and that is where the numerous examples of this technique could be observed (Pryce, 2016). Stability was achieved by erecting adjoining walls at the same time and assembling them at the corners, which were roughly notched. One of the oldest examples of such structures was encountered in Biskupin, on the territory of Poland (Figure 9). Wood from adjacent forests dated 750-708 BC was used for the construction of the Biskupin settlement and it represents outstanding technical and military expertise of architects of that time. The village was organized very efficiently on a small part of land, with strong fortifications made from logs. As the wood was the most accessible resource at that time and the easiest to manipulate, tree trunks were used also for the construction of residential buildings (Kopiasz, n.d.). Finds have shown that this way of erecting the structures was also used in Japan about 250-200 AD (Foliente, 2000).



Figure 9. Biskupin settlement reconstruction in Poland (Kozlowski, 2007)

Another type of construction, observed already in 6500 BC is timber frame (Foliente, 2000). It has coexisted with blockwork techniques in many counties for hundreds of years and it evolved later thanks to saws and nails (Langenbach, 2008). Due to the use of joints to link elements, the stability of the frame construction was no longer achieved by the weight of the material, but by its connections. The first forms of frame structures were tent-like, which evolved to simple crack frame. Through time, by the addition of supportive elements, a posts and truss/rafter frame structure was born (Pryce, 2016). To increase stability and earthquake resistance of timber frame structures, a timber infill-frame was used in ancient

Rome and Greece, and the same technique was applied later in Kashmir, a seismic-prone area of India, during the 12th century (Langenbach, 2008). A timber frame was also used to raise Roman households, even multi-storey ones called *insula* and after the shift from building in wood to building with stone in ancient empires, timber remained as the main material for roofs, ceilings and bridges (ARUP, 2019; Cuadrado et al., 2015; Foliente, 2000).

3.2. Fist tall timber structures

While timber frame spread into South-East Asia, Japanese and Chinese carpenters grew into the most specialized in this profession, developing sophisticated joints methods already by 1000 BC (ARUP, 2019). They were able to create complex multi-storey buildings that withstood meteorological conditions and earthquakes for centuries (Pryce, 2016; Youngs, 2009). The oldest existing testimonial structure built in the year 607 AD is a five-storey pagoda in Nara, Japan (Figure 10). It was rebuilt after a fire in 670 AD but its original parts have persisted until today (Pryce, 2016). Nevertheless, the oldest entirely preserved tall timber structure is Yingxian Pagoda in Shanxi, China. The temple, the tallest timber building until 2008, was built in the year 1056, has nine storeys and is more than 67 m high (Smith & Snow, 2008; UNESCO, n.d.).



Figure 10. Hōryū-ji Pagoda in Nara (663highland, 2009)

Both pagodas represent excellent examples of the advanced frame systems, with large, extensive roofs and invisible cross-bracing elements that survived in almost unaffected form, demonstrating the durability and time resistance of timber buildings (Pryce, 2016; Smith & Snow, 2008).

Timber continued as a leading building material throughout the Middle Ages in the territories of Mediterranean Sea basin. Wooden frame was found in 8th century Byzantine Empire and there are numerous two- and three-story urban buildings with wooden structure, visible in many European cities

(ARUP, 2019; Langenbach, 2008). The European Gothic roofs were made of substantial and heavy timber frame (Youngs & Hamza, 2016). Wood played an important role in the fields of industry, arts and culture, finding use in the production of tools, machines (Machine Age), bridges, furniture, shoes, fine arts items of great value, barrels and first printing press (ARUP, 2019; Foliente, 2000; Youngs, 2009; Youngs, 2001).

The golden period of utilization of timber in Europe fell on the 16th century, during the “water-and-wood” phase, with the inventions of new machines, inter alia the sawmill (ARUP, 2019; Youngs, 2009). With the improved process of cutting planks with rectangular section, the joints techniques also advanced, allowing construction at a larger scale. The structures up to six/seven storeys have been made with posts, trusses and masonry infill, with examples in England and Spain (Langenbach, 2008). On the other hand, after reaching timber's peak of consumption during this period, the rapidly growing economy and excessive extraction of forests for fuel, materials and expanding agriculture resulted in scarcity of the material and limitations in its accessibility at the accelerated rate (ARUP, 2019; Youngs, 2009).

Meanwhile, in the USA, before the arrival of immigrants at the turn of 17th and 18th centuries, the territory was abundant in forests and hence it was rich in timber, which was the primary construction material of native Indians (Youngs, 2009; Youngs & Hamza, 2016). Extensive areas of the American continent allowed the development of different topologies, so that in the north it was possible to find structures made with planks and gabled roofs. Poles covered with the bark and palisades of vertical logs dominated the eastern regions, while timber frame covered with earth evolved in the areas of Great Plains and western mountains (Youngs & Hamza, 2016).

With the arrival of the colonists from Europe, firstly the log cabin building technique started to spread through the territory leading to English frame houses with wattle and daub or brick infill (Youngs & Hamza, 2016).

Intensified use of wood by the new arrivals made the USA reach a peak of timber industry during the 19th century, two hundred years later than Europe. The planks, boards and nails produced by the expanding number of mechanical sawmills made the light balloon frame structures a dominant type of construction in the region of Chicago. The construction in timber became fast and easy with great flexibility of the design due to this big-scale prefabrication (Foliente, 2000). Americans adapted the practices, making most of the North Americans public buildings out of timber or a combination of timber and bricks, and converting wood into housing principal construction material to this day.

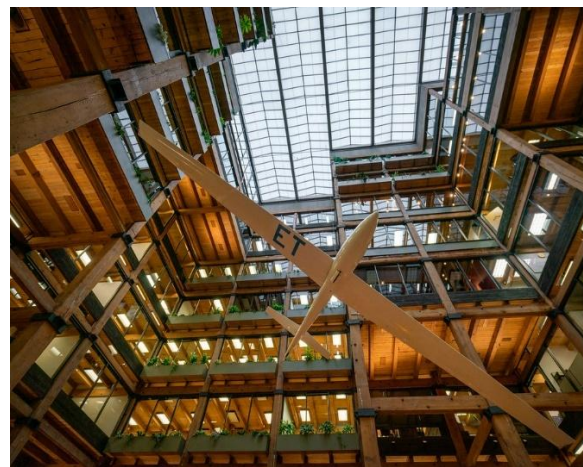
With the bloom of the industrial revolution, wood was replaced by coal, timber frame by cast iron and further on by reinforced concrete. This change went along with the new building codes that emerged after catastrophic fire events and constrained radically the use of timber in tall constructions. As a consequences of the Great Fire of London of 1666, the first regulation imposing the use of bricks and stone for all construction purposes was established- the London Building Act. After the Great Chicago fire in 1871, all new structures were required to be built with fireproof materials, thus all damaged buildings were reconstructed in fireproof materials like brick, stone and terra-cotta, and ten years later, the advent of reinforced concrete and steel frame construction comply with the safety standards, since wood was considered as a combustible material in all forms (Foliente, 2000; Green & Taggart, 2017).

3.3. 20th century

During the transition period, in the regions where the application of timber was not prohibited by codes, multi-storey wooden structures continued to be built. The Butler Square Building in Minneapolis (Figure 11), USA is a lasting example of such 8-floor construction. Today it serves as an office building, but in 1906 it was created as a warehouse with mass timber structure and a brick façade. At the same time, the 320 Summer Street building was constructed in Boston, also 8-storey, and so was the Landing, a 7-storey heavy timber and masonry warehouse situated in Vancouver, Canada. In 1913, the 7-floor high timber Perry House was built in Brisbane, in Australia, representing one more safe and durable wooden structure that has been standing for more than a century (Bowyer et al., 2015; Green & Eric Karsh, 2012; Green & Taggart, 2017).



(a)



(b)

Figure 11. (a) Butler Square building - outside view (McGhievery, 2015); (b) Butler Square building - inside view (Davis, 2019)

Even though from the second half of the 19th century and following the turn of the 20th, the scientific research began to cover the field of wooden structures, the 20th century construction market continued to be dominated by the reinforced concrete and steel (ARUP, 2019; Foliente, 2000). However, with the gradually growing interest and the critical look at the forestry and timber products, it was possible to form a viable basis for the use of timber for structural purposes. The first pioneering Forest Products Laboratory (FPL), created in 1910 in Wisconsin, played a major role in the studies on mechanical properties of timber under different conditions (use of preservatives, the effect of fire, drying), as well as on the design and behaviour of connections and assembly systems (Foliente, 2000). In 1935, the FLP published the first edition of the gathered knowledge in the form of the Wood Handbook. The publication was found with the great value by the professionals and the timber industry from USA, Europe and Australia (Foliente, 2000; Smith & Snow, 2008). Together with the US National Design specification for Wood Construction released by the National Lumber Manufacturers Association in 1944, the Wood Handbook contributed to the formation of the matrix for western wood-related standards and codes.

With the broad research, after the Second World War, new developments were made in the field of resin adhesives. This allowed much wider use of plywood and glulam, shifting rapidly their application from the interior to the exterior and structural purposes. With advanced numerical modelling techniques

timber products gained greater dimensional stability and structural strength, what increased their flexibility in the design. Another breakthrough moment for the long span timber structures and the wood-based products was the production of metal connecting plates and automation in the field of truss industry at the turn of the 1950s. In 1983, the International Council for Building Research Studies and Documentation released the “CIB-Structural Timber Design Code” that become a precursor of today’s codes in many countries (Smith & Snow, 2008). These advancements in timber technologies and increased scientific research, formed a practical and informative base for the use of wood-based materials in greater scale, since then, attracted investors to the construction sector. In the late 1980s, the leading European countries in use of solid wood and timber panel assemblies were the United Kingdom, Austria, Italy and Germany (FAO, 1971; Foliente, 2000; Hildebrandt et al., 2017; UNECE & FAO, 2011).

A breakthrough moment for tall timber structures was the introduction of CLT to the market. Gluing alternate layers of lumber perpendicular to one another allowed this new composite material gain stability and fire resistance at large size of the load-bearing panels. The first CLT structure was built in 1993 in Switzerland, following by one in Germany in 1995 and the first multi-story in Austria in 1998 (Bowyer et al., 2015).

The end of 20th century was marked by the advanced research focused on Performance-Based Regulatory Paradigms, to acknowledge that adequate performance can be attained through context-specific methods, thus avoiding restrictive prohibitions (Smith & Snow, 2008). It was also a time of new opportunities for modern wood-based composites. This has notably influenced the utilization of wood and has unlocked fresh prospects for innovative and adaptable products derived from an evolving wood resource (Bowyer et al., 2015; Smith & Snow, 2008; Youngs, 2009).

3.4. 21st century

The release of EN1955 Eurocode 5 – Design of Timber Structures in 2004 has supported advancements in the area of mass timber building and helped to create a framework to support the construction of taller wood buildings in most European countries in the following years (Green & Taggart, 2017).

A progress within the timber industry that marked the last decades of the 20th century endured until the economic crisis in 2007. The following years evidenced a global decrease in the construction and permits for new buildings (Hildebrandt et al., 2017).

Concern about climate change is another factor that came up with the beginning of the 21st century. Construction sector is urged to face the environmental issues and reconsider the way buildings are made. By searching for new solutions and for strengthening civil engineering capabilities, the interest in wood and wood-based products as a main fabric for construction started to increase (Hildebrandt et al., 2017; Smith & Snow, 2008). This is also due to the broad scientific research and laboratory tests on full-scale models that have been proving the safety and capacity of engineered mass timber solutions to respond to sustainability goals. Additionally, as previously noted, timber systems are derived from renewable resources, sequester carbon, and require relatively low embodied energy. Their versatility and ease of use make them an effective response to growing climate concerns (Ramage et al., 2017; Timmers & Tsay Jacobs, 2018). Thanks to innovations in the field of mass timber production, there has been a substantial shift from the construction of timber frame single-family houses to multi-storey buildings, with timber as the principal structural material

(Cuadrado et al., 2015; Hildebrandt et al., 2017; Reynolds et al., 2016). The first 6-floor timber structure was Sundsvall I, a residential building completed in 2005 in the Swedish city with the same name (Falk, 2005).

There has been a growth in the construction of the modern tall and high-rise timber structures since then. To respond to the expanding demand for such buildings, comprehensive construction requirements were fundamental. Thus, ICC included CLT in the IBC in 2015, recognized heavy timber provisions in 2018 and from 2021 IBC includes requirements for up to 18 floors of mass timber constructions (Breneman et al., 2022; International Code Council & American Wood Council, 2020). The European Union has conceded directives on several wood/timber products to guarantee safety and health. The relevant technical values are specified in harmonized European standards (EN standards), where EN 1995 - Eurocode 5 is dedicated to the design of structures made of solid timber, sawn, planed or in pole form, glued laminated timber or wood-based structural products, or wood-based panels jointed together with adhesives or mechanical fasteners (CEN, 2004a). The second generation of Eurocode 5 is currently under development where one of the initiatives is to implement also the design of CLT (Kurzinski et al., 2022). Additionally, to facilitate manufacturers in creating the declaration of performance and applying the CE marking for construction products not addressed by a harmonized standard, exist the ETA, that offers comprehensive information on the performance assessment of such products.

These timber building standards and policies triggered a surge for innovation in the timber industry and a competition to build higher and higher (Green & Eric Karsh, 2012; Hildebrandt et al., 2017; Ramage et al., 2017). New timber towers rise every year, surpassing their forerunners in height, creativity of design and beauty of architectural forms. A selection of tall and high-rise timber buildings completed around the World between 2005 and 2023 is presented in Figure 12 and discussed further in Chapter 5.

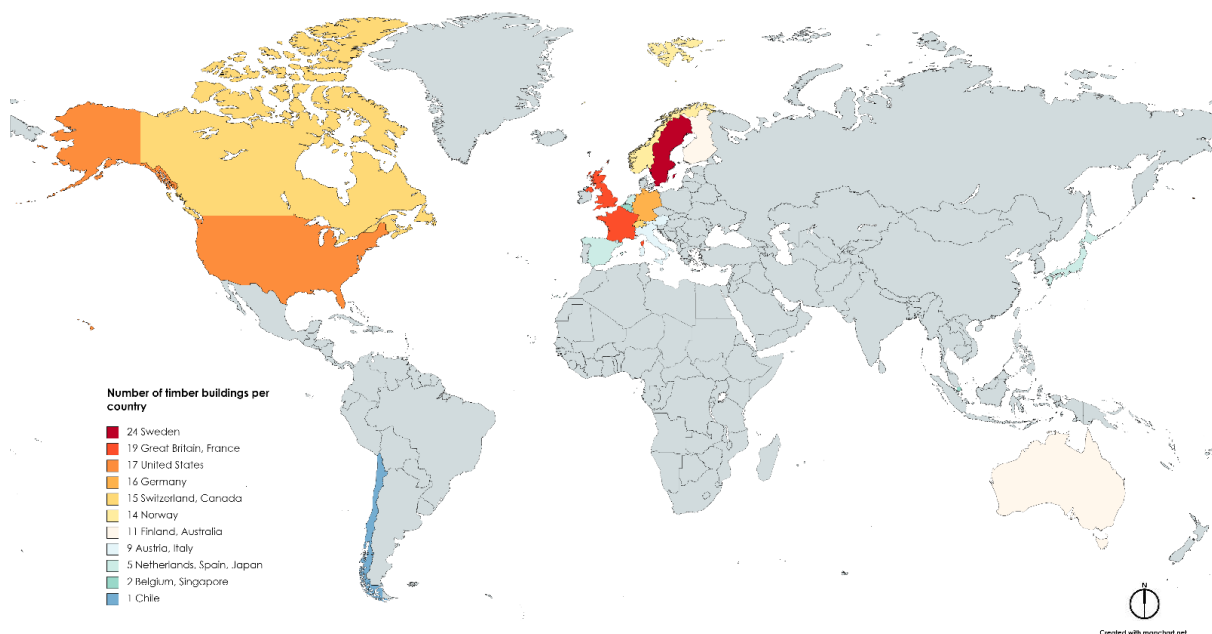


Figure 12. Tall and high-rise timber buildings around the World (created by using mapchart.net)

4. Summary of Part 1

The following chapter summarizes the state of the art of timber as a construction material and presents the highlights of the information presented in Chapter 2 and Chapter 3, focusing mainly on the multifaceted role of forests and timber in our environment and construction industry, the ecological, economic and social benefits of forests, emphasizing the importance of sustainable forest management and certification programs, the carbon cycle, highlighting the impacts of human activities on carbon levels and the advantages of timber over other materials in carbon sequestration. Furthermore, it recaps the properties of timber, including its strength, durability and the factors influencing its use in construction, the rise of mass timber construction, showcasing its environmental benefits, regulatory support and market potential. The text also addresses circular economy, focusing on timber recycling and wood cascading to enhance sustainability. Finally, it highlights the global trend towards high-rise timber buildings, reflecting on historical uses of timber and the modern innovations driving its resurgence in architecture.

Forest

Forests are crucial ecosystems that offer numerous ecological, economic, and social benefits. They constitute most of Earth's terrestrial biodiversity, supporting nearly all living organisms through carbon, water and nutrient cycles. Forests have been a source of oxygen and raw materials for centuries and play a vital role in combating climate change by storing carbon and ensuring a sustainable supply of wood products. However, they face numerous threats due to urban development. These challenges require comprehensive societal responses and strategies to ensure the resilience of forests and human communities.

Sustainable forest management is essential for maintaining forest health and diversity. Certification programs, such as those by PEFC and FSC, ensure responsible practices and promote consumer confidence. EPDs are also important for assessing and communicating the environmental impacts of wood products. Efforts to restore and establish new forests through reforestation and afforestation are gaining momentum, supporting both economic viability and carbon sequestration benefits.

Carbon cycle and footprint

The carbon cycle is essential for regulating Earth's climate and maintaining atmospheric CO₂ levels. Human activities, like burning fossil fuels and deforestation, have disrupted the carbon cycle, increased atmospheric CO₂ and contributed to global warming. Unlike fossil fuels, trees absorb CO₂ through photosynthesis, storing carbon in their tissues and releasing oxygen, which is vital for carbon sequestration. The effectiveness of carbon sequestration varies with forest age, species and management practices. Sustainable Forest Management protocols, tailored to specific climates and regions, help optimize carbon sequestration through appropriate harvesting rates.

The carbon footprint concept quantifies total greenhouse gas emissions from the lifecycle of a product, activity, or organization. It encompasses emissions from all stages, including raw material extraction, production, transportation, use and disposal. LCA methodologies provide comprehensive environmental impact analyses, expressed in climate metrics like GWP and CO₂e. Understanding carbon footprints enables informed decision-making by consumers, businesses and policymakers.

Timber, compared to concrete and steel by mass, has significant carbon sequestration advantages. However, its carbon footprint varies based on forestry practices, transportation distances, energy

sources used in processing and end-use. Sustainable forestry practices and shorter transportation distances reduce emissions, while energy-efficient processing facilities and renewable energy use further lower the carbon footprint.

Timber products' durability and intended use also impact their carbon footprint. Long-lasting products, such as those used in construction, store carbon for extended periods, potentially reducing total environmental impacts values. Overall, carbon footprinting is crucial for climate action, guiding decisions, shaping consumer choices and informing policy development to achieve greenhouse gas emission reduction targets and mitigate climate change impacts.

Timber as a resource and constructive material

Over the centuries, forests have thrived, adapting to diverse local climates and hosting a variety of species that shape timber's structure and properties globally. Consequently, numerous tree varieties are suitable for mass timber construction, each with unique traits, strengths and weaknesses. Wood exhibits significant variability among species, with each type having distinct characteristics crucial for construction material selection. Due to its high heterogeneity and anisotropy, it is essential to categorize different species and understand their key characteristics regarding construction suitability.

Wood is an intricate organic material with a cellular structure. Photosynthesis enables wood to convert water, solar energy and carbon dioxide into biomass and oxygen, giving it a natural capacity for water retention. Variations in the dimensions and structure of wood components significantly impact timber properties, determining whether it is lightweight or heavy, flexible or rigid, soft or hard and influencing its anisotropic and hygroscopic behaviours. Wood's strength and stability fluctuate with grain orientation and moisture levels, and mastering these factors is crucial for creating dimensionally stable, robust structures with enhanced durability.

Trees are categorized into hardwoods and softwoods. Both hardwood and softwood trunks consist of sapwood, responsible for sap conduction and biochemical synthesis and heartwood, composed of dead cells for long-term storage of extractives. All wood species are classified by durability levels: very durable, durable, moderately durable, slightly durable and not durable.

As a natural material, wood is hygroscopic, absorbing moisture from the air and being sensitive to humidity and temperature fluctuations, which directly influence its mechanical properties. High moisture content weakens wood, reducing its load-bearing capacity and structural integrity. The fibre saturation point, around 30%, is when wood's mechanical properties remain unchanged by moisture content. Beyond this point, wood maintains dimensional stability, but below it, swelling or shrinking can lead to warping, twisting, or cracking. Lower moisture content corresponds to higher strength and elasticity, and kiln drying to 12% moisture content enhances wood's strength.

Managing moisture content in humid environments is crucial to prevent deterioration. Elevated moisture levels promote decay, fungal growth and insect infestation, while drier conditions delay microbial growth and help maintain wood integrity. Moisture also increases wood's electrical and thermal conductivity, making it prone to corrosion in contact with metals and impacting its insulation suitability. Appropriate seasoning, storage, and treatment methods mitigate moisture's adverse impacts on wood. Material decisions must consider the building concept, wood type selection, building logistics,

and detailed architectural solutions to prevent water infiltration at cut surfaces. Addressing humidity and condensation control and implementing waterproofing strategies are crucial to avert damage.

The durability of a timber structure, which defines its lifespan, is influenced by timber species, natural properties, treatment methods, environmental exposure and maintenance practices. While some wooden buildings have endured for centuries, others deteriorate quickly. Identifying issues and defects that compromise construction quality helps emphasize essential durability requirements. Wood is vulnerable to biodegradation processes, such as thermal degradation, stress, weathering and chemical degradation. Eurocode 5 and other standards provide guidelines for assessing wood durability under adverse conditions.

Durability depends significantly on moisture exposure and subsequent biodegradation. Construction materials must meet minimum durability requirements and wood's propensity to absorb moisture demands by careful moisture management.

Maintaining timber at a moisture content of $\leq 20\%$ is essential for longevity. Moisture control involves physical and chemical treatments to enhance wood performance and design strategies. This includes avoiding exposure of wood ends, ensuring proper ventilation and using water-shedding barriers. Treated wood offers greater durability but will still deteriorate over time. Effective moisture control requires collaboration among manufacturers, architects, engineers and construction personnel. Comprehensive guidelines for moisture safety and thorough instruction for all involved parties are crucial to prevent moisture-related issues and ensure the long-term durability of timber structures.

Producing timber requires significantly less energy compared to steel and aluminium, making it more environmental-friendly. Timber's strength-to-weight ratio is impressive, allowing for lighter structures that can reduce foundation sizes and overall costs, without compromising its load-bearing capacity. Timber buildings also perform relatively well in seismic events due to their flexibility and natural damping properties. Advanced construction methods like engineered timber products enhance timber's versatility and structural performance.

Despite being lightweight, timber can meet stringent fire safety standards, with modern timber constructions demonstrating fire resistance comparable to other materials. Prefabricated timber construction offers numerous benefits, including speed, precision, cost efficiency and sustainability. Prefabrication also supports better planning and optimization, leading to reduced CO₂ emissions and a smaller ecological footprint.

Environmental concerns have led to increased efforts to reuse and recycle timber, promoting a circular economy and extending the material's lifespan. Timber buildings address environmental, financial and social sustainability objectives, offering a natural and aesthetically pleasing option. However, challenges exist, such as the need for specialized knowledge and careful planning, susceptibility to weather conditions, and the complexity of logistics and permits. Despite these challenges, the benefits of mass timber construction make it a competitive alternative to traditional methods.

Predicting the performance of natural wood is challenging due to its inherent inconsistency. As a result, researchers worldwide have spent decades developing engineered wood products to enhance wood strength and minimize its behavioural variations when used as construction material. The advent of innovative building systems, has expanded the structural use of wood across various building types, providing low-carbon options for designers. The wide range of new solutions, especially when combined

with other construction materials, makes it challenging to categorize all available innovations. Common solutions globally include products from laminated solid timber, veneer lumber and timber strands.

Laminated solid timber is made by bonding solid lumber pieces with adhesives, dowels, nails, or steel rods, resulting in improved strength and stability. Examples include Glulam, CLT, DLT, NLT and SLT. Glued veneer lumber is created by bonding thin veneer sheets with adhesives under heat and pressure, some oriented alternately to enhance strength and stiffness. Examples are LVL, plywood and PSL. Glued strand timber is made by bonding wood strands or particles with adhesives, compressing them into panels. Examples include LSL, OSB and various fibreboards.

Overall, these engineered wood products offer diverse structural and aesthetic applications, enhanced strength and stability, making them attractive options for modern construction projects.

Mass timber market

The mass timber market offers substantial advantages rooted in sustainability, making it a pivotal player in modern construction practices. Central to its appeal is wood's renewable nature, which supports environmental goals by sequestering carbon and reducing embodied energy in buildings.

Moreover, mass timber's circular economy potential is a significant advantage. Components can be designed for disassembly, enabling their reuse and recycling at the end of a building's life. This approach minimizes waste, aligning with circular economy principles aimed at prolonging material use and reducing resource consumption.

The integration of mass timber into sustainable development goals strengthens the construction industry's eco-friendly credentials, promoting responsible consumption and production. This alignment with global sustainability targets enhances its legitimacy and market momentum, driven by increasing awareness of climate change and a burgeoning demand for sustainable buildings.

Historically, concerns over fire safety restricted timber use in tall buildings, limiting applications to low-rise structures. Advances in fire-resistant technologies and updated building codes have, however, expanded timber's potential. Regulatory frameworks in Canada, the United States and Europe now accommodate taller mass timber buildings, reflecting growing confidence in its safety and environmental benefits. These standards, coupled with directives promoting sustainable forestry and product quality, create a robust regulatory framework supportive of timber's role in construction.

Globally, governments are encouraging sustainable timber construction through subsidies, grants and tax incentives. Such initiatives underscore the international drive towards decarbonizing construction and fostering a circular economy. These policies not only boost innovation but also make sustainable practices financially viable, driving widespread adoption of mass timber.

Overall, the convergence of supportive regulations, robust standards and economic incentives is accelerating the adoption of mass timber in construction. This transformative shift not only meets sustainability targets but also fosters a resilient built environment capable of addressing future challenges posed by climate change. As research continues to enhance fire performance and technological innovations advance, mass timber stands poised to play an increasingly integral role in sustainable urban development worldwide.

Several countries, including the UK, Austria and Norway, have established extensive networks that connect case studies and stakeholders within the timber construction sector. Such frameworks facilitate

the exchange of knowledge, best practices and innovations, accelerating the adoption of mass timber technologies. By bridging the gap between theoretical research and practical application, these networks enable collaboration among academia, industry and government, promoting sustainable and efficient timber construction methods.

Internationally, architects and firms showcase the potential of timber through landmark projects that highlight its versatility, sustainability and aesthetic appeal. They collaborate closely with engineers, builders and material scientists to innovate in design and construction techniques, pushing the boundaries of what is achievable with mass timber. Their efforts not only demonstrate the feasibility of using timber in large, complex structures but also educate stakeholders and the public about its benefits.

Timber engineering firms, on the other hand, play a critical role in the consistent advancement of mass timber construction, ensuring structural integrity, safety and compliance with building codes. Furthermore, the global mass timber market relies heavily on leading timber producers, particularly from Austria, Canada and Nordic countries.

In summary, architects, engineers and timber producers worldwide are pivotal in advancing mass timber construction. Through innovation, collaboration and expertise, they demonstrate the potential of timber as a sustainable, structurally sound, and aesthetically pleasing construction material, driving its adoption globally.

Circular economy

The transition from a traditional linear economy, marked by a 'take-make-dispose' model, to a more sustainable circular economy is increasingly urgent, particularly within the construction sector. The European Union has responded to global environmental concerns by heavily investing in circular economy policies, emphasizing principles of reduce, reuse, recycle and remanufacture. These policies are pivotal in addressing sustainability challenges and supporting governmental initiatives through enhanced research efforts on a global scale.

In the context of timber construction, the 10Rs strategies and wood cascading are central to achieving sustainability goals. However, challenges persist in widespread acceptance and reuse of reclaimed timber due to technological limitations and varying regulations on treated wood materials.

The environmental benefits of recycling timber are profound. Reused timber maintains sequestered carbon throughout its lifecycle, contributing to carbon emissions reduction. Despite challenges, ongoing research explores methods for efficiently reclaiming and repurposing timber or, in the last scenario, using wood in energy generation processes.

Wood cascading represents a strategic approach within the circular economy framework, aiming at maximizing the lifecycle of timber through repeated reuse in various forms and functions. This concept involves cascading in time, value and function, optimizing the utility and sustainability of timber products at each stage of their lifecycle.

Successful implementation of wood cascading requires comprehensive policy reforms, technical innovations and a skilled workforce. Policies must outline clear guidelines for timber reuse and recycling standards, while technical advancements are needed to facilitate efficient deconstruction and reuse processes in construction practices. Educating architects, engineers and construction workers on the benefits and methodologies of wood cascading is crucial for its widespread adoption.

In conclusion, while the concept of wood cascading holds promises for advancing sustainable construction practices, overcoming technical and regulatory challenges is essential. Addressing these challenges through continued research and collaborative efforts is instrumental in realizing the full potential of timber within the circular economy.

High-rise timber buildings

Wood has been a key construction material throughout human history due to its abundance, versatility and resilience. Timber can be traced from ancient structures to modern high-rise timber buildings, demonstrating its adaptability to various conditions and technological advancements. Timber construction evolved over millennia, from Neolithic nest residences and longhouses to complex frame structures in ancient Rome and multi-storey pagodas in Japan and China. In medieval Europe, timber frame buildings and Gothic roofs were prominent, while in America, timber remained the primary material for native structures and later for colonists' homes. The 16th century saw peak timber usage in Europe, but the industrial revolution shifted the focus to iron and concrete. Despite this, timber structures like the Butler Square Building in Minneapolis persisted into the early 20th century. Scientific research in the 20th century advanced timber construction, leading to innovations like engineered wood products. The 21st century has seen a resurgence in timber construction due to its sustainability and adaptability, supported by updated building codes and standards. This renewed interest has led to the rise of modern tall and high-rise timber buildings, highlighting wood's enduring legacy and future potential in construction.

By presenting this comprehensive analysis, the document illustrates the state-of-the-art in high-rise mass timber construction and underscores the critical requirements for sustainability that surge from its natural properties, manufacturing process and market dynamics. Understanding these aspects is crucial for developing strategies that promote the resilience and long-term viability of timber as a key material in sustainable construction.

In summary, the discussion of forests, the carbon cycle, timber resources, engineered products and the mass timber market demonstrates the multifaceted role of wood in advancing sustainable construction and responding to global climate challenges. Forest ecosystems not only sustain biodiversity and regulate carbon cycles but also provide renewable raw materials whose responsible management is critical to long-term environmental resilience. Life Cycle Assessment methodologies and carbon footprinting tools reveal timber's comparative advantages over carbon-intensive materials, particularly when supported by sustainable forestry, efficient processing and optimized logistics. At the same time, advances in engineered timber technologies and prefabrication have expanded wood's structural and architectural applications, making it a competitive solution for both low- and high-rise buildings. Furthermore, the integration of circular economy principles, extends timber's environmental benefits beyond its initial service life, aligning construction practices with broader sustainability targets. Nevertheless, challenges remain, including the need to refine regulatory frameworks, address fire and durability concerns and bridge knowledge gaps among stakeholders. Within the scope of this thesis, these insights reinforce the importance of promoting timber as a low-carbon, renewable and versatile construction material capable of contributing meaningfully to the decarbonization of the built environment and the achievement of global climate objectives.

Part 2. Building design and construction with timber

5. Case studies

The following section analyses the selection of 199 practical examples of tall and high-rise buildings, with timber as a material for main load-bearing structure. It characterizes high-rise timber structures and examines their geospatial distribution. It delves into the tallest examples of these structures, investigates the reasons behind their prevalence in Europe, and discusses the factors contributing to the increasing popularity of mass timber constructions globally.

To complete Table 11's information, containing the list of the gathered case studies, the Author considered different sources, such as architectural and engineering magazines, architects, constructors and manufacturers websites and available scientific research items. The preliminary studies identified 73 buildings. Furthermore, based on the reviews made by Svatoš-Ražnjević et al., (2022), Salvadori, (2021) and the geospatial data available in the arcgis.com with the "State of Mass Timber in Canada" (His Majesty the King in Right of Canada, n.d.) and the Tall Timber global Adit (CTBUH, 2017), 126 more buildings were added to the analysis. Due to constant upgrades in the market of mass timber buildings and difficulties in finding all completed projects in the world, the presented list does not represent all existing tall and high-rise structures made of wood.

For the purpose of this study, as there is no clear definition of a tall/high-rise building, the Author considered buildings with six or more floors, with a minimum height of 18 m, which allowed having a broader perspective on the state of tall and high-rise timber structures and provided significant coverage of countries with valuable case studies.

Case studies are presented in chronological order. A total of 199 buildings with six or more floors, with a minimum height of 18 m, with timber/wood-based elements as a main load-bearing structure were identified within 5 continents and are presented next.

Table 11. Modern tall and high-rise mass timber buildings by date of completion

N°	Name	N of floors	Height (m)	Year	Use	Structure**	PGA intensity***	City	Country	Continent	Reference
1.	Sundsvall I	6	-	2005	R	All-timber		Sundsvall	Sweden	Europe	(Falk, 2005)
2.	Holzhausen	6	20*	2006	R	Timber over concrete (1 st level) with concrete core		Steinhausen	Switzerland	Europe	(Lehmann, 2012; Renggli AG, n.d.)
3.	Casa Montarina	6	20*	2007	R	All-timber		Lugano	Switzerland	Europe	(Felder, 2008)
4.	Lagerhuset	10	31	2008	R	All-timber		Eslöv	Sweden	Europe	(Lagerhuset, n.d.; The Skyscraper Center, 2023)
5.	Limnologen	8	25*	2008	R	Timber-steel over concrete (1 st level)		Växjö	Sweden	Europe	(Jarnerö, 2008; Landel, 2018; Limnologen, 2023; Serrano, 2009b, 2009a)
6.	E3	7	22	2008	M	Timber-concrete with concrete core		Berlin	Germany	Europe	(Architecture Necessity, 2012; Kaden+ GmbH, n.d.; Kaden+Lager, 2015)
7.	Stradhouse- Murray Grove	9	29	2009	R	All-timber over concrete (1 st level)		London	UK	Europe	(Waugh Thistleton Architects, 2018)
8.	Portvakten Söder	8	25*	2009	R	All-timber over concrete (1 st level)		Växjö	Sweden	Europe	(Landel, 2018; Nyström, 2015)
9.	CSN-Fondaction	6	22.1	2009	O	Timber-concrete with concrete core		Quebec	Canada	Canada	(Hu, 2013)
10.	Älvsbacka Strand	7	-	2010	R	All-timber		Skellefteå	Sweden	Europe	(Daerga & Gustafsson, 2008; Skellefteå kommun, n.d.)
11.	Badenerstrasse	7	22*	2010	M	All-timber over concrete (1 st level) with concrete core		Zurich	Switzerland	Europe	(Green & Taggart, 2017; Kaufmann et al., 2018)
12.	Holz8	8	25	2011	M	Timber with concrete core		Bad Aibling	Germany	Europe	(H8 Achtgeschossiges Holzhaus, n.d.; Holz 8 - Acht-Stöckiges Holzhaus, 2022; Holz 8 - Wohn- Und Bürogebäude, DE, 2022)
13.	Bridport House	8	25.6	2011	R	All-timber		London	UK	Europe	(Bridport House, n.d.; Bridport House, 2022; Ground-Breaking Bridport House Built from PEFC Certified Spruce Wood, 2012; Storaenso, 2013; Waugh Thistleton Architects, 2018; Willmott Dixon, 2011)

Nº	Name	N of floors	Height (m)	Year	Use	Structure**	PGA intensity***	City	Country	Continent	Reference
14.	Kasukabe Convention Hall	6	27.086	2011	O	All timber over steel (4 levels)		Saitama Prefecture	Japan	Asia	(Koshihara, 2013)
15.	De Karel Doorman	22	70	2012	M	Timber-steel on existing building		Rotterdam	Netherlands	Europe	(De Karel Doorman, 2022; De Karel Doorman Rotterdam, n.d.; Romero, 2016)
16.	Rundeskogen A	10	33*	2012	R	Timber-concrete		Sandnes	Norway	Europe	(Dale, 2012; Rundeskogen, 2022; Rundeskogen / DRMM + Helen & Hard , 2015; Rundeskogen Three Towers on the West Coast of Norway, 2022; Undheim, n.d.)
17.	Forté	10	32	2012	R	All-timber over concrete (1 st level)		Melbourne	Australia	Australia	(Forté Apartments, 2018; Forte Living, 2020; Forte Tower Melbourne, 2019; Forte Tower Melbourne - KLH Massivholz GmbH, n.d.; Lend Lease, n.d.; Nieland, 2013; Wood Solutions, n.d.)
18.	Life Cycle Tower One	8	27	2012	O	Timber-concrete with concrete core, over concrete (1 st level)		Dornbirn	Austria	Europe	(LifeCycle Tower ONE, n.d.; LifeCycle Tower One - 8 Stories of Wood-Concrete, 2022; Lifecycle Tower One Building, n.d.)
19.	Whitmore Road	7	20.5	2012	M	Timber over concrete (1 st level)		London	UK	Europe	(Waugh Thistleton Architects, 2018; Whitmore Road From the Core, n.d.)
20.	3XGrün	6	20*	2012	R	Timber over concrete (1 st level) with concrete core		Berlin	Germany	Europe	(Becker et al., n.d.)
21.	Residence Alexander	6	-	2012	R	Timber with concrete core		Acquila	Italy	Europe	(Alexander Residence, n.d.)
22.	Residenza Sirio	6	-	2012	R	Timber with concrete core		Lugano	Switzerland	Europe	(Lignum, 2015)
23.	Mühlebachstrasse	6	20*	2012	M	Timber and timber-concrete with concrete core		Zurich	Switzerland	Europe	(Kämpfen Zinke + Partner, n.d.)
24.	Rundeskogen B	16	51*	2013	R	Timber-concrete		Sandnes	Norway	Europe	(Biro, n.d.; Dale, 2012; Rundeskogen, 2022; Rundeskogen / DRMM + Helen & Hard , 2015; Rundeskogen Three Towers on the West

Nº	Name	N of floors	Height (m)	Year	Use	Structure**	PGA intensity***	City	Country	Continent	Reference
											Coast of Norway, 2022; Undheim, n.d.)
25.	Rundeskokogen C	11	37	2013	R	Timber-concrete		Sandnes	Norway	Europe	(Biro, n.d.; Dale, 2012; Rundeskogen, 2022; Rundeskogen / DRMM + Helen & Hard, 2015; Rundeskogen Three Towers on the West Coast of Norway, 2022; Undheim, n.d.)
26.	Cenni di Cambiamento	9	27	2013	R	All-timber		Milan	Italy	Europe	(Cenni Di Cambiamento, 2020; Cenni Di Cambiamento: 9 Piani in Legno a Milano, 2020)
27.	Strandparken	9	28*	2013	R	Timber over concrete (1 st level) with steel rods		Stockholm	Sweden	Europe	(Griffiths, 2014; Strandparken, 2020; Wingårdh, 2013)
28.	Maison de l'Inde	8	25	2013	R	Timber with concrete core, over concrete (1 st level)		Paris	France	Europe	(Cité 2025: The Extension of the Maison de l'Inde, 2020; India House, Cité Internationale, n.d.)
29.	Palisaden	8	26*	2013	R	All-timber		As	Norway	Europe	(Grinderud, 2015; Joelson, 2013; Nygaard et al., 2016; Studentboliger ÅS, n.d.)
30.	Wagramer Strasse	7	22*	2013	R	Timber with concrete core, over concrete (1 st level)		Vienna	Austria	Europe	(Apartment Complex in Timber Construction, Wagramer Straße, n.d.; Holzwohnbau Wagramer Straße 2013, n.d.; Residential Building in Wagramer Strasse, Vienna Austria, n.d.)
31.	Panorama Giustinelli	7	22	2013	R	Timber with concrete core		Trieste	Italy	Europe	(Panorama Giustinelli, n.d.)
32.	Les Cadolles	7	22*	2013	R	Timber over concrete (1 st level)		Neuchâtel	Switzerland	Europe	(DRA5, n.d.; Svatoš-Ražnjević et al., 2022)
33.	Tamedia	7	26*	2013	O	Timber with concrete core		Zurich	Switzerland	Europe	(Tamedia New Office Building, n.d.; Tamedia Office Building / Shigeru Ban Architects, 2014)
34.	Lintuviita	6	-	2013	R	Timber over concrete (1 st level)		Seinäjoki	Finland	Europe	(ArchiEXPO, n.d.)
35.	Comtralaminada	6	18*	2013	R	All-timber		Lleida	Spain	Europe	(AlterMateria, 2016; Edifici de Fusta Contralaminada de 6 Plantes, n.d.; Ejecutado El Primer Edificio de Seis Plantas

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											de Madera En España., 2013; Llobera Serentill, 2020)
36.	Giesserei	6	21*	2013	M	Timber with concrete core		Winterthur	Switzerland	Europe	(Galli Rudolf, n.d.)
37.	SZU-Betrisbgebaude	6	-	2013	R	Timber with concrete core over existing building (2 levels)		Zurich	Switzerland	Europe	(Salvadori, 2021)
38.	District 03	6	18	2013	R	All-timber		Quebec	Canada	North America	(Beaucher, 2015)
39.	Stella	6	21*	2013	M	All-timber over concrete (1 st level)		Marina del Rey	USA	North America	(Stella Apartments, n.d.; WoodWorks, 2013)
40.	Bullitt Center	6	27*	2013	O	Timber with steel bracing over concrete (2 levels)		Seattle	USA	North America	(Hanford, n.d.)
41.	Jules Ferry Residence	8	-	2014	R	All-timber		St. Die-des-Vosges	France	Europe	(8 French Tall Timber Storeys, 2023; 26 Logements 8 Niveaux Bois-Paille Passif, n.d.; Résidence Jules Ferry à Saint-Dié-Des-*Vosges, n.d.; Ruppert, n.d.)
42.	Wood Innovation and Design Centre	8	29.5	2014	O	All-timber		Prince Gorge	Canada	North America	(Castro, 2021; Wood Innovation and Design Centre, n.d.)
43.	C13	7	23*	2014	M	Timber with concrete core		Berlin	Germany	Europe	(Kaden Klingbeil Architects, n.d.)
44.	Marina Verde	7	22*	2014	M	Timber with concrete core		Caorle	Italy	Europe	(Simone Micheli, n.d.)
45.	698 Wohnüberbauung Sihlbogen Areal B	7	22*	2014	R	Timber-concrete with concrete core		Zurich	Switzerland	Europe	(henauer gugler, n.d.)
46.	Kingsgate House	7	23	2014	R	Timber over concrete (2 levels)		London	UK	Europe	(Kingsgate House - London, UK, n.d.; Kingsgate House in Chelsea, 2020; Kingsgate House Scores UK Sustainable First, n.d.; Waugh Thistleton Architects, 2018)
47.	UEA Crome Court	7	24*	2014	R	All-timber		Norwich	UK	Europe	(LSI Architects, n.d.)
48.	N-Habit Belltown	7	25*	2014	M	Timber over concrete (2 levels)		Seattle	USA	North America	(N-Habit Belltown, 2015; N-Habit Belltown, 2023)
49.	Treet	14	49.4/52.8	2015	R	All-timber (with concrete slabs**)		Bergen	Norway	Europe	(Dale, 2016; Treet, 2020; Trifkovic, n.d.)

N°	Name	N of floors	Height (m)	Year	Use	Structure**	PGA intensity***	City	Country	Continent	Reference
50.	The Cube (Banyan Wharf/Wenlock Cross)	10	33.5	2015	R	Timber-steel with concrete core, over concrete (1 st level)		London	UK	Europe	(Banyan Wharf, n.d.; The Cube / Hawkins\Brown, 2015; Frearson, 2015; Waugh Thistleton Architects, 2018)
51.	Vallen Parts A and B	9	29	2015	R	Timber with concrete core, over concrete (2 levels)		Växjö	Sweden	Europe	(Johansson & Schauerte, 2015; Residential Complex Vallen, Växjö Sweden, n.d.; Vallen, 2023; Vallen in Växjö, 2023a; Vallen in Växjö, 2023b)
52.	Puukuokka One	8	27*	2015	R	All-timber		Jyväskylä	Finland	Europe	(Castro, 2018; Frearson, 2015b; Lassila, 2020; Puukuokka Housing Block, 2021)
53.	Eskolantie	7	23*	2015	R	Timber over concrete (1 st level)		Helsinki	Finland	Europe	(Iiramo & Viljakainen, 2020)
54.	Kampa K8	7	-	2015	O	All-timber		Aalen	Germany	Europe	(proHolzBW, n.d.)
55.	Siloah	7	21*	2015	H	Timber with concrete core		Bern	Switzerland	Europe	(Salvadori, 2021)
56.	Ywood Les Docks Libres	6	-	2015	O	Timber over concrete (1 st level) with concrete core		Marseilles	France	Europe	(Bouquet, 2015, 2016)
57.	Social housing in Saint-Denis	6	20*	2015	R	Timber over concrete (1 st level)		Saint Denis	France	Europe	(Trä magazine, 2015)
58.	Firenze Ex-Longinotti	6	-	2015	R	All-timber		Firenze	Italy	Europe	(Follesa et al., 2010)
59.	Studentboliger Remmen	6	19*	2015	R	Timber over concrete (1 st level)		Halden	Norway	Europe	(Archello, n.d.; BAS Arkitekter, n.d.)
60.	Åsbovägen	6	-	2015	R	All-timber		Fristad	Sweden	Europe	(Landel, 2018)
61.	Cobalt Place	6	19.3	2015	R	All-timber		London	UK	Europe	(Cobalt Place, n.d.; Cobalt Place, 2023; Surrey Lane, Cobalt Place, 2023; Waugh Thistleton Architects, 2018)
62.	Curtain Place	6	20	2015	M	Timber-steel		London	UK	Europe	(Curtain Place, n.d.; Curtain Place, 2023; Waugh Thistleton Architects, 2018)
63.	Moholt 50/50	9	28	2016	R	All-timber over concrete (1 st level)		Trondheim	Norway	Europe	(Moholt 50 50, 2016; Moholt Timber Towers / MDH Arkitekter, 2017)
64.	H7	7	24*	2016	O	Timber-concrete over concrete (1 st level) with concrete core		Münster	Germany	Europe	(Arup, n.d.)

N°	Name	N of floors	Height (m)	Year	Use	Structure**	PGA intensity***	City	Country	Continent	Reference
65.	Patch 22	7	30	2016	M	Timber with concrete core		Amsterdam	Netherlands	Europe	(FRANTZEN et al architects, 2017)
66.	T3	7	26*	2016	O	Timber with concrete core, over concrete (1 st level)		Minneapolis	USA	North America	(McKnight, 2016; T3, n.d.; T3 Minneapolis Office Building, n.d.)
67.	International House	7	29*	2016	O	Timber over timber-concrete (1 st floor)		Sydney	Australia	Australia	(Nimmo, 2018)
68.	Hummelkaserne	6	18*	2016	R	Timber with concrete core		Graz	Austria	Europe	(dataholz.eu, n.d.)
69.	Mäihä	6	-	2016	R	All-timber		Seinäjoki	Finland	Europe	(Architects a-live, 2016)
70.	DDTM	6	21.5	2016	O	Timber-concrete over concrete (1 st level) with concrete core		Vannes	France	Europe	(Prud'homme, 2018)
71.	Zollfreilager Housing	6	19.33	2016	R	Timber with concrete core		Zurich	Switzerland	Europe	(neue Holzbau AG, 2017)
72.	UEA Blackdale Student Residence	6	21.7	2016	R	All-timber		Norwich	UK	Europe	(UEA Blackdale Student Residences, 2019; UEA Hickling House & Barton House, n.d.; Waugh Thistleton Architects, 2018)
73.	Synergia	6	-	2016	M	Timber over concrete (1 st level)		Saint-Hyacinthe	Canada	North America	(Architizer, n.d.; Think Wood, n.d.)
74.	38 Davis	6	22*	2016	M	Timber over concrete (1 st level)		Portland	USA	North America	(Ankrom Moisan Architects, 2021)
75.	Clay Creative	6	26*	2016	M	Timber-steel over concrete (1 st level)		Portland	USA	North America	(WoodWorks, 2021a)
76.	Brock Commons	18	54	2017	R	Timber with concrete core, over concrete (1 st level), steel roof		Vancouver	Canada	North America	(Brock Commons Tallwood House, 2020; UBC Brock Commons Tallwood House, n.d.; Forest Innovation Investment Ltd, 2017; Staub-French et al., 2022)
77.	Origine Condos	13	40.9	2017	R	Timber over concrete (1 st level)		Quebec	Canada	North America	(Condos Origine, 2020; Origine Écocondos de La Pointe, 2020; Nordic Structures, 2020)
78.	Dalston Works (Dalston Lane)	10	33.8	2017	M	Timber over concrete (1 st level)		London	UK	Europe	(Dalston Lane, London Great Britain, n.d.; Ravenscroft, 2017; Waugh Thistleton Architects, n.d.-a, 2018)

N°	Name	N of floors	Height (m)	Year	Use	Structure**	PGA intensity***	City	Country	Continent	Reference
79.	Press House	9	28*	2017	R	Timber over concrete (1 st level)		London	UK	Europe	(Eurban, n.d.)
80.	Lucien Cornil Student Residence	8	23*	2017	R	Timber with concrete core		Marseilles	France	Europe	(Ahmed, n.d.)
81.	Opalia	8	28*	2017	O	Timber-concrete-steel		Paris	France	Europe	(Art Build, n.d.)
82.	Hotel Nautilus	8	27	2017	M	Timber over concrete (1 st level)		Pesaro	Italy	Europe	(Stora Enso, n.d.)
83.	Dramsvegen	10	30	2017	R	Timber over concrete (3 levels)		Tromsø	Norway	Europe	(Tulebekova et al., 2023)
84.	Highpoint Terrace	8	22*	2017	R	Timber-steel		London	UK	Europe	(Case Study - Highpoint Terrace, 2023; Highpoint Terrace, 2023)
85.	Arbora A	8	25	2017	R	Timber over concrete (1 st level)		Montreal	Canada	North America	(Arbora, 2020; Découvrez Notre Nouvelle Étude de Cas Sur Arbora!, 2020; Levée et al., 2021)
86.	Woodie	7	19*	2017	R	Timber over concrete (1 st level) with concrete core		Hamburg	Germany	Europe	(DV8 id, n.d.; Ingenieur Holzbau, n.d.)
87.	Holzwohnbauten im Dragoner-Quartier	6	-	2017	R	Timber-concrete with concrete core		Wels	Austria	Europe	(Obermayr, n.d.)
88.	Pihapetäjä	6	-	2017	R	Timber over concrete (1 st floor)		Joensuu	Finland	Europe	(OOPEAA, n.d.)
89.	30 Wood House	6	-	2017	R	Timber with steel elements		Modena	Italy	Europe	(ergodomus, n.d.)
90.	Schwarzensteinhütte	6	-	2017	M	Timber with concrete core		San Giovanni Valle Aurina	Italy	Europe	(Ainhauser, n.d.; Stifter + Bachmann, n.d.)
91.	Östra Sala Backe	6	22*	2017	M	Timber over concrete (1 st level)		Uppsala	Sweden	Europe	(ArchDaily, 2020)
92.	Träloftet	6	-	2017	R	Timber with concrete core and steel trusses		Linköping	Sweden	Europe	(Wigardt, 2017)
93.	Lakeside Resort Expansion	6	-	2017	M	Timber over concrete (1 st level)		Penticton	Canada	North America	(Forestry Innovation Investment, n.d.; HDR, n.d.)
94.	Kringsjå studentby	10	30*	2018	R	All-timber		Oslo	Norway	Europe	(FutureBuilt, 2021)
95.	Suurstoffi 22	10	36	2018	O	Timber-concrete with concrete core, over concrete (1 st level)		Risch-Rotkreuz	Switzerland	Europe	(Eisenlohr, n.d.; Suurstoffi 22, n.d.; Suurstoffi 22, 2022; Suurstoffi 22 Risch Rotkreuz, n.d.)

Nº	Name	N of floors	Height (m)	Year	Use	Structure**	PGA intensity***	City	Country	Continent	Reference
96.	Import Building, Republic at East India/Studio RHE	10	-	2018	S	All-timber		London	UK	Europe	(Ravenscroft, 2018)
97.	25 King	10	45	2018	O	Timber over concrete (1 st level)		Brisbane	Australia	Australia	(25 King Street, 2023; Tall Timber: Thinking beyond Concrete and Steel 25 King, 2023; Bates Smart, n.d.)
98.	Aveo Norwest	10	36*	2018	R	Timber over concrete (1 st level)		Sydney	Australia	Australia	(TTW, n.d.)
99.	Hotel Jakarta	9	31*	2018	M	Timber-concrete with concrete core		Amsterdam	Netherlands	Europe	(ArchDaily, 2018)
100.	Wood City (phase 1)	8	26*	2018	R	Timber over concrete (1 st level)		Helsinki	Finland	Europe	(Puuinfo, 2021)
101.	Green Office® Enjoy	8	34*	2018	M	Timber over concrete (1 st level) with steel bracing		Paris	France	Europe	(Arquitectura Viva, n.d.)
102.	Maskinparken TRE	8	25*	2018	R	All-timber		Trondheim	Norway	Europe	(Stora Enso, n.d.-b)
103.	Docenten	8	29*	2018	M	Timber over concrete (1 st level) with concrete core		Växjö	Sweden	Europe	(Salvadori, 2021)
104.	Vallen Parts C to F	8	-	2018	R	Timber with concrete core, over concrete (2 levels)		Växjö	Sweden	Europe	(Residential Complex Vallen, Växjö Sweden, n.d.; Vallen, 2023; Vallen in Växjö, 2023)
105.	Frostaliden	8	-	2018	R	Timber over concrete (1 st level) with concrete core		Skövde	Sweden	Europe	(White Arkitekter, n.d.)
106.	Arbora B	8	27*	2018	R	All-timber over concrete (1st level)		Montreal	Canada	North America	(Arbora, 2020; Arbora - Phases II & III, 2020; Découvrez Notre Nouvelle Étude de Cas Sur Arbora!, 2020; Levée et al., 2021)
107.	Carbon 12	8	26	2018	M	Timber with steel core		Portland	USA	North America	(Carbon12, n.d.; Carbon12, 2022; Carbon12, 2023; KAISER+PATH, n.d.-a)
108.	The Gardens Macarthur	8	25*	2018	R	Timber over concrete (1 st level)		Campbelltown	Australia	Australia	(Lloyd, 2017)
109.	Kibori	7	23*	2018	O	Timber-steel-concrete with concrete core		Nantes	France	Europe	(Cruard Charpente, n.d.)
110.	Perspective	7	27*	2018	O	Timber with concrete cores		Bordeaux	France	Europe	(Nicolas Laisné Architectes, n.d.)

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111.	Lynarstrasse Berlin	7	24*	2018	R	Timber over concrete (1 st level) with steel connecting staircase		Berlin	Germany	Europe	(Binderholz GmbH, n.d.-b)
112.	La Borda	7	24*	2018	R	Timber over concrete (1 st level)		Barcelona	Spain	Europe	(Divisare, 2020)
113.	Boiler House	7	23*	2018	R	Timber over concrete (1 st level)		London	UK	Europe	(Boiler House, 2023; The Boiler House, 2023; The Old Vinyl Factory, n.d.)
114.	Ellerslie Crescent	7	21*	2018	R	All-timber		Yoker	UK	Europe	(Best Social Housing Award for Scotland's Tallest CLT Building, 2018; Ellerslie Crescent, 2022; Scotland's Largest Cross Laminated Timber (CLT) Building, 2022; Yoker Riverside, 2022; Duncheva, 2021)
115.	Daramu House	7	29*	2018	M	Timber over concrete (1 st level)		Sydney	Australia	Australia	(Lam, n.d.)
116.	Hoho Next	6	23*	2018	O	Timber-concrete with concrete core		Vienna	Austria	Europe	(Swiss-Architects, n.d.)
117.	Kietude	6	17.5	2018	R	Timber-steel with concrete core		Namur	Belgium	Europe	(Ernest, 2018)
118.	Fagerlund Studenthybler	6	-	2018	M	Timber over concrete-steel (2 levels)		Horten	Norway	Europe	(Code Architecture, n.d.)
119.	ARV8	6	19*	2018	R	Timber over concrete (1 st level)		Madrid	Spain	Europe	(Ábaton, n.d.)
120.	Gibraltar Guest House	6	20*	2018	R	All-timber		Gothenburg	Sweden	Europe	(Brandt, 2019)
121.	Sue & Til	6	20*	2018	R	Timber over concrete (1 st level) with concrete core		Winterthur	Switzerland	Europe	(Implenia AG, n.d.)
122.	Virtuoso	6	22*	2018	R	All-timber		Vancouver	Canada	North America	(naturally:wood, n.d.)
123.	Flatiron PDX	6	23*	2018	M	Timber-concrete		Portland	USA	North America	(Works Architecture, n.d.)
124.	Hoho Vien	24	84	2019	M	Timber-concrete with concrete core		Vienna	Austria	Europe	(Information – HoHo Wien, 2021; Migl, 2020; Rüdiger Lainer + Partner Architekten, 2022; Urban Lakeside Development Aspern, 2022)
125.	Mjøstårnet	18	85.4	2019	M	All-timber		Brumunddal	Norway	Europe	(Abrahamsen, 2017; Mjøstårnet, 2019; Mjøstårnet, 2022;

Nº	Name	N of floors	Height (m)	Year	Use	Structure**	PGA intensity***	City	Country	Continent	Reference
											Mjøstårnet The Tower of Lake Mjøsa / Voll Arkitekter, 2020)
126.	Arbo	15	60	2019	M	Timber-concrete with concrete core		Risch-Rotkreuz	Switzerland	Europe	(Baufeld 1 Suurstoffi West, n.d.; Baufeld 1 Suurstoffi West, Risch Rotkreuz, n.d.; Büro Konstrukt AG + Manetsch Meyer Architekten AG, 2018; Eisenlohr, n.d.)
127.	Lighthouse Joensuu	14	50	2019	R	Timber over concrete (1 st level) with steel rods		Joensuu	Finland	Europe	(Dovetail, 2020; Lighthouse Joensuu, n.d.; Lighthouse Joensuu, 2023; Vara, 2019)
128.	Cederhusen	13	42*	2019	R	Timber over concrete (2 levels)		Haninge	Sweden	Europe	(Folkhem, n.d.)
129.	Eunoia Junior College	12	56	2019	E	Timber-concrete		Singapore	Singapore	Asia	(Biro, n.d.; CLT Facade in Singapore, 2020; Eunoia Junior College, n.d.; Eunoia Junior College, 2022)
130.	Ilôt Bois Sensations	11	38	2019	M	All-timber over concrete (1 st level)		Strasbourg	France	Europe	(146 Logements 11 Niveaux Bois, n.d.; Îlot Bois Sensations, n.d.; Ilôt Résidentiel Bois et Biosourcé à Strasbourg, n.d.; Sensations, n.d.; Sensations, 2019)
131.	Palazzo Nice Meridia	10	35	2019	O	Timber over concrete (1 st level) with concrete core		Nice	France	Europe	(Elioth, n.d.)
132.	Skaio	10	34	2019	R	Timber-concrete with concrete core		Heilbronn	Germany	Europe	(SKAIO, n.d.; SKAIO - Deutschlands Erstes Holz-Hybrid-Hochhaus, n.d.; SKAIO - the Highest Wooden House in Germany, 2016)
133.	Park Wood Takamori	10	33.7	2019	R	Timber-steel and timber-concrete		Izumi-ku	Japan	Asia	(Morishita, 2023; PARK WOOD Takamori, n.d.)
134.	Botanikern	9	26*	2019	R	Timber over concrete (2 levels)		Uppsala	Sweden	Europe	(Axeloth Arkitekter, n.d.; Thunberg, 2020)
135.	Kajstaden	9	31*	2019	R	All-timber		Västerås	Sweden	Europe	(C.F. Møller Architects, n.d.)
136.	Frostaaliden 5	9	-	2019	R	Timber with concrete core and steel bracing		Skövde	Sweden	Europe	(Moelven, n.d.; Peab, 2020)

N°	Name	N of floors	Height (m)	Year	Use	Structure**	PGA intensity***	City	Country	Continent	Reference
137.	Kambri-Student accommodation	9	29*	2019	R	Timber over concrete (2 levels)		Canberra	Australia	Australia	(BVN, n.d.)
138.	DAS Kelo	8	-	2019	R	Timber over concrete (1 st level)		Rovaniemi	Finland	Europe	(Saviaro, 2019)
139.	Jo&Joe	8	25*	2019	M	Timber-concrete with concrete core, over concrete (1 st level)		Gentilly	France	Europe	(Construction of a Jo&Joe Hotel Building in Gentilly, France, 2021; Jo&Joe Hotel, Gentilly, n.d.; Pintos, 2020)
140.	Pont de Flandres B. 007	8	31*	2019	O	Timber over concrete (1 st level) with concrete core		Paris	France	Europe	(RFR, 2019)
141.	Trummens Strand	8	28*	2019	R	Timber over concrete (2 levels)		Växjö	Sweden	Europe	(Stora Enso, n.d.-a)
142.	Arbora C	8	25	2019	R	Timber over concrete (1 st level)		Montreal	Canada	North America	(Arbora, 2020; Arbora - Phases II & III, 2020; Découvrez Notre Nouvelle Étude de Cas Sur Arbora!, 2020; Levée et al., 2021)
143.	Gesundheits.Quartiers	7	24*	2019	R	Timber and timber-concrete over concrete (1 st level) with concrete core		Vienna	Austria	Europe	(Archello, n.d.-a)
144.	Pop-Up	7	21*	2019	R	Timber over concrete (1 st level) with concrete core		Aubervilliers	France	Europe	(Archello, n.d.-b)
145.	Pulse	7	33*	2019	M	Timber over concrete (1 st level) with concrete core		Saint Denis	France	Europe	(bvf architectes, n.d.)
146.	WA14 West	7	23*	2019	R	Timber-concrete over concrete (1 st level) with concrete core		Munich	Germany	Europe	(Hafner et al., 2020)
147.	WA15 West	7	23*	2019	R	Timber over concrete (1 st level) with concrete core		Munich	Germany	Europe	(Hafner et al., 2020)
148.	Walden 48	7	22*	2019	R	Timber-concrete		Berlin	Germany	Europe	(Scharabi Architekten, n.d.)
149.	Eisberg	7	22*	2019	R	Timber-concrete-steel		Berlin	Germany	Europe	(Schoof, 2020)
150.	Lynar 38–39 Gemeinschaftswohnen im Wedding	7	24*	2019	R	Timber over concrete (1 st level)		Berlin	Germany	Europe	(SWP, n.d.)
151.	GreenTorino	7	-	2019	R	Timber over concrete (1 st level)		Torino	Italy	Europe	(Knauf Insulation, n.d.)
152.	Valle Wood	7	28*	2019	O	All-timber		Oslo	Norway	Europe	(Oslo tre, n.d.)

Nº	Name	N of floors	Height (m)	Year	Use	Structure**	PGA intensity***	City	Country	Continent	Reference
153.	Trikåfabriken Extension (Styrpinnen 15)	7	28*	2019	O	Timber over existing building		Stockholm	Sweden	Europe	(Tengbom, n.d.-b)
154.	The Green House	7	23*	2019	O	All-timber		London	UK	Europe	(The Green House, 2023; The Green House Exploring Office Sustainability, n.d.; The Green House Office Building / Waugh Thistleton Architects, 2021)
155.	T3 Atlanta	7	26*	2019	O	Timber over concrete (1 st level) with steel bracing		Atlanta	USA	North America	(StructureCraft, n.d.)
156.	Kambri-CLE	7	27*	2019	E	Timber over concrete (1 st level)		Canberra	Australia	Australia	(Miletic, 2020)
157.	Gleis 21	6	19*	2019	R	Timber-concrete over concrete (1 st level)		Vienna	Austria	Europe	(Mayr-Melnhof Holz Holding AG, n.d.)
158.	Seinäjoen Tuohi	6	-	2019	R	Timber over concrete (1 st level)		Seinäjoki	Finland	Europe	(Puuinfo, 2020)
159.	Bjergsted Financial Park	6	-	2019	O	Timber with concrete core		Stavanger	Norway	Europe	(Gerst, n.d.)
160.	SOTO	6	28*	2019	O	Timber over concrete (1 st level)		San Antonio	USA	North America	(Pintos, 2025)
161.	Los Bronces	6	-	2019	R	All-timber		Los Andes	Chile	South America	(Hotel Pérez Caldera En Los Bronces: Construcción Modular En Madera, 2020; Salazar Medina, 2021)
162.	Gillies Hall	6	20*	2019	R	Timber over concrete (1 st level)		Frankston	Australia	Australia	(Saint-Gobain Glass, n.d.)
163.	Pitfield Street	6	18.5	2020	M	Timber over concrete (1 st level)		London	UK	Europe	(Building with Timber: Hoxton Cinema, n.d.; Pitfield Street Behind the Screen at Hoxton Cinema, n.d.; Waugh Thistleton Architects, 2018)
164.	55 Southbank Boulevard	16	69.7	2020	M	Timber-steel over existing building		Melbourne	Australia	Australia	(55 Southbank, 2020; 55 Southbank Boulevard / Bates Smart, 2021; Saunders, 2022)
165.	FLATS WOOD Kiba	12	40.8	2020	R	Timber-concrete and steel		Tokyo	Japan	Asia	(FLATS WOODS KIBA, n.d.-a; Hanai et al., 2020; Takenaka Corporation, 2020)
166.	Klein Veldekens (Astor)	10	-	2020	R	Timber over concrete (1 st level) with concrete core		Geel	Belgium	Europe	(Osar, n.d.)

Nº	Name	N of floors	Height (m)	Year	Use	Structure**	PGA intensity***	City	Country	Continent	Reference
167.	ÖGK Turm II	9	38	2020	M	Timber and timber-concrete over concrete (1 st level) with concrete core		Salzburg	Austria	Europe	(Stadler, 2023)
168.	Supercell HQ	8	35*	2020	O	Timber over concrete (1 st level) with concrete core		Helsinki	Finland	Europe	(Puuinfo, 2021)
169.	Jack London Square – Site F2	8	26*	2020	M	Timber-steel over concrete (3 levels)		Oakland	USA	North America	(Channel House, n.d.; Channel House, 2023; Jack London Square Parcel F2, n.d.)
170.	HOLZSTUDENT SIEBEN— Ellener Hof	7	21*	2020	R	Timber over concrete (1 st level) with concrete core		Bremen	Germany	Europe	(Atelier PK Architekten, n.d.)
171.	WA 16 West Holzbausiedlung Prinz-Eugen-Park	7	24*	2020	R	Timber and timber-concrete over concrete (1 st level) with concrete core		Munich	Germany	Europe	(Hafner et al., 2020)
172.	Kilströmskaj	7	-	2020	R	All-timber		Karlskrona	Sweden	Europe	(KGC, n.d.)
173.	La Trobe University Student Dormitory	7	21*	2020	R	Timber with concrete cores		Melbourne	Australia	Australia	(JCB Architects, n.d.; La Trobe University, n.d.)
174.	6×6 block	6	18*	2020	R	All-timber		Girona	Spain	Europe	(Bosch.Capdeferro, n.d.; Dalmau, 2022)
175.	Kunskapshuset	6	-	2020	E	Timber-concrete-steel		Gällivare	Sweden	Europe	(Swedish Wood, n.d.; Tengbom, n.d.-a)
176.	6 Orsman Road (Storey 6)	6	20*	2020	O	Timber-steel		London	UK	Europe	(Binderholz GmbH, n.d.)
177.	Adidas North American Headquarters	6	22*	2020	M	Timber-concrete		Portland	USA	North America	(WoodWorks, n.d.)
178.	District Office	6	26*	2020	O	All-timber with steel connections		Portland	USA	North America	(WoodWorks, 2021b)
179.	The Canyons	6	20	2020	R	Timber over concrete (1 st level)		Portland	USA	North America	(KAISER+PATH, n.d.-b)
180.	Sara Kulturhus	20	75	2021	M	Timber and timber-steel		Skellefteå	Sweden	Europe	(Sara Cultural Centre, Skellefteå, n.d.; Sara Kulturhus Center / White Arkitekter, 2021; Schmitz, n.d.)
181.	Hypérion	16	55	2021	M	Timber over 3 concrete floors with concrete core		Bordeaux	France	Europe	(Hyperion, Bordeaux, 2020; Hypérion Wooden Tower, n.d.)
182.	Proud Kanda Surugadai	14	48*	2021	R	Timber-concrete		Tokyo	Japan	Asia	(Shizume, 2020; Ward, 2020)

Nº	Name	N of floors	Height (m)	Year	Use	Structure**	PGA intensity***	City	Country	Continent	Reference
183.	HOAS Tuuliniitty	13	42	2021	R	Timber over concrete (1 st level)		Espoo	Finland	Europe	(Tulonen et al., 2021)
184.	Stories	12	45	2021	R	Timber over concrete (2 levels)		Amsterdam	Netherlands	Europe	(Platowood, n.d.)
185.	Tallwood I	12	38*	2021	R	Timber with steel bracing over concrete (1 st level)		Langford	Canada	North America	(ASPECT Structural Engineers, n.d.)
186.	Malahat Skywalk	10	40	2021	S	Timber-steel		Malahat	Canada	North America	(CBC News, 2020)
187.	CNESST Head Office	8	42*	2021	O	Timber-steel		Quebec	Canada	North America	(LemayMichaud, n.d.)
188.	Althea	7	-	2021	R	Timber over concrete (1 st level)		Velizy	France	Europe	(CALQ, n.d.)
189.	Magasin X	7	30	2021	O	All-timber		Uppsala	Sweden	Europe	(Magasin X, 2022; Tväråna, n.d.)
190.	Ascent	25	86.6	2022	M	Timber over 6 concrete floors with concrete core		Milwaukee	USA	North America	(ASCENT, 2023; "The World's Tallest Mass Timber Tower: A Behind the Scenes Look at Ascent," 2022; Barera, 2022; Carlson, 2022; Post M., n.d.)
191.	HAUT	21	73	2022	R	Timber-concrete with concrete core		Amsterdam	Netherlands	Europe	(Arup, 2023)
192.	Port Plus	11	44	2022	O	All-timber		Yokohama	Japan	Asia	(Japan's First All-Timber Fire-Resistant High-Rise Building Construction Technologies, 2021; Takahashi & Hatsumi, 2023)
193.	Cirrus	7	25*	2022	R	Timber over concrete (2 levels)		Denver	USA	North America	(Kendall, 2021)
194.	INTRO	9	35	2022	M	Timber-concrete over concrete (1 st level)		Cleveland	USA	North America	(INTRO Cleveland, 2023; INTRO, Cleveland USA, 2022; Mitchell, 2022)
195.	Cirerers	8	26.5	2022	R	Timber over concrete (1 st level)		Barcelona	Spain	Europe	(Dlupal, 2022)
196.	T3 Sterling Road Development #2	8	40	2022	O	Timber-steel		Toronto	Canada	North America	(HASSLACHER, n.d.; WoodWorks, 2025)
197.	Nanyang Technological University's Academic Building South	6	30.4	2022	E	All-timber with concrete emergency staircases		Singapore	Singapore	Asia	(Academic Building South in Nanyang Technological University, 2022; Case Study: Nanyang Technological

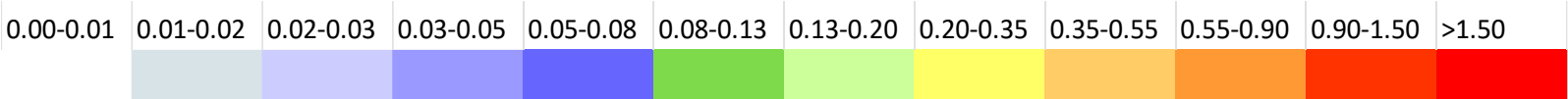
N°	Name	N of floors	Height (m)	Year	Use	Structure**	PGA intensity***	City	Country	Continent	Reference
											University's Academic Building South, Singapore, 2023; Gaia, NTU Academic Building South, Singapore, n.d.; NTU ABS/ Nanyang Technological University, 2022; NTU Building South – Gaia, 2023)
198.	Black & White Building	6	17.8	2022	O	All-timber		London	UK	Europe	(The Black & White Building 21st Century Timber, n.d.; Waugh Thistleton Architects, n.d.-b; Williams, 2023)
199.	Le Tour de Berlier	15	50	2023	R	Timber over concrete (1 st level)		Paris	France	Europe	(Editorial Arquitectura Viva SL, 2025; Schoof, 2024)

R-Residential, O-Office, M-Mixed uses, E-Educational, S-Structure, H-Hospital

* Google Earth.

** All-timber: Both the main vertical/lateral structural elements and the floor spanning systems above the ground are made of timber; it may include the use of localized non-timber connections between timber elements as well as concrete/steel elements that are not acting as the primary structure

*** Peak ground acceleration (PGA) (g)



5.1. Analysis of modern high-rise timber buildings

The dispersal of mass timber buildings around the world has been growing steadily, with increased interest and adoption in various regions. After analysis of the set of the 199 cases, it is observed that the great majority of tall and high-rise timber buildings, as much as almost three quarters, is located on Europe, followed by North America (16%), Australia (6%) and Asia (4%). European countries have been pioneers in mass timber construction, but since 2019, countries in Asia have been further exploiting the use of wood in architectural projects, while the United States and Canada have been presenting progressively new timber structures over the last 10 years, with the exception of years 2015 and 2023, as shown in Figure 13. There were no examples registered in Africa and only one case in South America so far. Although there were no widely reported high-rise mass timber buildings in Latin America, mass timber construction is gaining popularity due to its sustainability, aesthetics, and structural performance. That has resulted in the construction of South America's first certified CLT manufacturing plant in Uruguay and 40 Mass Timber building projects are expected to be built in Uruguay between 2024 and 2025 (Lyonnet, 2022; *Uruguay Will Have the Tallest Wooden Building in Latin America*, 2023).

When it comes to the number of cases per country, the significant lead is taken by Sweden, with 12% (24 buildings), followed by Great Britain and France, 10% (19), United States of America with 9% (17), Germany with 8% (16), and Switzerland and Canada (15 each). The percentage distribution of the buildings across the continents and per country is presented in Figure 14.

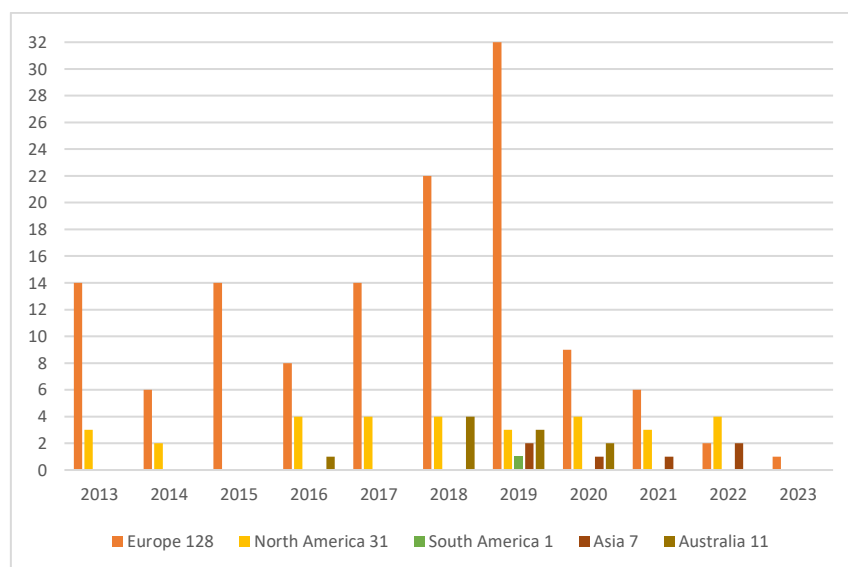


Figure 13. Number of completed timber buildings per continents during the last 10 years

In Europe, the leading countries are Sweden, Great Britain and France. However, these differ from those ranking highest in the study by Svatoš-Ražnjević et al. (2022), which examined timber buildings with three or more storeys. In that study, Germany recorded the highest number of cases (47), followed by Switzerland (41) and Austria and Great Britain (37 each). A comparison between buildings with three or more storeys and those with six or more storeys reveals significant differences. Germany shows a decrease of 31 cases (from 47 to 16), Switzerland 26 (from 41 to 15), Austria 28 (from 37 to 9), and Great Britain 18 (from 37 to 19). Considering the historical and cultural context, these results suggest

that smaller-scale timber buildings are considerably more prevalent in Germany, Switzerland and Austria. Although these countries are not far in the classification made in this analysis, in recent years, the tall and high-rise wooden buildings were more prevalent in Sweden and France and Great Britain builds equally timber buildings with three or more stories and with six or more stories.

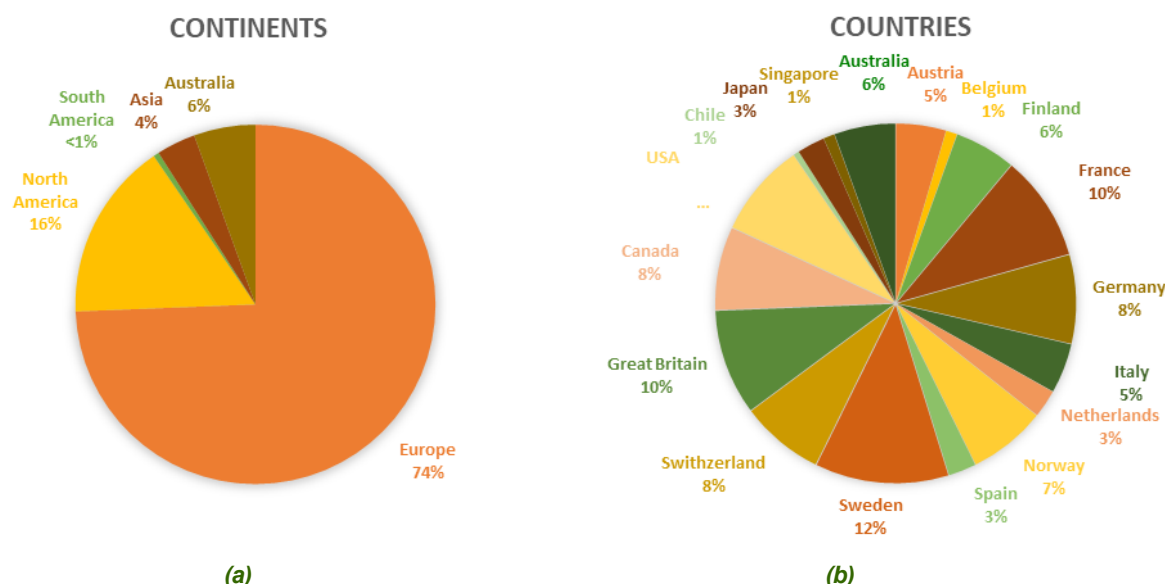


Figure 14. (a) Percentage of tall and high-rise timber buildings per continent; (b) Percentage of tall and high-rise timber buildings per country

Analysing the spatial diffusion of mass timber buildings involves considering various factors that influence their placement within urban or rural environments, such as economic, environmental and regulatory remarks, market demand, other regional factors, construction practices, the availability of materials, capacity of production, historical context and the existence of tradition to build with timber. Such a large discrepancy in the number of cases between Europe and the rest of the continents may derive from significant differences in the aspects mentioned above.

Based on the previous sections, it is concluded that Europe has many countries with a rich history of building with timber and with extensive mature forest areas. European countries, including those in Scandinavia, have a history of efficient sustainable forest management (Paletto et al., 2008). Timber availability is generally good and responsible forestry practices contribute to long-term resource sustainability (Green & Eric Karsh, 2012; Woodard & Milner, 2016). Alike European countries, the United States and Canada have extensive forest resources and well-established timber industries with generally ample wood supply for mass timber construction. The Asia-Pacific region, including countries like Russia, China and Australia, has diverse timber sources. However, sustainable forestry practices may vary and some areas may face challenges related to deforestation and illegal logging. Similar situations may occur in the regions of South America and Africa.

Additionally, Europe's strong focus on sustainability and stringent environmental standards has contributed to the popularity of mass timber as a building material alternative to high-energy consuming concrete and steel. Climate change issues have been strongly confronted by the European Union, fuelling the innovations in bioengineering industry. Growing awareness of environmental issues and a

preference for sustainable construction practices drive demand for materials with strong renewable credentials, making high-rise timber buildings attractive.

Looking at the much larger numbers of examples completed in Europe, until now, European codes seem to be more supportive when it comes to building with mass timber systems. These robust regulatory frameworks support low-carbon construction, energy efficiency and the use of renewable resources (Galloway, 2014). Additionally, the regulatory provision, government policies and market incentives encourage architects and developers to choose wood as a primary construction material and, whether directly or indirectly, promote tall wood and mass timber construction (Bowyer et al., 2015; Green & Eric Karsh, 2012). However, with North American standards changing toward taller timber building provisions, it will not take a long time before even more mass timber structures appear in the New World (Dovetail, 2020). As supportive policies and financial incentives from governments can encourage developers to choose high-rise timber construction, the regions that update their codes to accommodate mass timber construction can stimulate market demand for such structures.

Despite the codes not being yet very favourable to build high-rise with timber, the tallest and with the largest floor number mass timber building was completed in Milwaukee, US, in 2022. ASCENT, with a total of 25 floors and 86.6 m, comprises 19 residential levels constructed primarily of mass timber, with support from a six-level concrete podium structure (Figure 15). The building utilizes a framework of glulam beams and columns to support CLT floors and two reinforced concrete cores to provide lateral stability (ASCENT, 2023; Arup, 2023). To obtain the approval from the authorities and to comply with the building code requirements, extensive research, analysis and testing were performed. The second tallest building in terms of height is Mjøstårnet, with only 18 floors (6th in the classification by floor number) but, being 85.4 meters high, it holds the title of the tallest timber building in Europe and it only lost its title of the tallest timber building worldwide in 2022 with the completion of ASCENT. The second with the highest number of floors example was completed in 2019 in Vienna, Austria. HoHo Wien, one level away from its competitor across the Atlantic, displaying 24 floors. The structure uses four forms of highly prefabricated, serial building elements: studs, joist, ceiling panels and solid wood facade elements. Columns and the supporting core structure secure the wood-concrete composite floors. Notwithstanding the advantages of hybrid wood construction, timber constitutes approximately 75% of the building, starting from the ground floor upward (Rüdiger Lainer + Partner Architekten, 2022; Urban Lakeside Development Aspern, 2022). These three structures are the only ones surpassing the height of 80 meters.

In total, only five mass timber buildings with twenty or more floors were identified. The next two are located in the Netherlands. Classified as 3rd in terms of number of floors and 6th in terms of height, De Karel Doorman, the residential extension on existing six-story shopping building, completed already in 2012, demonstrates the advantages of lightweight properties of timber structures. The addition of 16 new levels was possible due to the use of wooden floors in combination with a steel frame. The structure represents both a noteworthy renovation and new development (*De Karel Doorman*, 2022; *De Karel Doorman Rotterdam*, n.d.). The 21-story timber-hybrid HAUT is another example of sustainable and high-quality architecture. The use of lightweight prefabricated extremely facilitated the construction delivery in the busy centre of Amsterdam. HAUT, with its design principle “timber where possible, concrete and steel when necessary” is currently certified with BREEAM-NL Outstanding acknowledgement and is the first

high-rise residential building to receive such award in the Netherlands (Arup, 2023).



Figure 15. The three timber buildings with the highest number of floors: (a) Ascent (Barera, 2022); (b) HoHo Wien (Migl, 2020); (c) De Karel Doorman (Romero, 2016)

The increased use of timber in the construction industry brings many advantages. Its efficiency, seen in off-site prefabrication, reduces construction time and costs. Lightweight and thermally insulating, it contributes to energy savings. With an appealing aesthetic and flexibility, mass timber suits various designs and locations. Its carbon sequestration, low embodied energy and reduced waste enhance sustainability. Thus, the use of timber aligns with the world's commitment to reduce carbon emissions and promoting eco-friendly building practices. Nevertheless, timber buildings present some limitations, particularly concerning biological degradation and performance challenges. Timber structures are vulnerable to moisture, which can lead to rot, mould and fungal growth. Also, timber can be susceptible to biological attacks from insects such as termites and wood-boring beetles. In regions where termites are prevalent, they pose a significant threat to timber buildings. Ensuring proper design, construction techniques and protective or maintenance measures to prevent water infiltration or biological attacks is crucial to maintaining the integrity of timber structures. While modern mass timber products have improved fire resistance, timber is still a combustible material. Designing with fire safety in mind is essential for high-rise timber buildings. Another important issue is seismic performance, which involves careful consideration of the building's structural system and connections to ensure it can absorb and dissipate seismic energy effectively. Additionally, timber buildings can face challenges related to sound insulation and transmission. To achieve acceptable acoustic performance, appropriate design strategies and materials must be used to mitigate sound transfer between compartments. Addressing these limitations requires a combination of adequate innovative design, advanced technological solutions and rigorous construction practices. However, in most cases, wood is being utilized alongside concrete and steel, resulting in more resilient and sustainable solutions. New hybrid systems have been developed to guarantee the building performance at the highest level, merging the best that each of the materials can offer.

The lists of the highest ten structures by number of floor and by height in meters are presented in Table 12 and Table 13.

Table 12. The tallest mass timber structures in the world by number of floors

Name	No of floors	Year	City	Country
Ascent	25	2022	Milwaukee	USA
HoHo Wien	24	2019	Vienna	Austria
De Karel Doorman	22	2012	Rotterdam	Netherlands
HAUT	21	2022	Amsterdam	Netherlands
Sara Kulturhus	20	2021	Skellefteå	Sweden
Mjøstårnet	18	2019	Brumunddal	Norway
Brock Commons	18	2017	Vancouver	Canada
Hypérion	16	2021	Bordeaux	France
Rundeskogen B	16	2013	Sandnes	Norway
55 Southbank Boulevard	16	2020	Melbourne	Australia

Table 13. The tallest mass timber structures in the world by height in meters

Name	Height (m)	Year	City	Country
Ascent	86.6	2022	Milwaukee	USA
Mjøstårnet	85.4	2019	Brumunddal	Norway
HoHo Wien	84	2019	Vienna	Austria
Sara Kulturhus	75	2021	Skellefteå	Sweden
HAUT	73	2022	Amsterdam	Netherlands
De Karel Doorman	70	2012	Rotterdam	Netherlands
55 Southbank Boulevard	69.7	2020	Melbourne	Australia
Arbo	60	2022	Risch-Rotkreuz	Switzerland
Eunoia Junior College	56	2019	Singapore	Singapore
Hypérion	55	2021	Bordeaux	France

By analysing the selection of case studies, the buildings with a smaller number of floors are predominant. Slightly more than 80% of the data set consist of the structures with less than ten floors. As much as 61 cases are 6-story constructions, which corresponds to 31%. 7-story and 8-story buildings represent another 25% and 17% consequently. The average height of mass timber structure in this study is eight floors. The distribution of the buildings by the number of floors can be seen in Figure 16.

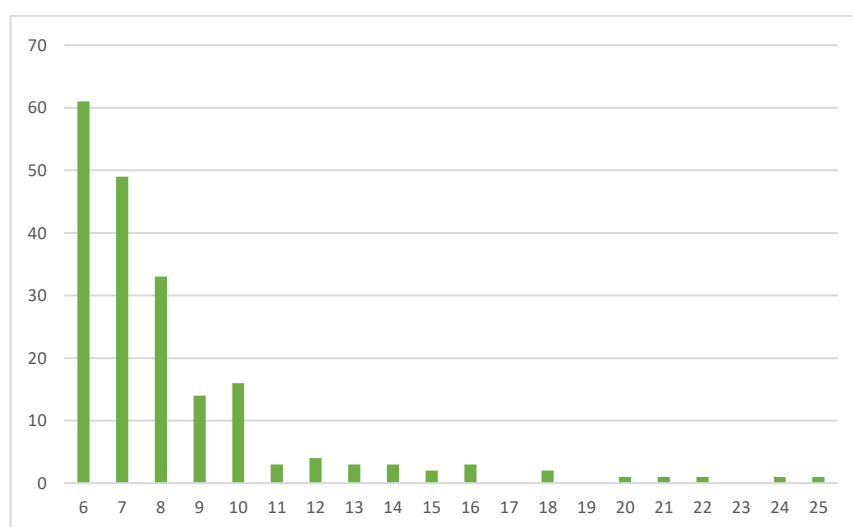


Figure 16. Timber buildings by number of floors

The data presented in Figure 17 depict a fluctuating trend of the completion of mass timber buildings over the years from 2005 to 2023. For the initial three years, only single examples were accomplished annually. A slight increase can be observed in 2008 followed by relative stability until 2012. Subsequently, there's a remarkable surge in 2013, followed by a constant increase over the years 2015-2018, reaching its peak in 2019 with 41 buildings completed. However, this peak is followed by a decline, with values dropping notably in 2020 and 2021, before stabilizing at eight case studies by 2022 and further decreasing to only one building by 2023 so far.

The surge in mass timber buildings in 2019 likely resulted from a combination of factors, including increased awareness, regulatory support, technological advancements, successful demonstration projects and environmental remarks. During the research, many projects under construction were identified, which may influence the results in the following years.

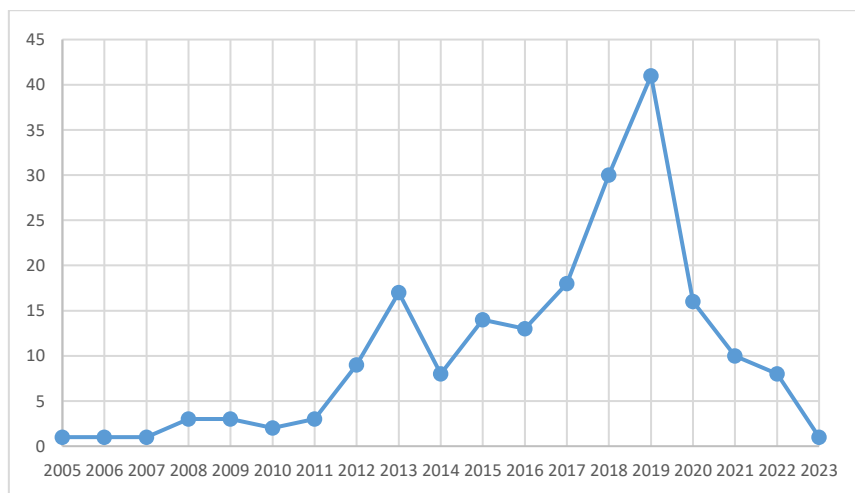


Figure 17. Timber buildings by year of completion

In summary, the 199 selected buildings span five continents, predominantly in Europe (almost three-quarters), followed by North America (16%), Australia (6%) and Asia (4%). Sweden leads with 24 buildings, followed by Great Britain, France, the US, Germany, Switzerland and Canada. Despite fewer high-rise timber buildings, smaller timber structures are popular in Germany, Switzerland and Austria.

Europe's extensive timber history, sustainable forestry practices and stringent environmental standards contribute to the region's dominance in mass timber construction. The US and Canada, with their vast forest resources and established timber industries, are also significant players. Asia-Pacific faces challenges like deforestation, impacting sustainable timber use. Europe's supportive regulatory frameworks and sustainability focus have spurred mass timber adoption. Despite the impressive 25-storey height of the ASCENT building in Milwaukee, only a very small number of timber buildings worldwide exceed 20 storeys. This highlights the predominance of smaller structures, with approximately 80% comprising fewer than ten floors. The completion rate of mass timber buildings shows a fluctuating trend from 2005 to 2023, peaking in 2019 with 41 buildings. This surge is attributed to increased awareness, regulatory support and technological advancements.

6. Building design, process and performance

The successful delivery of high-rise mass timber buildings demands a holistic approach that integrates architectural vision, engineering precision and performance-driven strategies. As timber gains momentum as a structural material for tall buildings, the complexity of design and construction increases, requiring a high level of coordination across disciplines.

This chapter examines the critical aspects that shape the design and realisation of tall timber structures, focusing on the architectural and construction processes as well as performance domains that are key to building safety, comfort and efficiency. These include fire safety, seismic resilience, thermal efficiency and acoustic comfort. Each of these areas presents specific demands that must be addressed through careful integration of materials, systems and detailing practices.

Regardless of a project's size, complexity, or location, design and detailing play a fundamental role in ensuring the success of the construction process and the long-term performance of the built structure. Accurate and comprehensive project planning can contribute to reduced labour costs, faster delivery times, minimised material waste and enhanced construction quality. However, these outcomes are highly dependent on the depth and clarity of the design details developed during the architectural and structural design phases, as well as on their effective coordination and communication among all project stakeholders.

By examining both the design process and building performance requirements, this chapter aims to outline best practices and highlight the critical interdependencies necessary to support the realisation of resilient, efficient and sustainable high-rise mass timber buildings.

6.1. Building design

The design and construction of high-rise mass timber buildings requires a comprehensive, integrated approach that unites architectural creativity, engineering precision and logistical coordination across all phases of the project lifecycle. From initial concept to handover, the building process is shaped by timber's unique material characteristics and the specific technical and regulatory demands of tall wood structures.

As illustrated in the construction project life cycle (Figure 18), each phase plays a critical role in shaping project outcomes. During the conceptual and preliminary design phases, feasibility studies, team formation and budget frameworks are established, providing the foundation for informed decision-making. The detailed design phase requires high levels of coordination between architectural, structural and building systems design, especially due to timber's material-specific challenges, such as fire performance, moisture sensitivity and prefabrication constraints. Construction planning then transitions into execution, where effective scheduling, resource management and quality assurance are essential to maintaining project integrity. Finally, the testing, commissioning and handover phase ensures that the finished building meets performance targets and regulatory approvals.

By understanding the interdependencies between design intent and construction strategy, this chapter intends to provide a comprehensive overview of the factors that shape the planning and execution of mass timber buildings at height. It lays the groundwork for the detailed discussions that follow, focusing on architectural design and construction process.

Conceptual Design	Preliminary Design	Detailed Design	Construction	Testing, Commissioning, and Handover
• Identification of need • Feasibility	• General scope of work/basic design • Regulatory approval	• Detail design of the works • Regulatory/authorities' approval	• Mobilization • Execution of works	• Testing • Commissioning
• Identification of project team • Identification of alternatives	• Budget • Schedule	• Contract documents and specifications • Detail plan	• Planning and scheduling • Management of resources/procurement	• Regulatory/authorities' approval • As-built drawings/records
• Financial implications/resources • Time schedule • Development of concept design	• Contract terms and conditions • Value engineering study	• Budget • Estimated cash flow • Tender/bidding	• Monitoring and control • Quality • Inspection	• Technical manuals and documents • Training of user's Personnel • Handover of facility to owner/end user • Move-in plan • Substantial completion

Figure 18. Construction project life cycle (Rumane, 2011)

6.1.1. Architectural design

This section explores the core architectural details, typologies and emerging trends in the design of tall timber buildings. It integrates findings from academic literature (e.g. Ilgin, 2023), global case studies and performance-driven design strategies. The goal is to outline both the current state of practice and critical architectural opportunities and constraints.

6.1.1.1. Design typologies and architectural identity

The architectural identity of high-rise mass timber buildings is defined not only by their structural and environmental performance, but also by a distinct design language rooted in material authenticity, spatial clarity and cultural resonance. Timber offers a warm, tactile and biophilic aesthetic that distinguishes it from conventional construction materials such as steel and concrete (Kremer et al., 2024). Its visible grain, texture and natural variability foster sensory richness and emotional engagement, which is particularly valuable in dense urban environments that often lack material warmth and human scale (Kaufmann et al., 2018; Whyte et al., 2024).

Rather than emulating the visual and spatial expressions of concrete or steel towers, mass timber architecture benefits from embracing timber's natural qualities. Exposed wood surfaces, modular repetition and clear articulation of structure enable the development of a coherent architectural language that reflects the material's physical and expressive properties. This approach draws inspiration from traditional construction methods while avoiding mimicry, allowing for a reinterpretation of tall building typologies that celebrates timber's unique identity.

Cultural acceptance also plays a central role in shaping architectural expression. In regions with a strong tradition of timber construction, such as Scandinavia, Japan, or Central Europe, there is broader public acceptance and expectation for timber to be visibly and meaningfully integrated into design. In contrast, in

contexts where timber is perceived as secondary or outdated, architects may face challenges in redefining its contemporary relevance. Therefore, the articulation of timber in high-rise buildings must balance material expression with local cultural, climatic and regulatory conditions (Ilgin, 2023; Smith & Snow, 2008b).

The formal typologies of mass timber high-rises are also shaped by structural and constructional imperatives, particularly the logic of prefabrication. A comprehensive review of 350 multi-storey timber buildings from 2000 to 2021 by Svatoš-Ražnjević et al. (2022) reveals a strong dominance of rectilinear and orthogonal geometries. The most prevalent plan forms include rectangular and linear bar configurations, often paired with centralized or hybrid structural cores to provide vertical circulation, fire separation and seismic stability (Svatoš-Ražnjević et al., 2022). Courtyard, polygonal and freeform geometries remain uncommon, typically due to limitations in prefabrication and regulatory constraints. Similar conclusions were driven in the study of Salvadori (2021): when design complexity is introduced, it tends to occur through façade articulation, indented volumes and programmatic variation rather than dramatic spatial transformations. Hybrid structural systems that combine timber with concrete or steel offer greater flexibility, allowing for more expressive layouts and enhanced performance criteria in terms of fire, acoustic and seismic safety.

The widespread use of prismatic forms is particularly associated with geometric efficiency, construction speed and economic rationality. It supports straightforward detailing, minimize construction errors and aligns with standard material dimensions, which is essential in off-site manufacturing processes. Additionally, their simple shapes improve internal space utilization, reduce waste and enhance coordination between structural and mechanical systems (Mori et al., 2024).

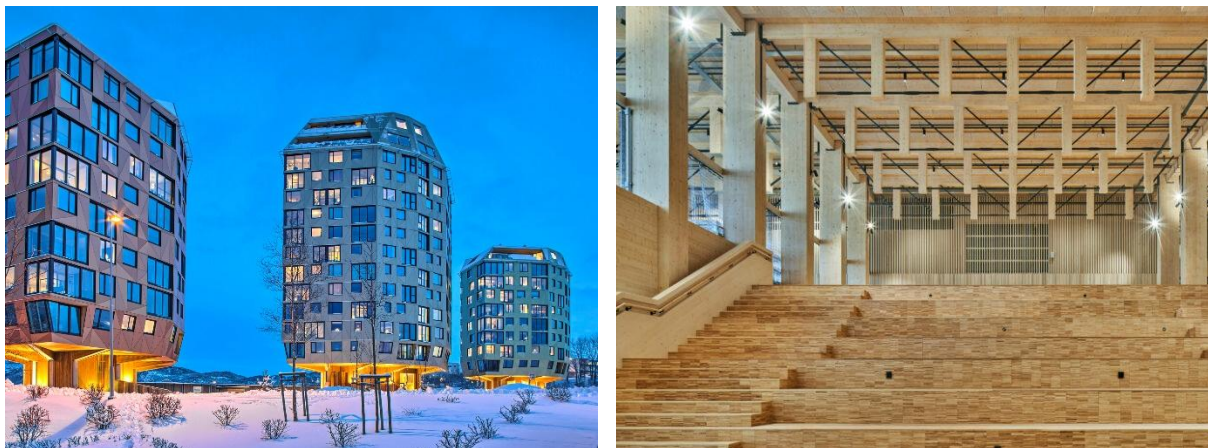


Figure 19. Architectural forms with mass timber, left: Rundeskogen (Rundeskogen / DRMM + Helen & Hard, 2015), right: Sara Kulturhus (Sara Kulturhus Centre / White Arkitekter, 2021)

Nonetheless, architects are increasingly attempting to create impactful forms and spaces that elevate timber beyond its structural role (Figure 19 and Figure 20). However, the architectural potential of timber remains underutilized in many projects, where performance-driven imperatives and regulatory compliance often overshadow spatial and experiential innovation. Moving forward, a key opportunity lies in developing design typologies that more fully explore timber's material expressiveness and cultural meaning, buildings that not only perform well, but also resonate with place, identity and human experience. Architects are thus called to engage with timber not merely as a low-carbon substitute for concrete or steel, but as a primary design driver capable of redefining the architectural language of tall buildings. By doing so, mass timber

architecture can move toward more contextually sensitive, experientially rich and symbolically powerful forms that contribute meaningfully to the evolution of sustainable urban environments.



Figure 20. Building volumes examples (a) Regular, (b) Pitched roof, (c) Varying heights, (d) Irregular (Salvadori, 2021)

6.1.1.2. Building form and core configuration strategies

The architectural and structural configuration of high-rise mass timber buildings is largely influenced by material properties, fire and seismic requirements, prefabrication strategies and spatial performance objectives. Two of the most critical parameters in this context are the building's form and the core configuration, as they directly affect structural stability, architectural expression and construction feasibility.

Building form

Prismatic building forms dominate the design of tall timber structures (Figure 21). According to Mori et al. (2024), 85% of examined high-rise timber offices adopt prismatic shapes due to their geometric simplicity, which facilitates modular construction, structural efficiency and spatial rationalization. These forms typically consist of regular, orthogonal geometries aligned with panelised or modular timber elements such as CLT or glulam. Intrinsically, they are well suited for the integration of repetitive components, ease of prefabrication and standardized detailing. This preference is also reflected in other large-scale surveys, including the study by Svatoš-Ražnjević et al. (2022), which found that 76% of 350 timber projects featured orthogonal massing and 82.8% had symmetrical floor plans.

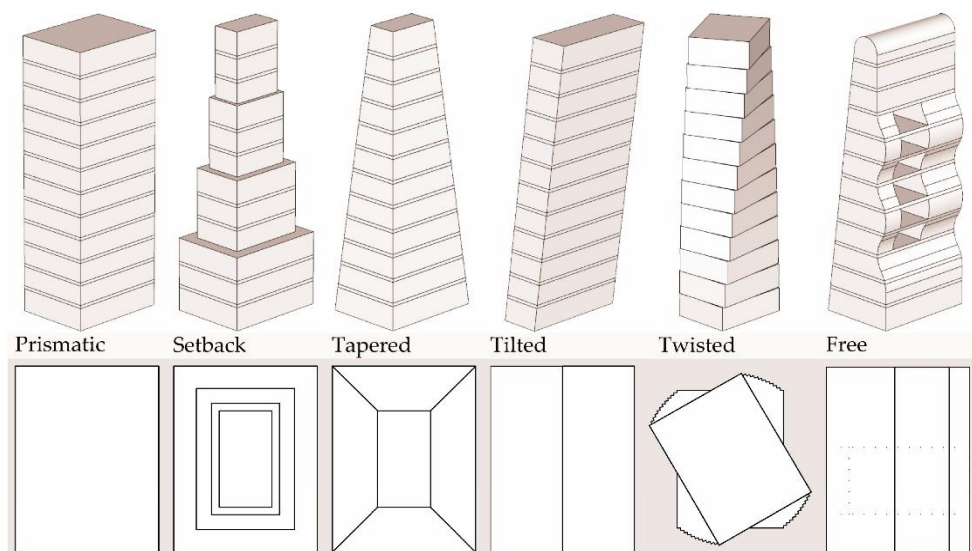


Figure 21. Building forms (Mori et al., 2024)

The prevalence of prismatic forms is not merely a structural necessity but also a strategy for cost-effectiveness and construction speed. Rectangular layouts simplify load distribution and allow efficient use of space by minimizing circulation loss and unnecessary corners. Their compatibility with conventional construction techniques also reduces labour and material costs, improving buildability and reducing on-site errors (Mori et al., 2024).

Despite these advantages, recent trends indicate a growing interest in non-prismatic forms, such as setback, tapered, twisted and free-form geometries. These alternatives offer more architectural diversity and potential for iconic design but are less common due to added complexity in structural design and prefabrication. Such configurations remain limited to pioneering projects with specific architectural goals and advanced technical coordination (Mori et al., 2024; Salvadori, 2021).

Core configuration

The spatial arrangement of vertical circulation and service cores is another defining feature in the design of tall mass timber buildings. Among the 27 high-rise timber offices studied by Mori et al. (2024), 67% employed a central core layout, while peripheral cores accounted for 22%. Central cores offer structural, architectural and fire safety benefits. Structurally, they enhance lateral stiffness and facilitate the concentration of shear resistance elements, which is particularly advantageous in timber buildings where achieving high stiffness can be challenging. Architecturally, a central core facilitates integration of vertical services such as elevators, stairwells, risers and mechanical shafts, reducing the complexity of systems distribution across floorplates. In residential applications, the central core supports symmetrical apartment layouts and centralized access, reinforcing its status as the most efficient and functional configuration in typical tower schemes, freeing the perimeter for open-plan layouts and flexible use of space. This strategy also aids in acoustic separation and fire compartmentalization.

Peripheral and external core arrangements are used less frequently and are typically employed in projects that aim for unique spatial experiences or require alternative layout solutions, such as those with atria, in narrow floorplans or context-constrained sites. Furthermore, atrium or core-less layouts, much less common in high-rise timber typologies, are occasionally employed in buildings emphasizing transparency, daylight access, or spatial fluidity. While they allow for novel spatial layouts and may improve daylight penetration or exterior views, they introduce spatial trade-offs, often reducing net internal floor efficiency and flexibility or complicating structural bracing due to the eccentric placement of lateral load-resisting elements. These configurations are more likely to be found in architecturally expressive buildings, where the form or facade composition demands greater freedom in internal layout (Ilgin, 2023). The graphical representation of the core types and their location within the building structure is represented in Figure 22.

In all core configurations, the material choice for the core remains crucial. Even though all-timber cores exist in various analysed buildings (Magasin X, Black & White Building, Port Plus, Green House), many high-rise timber buildings use hybrid core systems combining concrete or steel with timber. Examples of different core materials can be seen in Figure 23. The choice of material for the core plays a critical role in overall building performance. A concrete core, for example, improves sway control, enhances seismic resistance and provides intrinsic fire protection (Salvadori, 2021). This hybrid approach aligns with the trend toward composite structures observed in tall timber design, where timber-

concrete composites (TCCs) are used to reconcile the lightweight nature of timber with the performance demands of tall buildings (Svatoš-Ražnjević et al., 2022).

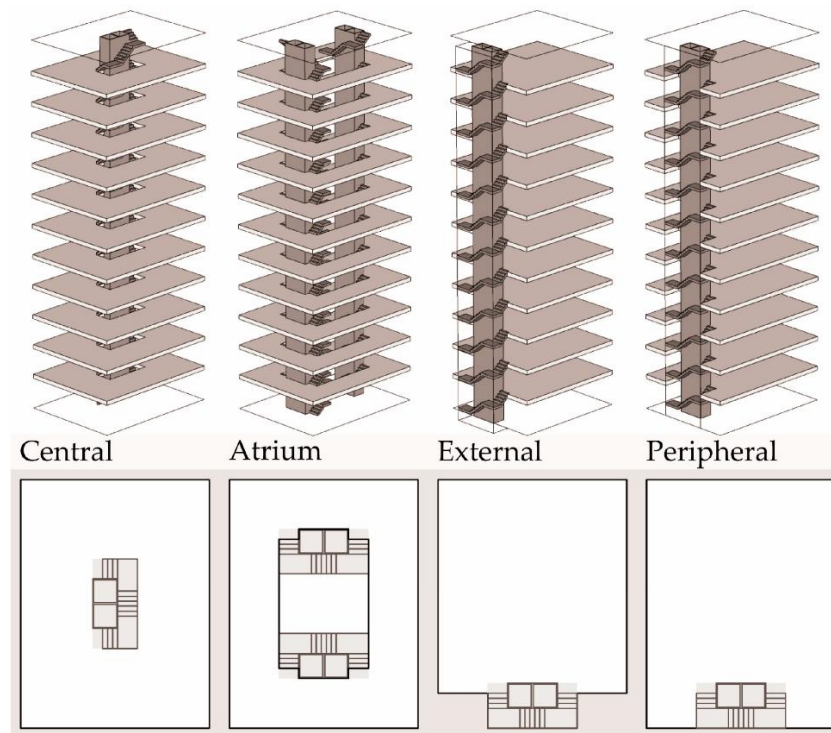


Figure 22. Core types (Mori et al., 2024)

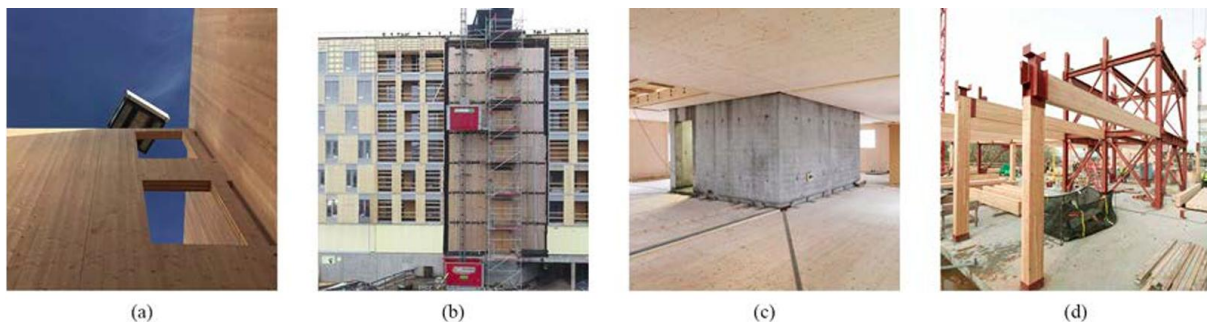


Figure 23. Core examples: (a) CLT, (b) LVL, (c) Concrete, (d) Framed steel (Salvadori, 2021)

6.1.1.3. Façade and envelope issues

The façade and envelope design of high-rise mass timber buildings plays a critical role in balancing architectural expression with thermal performance, weather durability and moisture control. As timber continues to gain prominence as both a structural and aesthetic material, its application in external envelopes must address specific performance-related challenges without compromising design quality or building integrity.

Timber's visual warmth, natural grain and biophilic qualities offer compelling aesthetic advantages that distinguish it from steel and concrete alternatives. These characteristics make it a popular material for visible façade applications, particularly in regions where sustainable architecture is actively promoted. Nevertheless, timber façades may present certain limitations when exposed to harsh environmental conditions or where stringent fire performance requirements apply. Consequently,

concrete or metal spandrels are often employed in highly exposed areas, while timber is reserved for more sheltered zones or used as accent elements, highlighting specific architectural features and contributing to the overall aesthetic composition. Glass is often employed to enhance daylight access, visibility and openness, supporting both passive design goals and user experience (Finch, 2016; Mori et al., 2024).

Detailing challenges

The effective thermal design of mass timber façades is particularly sensitive to detailing. While timber exhibits low thermal conductivity and contributes positively to envelope insulation, its comparatively low density and thermal mass pose limitations in cold climates, where heat retention and buffering capacity are essential (Finch, 2016). More detailed analysis of thermal performance can be found in section 6.4.

Timber, as a façade material, presents three main performance concerns: combustibility, dimensional non-uniformity and moisture sensitivity (Davies et al., 2012). Addressing these requires an integrated approach combining material selection, treatment, protective detailing and strategic façade composition. The analysis by Salvadori (Salvadori, 2021) of MTB envelopes reveals significant regional variation in cladding choices, with no universally dominant material (Figure 24). While timber cladding is more prevalent in some Northern and Central European countries, other regions favour materials such as plaster, brick, or composite panels. This reflects local construction practices, climate remarks and cultural preferences. Importantly, the presence of a timber structure does not necessarily correlate with its visual expression in the façade design. Architects must consider not only species selection and coating systems but also joint detailing, overhangs and façade zoning to manage exposure.

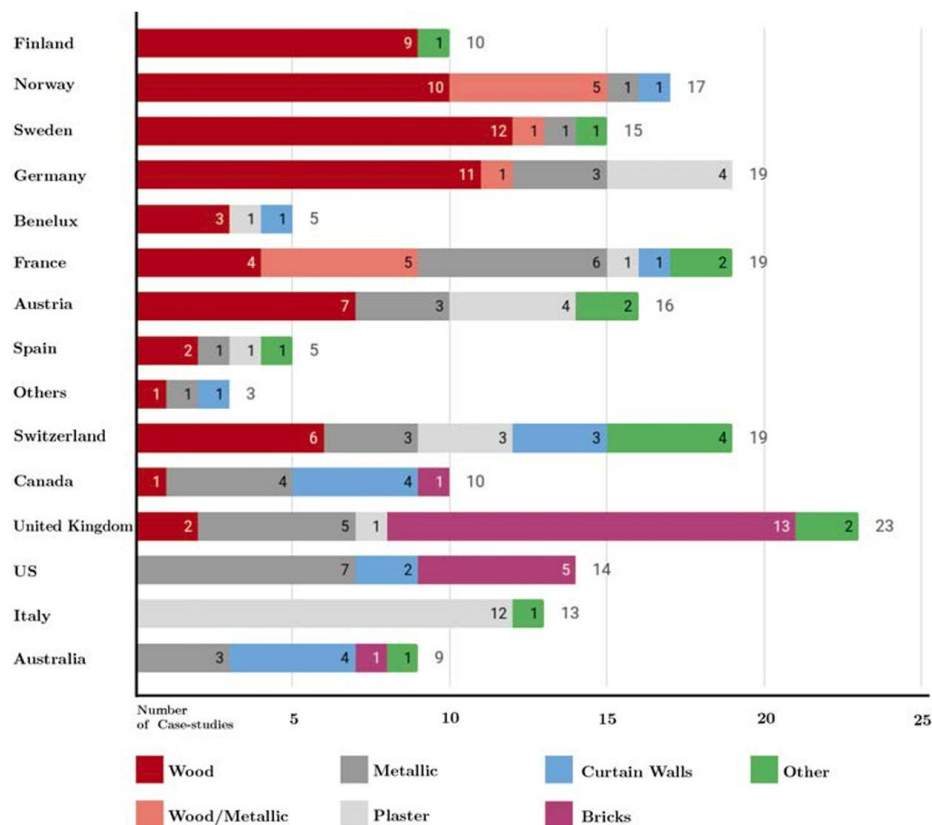


Figure 24. Facade material per country in the buildings analysed by Salvadori (2021)

One common strategy for enhancing weather protection is the use of vertical rainscreen cladding, paired with robust backing structures and moisture-resistant membranes. This system allows for drainage and ventilation, reducing the risk of fungal growth or dimensional instability. Additionally, façade segmentation, where timber is used primarily on recessed or shaded surfaces while more resilient materials are applied to windward or sun-exposed façades, can significantly improve long-term performance without compromising the architectural identity of the building.

Ageing is another important design factor. As timber weathers, its colour, texture and mechanical properties may change, which can affect both aesthetics and integrity. Rather than resisting this natural transformation, some projects embrace a design language that accommodates or celebrates material patina. In other cases, surface treatments such as oils, paints, or thermal modification are employed to slow degradation and maintain a desired visual appearance.

The envelope must also accommodate daylighting and solar control strategies. Timber elements, when integrated with operable glazing and external shading devices such as timber louvres, can enhance indoor environmental quality while reducing overheating risk. Particularly in high-rise applications, where glazed surface ratios are often high, the thoughtful placement of shading structures can improve visual comfort, reduce glare and moderate solar gains. Façade orientation and context-sensitive design, accounting for prevailing winds, sun angles and adjacent structures, further influence the thermal and lighting performance of timber envelopes.

6.1.1.4. Functional layout and spatial planning

The spatial configuration of high-rise mass timber buildings is fundamentally shaped by the structural logic and fabrication constraints of engineered timber systems. Functional layouts, particularly in residential and mixed-use towers, must negotiate between standardized modularity for construction efficiency and architectural flexibility to meet user needs and site-specific conditions.

Unit configurations in residential timber towers often follow regular, orthogonal grids derived from the dimensions and spanning capabilities of engineered timber elements. Studies show that the majority of tall timber buildings use structural grids with repetitive modules, typically ranging from 3 to 5 meters in span, to optimize panel sizes, reduce material waste and support prefabrication workflows (Svatoš-Ražnjević et al., 2022). These span limitations constrain room sizes and influence how spaces such as living rooms, bedrooms and kitchens are organized. As a result, floorplates are often designed with efficient linear or L-shaped unit layouts that align with the structural rhythm, ensuring load paths are maintained and connection points remain accessible. Ordering system classification used by Svatoš-Ražnjević et al. (2022) is presented in Figure 25.

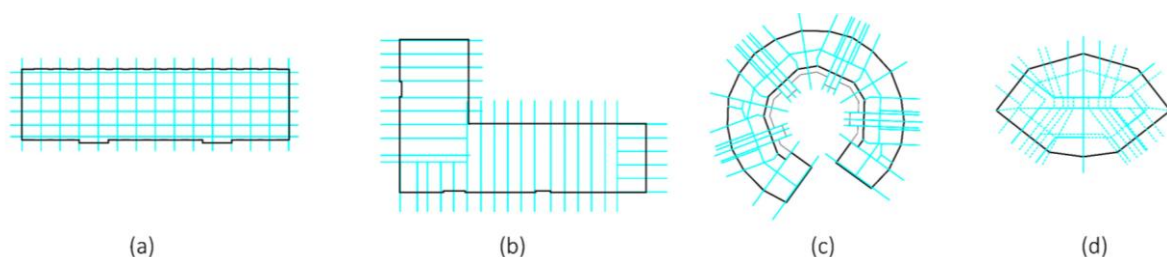


Figure 25. Ordering system classification: (a) grid; (b) grid-based and linear array; (c) linear; (d) irregular (Svatoš-Ražnjević et al., 2022)

The use of MT products for interior partitions is increasingly common, particularly in load-bearing internal walls or where acoustic or fire separation is required. These solid timber elements (mostly CLT and glulam) contribute to the structural stability of the building, reduce reliance on steel or concrete cores and offer improved thermal and acoustic mass. However, the rigidity of these systems limits post-occupancy adaptability, which must be anticipated in the planning phase.

Vertical circulation systems, including stairwells and elevator shafts, are typically centralized to optimize core efficiency and minimize corridor lengths, especially in residential buildings where repeated unit layouts are stacked floor-to-floor. In office or mixed-use towers, the placement of cores may vary, with some projects opting for offset or dual-core solutions to increase flexibility in leasable space or to accommodate atrium-based designs (Ilgin, 2023; Whyte et al., 2024). Shared spaces, such as lobbies, communal lounges, or rooftop amenities benefit from the warm tactile quality of exposed timber surfaces, enhancing the overall user experience and promoting biophilic design principles (Kremer et al., 2024).

Despite the efficiencies gained through systemized modularity, design freedom is often constrained by the performance and fabrication requirements of timber components. For instance, connection detailing, shrinkage behaviour and vibration control influence the allowable room sizes and span configurations. Future advancements in hybrid systems and connection technology may offer greater design flexibility without compromising structural integrity. These technical factors require close collaboration between architects, engineers and manufacturers early in the design process to balance structural efficiency with architectural ambition (Kaufmann et al., 2018; WoodWorks & Think Wood, 2021).

6.1.1.5. Architectural challenges

The architectural design of high-rise mass timber buildings is governed not only by the creative intent but also by complex regulatory frameworks, performance expectations and material-specific limitations. Timber's unique aesthetic, modularity and sustainability credentials position it as a compelling material for future urban development, yet its architectural deployment in tall buildings is marked by several interrelated challenges. These include:

- Fire safety and façade planning (see section Fire performance);
- Acoustics and vibration mitigation (see section Acoustic performance);
- Service integration and detailing constraints;
- Maintaining design intent under regulatory pressure.

Design intent and detailing constraints

Timber structures also impose unique constraints on service integration. Routing ducts, risers and electrical conduits through mass timber elements requires precise coordination due to the limited capacity for onsite modifications. Unlike steel or concrete, where core drilling is standard practice, penetrations in CLT or glulam must be prefabricated or meticulously coordinated to avoid compromising structural or fire performance. These constraints limit post-design flexibility and place a greater burden on architects and engineers to resolve conflicts during the design phase. Moreover, vertical service zones often compete with structural requirements, particularly in narrow floorplates where the core, risers and circulation spaces are condensed. In tall residential towers, this can lead to trade-offs in apartment layout, reduced storage space, or compressed bathroom and kitchen configurations.

Architects must therefore adopt a proactive and collaborative approach, engaging acoustic, fire and structural consultants early in the design process to preserve the project's conceptual integrity while satisfying code compliance.

In this context, digital modelling and building information modelling (BIM) play an essential role in managing coordination and reducing detailing errors. High-quality prefabrication also demands an elevated level of documentation and design resolution early in the process, underscoring the importance of integrated project delivery (IPD) methods for MTBs. As exemplified in recent case studies, successful projects rely on embracing the constraints of timber as generative design parameters rather than obstacles, allowing regulatory and technical demands to inform and enhance the final architectural expression (Ilgin, 2023; Kaufmann et al., 2018). By anticipating these difficulties, architects can develop innovative, efficient and contextually sensitive designs that push the boundaries of contemporary timber construction.

6.1.2. Structural design

The structural design of high-rise mass timber buildings presents a unique set of challenges and opportunities, largely distinct from those associated with low-rise timber structures or conventional high-rise construction using steel or reinforced concrete. Timber's advantageous strength-to-weight ratio, renewability and prefabrication potential have driven its adoption in taller structures, but its application at height demands rigorous engineering strategies to address lateral loads, fire resistance, service integration and long-term durability.

The key structural design aspects must take into consideration the wood and products properties, load systems, serviceability and connections, and include:

- Strength and stiffness;
- Loads paths and lateral stability;
- Connection design;
- Fire, acoustic, thermal engineering.

The following section provides a concise overview of the most prevalent structural systems currently employed in the construction of high-rise timber buildings.

6.1.2.1. Structural systems

High-rise mass timber buildings commonly utilize engineered wood products such as CLT, glulam, LVL and NLT for their primary load-bearing systems. As mentioned in section 2.3.1 about mass timber products, many hybrid solutions emerge in the market to enhance structural, fire, thermal, seismic and thermal performance of these buildings. The integration of diverse building components to create hybrid structures has become a standard practice in contemporary construction. By combining various structural elements, each with distinct material properties, designers can better address the multifaceted performance requirements placed on a building system (Pastori et al., 2022). As these demands become more specific and complex, the feasibility of relying on a single, uniform construction system throughout the entire structure becomes increasingly limited, both in terms of efficiency and cost-effectiveness.

Consequently, traditional classifications of timber construction into panel, frame, or solid wood systems no longer adequately reflect the nuanced and adaptable nature of modern practice. Instead,

the intelligent integration of complementary systems allows for tailored solutions that respond to project-specific needs. This approach not only enhances structural and functional performance but also expands the architect's and engineer's design flexibility, enabling the development of context-sensitive, high-performing buildings (Kaufmann et al., 2018).

The transition from linear to planar behaviour in timber structures marks a fundamental shift in structural performance for high-rise applications. While systems such as dowel laminated timber or log walls function as assemblies of individual rods, primarily bearing loads in one direction, panelised systems achieve multidirectional load-bearing capacity by integrating elements like sheathing or cross lamination. This composite transformation enables the entire assembly to act as a unified plane, greatly enhancing stiffness and load distribution, resulting in a system capable of resisting complex forces. This shift from linear to planar action represented in Figure 26, plays a pivotal role in taller timber buildings, as it ensures structural continuity, greater design flexibility and the capacity to meet advanced performance demands (Kaufmann et al., 2018).

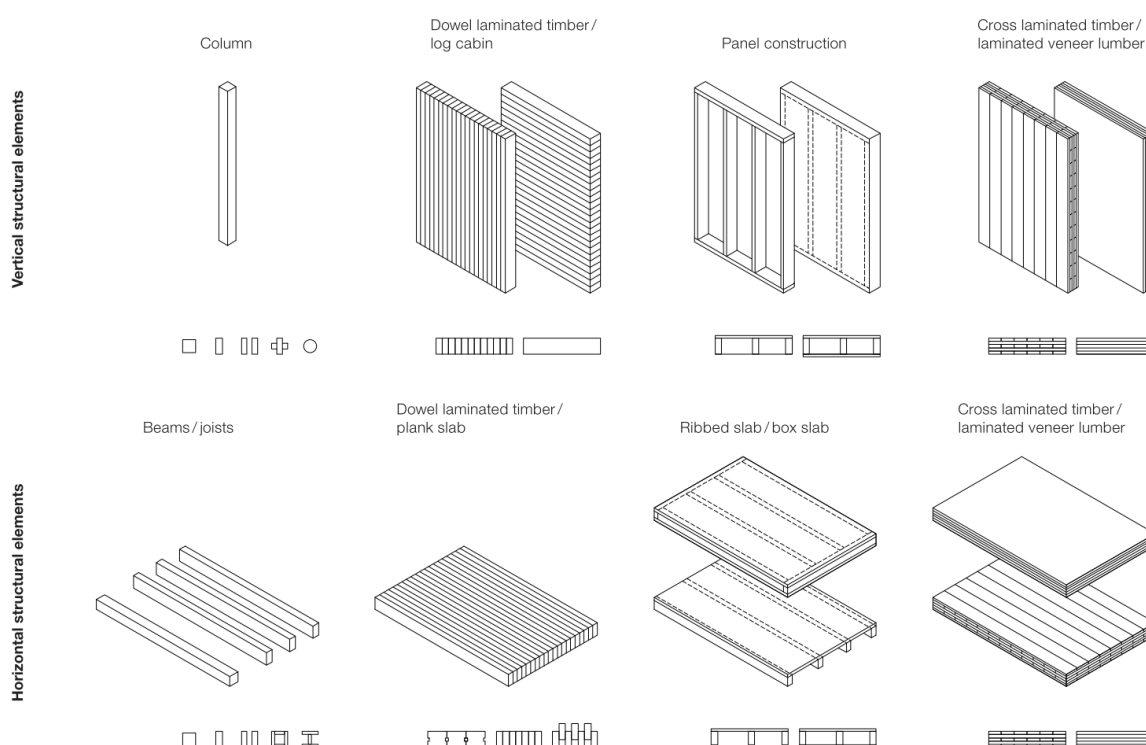


Figure 26. A shift from linear member to plane structural element (Kaufmann et al., 2018)

Thus, structural systems typically fall into several configurations, each of which can be subcategorised according to the material use (all-timber, timber-concrete, timber-steel, timber-concrete-steel) (Hens et al., 2021; Ilgin, 2023; Mori et al., 2024; Salvadori, 2021):

- Platform systems or panelised systems, where engineered timber or hybrid panels serve both as floor diaphragms and shear walls;
- Post-and-beam frames using engineered timber or hybrid columns and beams with lateral resistance provided by the core(s);
- Post-beam-panel systems, with a gravity system that consists of columns and beams and floor plates, and a lateral system that consists of diagonal braces located in the facade in one direction and next to

the core in the other direction;

- Post-and-platform systems, with a gravity system that consists of columns, perimeter beams and floor plates, and a lateral system that consists of the core;
- 3D modules, fully pre-constructed, spatially defined prefabricated volumetric units that typically arrive on-site as completed rooms, already equipped with doors, windows, electrical systems, heating, plumbing and ventilation installations;
- Hybrid systems, which integrate steel or reinforced concrete components (often cores or podiums).

The graphical representation of the structural categorisation used for high-rise mass timber, that facilitated the understanding the differences between each system and nuances related to the existence of hybrid components is presented in Figure 27.

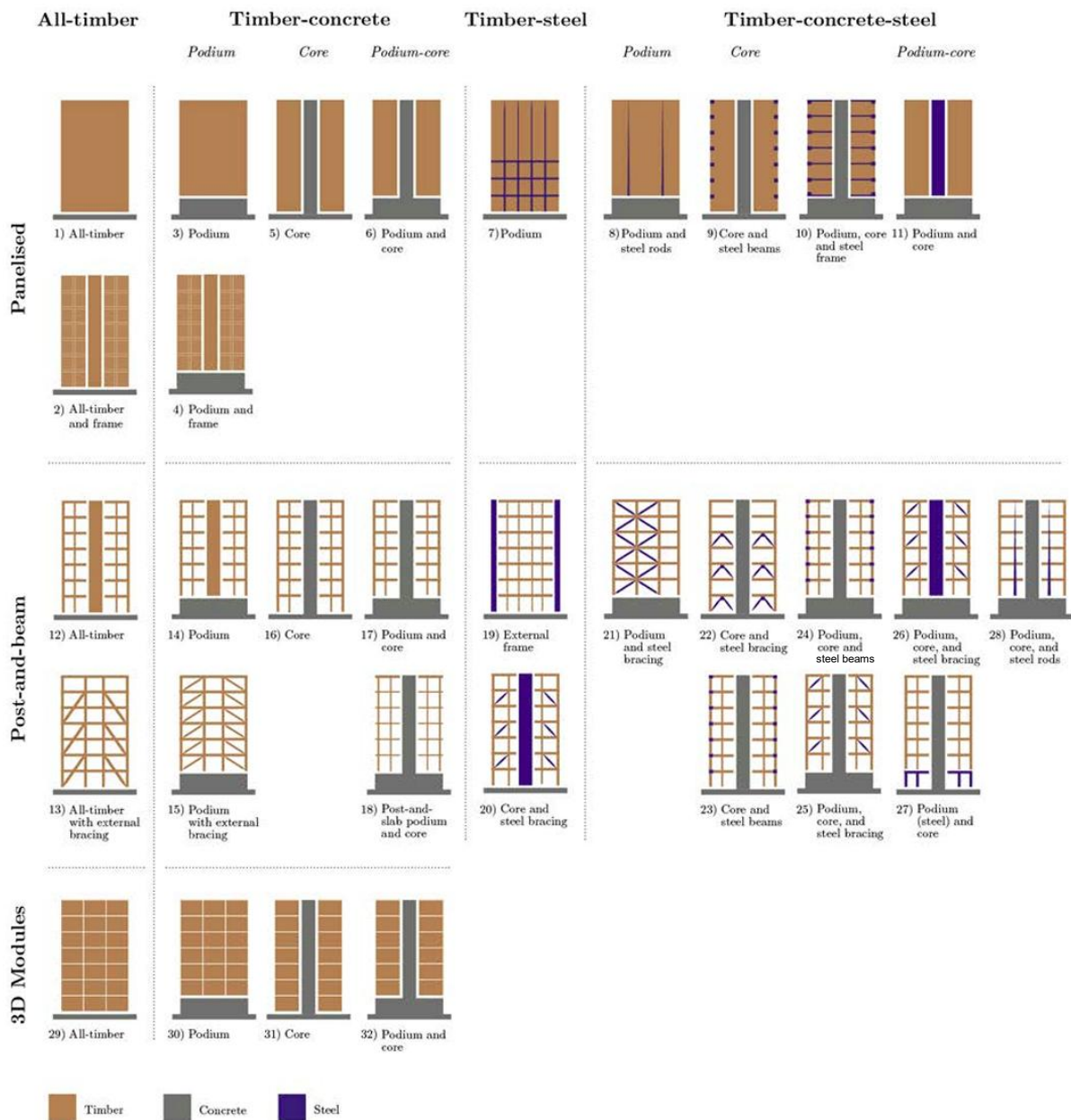


Figure 27. Structural categorisation of high-rise mass timber buildings (Salvadori, 2021)

Panel systems in high-rise timber construction are based on planar structural elements such as

walls and floors and are primarily categorized into light frame, solid wood and engineered wood product systems. These systems allow for a high degree of prefabrication and are typically delivered to the construction site in full-size or partitioned panels for ease of transportation (Swedish Forest Industries Federation, 2022). These walls often serve both structural and enclosure functions, forming honeycomb or party-wall configurations that carry vertical and lateral loads. However, this reduces internal flexibility since many walls cannot be removed. In hybrid configurations, load-bearing capacity is shared with reinforced concrete or steel elements, such as cores or podiums, to meet structural performance requirements (Kaufmann et al., 2018). Three main subtypes of panelised construction are observed. Panelised all-timber systems rely predominantly on CLT or engineered wood products for both walls and slabs, with optional glulam beams and columns to assist with load transfer. Timber-concrete hybrid systems incorporate concrete podiums or cores to support timber superstructures, requiring advanced detailing for connections. Panelised timber-steel systems utilize steel podium frames or columns combined with CLT walls and floors for enhanced rigidity, particularly at lower levels. Across all types, the integration of prefabricated panels facilitates efficient construction and structural regularity, though it requires careful consideration of detailing, especially at the interfaces between different materials. The balance between modularity, structural performance and architectural flexibility defines the viability and evolution of panel systems in mass timber high-rise design (Salvadori, 2021). Example of panelised system on the concrete podium is presented in Figure 28.

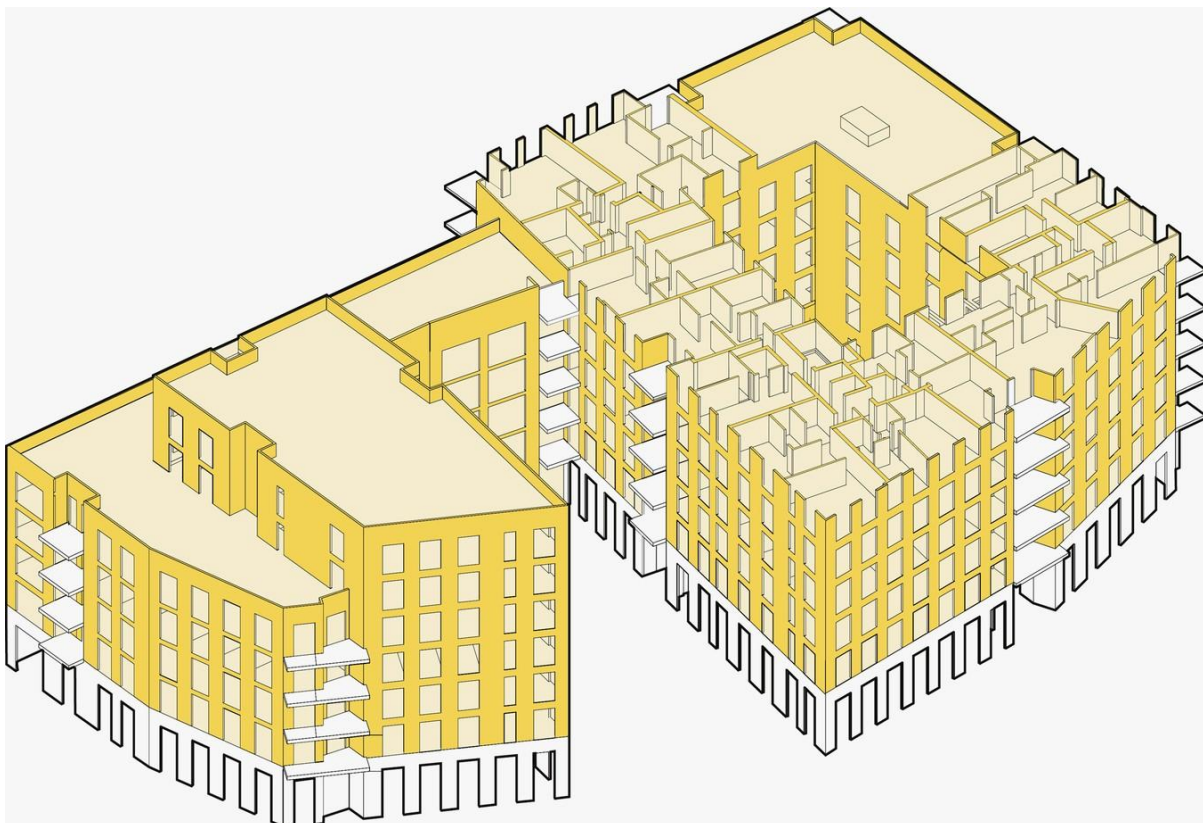


Figure 28. Panelised structural system in Dalston Works (Vaugh Thistleton Architects, n.d.)

Post and beam systems, also referred to as big frame structures are a well-established and versatile solution in timber construction, commonly used for industrial, commercial and increasingly for high-rise

buildings. Characterized by a structural grid of columns and beams, typically with pinned connections, these systems are stabilised through additional elements such as diagonal bracing, shear walls, or central cores (Green & Taggart, 2017). With the advent of engineered wood products like glulam and LVL, post and beam systems have experienced a resurgence due to their ability to accommodate larger spans and heavier loads (Salvadori, 2021). These systems are frequently used in visible load-bearing structures and are often paired with composite timber-concrete floor systems for added structural and acoustic performance.

Post-and-beam systems can be realized in various configurations. In all-timber solutions, stability is achieved either through a stiff frame and core made from engineered wood products or by integrating continuous bracing elements such as diagonal beams. Some designs include steel elements for additional stiffening, although their role is typically secondary. Hybrid systems are increasingly prevalent. In timber-concrete configurations, timber frames may sit atop concrete podiums or be anchored to concrete cores that assume primary lateral load resistance. Floor slabs in such buildings are often constructed from engineered wood products or hybrid timber-concrete systems. Notable examples include buildings like Treet and Mjøstårnet (Figure 29), which are classified as post and beam despite including some concrete components, as per CTBUH standards (Safarik et al., 2022).

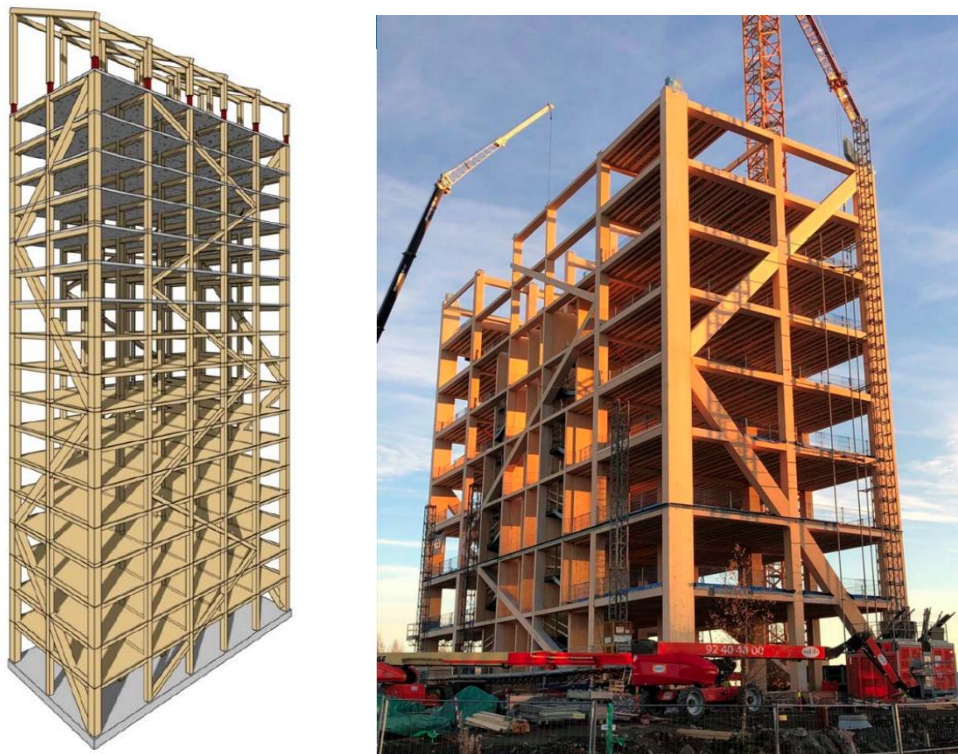


Figure 29. Mjøstårnet trusses, posts-and-beams structure (Abrahamsen, 2017)

More complex hybrids incorporate combinations of timber, concrete and steel. In some buildings, external or internal steel frames provide additional stiffness to the timber superstructure, while others rely on concrete cores with steel bracing or podiums to enhance lateral stability. Floors are typically constructed using CLT or other engineered wood solutions and innovations such as post-and-slab systems, where floor slabs functionally replace beams through specialized load-transferring connections, have also emerged (Hens et al., 2021).

Overall, post-and-beam systems offer design flexibility, clear structural logic and compatibility with prefabrication methods, making them a key structural typology for contemporary high-rise mass timber architecture. Their adaptability allows for a wide range of material combinations, structural strategies and architectural expressions, while meeting performance demands related to height, seismic resilience and fire safety.

Modular systems, also referred to as volumetric or three-dimensional modular construction, represent an increasingly adopted method in mass timber building design. This approach is characterized by the off-site prefabrication of complete volumetric units, that comprise floors, walls, ceilings, interior finishes and integrated building services such as plumbing, electrical wiring, HVAC and glazing. These fully equipped modules are transported to the construction site and assembled into a finished structure with minimal additional work. Due to transport limitations, modular spans are restricted to approximately 4 meters. This type of construction is less common among mass high-rise and building heights generally do not exceed 5 to 8 storeys (Svatoš-Ražnjević et al., 2022).

From a typological standpoint, modular buildings can be categorized as all-timber or hybrid systems. All-timber modular systems consist entirely of prefabricated timber modules, using either light-frame or solid wood construction. These may be used in conjunction with modular or separately erected engineered wood product cores. The example of timber boxes with timber trusses braces and panelised core is Gibraltar Guesthouse in Gothenburg, presented in Figure 30. Hybrid timber–concrete modular buildings incorporate concrete elements in various configurations. In some cases, timber modules are stacked atop concrete podiums or stabilized by concrete cores. Other buildings feature both concrete podiums and cores, offering increased structural stiffness and fire resistance, while still maintaining the benefits of prefabrication and timber's low-carbon footprint. Floor systems in these hybrid approaches may be composed of engineered wood, hybrid timber–concrete composite slabs, or CLT elements.



Figure 30. Gibraltar Guesthouse - Modular timber boxes building in Gothenburg

Despite certain span and height limitations, modular systems offer significant benefits. 3D volumetric modular construction significantly accelerates project schedules, enhances quality through controlled factory conditions, reduces material waste and improves on-site safety. However, it is limited by road-transport size restrictions, constraining architectural flexibility and demands complex logistics coordination and specialized handling (Khan et al., 2023). It also often involves higher upfront capital costs and can face financing and resale uncertainties in secondary markets. Nevertheless, modular volumetric construction represents a promising direction for the future of high-rise timber architecture, particularly in contexts requiring rapid delivery, repetitive layouts and optimized resource efficiency.

6.1.2.2. Load transfer and connections

A continuous load path is fundamental to the structural integrity of any building. In mass timber high-rises, this means that all forces, from gravity, wind and seismic action must flow uninterrupted from the roof and envelope through floors, walls and connections, and finally into the foundation (Zisis & Stathopoulos, 2013). Discontinuities or weak links in this chain can lead to stress concentrations, excessive deflections, or even progressive collapse. In tall timber buildings, both vertical and lateral load paths present unique challenges that demand rigorous experimental validation and numerical modelling to verify performance under service and extreme loads.

There are three main types of forcers acting on the building, the gravitational loads, wind pressure loads and inertial loads caused by seismic activity (Figure 31). To understand how vertical and lateral loads transfer in high-rise mass timber buildings, it is essential to consider the structural elements and systems involved in these processes.

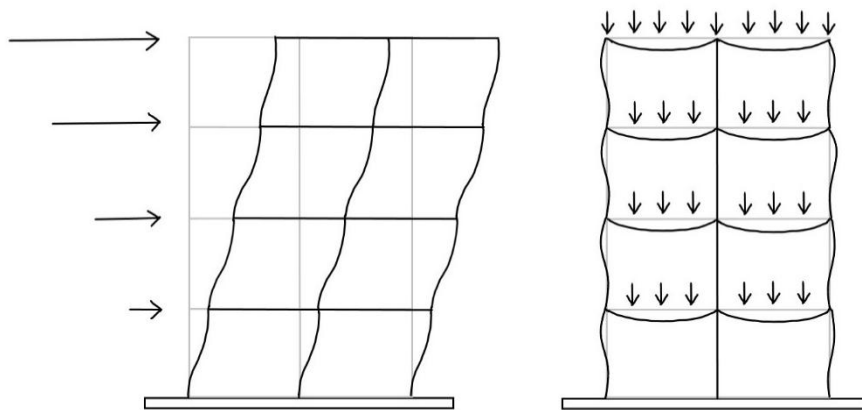


Figure 31. Left- Lateral load scheme, Right- Vertical load scheme (Guerreiro, 2021)

Gravity loads in a high-rise timber building comprise dead loads (self-weight and permanent finishes) and live loads (occupancy and equipment). Floors and vertical elements (columns or shear walls) form the primary gravity load-resisting system. Floors, which account for majority of the material in a typical story (Hens et al., 2021), are usually idealized as simply supported panels due to the difficulty of restraining end rotations in timber members. This simplification, however, underestimates the importance of long-term deformations and creep, since timber's strength-to-stiffness ratio means deflection under sustained load can govern design more than immediate bending capacity (Guerreiro, 2021).

Given the repetitiveness of floor panels in tall buildings, factory-prefabricated solutions are preferred. Structural box slabs and ribbed CLT or glued-laminated timber panels, customized to integrate non-structural elements such as insulation, services and finishes, offer rapid on-site assembly and tight quality control.

Vertical loads are transferred from upper floors into columns and walls, which accumulate greater forces at lower levels due to stacking of stories. Jockwer et al. (2018) demonstrate that design must account for incremental increases in permanent load during erection, ensuring that compression checks reflect the worst-case loading at each level. The examples of vertical load transfers are presented in Figures 32, 33 and 34. (panelised, post-and-beam and 3D modular systems respectively).

Panelised structural systems, commonly employed in high-rise mass timber buildings, rely on planar load-bearing elements such as CLT or LVL for walls and floors. These systems are particularly suited to modular designs due to their high prefabrication potential, allowing for efficient and clean on-site assembly. Connections typically involve self-tapping screws, metal plates and angle brackets, often prefabricated with embedded inserts to ensure speed and accuracy. However, one critical challenge lies in the detailing of load transfer connections between floor slabs and wall panels, which must accommodate structural loads and mitigate the effects of timber shrinkage (Salvadori, 2021). For instance, in projects like Stadthaus (Stadthaus, 2020) and Cenni di Cambiamento (Cenni Di Cambiamento, 2020), socket connections and metal plates with dowels were used, respectively, while in taller structures like Dalston Lane (Ravenscroft, 2017), concrete grout was applied to mitigate the risk of increased shrinkage and to ensure the direct transfer of vertical loads through the grout into the vertical panel. These examples highlight the importance of carefully engineered floor-to-wall interfaces, not only for structural continuity but also to address issues of acoustic insulation, airtightness and moisture protection.

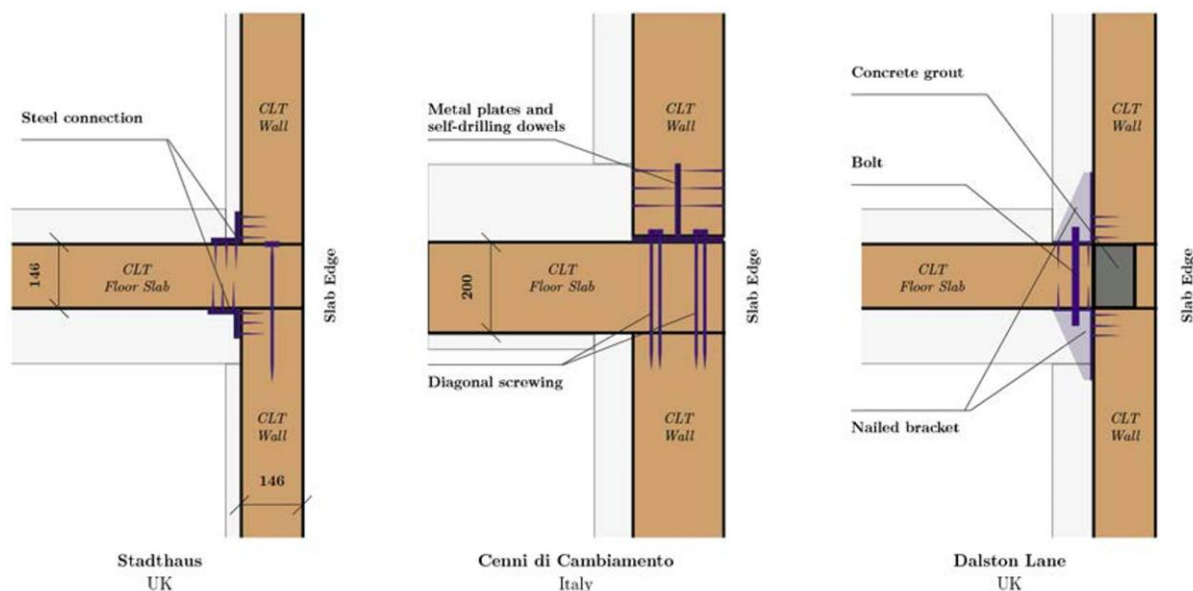


Figure 32. Vertical load transfer in panelised systems (Salvadori, 2021)

In post and beam high-rise mass timber systems, vertical load transfer between columns and floor elements is achieved through a range of engineered connection strategies, often tailored to

accommodate the specific structural configuration and assembly sequence. Common solutions include steel knife plates (Life Cycle Tower and UBC Brock Commons), dowel or bolted joints and integrated edge beams (Skaio), either of concrete or steel, which support floor slabs and connect successive columns (Figure 33). These connections are designed to ensure precise alignment, structural continuity and ease of installation, while often incorporating non-shrink grout to enhance load-bearing contact. Despite their advantages in enabling long spans and open-plan layouts, these systems demand particular attention to fire protection of exposed elements, vibration control and the detailing of lateral stability systems, such as bracing or cores (Salvadori, 2021). The diversity in connection approaches reflects the adaptability of post and beam systems but also underscores the need for thorough coordination, added attention during the design and the production of the element and high construction tolerances.

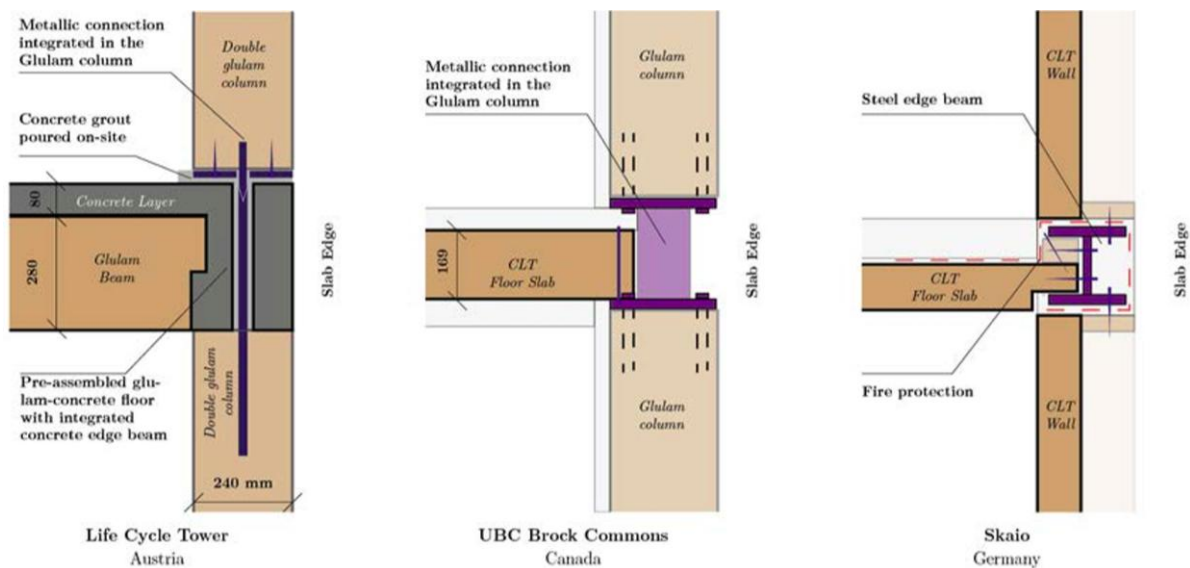


Figure 33. Vertical load transfer in post-and-beam systems (Salvadori, 2021)

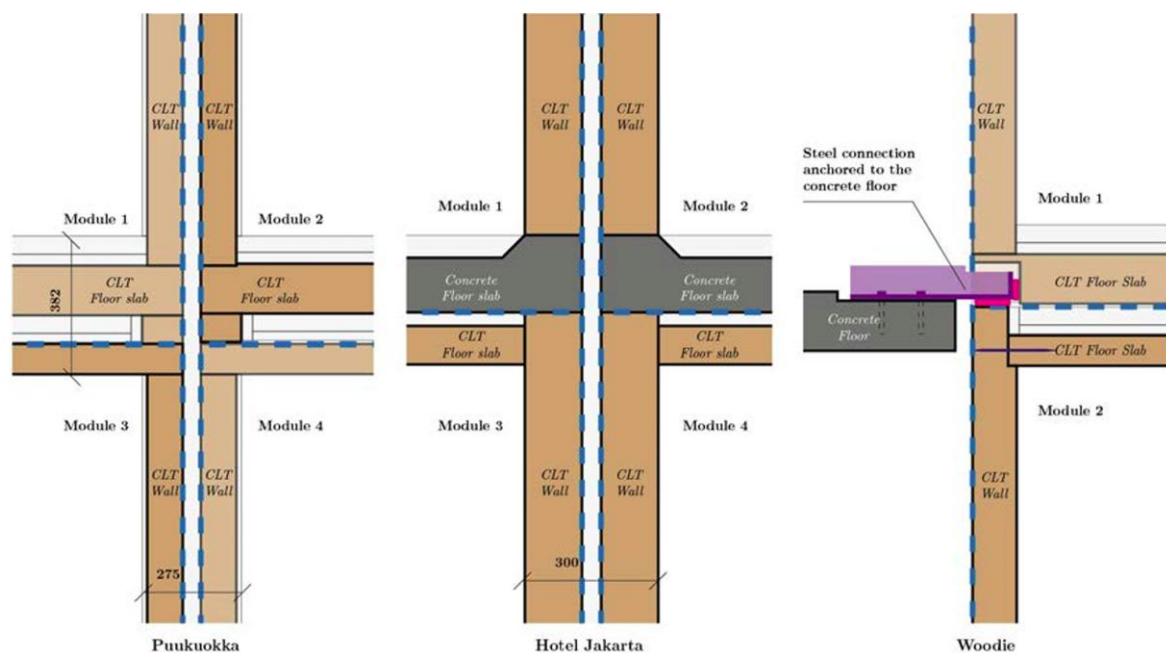


Figure 34. Vertical load transfer in 3D modules systems (Salvadori, 2021)

Three-dimensional modular systems in high-rise mass timber buildings share similarities with panelised systems due to their assembly from planar surfaces such as walls, floors and ceilings. These modules, whether all-timber or hybrid are prefabricated as volumetric units and stacked on-site, typically aligned and connected through engineered interfaces along the base and top edges. Common solutions include integrated timber or concrete base plates that rest on the modules below, with connection gaps used for acoustic and thermal insulation. Steel connectors and anchoring systems are often employed to ensure alignment and structural continuity between modules and with surrounding cores or corridors (Salvadori, 2021). While offering rapid construction and factory-level quality, these systems require precise detailing to address insulation, vibration control and differential material behaviour.

Wind and seismic actions introduce primarily horizontal forces but also impose vertical components that can exacerbate uplift (Guerreiro, 2021). Conceptually, a tall building behaves like a cantilever: lateral loads induce overturning moments resisted by the lateral system and balanced by foundation reactions. Compared with low-rise structures, high-rise timber faces amplified drift and dynamic response concerns under wind gusts or earthquakes.

Depending on structural and architectural objectives, three principal lateral-load-resisting systems might be employed:

- Braced frames (Figure 35-a): Timber or hybrid frames with diagonal members that channel lateral forces into axial action. Braced frames can be lighter than shear walls but require careful detailing at connections to avoid buckling of braces (Kaufmann et al., 2018);
- Shear walls (Figure 35-b): Typically, CLT panels or framed timber walls that carry in-plane shear. Short shear walls resist overturning with deep anchorage or tie-down systems. Incorporating structural fuses or energy-dissipating connectors into shear walls enhances seismic performance by localizing damage (Zisis & Stathopoulos, 2013);
- Moment-resisting frames (Figure 35-c): Glulam beam-column connections designed for rotational stiffness offer architectural flexibility and resilience. The main challenge lies in achieving semi-rigid joints with predictable deformation characteristics, a topic explored by Vilguts et al. (2024), who underline the need for rigorous testing to confirm joint behaviour under cyclic loads.

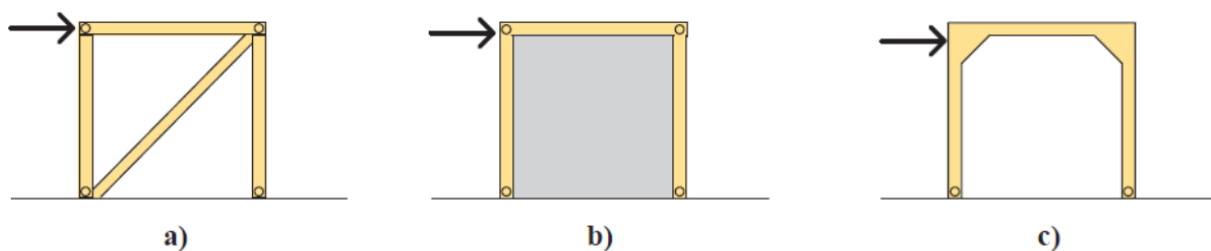


Figure 35. Lateral resisting systems: a) Braced frames; b) Shear walls; c) Moment frames (Guerreiro, 2019)

Regardless of system choice, a lateral system must satisfy three design criteria:

- Strength: All components and their connections must resist maximum expected loads;
- Stiffness: Drift limits under service loads must be met to prevent occupant discomfort and non-structural damage;

- Uplift control: Overturning moments from lateral loads must be countered by sufficient gravity loads or supplemental anchor bolts, hold-downs and tie-down elements, especially critical in seismic regions where vertical accelerations can reduce net gravity preload. More detailed solutions with seismic risk are approached in section 6.6, Seismic performance.

For any load combination, equilibrium requires that foundation reactions exactly balance applied loads. The selected structural elements (floors, walls, columns, braces) link external forces to foundation reactions. Element strength hinges on material properties and cross-sectional geometry, while overall rigidity ensures deflections remain within acceptable limits (Guerreiro, 2021). In timber high-rises, designers must explicitly model creep, shrinkage and connection slip to predict long-term deformations and verify that drift and vibration criteria are upheld.

Connection design is central to a truly integrated structural strategy. Choosing the right connectors goes together with selecting timber products, meeting performance targets and satisfying program constraints. It must align with local construction practices and budgetary realities, because connections ultimately govern load transfer continuity, stiffness, ductility and long-term behaviour (creep and shrinkage) (Näslund & Johnsson, 2014). Thoughtful connection detailing not only ensures structural resilience under gravity, wind and seismic actions but also streamlines prefabrication, transportation and on-site assembly, making it a pivotal driver of both safety and efficiency in tall timber buildings (Green & Taggart, 2017).

Compared to low-rise timber buildings, high-rise mass timber structures demand more rigorous consideration of cumulative vertical loading, creep, differential shrinkage and vibration control. Efficient load transfer is fundamental to ensuring structural integrity and safety. The uninterrupted flow of forces from the building envelope through the structural frame to the ground is essential for resilience. Achieving this requires cautious coordination of structural systems, precise alignment of prefabricated components and adequate connections at all joints. Recent advancements in hybrid timber-concrete floor systems and post-tensioned CLT walls have allowed improved load distribution, greater diaphragm stiffness and enhanced seismic performance (Dias et al., 2016, 2018; Pei et al., 2023). These systems also enable larger spans and improved vibration damping. Additionally, engineered connection systems are increasingly optimized through full-scale testing and numerical modelling. From a technical standpoint, unlocking the full structural potential of tall timber buildings largely depends on the precision enabled by digital design tools and advanced fabrication processes, which ensure dimensional accuracy, optimize load paths and reduce on-site tolerances.

6.2. Construction process

The construction of high-rise mass timber buildings involves several innovative techniques and processes that distinguish it from traditional concrete and steel construction.

The construction of high-rise mass timber buildings represents a paradigm shift in contemporary architecture and engineering, integrating sustainability, prefabrication and digital innovation. Unlike traditional concrete or steel systems, mass timber construction is characterized by a high degree of precision and planning, where most structural elements are prefabricated off-site and assembled on-site in a streamlined

and coordinated sequence. This section outlines the critical phases and processes that underpin the successful realization of tall timber structures, from the early planning stages to final on-site quality control.

With an exploration of construction planning, emphasizing the importance of scheduling, sequencing and stakeholder coordination specific to timber systems, the following section discusses technological enablers, including the roles of Building Information Modelling (BIM), Computer Numerical Control (CNC) manufacturing and the Integrated Design Process (IDP), all of which are essential in achieving the precision required for off-site fabrication and seamless on-site assembly.

Subsequent sections examine transport and storage logistics, which are crucial for maintaining the dimensional stability and integrity of timber elements during delivery and staging. The erection phase addresses the methodologies for lifting, aligning and connecting prefabricated components on-site, highlighting the differences in approach when compared to steel or concrete assemblies. Finally, the chapter concludes with a review of quality assurance (QA) and quality control (QC) practices, including moisture management, dimensional verification and performance testing, which are vital to ensuring the structural, thermal and acoustic reliability of the completed building. Together, these interrelated processes demonstrate how the construction of high-rise timber buildings demands an integrated, detail-oriented approach to meet performance, durability and sustainability goals.

6.2.1. Planning in the building process of high-rise mass timber buildings

In the construction of high-rise mass timber buildings, effective planning is indispensable. As the point where conceptual ideas transition into practical realization, the planning phase sets the stage for the performance, cost-efficiency, sustainability and constructability of the entire project. For mass timber structures, this stage is particularly critical due to the integrated nature of prefabrication, tight tolerances, material-specific detailing and the multifunctionality of timber components. Given the complex and collaborative nature of these projects, the planning process must begin early and involve all stakeholders, from clients, architects and engineers to contractors, suppliers and fabricators (Green & Taggart, 2017; Rumane, 2011).

Project planning ensures that the entire construction process is carried out in an organized and structured manner. According to Rumane (2011), planning reduces uncertainty, manages risk, sets quality standards and helps achieve project objectives within budget and time constraints.

Unlike conventional construction, in high-rise timber projects, which often involve unprecedented combinations of systems and require performance under strict regulatory frameworks, planning cannot be an isolated effort. It must be a dynamic, inclusive process that engages every discipline from the outset.

The unique material characteristics of timber (anisotropy, moisture sensitivity, combustibility and jointing complexity) demand that fire safety, acoustics, thermal insulation and moisture management be designed concurrently with the structural and architectural systems. The performance of many of these layers is interdependent and thus, planners must consider wall assemblies, façade design, prefabrication logistics and service integration as part of a single, unified planning effort. Layered construction systems (e.g. floor slabs that also serve as acoustic barriers or fire-rated elements) further require comprehensive coordination across trades and design teams (Kaufmann et al., 2018).

6.2.1.1. Project planning tools and methods

A project plan is a formal, approved document used to manage and control project execution. It is the framework through which tasks, schedules, resource allocation and quality benchmarks are established and communicated. Based on finalized engineering and architectural documentation, this plan provides a roadmap for procurement, off-site production and on-site assembly. A comprehensive project plan, such as the one outlined in Figure 36, serves as a central document that defines responsibilities, timelines, organizational structure, quality control, risk management and communication protocols, ensuring that all stakeholders are aligned throughout the construction process.



PROJECT PLAN

EXAMPLE OF A TABLE OF CONTENTS

- 1 INTRODUCTION**
 - 1.1 INTRODUCTION TO THE PROJECT
 - 1.2 VISION AND SUCCESS CRITERIA
 - 1.3 BEHAVIOUR AND CULTURE IN THE PROJECT
- 2 ORGANISATION**
 - 2.1 PARTIES TO THE CONSTRUCTION PROJECT AND THEIR FUNCTION
 - 2.2 CONTRACT ORGANISATION
 - 2.3 DECISION HIERARCHY AND PROCEDURES
 - 2.4 OTHER STAKEHOLDERS AND INTERFACES
- 3 GENERAL ASSUMPTIONS AND REQUIREMENTS**
- 4 PROJECT PHASES AND TIMETABLE**
- 5 USER INVOLVEMENT**
- 6 FINANCIAL MANAGEMENT**
- 7 TIME AND ACTIVITY MANAGEMENT**
- 8 QUALITY ASSURANCE**
- 9 RISK MANAGEMENT**
- 10 HEALTH AND SAFETY**
- 11 TENDERING STRATEGY**
- 12 SUSTAINABILITY**
- 13 COMMUNICATION AND DOCUMENT MANAGEMENT**
- 14 CONFLICT HANDLING**
- 15 REFERENCES**
- 16 APPENDICES**

Figure 36. The project plan (Værdibyg, 2020)

The most widely adopted project scheduling methodology is the Critical Path Method (CPM), which identifies the longest chain of dependent tasks and thereby determines the minimum project duration.

CPM is essential in prefabricated construction projects where delays in any single task can have cascading effects on manufacturing and delivery timelines. In parallel, Gantt charts serve as visual tools to illustrate the start and finish dates of tasks, their durations, dependencies and the project's overall work breakdown structure (Rumane, 2011). These tools are especially effective in timber projects, where prefabrication requires detailed scheduling of off-site fabrication, transport logistics and on-site assembly. An example of the Gantt chart of a high-rise timber building project is presented in Figure 37.

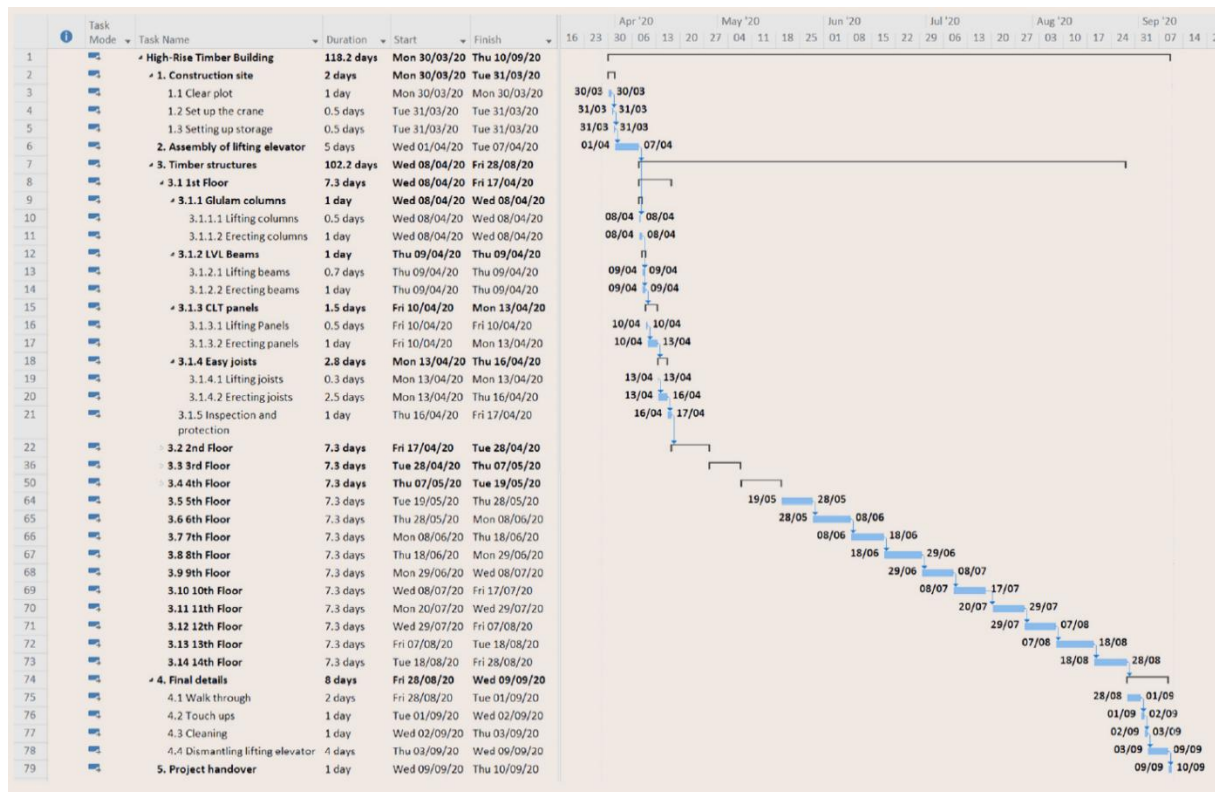


Figure 37. Gantt construction time schedule (Raspa et al., 2020)

In contemporary practice, Building Information Modelling (BIM) supports these planning tools by offering a shared digital platform for design coordination, clash detection and performance simulations. BIM facilitates data-rich models that integrate architectural, structural and mechanical systems into a unified workflow. It is particularly effective for identifying interface conflicts, planning prefabrication sequences and supporting accurate quantity take-offs and just-in-time delivery. Additionally, distributing a single, unified model to all subcontractors ensures greater consistency (Smith et al., 2018).

6.2.1.2. Integrated Design Process (IDP)

The Integrated Design Process (IDP) is increasingly used to bring together all key participants from the earliest conceptual stages. This model contrasts with traditional linear design workflows and promotes a collaborative environment in which decisions are optimized across disciplines (Figure 38) (Staub-French et al., 2022). IDP is essential for timber buildings, where components often perform multiple functions: for instance, a structural glulam beam may also provide fire resistance and serve as an interior finish (Green & Taggart, 2017).

By evaluating alternative solutions early through simulations and prototyping, IDP minimizes the risk of rework and ensures that cost, environmental performance and reliability are considered concurrently. For example, window placements affect thermal comfort, solar gain and mechanical system sizing, requiring input from architects, engineers and sustainability consultants alike. The benefits of this process are especially evident in complex projects such as tall wood towers, where prefabrication leaves little room for on-site improvisation.

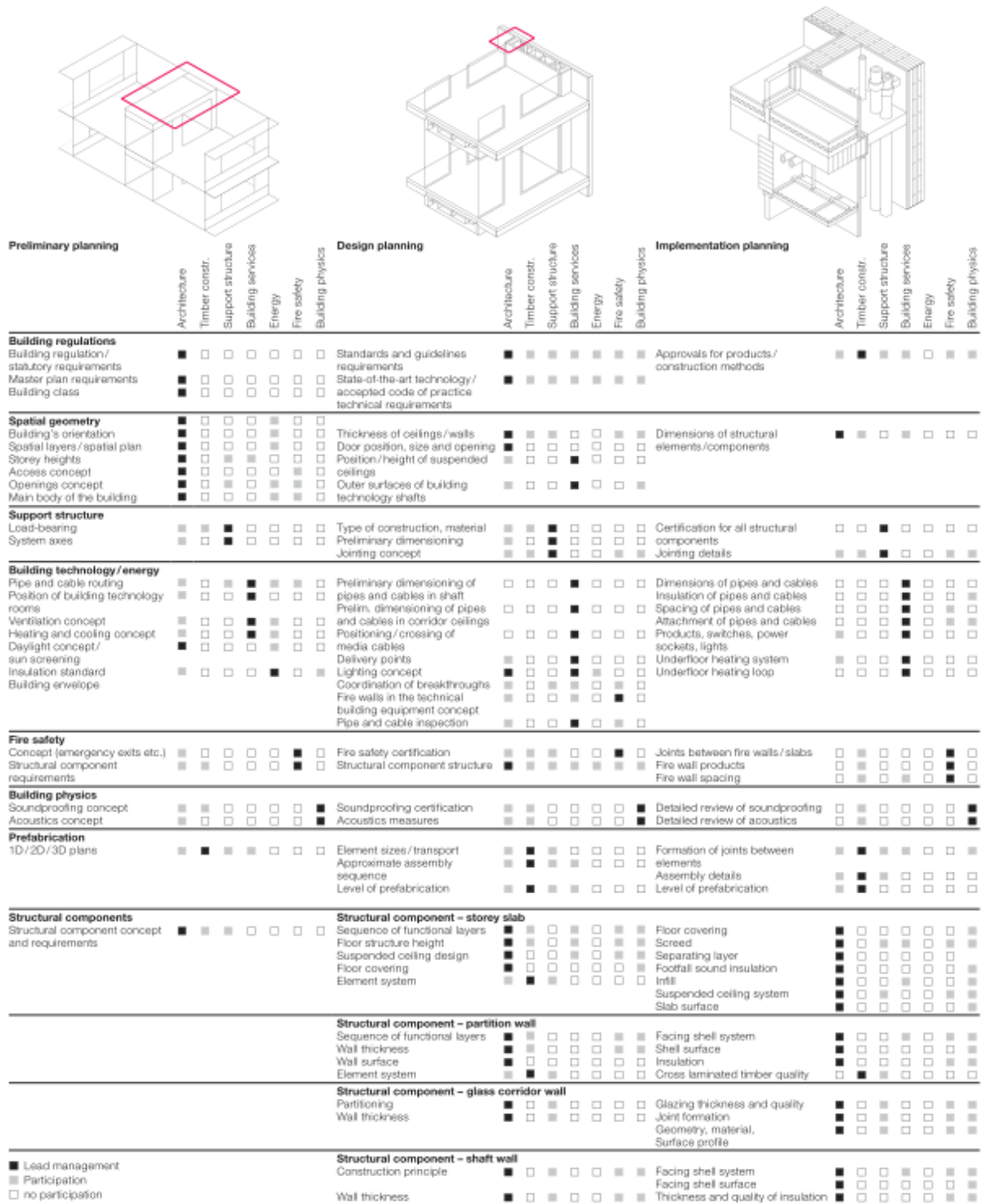


Figure 38. Example of decisions and the participants in the planning process (Kaufmann et al., 2018)

6.2.1.3. Specific planning phases in mass timber construction

The planning of mass timber buildings typically follows these interlinked phases:

- Preliminary design phase: Key performance requirements: fire safety, acoustics, energy performance, structural integrity and prefabrication are defined and integrated into spatial design concepts. Critical interfaces, such as those between fire protection layers and HVAC installations, must be clearly identified and resolved;
- Design development: This phase involves the refinement of structural systems, material choices, jointing methods, prefabrication levels and architectural finishes. All assemblies must be detailed in relation to both performance and production constraints;
- Construction planning: Specific tasks include sequencing of erection, site access coordination, hoisting logistics, element tolerances, and interface design. Collaborating manufacturers must confirm their capacity to deliver elements within prescribed tolerances;
- Implementation planning by contractors and producers: Final detailing is completed based on approved products and manufacturing capabilities. Specifics such as moisture protection, fire barriers and joint durability are resolved. This phase includes obtaining approvals for project-specific solutions not covered by general building codes.

6.2.1.4. Cooperation models and risk mitigation

The choice of project delivery and cooperation model significantly affects project performance. Cooperative models (Figure 39), where fabrication and construction firms are engaged during design development, promote innovation and efficiency. These arrangements facilitate creative problem-solving and reduce the risk of costly change orders during construction. When the team adopts cooperative planning and concept development, the building's form, materials and structure can be aligned to maximize both profitability and quality. Though evaluating bids becomes more complex due to qualitative factors, the benefits, such as better schedule adherence, cost predictability and coordinated technical integration are especially valuable in mass timber construction (Kaufmann et al., 2018).

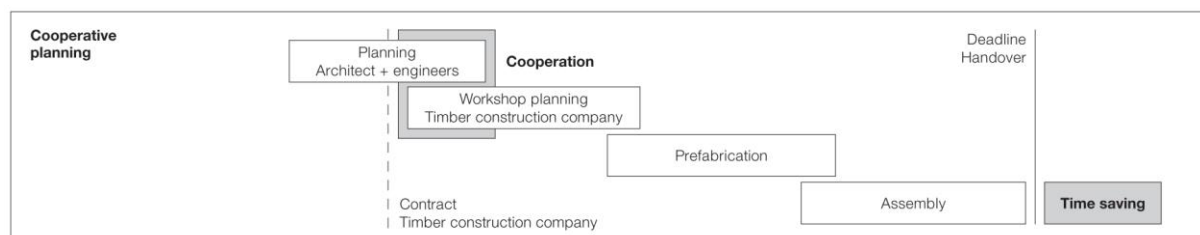


Figure 39. Cooperative planning process (Kaufmann et al., 2018)

6.2.2. BIM, CNC and prefabrication in mass timber high-rise buildings

The integration of digital design tools, manufacturing precision and off-site construction has transformed the planning and realization of mass timber high-rise buildings. Central to this transformation are Building Information Modelling (BIM), Computer Numerical Control (CNC) technologies and prefabrication, three interconnected strategies that enhance efficiency, accuracy and quality throughout the project life cycle.

Building Information Modelling (BIM) plays a foundational role in the coordination and optimization of high-rise timber projects. It enables early-stage integration of architectural, structural and mechanical systems into a single digital model, promoting interdisciplinary collaboration. Unlike traditional 2D documentation, BIM provides a comprehensive 3D representation of the building, making it easier to detect and resolve spatial conflicts such as service clashes, fire-rated separations and structural misalignments (Green & Taggart, 2017). This process also allows for better cost forecasting, performance analysis and material quantification at early stages of design, minimizing unforeseen adjustments during construction. Importantly, because timber buildings, particularly those employing prefabrication, require early design finalization, BIM becomes an essential framework for aligning architectural intent with technical feasibility (Staub-French et al., 2022).

Computer Numerical Control (CNC) technologies are closely tied to BIM workflows, enabling the high-precision fabrication of timber components. CNC machines translate digital files into physical operations with millimetric tolerances, cutting, drilling and milling elements such as CLT panels, glulam beams and dowel-laminated members (Green & Taggart, 2017). These technologies allow not only for intricate joinery such as dovetail connections but also for embedding service openings, thereby minimizing the need for on-site adjustments. CNC milling accommodates traditional subtractive methods, while recent advancements introduce additive techniques, including robot-assisted assembly for fastening operations (Figure 40). Such technological convergence allows for factory environments to handle both complex detailing and mass customization efficiently.



Figure 40. Prefabrication of an engineered timber panel (Kaufmann et al., 2018)

Prefabrication is the third critical pillar and arguably the most transformative in mass timber construction. By moving most of the construction process off-site, prefabrication ensures better quality control, faster installation, reduced on-site waste and improved weather protection, principally important for moisture-sensitive materials like timber (Smith et al., 2015; Green & Taggart, 2017). In high-rise applications, prefabrication often involves large CLT or glulam panels, modular floor systems and even volumetric 3D modules, where entire rooms are factory-built with finished surfaces, MEP installations, doors and windows already in place. These volumetric systems, while logistically limited by transportation dimensions (e.g. 13.5 m by 3.5 m), allow on-site assembly to be reduced to mere days or weeks (Figure 41).

The fabrication process leverages CNC technology to ensure tight tolerances, minimizing inconsistencies between factory-made elements and on-site construction. Nevertheless, the interface between CNC-precise components and other trades, who may work with less exact tolerances, requires

detailed planning and careful design of joints and tolerances to avoid cumulative errors (Green & Taggart, 2017).



Figure 41. Assembly of prefabricated elements in Brock Commons, two new storeys added each week (Kaufmann et al., 2018)

Moreover, prefabrication impacts the architectural design itself. Planners must consider not only the structural performance and detailing but also the constraints of transportation, lifting and module interconnection. For instance, wall-to-wall connections, floor junctions and module stacking must fulfil both physical and performance criteria (e.g. fire, acoustics and thermal bridging), while also being manufacturable and installable. In many projects, this necessitates a collaborative effort between architects, structural engineers, fabricators and contractors from the earliest stages. While prefabrication can reduce on-site construction durations and improve overall quality, it also requires a more intensive and front-loaded design process. Any delays or errors in early decision-making can have cascading effects later in production and assembly. Therefore, planners must finalize material selections, service coordination and structural detailing much earlier than in conventional construction processes. This necessity parallels the BIM methodology and underlines the importance of integrated, multidisciplinary planning.

Finally, the economic and environmental benefits of prefabrication are significant. Controlled factory environments enable optimized material usage, waste recycling and improved working conditions. Prefabrication supports circular economy principles by allowing for disassembly and reuse in future applications. Moreover, faster installation reduces traffic, noise and dust on construction sites—particularly valuable in dense urban settings (Green & Taggart, 2017).

In conclusion, the combined application of BIM, CNC and prefabrication defines a new paradigm for mass timber high-rise construction. These technologies and methodologies work synergistically to deliver precision, reduce risk and improve sustainability. Yet they also demand a cultural and operational shift toward early collaboration, detailed planning and rigorous quality control throughout the project timeline.

6.2.3. Quality control

The construction phase is a critical stage where the architectural and structural intentions of a project are physically realized. To ensure that this process unfolds efficiently and according to plan, it is essential to define clear performance requirements and establish a comprehensive control framework. This includes setting out the expected conditions under which construction activities must be carried out, as well as the

criteria by which materials, processes and workmanship will be assessed. The durability and long-term performance of the building are directly linked to the ability to monitor and evaluate these aspects throughout the construction process. Quality control is achieved through systematic inspection of works, verification of compliance with technical standards and the use of certified materials and construction methods. By identifying and addressing deviations in real time, the control system ensures that the completed structure meets the intended specifications and regulatory requirements (Rumane, 2011).

As previously discussed, while numerous timber structures have demonstrated exceptional longevity across diverse climatic conditions, some lasting several centuries, others have required demolition only a few years after construction due to premature degradation. Understanding the root causes of such failures is essential for identifying key durability requirements and ensuring the long-term performance of high-rise mass timber buildings.

Timber durability is influenced by several degradation mechanisms, including:

- Thermal degradation (e.g. fire exposure);
- Mechanical loading (stress and fatigue);
- Environmental weathering (moisture, ultraviolet radiation);
- Chemical degradation;
- Biological attack (fungi, insects and marine borers).

Ensuring construction quality in this context becomes an extensive and multidisciplinary task. Effective quality control involves not only structural integrity and material performance, but also intersects with regulatory compliance, financial oversight, scheduling and logistics, workforce coordination, equipment readiness, on-site safety and the precision of construction execution. Each of these dimensions plays a critical role in determining the success and longevity of the building. While specific topics such as fire and thermal performance are addressed in dedicated sections, it is important to highlight that among all contributing factors, moisture management stands out as the most critical for timber construction.

Although all construction materials are susceptible to water-related damage, stemming from condensation, leaks, envelope penetration, or poorly drained foundations, timber's hygroscopic nature renders it particularly vulnerable. It absorbs moisture rapidly and releases it slowly, creating conditions favourable to biological decay, degradation of adhesive bonds in engineered products and long-term structural weakening (Wang, 2016; Wang et al., 2019).

Moisture-induced issues can also affect non-structural components and occupant comfort. High humidity promotes mould growth, which can compromise indoor air quality and lead to user discomfort and, in the worst-case scenario, costly repairs. In addition, the anisotropic nature of timber causes it to expand and contract unevenly in response to moisture fluctuations: a 1% change in moisture content results in dimensional changes of approximately 0.2% tangentially, 0.1% radially and 0.01% longitudinally (Forest Products Laboratory, 2010). These changes may result in shrinkage, swelling, nail popping, drywall deformation and cracking. The last one, although it may not threaten structural stability, can negatively influence perceptions of safety and material reliability.

Therefore, managing moisture effectively is a foundational aspect of durable timber construction and must be addressed from the earliest planning stages through to post-construction maintenance. A dedicated moisture control strategy should include the appointment of quality management personnel, moisture-specific supervision and the establishment of monitoring and documentation procedures.

Clear protocols, site training and an enforceable hierarchy of control are essential to ensure consistent implementation and safeguard both structural and perceptual integrity.

Quality control in construction projects is a continuous process carried out throughout all phases of development. It involves the systematic application of tools such as control charts, diagrams and checklists to ensure compliance with project specifications. Quality control can be broadly defined as the verification of executed or installed works to confirm that they have been completed in accordance with approved materials, installation methods and applicable codes and standards, thereby ensuring fitness for the intended use. In addition to technical verification, quality control also encompasses the oversight of project budgeting, as well as the planning, monitoring and management of the construction schedule to maintain alignment with project goals and timelines (Rumane, 2011).

To ensure the durability, safety and performance of high-rise mass timber buildings, a structured and continuous quality control approach must be adopted throughout the construction process. This involves clearly defining how control is implemented, including:

- Timing (continuous or periodic);
- Frequency (throughout construction or after specific phases);
- Degree of team integration (embedded vs. external oversight);
- Presence on site (permanent or scheduled inspections).

The PDCA cycle (Plan, Do, Check, Act) offers a robust framework for this continuous improvement process (Figure 42). It begins with defining objectives and methods (Plan), executing actions such as inspections and installations (Do), reviewing results against requirements (Check) and implementing corrections or further improvements (Act) (Rumane, 2011). This iterative loop ensures that each construction phase informs the next, maintaining process integrity and promoting quality enhancements over time. Accurate documentation of specifications, inspections, material approvals, contracts and meeting outcomes are essential to track performance and adherence to moisture control and quality assurance plans. Quality is not an isolated goal but a result of integrated control across scheduling, cost, safety, environmental factors and technical decisions. Key control actions include verifying compliance with the project design, monitoring construction timelines, ensuring proper material selection and use, executing approved installation methods, coordinating across trades and conducting ongoing inspections by qualified personnel.

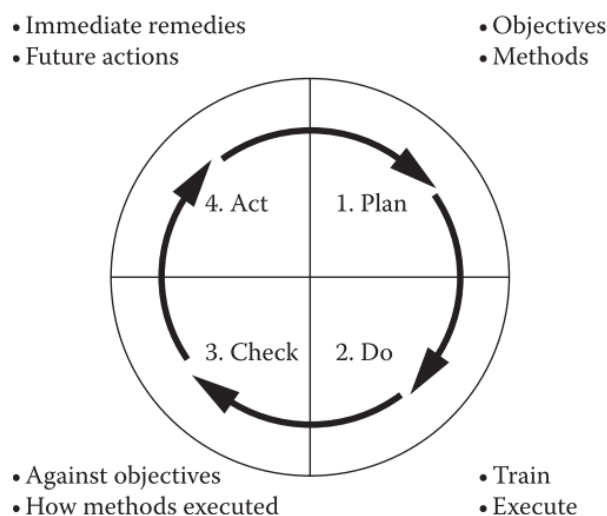


Figure 42. PDCA cycle model (Rumane, 2011)

The PDCA model should already be applied during the design phase, guiding scope definition, design development, evaluation and corrective action. A zero-defect policy, especially for critical elements, requires rigorous execution according to approved drawings, trained labour, continuous supervision and proactive identification of deficiencies (Rumane, 2011). Through this systematized and transparent process, quality assurance becomes a dynamic component of construction management, adaptable to evolving site conditions and project requirements. Some of the key measures that contractors should follow include (Rumane, 2011):

1. Executing work in accordance with approved shop drawings and using specified, approved materials;
2. Following approved method statements or the manufacturer's recommended installation procedures;
3. Conducting continuous inspections throughout the construction and installation processes;
4. Employing a properly trained and qualified workforce;
5. Always maintaining a high standard of workmanship;
6. Identifying and correcting any deficiencies before submitting checklists for inspection and approval;
7. Coordinating with other trades to accommodate requirements early in the process.

6.2.4. Transport, storage and erection

6.2.4.1. Transport

The transportation of mass timber components, particularly cross-laminated timber (CLT), requires careful consideration due to their size and the need for timely delivery. Transporting mass timber components (MTC) often requires additional permits and weight requirements depending on the travel route and restrictions on shipping containers and trucks must be evaluated from the fabricator to the job site (Staub-French et al., 2022). It is also important to note that shipping wood panels between states may be restricted due to concerns about invasive species or bringing foreign material into a state (Smith et al., 2018). The size of transport is constrained by road-permit limits, typically allowing up to 5 meters wide and 18 meters long, while adhering to local axle-load regulations (Beck, n.d.). Oversized panels may need to be segmented into modules that can safely navigate bridge clearances and turning radii, then reassembled on site.

Most panels are shipped via truck or container and it is crucial that shipments are arranged to arrive at the site in the correct order for erection, from foundation to vertical termination, with the first piece to be erected placed on top of the shipment. This "just-in-time" (JIT) or sequenced delivery approach is critical as it minimizes on-site storage requirements, reduces the risk of damage and streamlines crane and crew deployment (Staub-French et al., 2022). Re-arranging panels or temporary storage on site is costly and wastes time. SmartLam (2020), for instance, notes that JIT delivery is their most common method. Alternative delivery methods include a one-time shipment of all panels, which requires large staging areas, or phased shipments for projects designed and constructed in stages.

Commercial trucking is the most common shipping method, though freight rail can offer cost savings for projects located over 1,000 miles from the manufacturing facility, often requiring additional trucking from rail yards to the job site. Transportation planning must also account for specific state laws and regulations (Kaufmann et al., 2018). When loading for delivery to the site, members should be organized and braced to facilitate easy rigging and offloading by field crews (Beck, n.d.). Improper handling during

transit, such as dragging panels or stacking without protection, increases the risk of edge damage, twisting and connector misalignment, compromising structural integrity (Kaufmann et al., 2018).

6.2.4.2. Storage

Upon arrival at the job site, all mass timber materials and equipment must undergo quality control inspections by an inspection team to ensure they match approved designs and specifications, and their physical condition is acceptable, noting any defects or quantity discrepancies. This includes verifying product compliance certificates, technical specifications, test reports, manuals and relevant certifications. Any damages or inaccuracies found must be documented, reported and repaired if possible (Wang, 2016). Producers typically provide certified documentation and recommendations for product transportation, storage and assembly, which must be strictly followed.

Mass timber elements, such as CLT and glulam, are typically factory-dried to a low moisture content (e.g. 12–14%) (Kaufmann et al., 2018). However, they are hygroscopic, meaning they can absorb significant moisture if exposed to rain or high humidity, potentially leading to moisture content exceeding 20% within hours, which can invite mould, delamination and long-term creep (Forest Products Laboratory, 2010). Therefore, a project-specific moisture-management plan is essential. Key aspects of proper storage include:

- Never storing panels directly on the ground or in standing water;
- Placing panels on elevated structures (at least 15 cm or 6 inches above pavement, or 30 cm above fresh ground) to guarantee airflow below the material;
- Ensuring the storage area is clean, level, has good drainage and adequate air flow to prevent fungal growth;
- Securing packages with wraps and straps, leaving the bottom side open as an additional water safety measure;
- Using simple cover material providing water and ultra-violet (UV) protection, or specific shelters with controlled humidity conditions, as appropriate for the budget and wetting potential;
- Avoiding plastic coverings that can cause moisture accumulation and clear coverings that allow "sun tanning". Instead, moisture-resistant paper wraps or canvas tarps are recommended;
- If factory wrap is present, slitting or puncturing the wrapping on the bottom of the panel to allow for drainage;
- Opening up tarps after heavy rain to allow moisture to escape;
- Avoiding walking on unprotected panels or handling them with soiled hands or equipment.

Sources of damage during storage include (SmartLam, 2020):

- Rain and excessive moisture: Can cause CLT to swell, leading to installation issues and may cause staining of panels or rust from unprotected steel/fasteners;
- Sun exposure: Direct or indirect sunlight can cause "sun tanning" where the timber changes colour, especially if the factory wrap tears or opaque tarps are not properly used. Long-term storage with manufacturer's wrap containing printing can also "bake" the printing into the surface, causing permanent suntanning;
- Cold weather acclimation: Rapid changes in moisture content, such as when heat is suddenly applied

to a structure, can cause checking and splitting of panels. Raising the temperature slowly over several weeks can minimize this. Sealers or coatings can help regulate moisture content changes;

- Improper handling: Surface marring, gouging, scraping and soiling are common but avoidable with proper equipment and procedures. Minimizing handling and on-site storage through JIT delivery is the best practice to avoid such damage.

Manufacturers like SmartLam take measures such as applying sealers (e.g. Sansin KP12W) to all faces and edges for temporary protection against extreme conditions, factory wrapping panels with lumber paper, stacking with dunnage to separate panels and tarping shipments with heavy-duty opaque tarps during transport (Figure 43).



Figure 43. Temporary protection against weather conditions (SmartLam, 2020)

Some projects opt for an off-site timber yard for storage (Figure 44), offering benefits such as more flexibility in shipping from the manufacturer, maximizing shipping loads, confirming all members are in the yard ahead of erection, allowing for pre-installation of hardware and screws and enabling modifications to timber resulting from changes ahead of erection (Beck, n.d.). This strategy helps minimize erection time due to material availability issues. However, this also incurs costs for tradespeople, load planning management, equipment rental and winter weather protection. The timber yard should be laid out to minimize handling of the product and stack timber members similarly to how deliveries will be made to the site (Kaufmann et al., 2018). Specific equipment like forklifts with 8-foot long, 1.75-inch-thick attachments, combi lifts with bi-lateral movement and safety tie-off beams for tall stacks are necessary. Using thicker stickers (dunnage) between members and proper strapping of loads can prevent damage during shipping and aid unloading (Beck, n.d.).

6.2.4.3. Erection

Meticulous planning of all construction activities is crucial before going to the building site. During the building process, the moisture content and execution environment should be continuously measured and monitored to guide decisions about protection, drying and necessary repairs. Mass timber erection can be remarkably fast. For example, one project involved erecting 1,900 pieces over a 12-week duration (Beck, n.d.).

General principles for protecting load-bearing wooden wall panels during erection include:

- Minimizing the time structures are open to the elements;
- Treating load-bearing wood elements with a hydrophobic coating by the factory to inhibit water infiltration;

- Protecting connections between elements with exterior covers;
- Covering window and door openings with double-layer plastic covers to manage the indoor climate;
- Delaying the installation of moisture-sensitive materials until the external envelope has been closed.

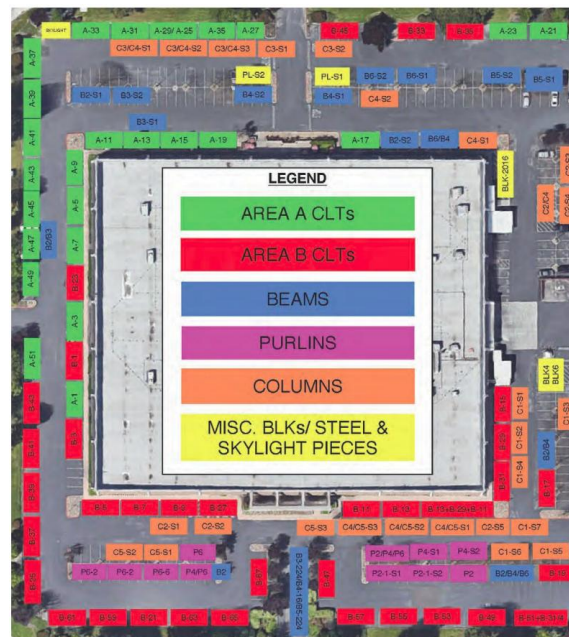


Figure 44. Timber yard storage example (Beck, n.d.)

For intermediate floor slabs, top surfaces, edges and exterior sides of edge beams should be treated with a hydrophobic coating by the manufacturer. Recesses for prefabricated bathrooms, stairwells and lift wells must be protected with lightweight covers on-site, which are then transferred to the next floor as erection progresses. Timber planks should be installed to create drainage troughs following the unit walls, sealed to prevent water from entering connections and connected to drainpipes for water removal. Connections between wall and floor elements can be protected by EPDM-rubber (Ethylene propylene diene monomer) strips installed by the manufacturer. If building materials are stored on intermediate floors, they should be raised on timber beds to ensure no water collection beneath them. Non-load-bearing external wall panels should have openings protected by plywood sheets or double-layer plastic or be covered by a weather shield if uninsulated. The roof, eaves, covering and temporary draining system must be assembled promptly after erecting the frame structure.

Effective management of indoor environmental conditions during construction is essential to ensuring the long-term durability and performance of mass timber buildings. This process begins once the load-bearing walls and intermediate floor structures are in place and the building envelope has been sealed. At this stage, temporary heating systems should be installed in all enclosed spaces to initiate the controlled drying of structural components. Relative humidity levels must be maintained below 75% during the initial construction phases and, after the installation of thermal insulation, reduced to a target range of 45–55%, with indoor temperatures maintained above +10 °C. To ensure these targets are met, environmental monitoring stations should be deployed to measure and log humidity and temperature data regularly. Weekly analysis of this data enables timely adjustments in environmental control strategies.

Prior to the installation of coatings or finishes, comprehensive inspections are required to verify the

hygrothermal performance of all internal and external assemblies. This includes assessing the condition of wood surfaces using calibrated sensors, measuring moisture content and documenting results systematically. Any materials exhibiting damage or excessive moisture content must be replaced to avoid compromising structural integrity or indoor air quality.

Weather protection throughout the construction phase is another critical issue, particularly due to timber's sensitivity to moisture. While the use of prefabricated components enables rapid on-site assembly and offers flexibility in response to changing weather, this must be supported by a detailed assembly plan that accounts for climatic variability. Where feasible, structural framing and enclosure should be scheduled during drier seasons and JIT delivery strategies should be adopted to limit exposure of sensitive materials (Coulson, 2021). Though advanced weather protection systems such as mobile enclosures or retractable roofing (Figure 45) can significantly reduce moisture risks, their high cost and logistical demands, especially regarding crane operations must be carefully evaluated during the early planning stages.

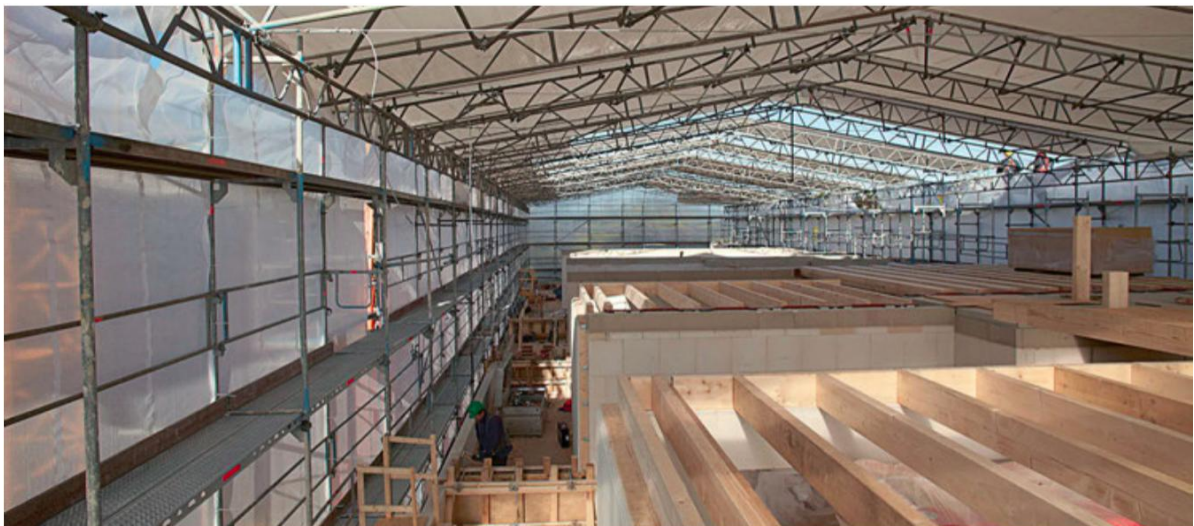


Figure 45. Construction under a temporary roof (Kaufmann et al., 2018)

Key factors to consider when planning weather protection from the project's beginning include:

- Weather conditions and wetting/drying potential;
- Durability risks;
- Geographical location and associated risks;
- Location of the members in the building;
- Cost of protection methods *versus* cost of mechanical manipulations of moisture content.

Experienced project teams often mitigate moisture risks by designing the construction sequence in a floor-by-floor manner, allowing slabs to be covered overnight or during precipitation events with large waterproof tarpaulins. This strategy prevents water accumulation and limits exposure of open wall systems. In some cases, construction is carried out entirely under protective canopies or tents; while these provide exceptional environmental control, they introduce spatial limitations and may require alternative lifting solutions. Ultimately, the selection of protection strategies must be made collaboratively by project stakeholders early in the planning process, considering both technical and economic implications.

6.3. Fire performance

In addition to offering a load-bearing stability, timber must also address the other crucial requirements, particularly its inherent fire risk. Fire is a dangerous force that causes significant property damage and loss of life each year. A comprehensive understanding of fire behaviour is essential for effective prevention, management and control during incidents.

While fires are relatively infrequent, the extent of damage they cause far exceeds that of other issues like water damage. This has led to considerable concern among insurance companies, given the potential for catastrophic losses (O'Brocki, n.d.).

Contrary to the common concerns about wood susceptibility to burn, well-designed mass timber structures using engineered wood products meet stringent fire safety requirements. These structures have been recognized for their excellent fire performance by international standards and outperform steel in fire conditions, as their mechanical properties remain relatively stable at high temperatures. Furthermore, once ignited, mass timber exhibits impressive resilience under fire exposure (Asdrubali et al., 2017 Green & Eric Karsh, 2012). Wood is inherently a poor thermal conductor, meaning it has low thermal conductivity and thus, resists heat transmission through its structure. The fire behaviour of wood largely depends on its specific surface (surface area to volume ratio) and density (Kaufmann et al., 2018). Thicker wood elements provide greater fire protection. Furthermore, wood does not spontaneously ignite and during combustion, it forms a charred layer on the fire-exposed surfaces. This charred layer acts temporarily as a thermal insulator, shielding the inner areas from heat and maintaining the structure's load-bearing capabilities for a given time (Dagenais et al., 2019).

The following section explores the fundamentals of fire dynamics and wood behaviour in case of fire, as well as the key aspects of the fire prevention and fire safety for design and construction of high-rise timber buildings.

6.3.1. Fire fundamentals

Fire is a heat-releasing chemical oxidation process that requires four elements to happen: fuel, oxygen, heat and chain reaction. It is commonly known as fire tetrahedron as presented in Figure 46. Combustion involves fuel source - a material to burn and oxygen (fire consumes oxygen and gives off gases such as carbon dioxide). To ignite fuel and reach the minimum temperature for it to maintain burning independently, heat energy is essential. As the combustion is an exothermic reaction, it releases heat energy in a consequence of breaking the chemical bonds. Since these reactions occur continuously, burning emits more heat than necessary to sustain a fire and contributes to its high temperature. Apart from heat, the light (flames) and reaction products (smoke) are produced during the fire. The process persists until elimination of any of the three essential elements, as it disrupts the chemical reaction, causing the fire to extinguish. Most fire extinguishers or suppressants function by breaking the fire's chain reaction - either the fuel or oxygen is depleted, or the heat output decreases (Telgian, 2022).

In high-rise timber buildings the fuel component consists not only in furniture, kitchen or office equipment and the human belongings, but also the structure itself may count as a fire load due to its combustibility. This is why it is crucial to understand and consider fire-specific design, as various factors

can influence the performance of mass timber in a fire scenario. These factors include, but are not limited to, wood species, the type of adhesive used, panel thickness (number of laminates), laminate thickness, type of fire exposure, joints configuration and the prevention and protection methods employed.

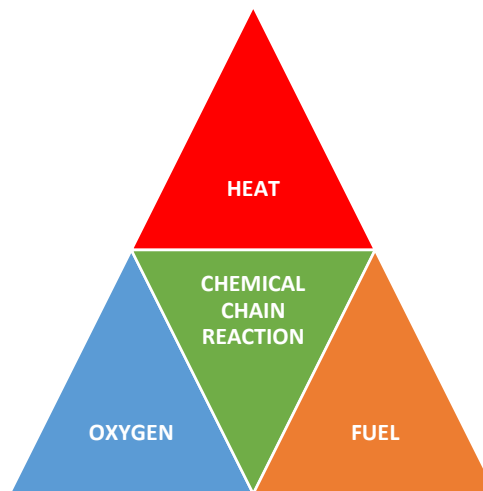


Figure 46. Fire tetrahedron

When analyzing the component of the oxygen, it is important to mention that its quantity depends on the ratio of the openings in the building enclosure and the floor area or the total enclosure area and can be defined in accordance with the opening factor - O , defined in Eurocode 1 (2002). The thermal inertia of the enclosure also impacts the fire speed and temperature.

When a fire occurs, it spreads in three ways:

- By conduction: Heat transfers from molecule to molecule along a material. Timber has a low heat conductivity and timber structures, when well designed, can help to prevent fire spread. However, as metals are good heat conductors, the conduction is critical for connections integrity, that are mostly made of steel in timber structures. To prevent the connections from exposure to fire, the adequate design needs to consider their protection;
- By convection: Heat transfers in liquids and gases. Hot and thinner air rises and spreads under ceilings, igniting materials as it moves through the building. This is the primary way fires spread in buildings. To reduce fire spread by convection, adequate design requires subdivision of a building into fire-rated compartments;
- By radiation: Heat travels in straight lines as rays, igniting combustible materials without passing through a medium. To delay further ignition by radiation and spread of heat and smoke, it is crucial to keep fire doors closed.

Fire prevention, prediction and calculation are inherently complex tasks due to the multitude of factors involved and possible scenarios. Accurate prediction requires a deep understanding of various variables, such as fuel types, environmental conditions and fire behaviour. Prevention strategies must consider building materials, structural designs and human activities to effectively minimize fire risks. Calculating fire dynamics involves intricate models to simulate fire growth, spread and impact, incorporating aspects like heat transfer, combustion and ventilation. Research has demonstrated that the life safety performance of buildings is more heavily influenced by design solutions than by the

building's typology (Asdrubali et al., 2017). Effective design strategies play a critical role in ensuring the safety and resilience of a structure.

6.3.2. Fire resistance

To ensure that the structure meets safety standards during a fire (adequate time for occupants to evacuate safely, to minimize property damage and to allow emergency responders to perform their tasks effectively), it is necessary to establish its fire resistance. Fire resistance is the duration during which a building element, component, or assembly can withstand fire exposure while maintaining its intended function. This includes confining the fire by preventing or slowing the spread of excessive heat, hot gases, or flames and continuing to support its load-bearing role. Fire resistance is determined under specific test conditions and performance criteria (Asdrubali et al., 2017b). The assembly's fire resistance is defined by time when one of the following criteria is no longer assured (Stora Enso Wood Products, 2013):

1. Structural resistance: The assembly must sustain the applied load throughout the test duration, ensuring it retains its load bearing capacity;
2. Integrity: The assembly must stop the passage of flames or gases hot enough to ignite a cotton pad, ensuring it maintains its separating function;
3. More than 180 °C at any single point, or an average of 140 °C across multiple points, above the initial temperature, thereby maintaining its insulating function (Dagenais et al., 2019). As mentioned previously, timber has low thermal conductivity and it works as a thermal insulator. Consequently, the heat transfer by conduction through mass timber is relatively low, both in transient and steady-state conditions, compared to other materials with higher thermal conductivity. This can be illustrated with the following examples:
 - A non-combustible steel support, classified as class A building material, typically loses its load-bearing capacity within 30 minutes if not protected by fire-resistant cladding or coating. In contrast, a glued laminated timber support with adequate cross-section will char on the outside but can maintain its structural integrity for over 90 minutes in a fire without any additional protective cladding or coating;
 - A non-combustible glass allows the heat to pass through almost immediately. Contrarywise, a 30 mm-thick softwood fibre panel will burn, but it significantly prevents heat transfer, causing a temperature rise on the unexposed side only after about 15 minutes at the earliest (Kaufmann et al., 2018).

To improve the fire resistance of timber elements, several methods can be employed, that includes the use of protective membranes or the fire retardants. The protective membranes can significantly increase fire resistance by delaying the onset of charring in the wood beneath. The most frequent approach for meeting interior finish requirements for flame spread rating (FSR) and smoke development class (SDC) is the use of fire-rated (either Type X or Type C) gypsum board (Asdrubali et al., 2017). Other types of boards with the chemical treatment can be used when lower FSR interior finishing is required. Additionally, wood products can be treated with fire retardants to enhance their fire performance, which can be applied in the form of surface coating or pressure-impregnated chemical. These treatments contribute to delaying ignition time, reducing the heat release rate and lowering the FSR. Although fire retardant treatments (FRT) improve flame spread performance, they do not render wood and wood-based products non-combustible (Dagenais et al., 2019).

6.3.3. Charring

In engineered timber construction, the wood possesses enough mass to form a char layer during incomplete combustion, preventing the structure from collapse during a required by code time. Wood has a flashover temperature of approximately 220-250 °C and produces significant combustion energy, around 4400 kcal/kg. The combustion process can be divided into four primary phases. Initially, up to 110-115 °C, the mechanical properties of wood remain stable. This is followed by the propagation phase, continuing until the temperature reaches about 200 °C, at which point the flashover occurs. Beyond this stage, the intensity of the fire diminishes due to the depletion of combustible materials (Asdrubali et al., 2017). When exposed to flames, the outer layer of wood reaches its ignition point and start to burn. This chemical reaction involves heat driving off hydrogen and oxygen from the solid wood, leaving a char layer predominantly composed of carbon (Dagenais & Chen, 2023). This char layer has low thermal conductivity and acts as an insulator, protecting the remaining wood from further acceleration in combustion. Beyond the char layer lies the pyrolysis zone (Figure 47), where the elevated temperatures cause the wood to decompose. The inner core of the wood is minimally affected by the temperature increase, primarily experiencing moisture loss. Consequently, the fire-resistance rating of large-sized members can be determined by calculating the minimum structural thickness and the remaining sacrificial thickness available for charring (Green & Eric Karsh, 2012).

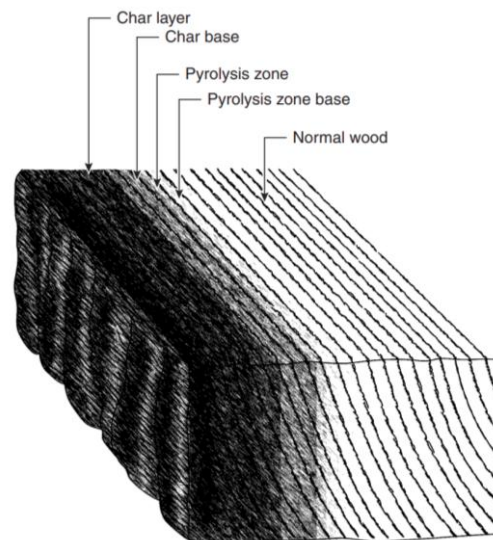


Figure 47. Charring degradation zones caused by fire in a wood section (DiNenno et al., 2002)

A consistent rate of material reduction will occur. This steady burning rate varies from wood species to wood species, but it is generally less than 1 mm per minute, Eurocode 1-2 prescribes 0.65 - 1.0 mm/min (CEN, 2007). This is very important when designing timber members intentionally exposed to potential fire. Eurocode 5 provides a straightforward approach called reduced cross-section method (RCSM) (CEN, 2004a). This method uses an effective cross-section and mechanical properties at normal temperature. The structural approach for verifying fire resistance starts by considering the charring rate and resistance time, which are used to define an effective reduced cross-section of the structural elements (Asdrubali et al., 2017; CEN, 2004a).

6.3.4. Fire safety measures

For the efficient fire safety strategy, the following points should be addressed:

- Prevention of ignition: In addition to the proper execution of building elements and the installation of fire safety features and the adherence to basic fire prevention strategies, it is crucial to undertake informative actions that address the human factor. Many fires are caused by human errors like forgotten electrical equipment, lit candles, or smoking (Kaufmann et al., 2018);
- Fire detection and alarm: Fire detection must be immediate and can be achieved through smoke detectors, fire alarms, or manual means. The rapid response should activate auditory and/or visual warnings, shut fire doors, stop elevators, activate or deactivate ventilation systems and, in some cases, alert the fire station;
- Escape routes: After the alarm is triggered, having adequate means of escape is crucial for the fast and effective evacuation of occupants. Whether the firefighting strategy is to stay in a designated area or move to a nominated safe location, the information should be clear and easy to understand and evacuation routes should be unobstructed and well-signalled. Additionally, access ways to the building and its surroundings should be considered to ensure a rapid emergency response;
- Fire control: Strategies to prevent fire from spreading both internally and externally, through walls, openings, or other penetrations, should be implemented during the design stage, executed properly during construction and controlled and maintained throughout occupancy. These strategies include compartmentalization, sprinkler systems and partial encapsulation of flammable surfaces, especially in critical areas;
- Fire performance: The design of the structure must stringently fulfil fire performance requirements and ensure a low probability of structural failure both during and after a fire. Additional precautions should be taken in locations with highly flammable or chemical substances and in situations where special protection of the environment is required, such as near water supplies, streams and agricultural areas.

6.3.4.1. Fire alarms, smoke detectors

Alarm systems installation is one of the most effective ways to decrease the number of casualties in fires (DiNenno et al., 2002). When functioning properly, smoke and heat alarms ensure rapid egress and facilitate fire-fighting efforts. These alarms can integrate multiple functions, such as alerting the fire brigade, opening smoke ventilation systems, closing fire doors, stopping elevators, activating flashing light warnings and providing auditory evacuation directions.

A pre-action system can be installed to enhance safety measures. It typically includes either heat detectors, which react to elevated temperatures, or smoke detectors, which respond to changes in optical density. Smoke detectors are more effective than heat detectors in detecting fires in residential homes (National Fire Protection Association, 2014). However, heat detectors tend to have a lower false alarm rate, as they have a slower reaction time compared to smoke detectors, making them beneficial in specific contexts. The primary purpose of a pre-action system is to prevent accidental water discharge from sprinklers due to false alarms, what could be catastrophic for timber assemblies. It also serves to fill empty pipes leading to sprinklers in cold conditions, such as those outside for façade sprinkling, ensuring readiness without the risk of freezing.

6.3.4.2. Escape routes

Emergency escape routes in high-rise timber buildings must meet strict standards to ensure occupant safety, similar to those in buildings constructed with other materials. These key requirements include:

- Clear and obvious emergency exit routes: Emergency exit routes must be clearly marked, well-lit (including backup emergency lighting) and easily identifiable to ensure that occupants can quickly and safely find their way out during an emergency;
- Accessibility: Exit routes must be accessible to all occupants, including those with disabilities. This involves ensuring that exits are wide enough, free of obstructions and equipped with appropriate signals and alarms for those with hearing or visual impairments;
- Adequate number of exits: There should be a sufficient number of exits to accommodate the maximum occupancy load. Ideally, there should be at least two fixed emergency exit routes, particularly in areas that may contain a large number of people, such as conference rooms or assembly areas (Kaufmann et al., 2018);
- Fire resistance and protection: Exit routes and stairwells must be constructed with materials that provide adequate fire resistance, ensuring they remain passable during a fire. This includes using fire-resistant and smoke control doors and safeguarding that the walls, floors and ceilings of escape routes are designed to resist fire and smoke penetration;
- Regular maintenance and drills: Emergency exit routes must be regularly inspected and maintained to ensure they remain functional and clear of obstructions. Regular fire drills should be conducted to familiarize occupants with the evacuation procedures and routes.

In tall and high-rise buildings, the Emergency Action Plan might advise residents to remain inside their apartments, close doors and make themselves visible at windows rather than attempting to evacuate (National Fire Protection Association, 2014). This strategy is effective because modern high-rise buildings are designed with compartmentalization features that prevent the spread of fire (Day, 2006). The use of fire-resistant walls, floors and doors creates individual compartments that can contain the fire within a specific area, limiting its ability to spread. Additionally, keeping doors closed and windows shut reduces the fire's access to oxygen, thereby slowing its progression. This method allows emergency responders more time to control the fire while ensuring occupants are better protected from immediate danger.

Additionally, lifts should never be used for evacuation during a fire. Following the guidelines of EN 81-73: 2020 (CEN, 2020), in buildings equipped with a fire alarm system covering common areas and an appropriate electrical output signal, all lifts, except those designated for firefighting or emergency evacuation, should be automatically recalled to the exit floor and disabled. In the absence of a suitable fire alarm system, lifts should be recalled manually using a designated device.

By meeting these requirements, like any high-rise buildings, timber buildings can ensure that occupants have safe and effective means of egress in the event of an emergency, thereby enhancing overall building safety (Kaufmann et al., 2018).

6.3.4.3. Control of fire spread: Compartmentation

To prevent fire spread and the risk of structural collapse, the building should be divided into fire-rated compartments. A fire compartment is a confined area within a building, separated from other sections by

specific design features and suitable materials, ensuring a fire separation with a designated fire-resistance rating. The purpose of compartmentalization is to contain the fire to the sector of its origin, by employing boundary elements like walls, ceilings and floors, which have fire resistance ratings that comply with or exceed the minimum time requirements set by the code (Dagenais et al., 2019, Asdrubali et al., 2017).

Additionally, it is critically important to ensure proper design details and high-quality field installation to prevent flame-through by conduction between joints due to the absence of sufficient fire-resistant caulking (Smart, 2024). Failure to seal the construction joints can result in fire penetration and large flames outside the compartment. A special attention should be given to cavities, penetration elements, steel components and metal fasteners, such as bolts, dowels and steel plates or brackets. The penetration should be avoided whenever possible and any gaps fully insulated with mineral wool or fire-resistance rated caulking and steel components and fasteners protected by wooden cladding or other classified for fire protection material (Smart, 2024).

Several commercially available fire-rated joint fillers, caulking and sealing tapes, approved for use with concrete assemblies, have demonstrated the ability to achieve 1½- or 2-hour fire-resistance ratings when used with mass timber elements (Dagenais et al., 2019).

6.3.4.4. Control of fire spread: Sprinklers

If wood is intended to remain exposed for architectural reasons, the installation of automatic fire sprinklers becomes essential. Sprinklers are among the most effective methods for delaying or halting the spread of fire. By dispersing water droplets over the affected area, they extract heat from the fire, disrupting one of the four critical components of the fire tetrahedron. In tests presented in CLT Handbook (Dagenais et al., 2019), the sprinklers were effective at lowering temperatures within a few minutes and preventing flashover from occurring.

In certain buildings and occupancies, the code may mandate the installation of an approved automatic sprinkler system. Incorporating such a system can offer significant advantages, including increased allowable building heights and areas, reduced fire resistance requirements for structural elements and the ability to use higher flammability interior finishes, such as exposed timber. These benefits sustain safety but also provide greater flexibility in architectural and interior design.

The coverage area for a sprinkler system is influenced by its nozzle layout and operating pressure. Among the various solutions available, mist systems are particularly effective. These systems use only about 1% of the water that traditional sprinklers require as seen in Figure 48. The much smaller droplet size in mist systems offers a larger surface area to absorb heat from fires, making them more efficient at extinguishing flames. Additionally, the reduced water usage means mist systems need smaller pipes, saving space in the building's infrastructure. This lower water volume also reduces the potential for water damage during system activation, including false alarms. This combination of efficiency, space-saving and reduced damage makes mist systems a superior choice for fire suppression.

The relevant standards for automatic sprinkler systems are NFPA (National Fire Protection Association) 13, 13R and 13D (Dagenais et al., 2019).

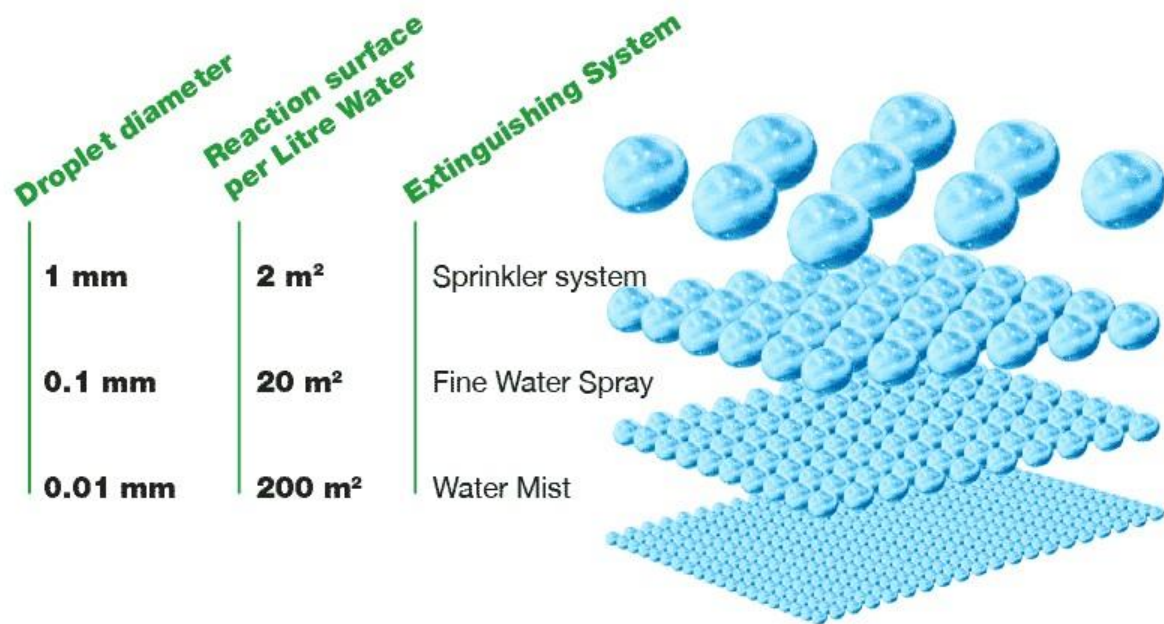


Figure 48. Type of extinguishing system and coverage area of one liter of water (Plumis Ltd, 2024)

6.3.4.5. Control of fire spread: Connections

Connections in mass timber construction are crucial for ensuring the overall strength, stiffness, stability, ductility and structural fire resistance of the building. However, in assemblies that combine steel and wood, the metallic connections like bolts, dowels and steel plates or brackets can become the most vulnerable components during a fire (Asdrubali et al., 2017). Steel rapidly loses its mechanical properties when exposed to high temperatures and its high thermal conductivity allows heat to be transferred quickly to the interior parts of the wooden sections, accelerating the charring process beyond just the external surfaces (Smart, 2024). As a result, the capacity of a metallic connection is diminished due to the reduced strength of the steel fastener at elevated temperatures and the charring of the surrounding wood members. The absence of fire-tested approvals for products and assemblies has posed significant challenges for the mass timber industry, unlike in more established construction methods such as concrete (Dagenais & Chen, 2023). However, research suggests that steel connections, when concealed within a protective layer of wood, exhibit strong fire resistance (Green Building Advisor, 2014). Nevertheless, given their crucial importance, it is essential that designers thoroughly consider the performance of these connections under fire conditions.

Therefore, the principle of the fire safety design is to retain the connection strength during a fire while minimizing unnecessary heat transfer into the wood, which could compromise the structural integrity of the timber elements. Thus, to safeguard connections and fasteners that are not integrated inside the assembly, it is necessary to enclose them with wood, gypsum board, or other protective materials approved for the required fire rating (Asdrubali et al., 2017; Smart, 2024). Additionally, the construction joints need to provide a fire stopping barrier where gaps could permit the passage of hot gases during a fire (special attention should be given along the continuous linear openings between fire-resistance-rated assemblies). Smoke-tight joints are crucial wherever fire barriers intersect with floors, walls, or roofs to maintain the integrity of the fire separation. This also applies to door installations, where it is important to protect the edges around the opening from hot gases and heat.

This can be achieved by filling the void space behind the door frame with rock wool insulation and applying a fire-resistant membrane, such as 16-mm Type X gypsum board, to the top and sides of the opening. Additionally, a layer of non-combustible material, like 11-mm cement board, should be installed under the threshold to ensure durability and resistance to repeated physical impact (Dagenais et al., 2024). To prevent the passage of smoke and hot gases at the interface, maintaining continuity between all elements is essential. This can be achieved by applying a continuous bead of firestop caulking along the edges, corners and thresholds, ensuring a tight seal that blocks any potential gaps.

The behaviour of timber connections under fire conditions can be highly intricate, influenced by various factors including the type of fastener used, the connection's geometry, potential failure modes and the differing thermal conductivity properties of steel, wood and the charred layer. These parameters collectively determine the performance and resilience of the connection when exposed to fire (Dagenais et al., 2019).

Additionally, it is important to mention that any through penetrations in mass timber construction should be carefully insulated and kept separate from the timber components. This prevents direct contact, minimizing heat transfer from the penetrating item to the timber, thereby reducing the risk of premature ignition, charring and potential flame penetration. Proper insulation around these penetrations is vital to maintaining the structural integrity and fire resistance of the timber elements (Dagenais et al., 2019).

To ensure that the connections and fire stops are well installed and perform as designated, early-stage project detailing, installation, inspections and maintenance are critical. Moreover, it is crucial to engage all project stakeholders in this process from the earliest stages to guarantee clear and effective communication, as well as addressing concerns from Authorities and the Fire Service early on can help in developing a robust design that is more likely to meet approval standards and streamline the approval process.

6.3.4.6. Control of fire spread: Encapsulation

An effective method for ensuring the fire performance of mass timber assemblies is the partial or total encapsulation approach (Asdrubali et al., 2017). This approach involves applying two layers of fire-rated gypsum board within each compartment and throughout the building. The encapsulation technique is similar to standard construction practices used in buildings with both combustible and non-combustible materials, to create fire-rated floors, roofs and walls, making it a practical and code-compliant solution (Green & Eric Karsh, 2012).

Research shown in CLT Handbook (Dagenais et al., 2019) demonstrates that the encapsulation effectively delays or prevents the involvement of mass timber (CLT in this case) in a fire, thereby limiting or eliminating its contribution to the fire's intensity. In the new Mass Timber Code Provisions, it is referred that two thirds of fire resistance must come from non-combustible protection (Smart, 2024). However, when more mass timber is left exposed, its contribution to the fire increases. Smaller window openings can exacerbate fire conditions within compartments, leading to more severe fire scenarios. These findings underscore the fire hazards associated with CLT construction, particularly in situations where there is no active fire protection (sprinkler systems) and where fires may burn for extended periods without intervention from fire services (Dagenais et al., 2019).

Although encapsulated mass timber construction can meet the necessary fire performance

standards, designers are likely to prefer incorporating some exposed wood surfaces for aesthetic or architectural reasons. To achieve both exposed mass timber aesthetics and fulfil fire safety requirements, a combination of encapsulation techniques and advanced fire protection strategies should be considered. Additionally, fire-resistant coatings and treatments that enhance the wood's fire performance without compromising its appearance can be integrated and the automatic sprinklers or other active fire protection systems installed to provide additional safety measures. By carefully balancing design and fire protection, the desired exposed timber look while meeting stringent fire safety standards can be achieved.

6.3.5. Fire safety during the construction

During the construction phase, wooden buildings are particularly vulnerable to fire risks, primarily because many safety systems, both active and passive, have not yet been fully installed. It is therefore crucial to recognize these risks early on, allowing for the implementation of appropriate precautions during the design stage and ensuring their effective execution prior to the beginning of construction. This proactive approach is essential for safeguarding all personnel on-site.

Ensuring that all on-site personnel are well-educated about fire risks is critical, as is the establishment of effective systems to promptly alert workers in the event of a fire and the creation of reliable evacuation routes to guarantee protection of everyone on site (Kaufmann et al., 2018). A comprehensive fire safety program must be developed for the construction phase, outlining all necessary measures to be taken by everyone involved in the process. This program should encompass fire protection systems for the ongoing construction, site organization, employee training and on-site security, among other critical aspects (O'Brocki, n.d.).

All stakeholders in the construction process must prioritize fire safety awareness and actively engage in adhering to fire safety regulations. This includes the immediate reporting and mitigation of potential fire hazards. Construction fires often originate from activities such as hot work, the use of heaters, or careless fire safety practices, such as the improper disposal of cigarettes. Mitigating these risks can be straightforward, for instance, by eliminating hot work where feasible and enforcing strict no-smoking policies on-site (Dagenais et al., 2019).

To uphold the highest standards of fire safety during construction, it is imperative to appoint a dedicated fire safety manager. This individual will be tasked with several critical responsibilities, including providing comprehensive training on the proper use of fire protection equipment, developing a pre-fire plan in collaboration with the local fire department and overseeing high-risk activities such as hot works. Moreover, the fire safety manager will manage a 24-hour guard service, implement a weekly inspection program and authorize any necessary impairments, thereby ensuring that all fire safety protocols are meticulously followed throughout the construction process (O'Brocki, n.d.).

As part of the responsibilities of the authority having jurisdiction, it is essential that the building department oversees the entire construction process. Collaboration with the fire service during the design phase is crucial to ensure they are fully aware of the risks associated with the construction and familiar with the site and building details. Also, the fire suppression division should be involved in creating a pre-fire plan that includes tactics, strategies, site water supply, access and exposure

protection assessments. This proactive engagement significantly enhances their ability to respond effectively in the event of a fire (National Fire Protection Association, 2014; O’Brocki, n.d.).

To enhance fire safety further, temporary or permanent standpipes must be installed during construction, along with a reliable water supply for fire department operations. The application of interior finishes, such as gypsum board, reduces the ignition potential of surfaces. Nevertheless, until permanent fire safety systems are fully installed, it is essential to provide fire protection features during construction for up to four stories below the active construction floor (Smart, 2024). Additionally, progressive cladding of exposed combustible materials with fire-resistant coverings and the phased commissioning of sprinkler systems should be implemented as construction progresses (Dagenais et al., 2019).

6.3.6. Fire safety measures in practical examples

This section presents a detailed analysis of fire safety features across five practical case studies: Wood Innovation and Design Centre, Treet, Ascent, HoHo Vienna and Forté, each representing a distinct approach to ensuring fire resilience in mass timber and complex building projects and responding to the code requirements in five different locations: Canada, Norway, USA, Austria and Australia. Table 14 summarizes the fire safety measures employed in these examples, highlighting both common practices and unique strategies tailored to the specific needs of each building. Through this comparative examination, the table illustrates the diverse ways in which fire prevention, detection and suppression systems can be integrated to enhance overall safety. Further analysis underscores the importance of a holistic, customized approach to fire safety, where the integration of multiple systems and redundancies is key to protecting both structures and occupants.

Across all cases, several common features contribute to robust fire safety strategies. Firstly, all cases include sprinkler systems, sometimes complemented by additional measures such as standpipes and smoke detectors, providing a comprehensive approach to fire suppression. Fire-resistant treatments are also consistently applied, particularly in critical areas where timber is exposed. These treatments vary from intumescent paint to other fire-resistant coatings, but the most prevalent method of timber protection is encapsulation, typically using one or two layers of gypsum board.

Smoke detection systems are another key feature, present in the WIDC, Ascent and Forté projects, enhancing early fire detection capabilities. Moreover, nearly all cases prioritize well-designed escape routes or access points for fire brigades, ensuring that safety and rapid response are integral to the building’s layout. Finally, three of the cases highlight the importance of sealing penetrations to prevent fire spread, using fire-rated caulking or similar materials, further reinforcing the buildings’ fire resistance. These commonalities underscore the importance of a multi-faceted approach to fire safety in timber construction, combining active and passive measures to protect both the structure and its occupants.

Among the five presented case studies, each building incorporates unique features that enhance fire safety in innovative ways. The Treet incorporates a system that maintains elevated pressure within the escape shafts, preventing smoke infiltration during a fire, while its horizontal concrete divisions at two levels significantly enhance the building’s overall fire resistance.

Table 14. Fire safety measures employed in selected examples

Name	N° Floors	Timber elements	Exposure	FR requirements	FR provided	Fire safety measures
Wood Innovation and Design Centre	8	Glulam posts and beams, CLT floors, CLT core, some LVL and PSL elements	Much of the structure, whenever possible	60 min for CLT walls and floors, 60 min for glulam posts and beams	60 min CLT floor, 90 min CLT walls, 60 min glulam posts and beams	- Intumescent paint on inside surfaces of elevator core, exit stairs, mechanical shafts and interior of mechanical room on the roof with effective smoke and fire separations - Penetrations through floors, core walls and connections sealed with fire-rated caulking - Sprinklers and smoke detectors - 2 unobstructed fire department access doors on every floor from level 2
Treet	14	Glulam beams and columns, CLT elevator shaft, internal walls and balconies	Glulam beams and columns whenever possible	Main load-bearing system 90 min, Secondary load-bearing system 60min	Main constructive parts 90 min, Modules 74 min	- Fully sprinklered, including the balconies - Elevated pressure in escape shafts - Fire resistant treatment on exposed surfaces - No cavities with combustible materials are left uninsulated - Horizontal concrete division at two levels to help the total fire resistance
Ascent	25	CLT floors and Glulam beams and columns	About 50%	120 min for beams, 180 min for columns	Test exceeded code prescriptions (approved by PBD)	- 50% of columns encapsulated with 3 layers of drywall, no exposed timber in places where there was no need (bathrooms) - Two water supplies for standpipes and fire sprinklers (in case one fails) - Enhanced smoke detection within each living unit
Ho Ho Vienna	24	75% of the structure is timber: CLT walls and Glulam columns	Ceilings, wall and columns left uncovered	90 min	The wooden components dimensioning exceeds the required level of E90 fire resistance	- Short escape and fire brigade routes - No vertical shafts in the wooden construction - Composite ceiling panels made of concrete and cross-laminated timber - From 3rd floor upward the façade is clad with fibre cement panels - Automatic fire extinguishing system - Small fire compartments
Forté	10	CLT panels	Feature walls, undersides of balconies, fire stairs and stairs well	FRL 90 min	FRL 90 min	- Fully sprinkled - Building design through disproportionate collapse - Walls with 13 mm fire resisting plasterboard on both sides - Floor panels with 2 layers of 16mm fire resisting plasterboard - External walls with fire resistant plasterboard - Connection between panels incorporated into the middle layer - Double shaft system without structural connection - Additionally: fire hydrant active from the beginning of the construction, 2 exits available off the site, no welding works one hour before closing works of the day

In contrast, the Hoho Vienna takes a different approach by eliminating the use of wood in vertical shafts altogether, thereby reducing the risk of vertical fire spread. Meanwhile, Forté introduces a distinctive double shaft system without any structural connection between them, adding an additional layer of fire resistance and further safeguarding against the spread of fire through the building's core. Each of these unique strategies contributes to the overall resilience of these timber structures, demonstrating varied approaches to achieving high standards of fire safety.

In conclusion, all five cases exhibit a high level of integration between fire prevention, detection and suppression systems, which is essential for ensuring safety in mass timber or complex construction projects. Although each case employs fire-resistant materials and systems, the methods differ significantly—from encapsulating timber and incorporating additional sacrificial layers to utilizing specialized construction techniques like composite panels. The importance of redundancy and multiple systems is particularly evident in the Ascent and Forté projects, where the inclusion of features like dual water supplies and double shaft systems ensures that fire protection remains effective even if one system fails. This highlights the need for robust, layered defences in fire safety planning.

Moreover, each case customizes its fire safety measures to the specific building design and potential risks, emphasizing that a one-size-fits-all approach is inadequate for complex buildings. Different fire safety provisions are necessary depending on the building's location and characteristics.

In summary, while all cases prioritize fire safety through a blend of active and passive measures, the specific strategies employed are tailored to the unique challenges of each project. This integration of diverse approaches underscores the critical need for customized fire safety planning in modern building design and construction.

6.3.7. Project team handout summary: Fire safety for high-rise timber buildings

Objective: To ensure fire-safe, code-compliant and occupant-safe mass timber buildings using an integrated, performance-based approach.

What must be done:

- ✓ Design timber elements to resist fire using mass and charring;
- ✓ Add gypsum or concrete layers where fire exposure is high;
- ✓ Install sprinkler systems and alarms as standard practice;
- ✓ Build fire-rated compartments and protect all penetrations;
- ✓ Plan for construction phase risks: fire manager, water access, covering timber early;
- ✓ Model, test and inspect regularly;
- ✓ Collaborate with fire engineers and authorities from day 1;
- ✓ Learn from successful case studies.

Why it matters:

Failing to integrate fire protection from the start can compromise structural integrity, violate code and put lives at risk. Fire-safe mass timber design is not only feasible but proven, when supported by proper detailing, planning and collaboration.

6.4. Thermal performance

Much like the innate, organic connection between wood and the human body, mediated through its favourable thermal properties, mass timber construction has the potential to foster emotional well-being and enhance the overall quality of life within residential and occupational environments. Timber distinguishes itself in construction through its beneficial thermal performance, primarily attributed to its inherently low thermal conductivity and natural insulation properties (Caniato et al., 2017). The first characteristic is readily observable: when both wood and metal surfaces are at the same temperature, the wooden surface feels warmer to the touch due to its significantly lower rate of heat transfer. As timber's thermal conductivity is substantially lower than that of most conventional construction materials, it makes it particularly effective in minimizing heat flow. This results in improved thermal insulation, thereby reducing the demand for heating and cooling and enhancing the overall energy efficiency of buildings throughout their lifecycle (Dodoo et al., 2014; Forest Products Laboratory, 2010; Pryce, 2016). Despite these advantages, the thermal performance of mass timber must be carefully addressed in high-rise design, with attention to insulation detailing, potential thermal bridging at joints or interfaces and compliance with energy performance standards to optimize energy efficiency, structural integrity and occupant comfort.

6.4.1. Thermal properties of timber

When assessing timber's thermal performance, four key properties are considered: thermal conductivity, heat capacity, thermal diffusivity and the coefficient of thermal expansion, as well as some other factors as thermal mass, density and moisture content (Asdrubali et al., 2017; Forest Products Laboratory, 2010).

6.4.1.1. Thermal conductivity

Thermal conductivity ($\text{W/m}\cdot\text{K}$) is defined as the measure of the rate at which heat flows through a material under a unit temperature gradient across a unit thickness (Forest Products Laboratory, 2010; Qiu et al., 2017). Figure 49 shows a comparative overview of thermal conductivity values (in $\text{W/m}\cdot\text{K}$, log scale) across various construction and insulation materials. Thermal conductivity is a key property that indicates a material's ability to conduct heat, the lower the value, the better the insulation performance.

Wood (including mass timber products) is shown with a thermal conductivity range between 0.05 and 0.4 $\text{W/m}\cdot\text{K}$, placing it significantly below conventional structural materials such as:

- Concrete and stone (0.1–3.8 $\text{W/m}\cdot\text{K}$);
- General structural materials (0.1–3.8 $\text{W/m}\cdot\text{K}$);
- Metals and alloys, which have extremely high conductivity (13–380 $\text{W/m}\cdot\text{K}$);
- With carbon structural materials reaching up to 1000 $\text{W/m}\cdot\text{K}$.

This demonstrates that wood provides substantially better insulation than standard construction materials, although it is not as insulating as dedicated materials like:

- Insulation materials (0.02–0.2 $\text{W/m}\cdot\text{K}$);
- Polymer foams (0.02–0.2 $\text{W/m}\cdot\text{K}$);
- Aerogels, the most insulating class (as low as 0.01 $\text{W/m}\cdot\text{K}$).

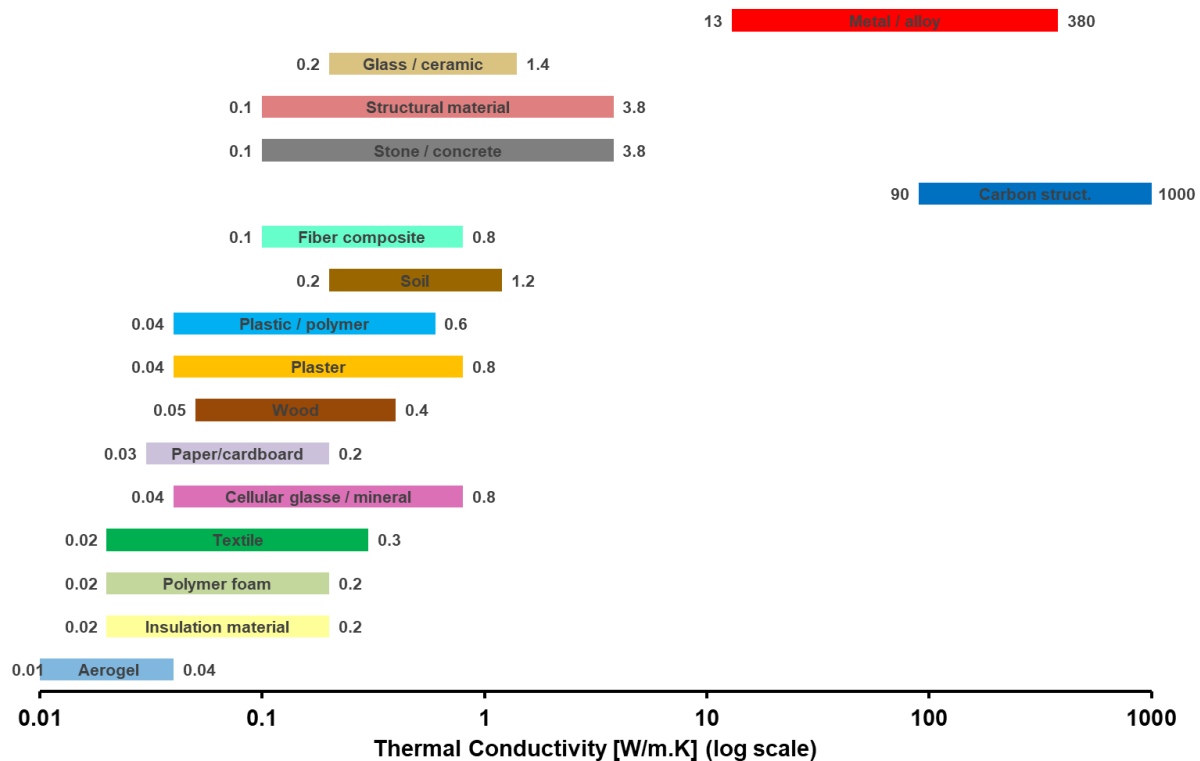


Figure 49. Thermal conductivity of building materials (log scale) (Johra, 2021)

As wood occupies an intermediate position between structural and insulating materials, it is not a pure insulator. However, its relatively low thermal conductivity can significantly contribute to improved energy efficiency in buildings. This characteristic makes mass timber a particularly advantageous material in the context of sustainable and thermally efficient design, as it combines adequate structural performance with superior thermal behaviour compared to conventional construction materials such as concrete and steel.

The thermal conductivity of timber is influenced by a range of intrinsic factors, including its density, moisture content, chemical extractive composition and the presence of structural irregularities such as checks, knots and deviations in grain orientation, as well as the ambient temperature. In general, increases in any of these parameters tend to elevate thermal conductivity. Reflecting the anisotropic nature of wood's cellular structure, thermal conductivity along the grain (longitudinal direction) is typically 1.5 to 2.8 times higher than across the grain (radial and tangential directions). In contrast, conductivity in the radial and tangential directions tends to be nearly identical (Forest Products Laboratory, 2010; Shi & Chew, 2023). This directional variation highlights the importance of grain orientation in thermal performance issues for timber in building applications.

6.4.1.2. Specific heat capacity

Heat capacity, also known as thermal capacity (J/kg·K), is defined as the amount of energy (J) required to raise by one unit of the temperature (K) of one unit of mass of a material (kg) and is a key indicator of a material's ability to store thermal energy (Forest Products Laboratory, 2010). In the case of wood, heat capacity is primarily influenced by two variables: temperature and moisture content. It is largely independent of the wood's density or species.

Notably, the presence of moisture significantly increases wood's heat capacity. This is because

water has a high specific heat capacity and when absorbed into the wood matrix, it contributes substantially to the overall thermal inertia of the material. As a result, moist wood can store and release greater amounts of thermal energy compared to dry wood, which has implications for its thermal buffering capacity and its performance in dynamic thermal environments.

Figure 50 illustrates the specific heat capacity of various construction and insulation materials.

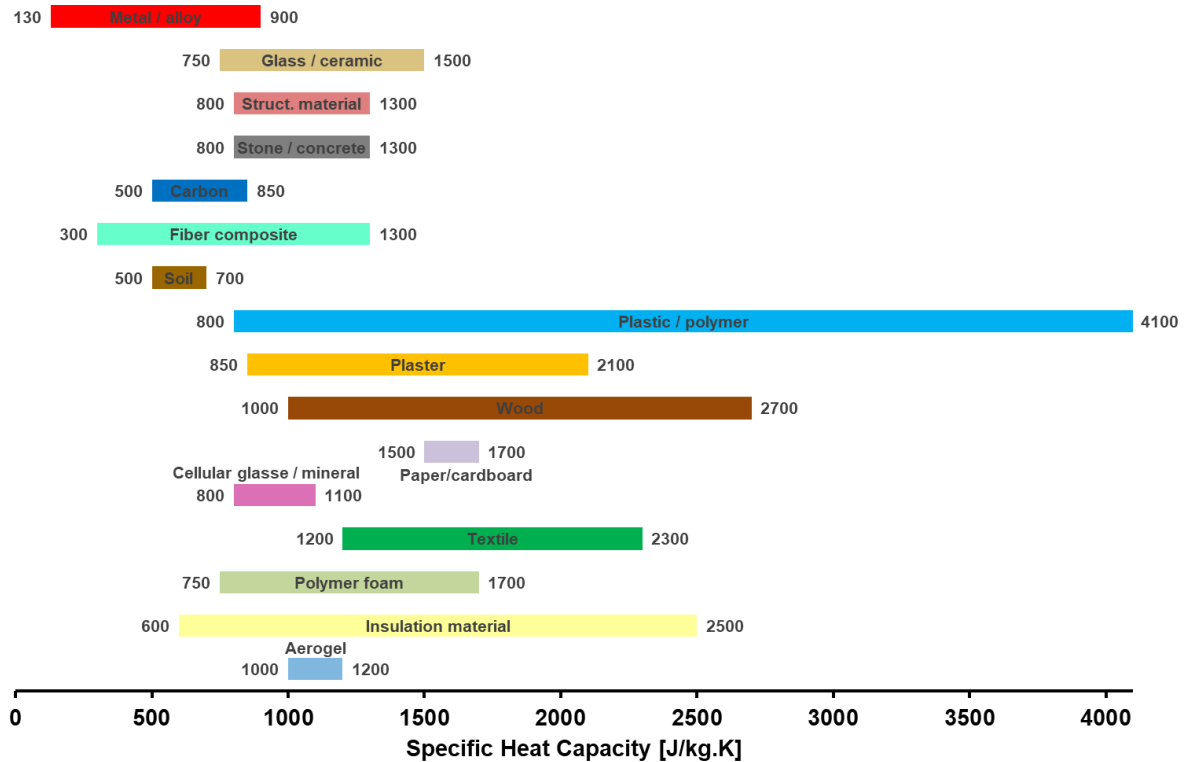


Figure 50. Specific heat capacity of building materials (log scale) (Johra, 2021)

Wood, including mass timber products, exhibits a relatively high specific heat capacity, ranging from 1000 to 2700 J/kg·K. This positions it as one of the most thermally responsive structural materials. As mentioned previously, the direct relation of the heat capacity of wood and moisture content explains the wide range observed. In general, its thermal mass enables it to absorb and store significant amounts of heat, thereby contributing to thermal stability and delayed heat transfer in building interiors.

Relative to traditional structural materials, wood demonstrates superior specific heat capacity. Concrete, stone and general structural materials typically range from 800 to 1300 J/kg·K, while metals and alloys, such as steel, show much lower values, between 130 and 900 J/kg·K. These materials, although mechanically robust, store significantly less heat and react more quickly to external temperature changes.

Wood's thermal performance also compares favourably with certain non-structural and insulating materials. For example, plaster and paper-based materials reach similar ranges (up to 2100–2700 J/kg·K), while insulation materials go in the range of 600–2500 J/kg·K. However, these materials do not contribute structurally and are typically used in combination with a load-bearing system.

Overall, the dual function of wood, as both a structural material and a thermal energy buffer, makes it particularly advantageous in sustainable building design. Its relatively high heat capacity can enhance

occupant comfort by regulating indoor temperatures, reducing peak thermal loads and supporting passive heating and cooling strategies. These characteristics underscore the relevance of mass timber in the context of energy-efficient, climate-responsive architecture (Khavari et al., 2016).

As discussed in the fire performance section, specific heat capacity plays a supporting role in timber's response to fire. It represents the amount of thermal energy a material can absorb before experiencing a temperature increase. In fire conditions, materials with higher specific heat capacity heat up more slowly, as they require more energy to raise their temperature. For timber, this means that the inner mass of the element remains cooler for longer, contributing to delayed ignition and a slower inward progression of combustion. When combined with timber's low thermal conductivity and moderate density, this property enhances its thermal inertia (the resistance to rapid temperature change) (Dagenais et al., 2019; Kaufmann et al., 2018). As a result, timber exhibits more gradual and predictable fire behaviour than highly conductive materials like steel, supporting its effective use in fire-safe structural design.

6.4.1.3. Thermal diffusivity

Thermal diffusivity is a material property that quantifies the rate at which heat is conducted through a material relative to the rate at which it is stored. It is defined as the ratio of thermal conductivity to the product of density and specific heat capacity, and is expressed in units of square metres per second (m^2/s) (Forest Products Laboratory, 2010; Owczarek et al., 2021). This parameter characterizes how quickly a material responds to changes in thermal conditions, with higher values indicating faster heat propagation and lower thermal inertia. The thermal diffusivity of mass timber is influenced by several factors, including its composition, moisture content, density and microstructural characteristics (Forest Products Laboratory, 2010; Shi & Chew, 2023). Due to its combination of low thermal conductivity, moderate density and specific heat capacity, wood exhibits significantly lower thermal diffusivity compared to most conventional structural materials. This indicates a slower rate of internal heat propagation, contributing to its favourable thermal inertia. These findings are supported by the studies conducted by Johra (2021) and can be observed in Figure 51, which confirm the superior thermal buffering characteristics of wood in building applications.

6.4.1.4. Thermal expansion

Thermal expansion refers to the tendency of materials to undergo changes in dimension and density in response to temperature fluctuations (Forest Products Laboratory, 2010). Wood, as an anisotropic material, exhibits direction-dependent thermal expansion, with different coefficients observed along the longitudinal, radial and tangential directions (Miki et al., 2014). The coefficient of linear thermal expansion (CLTE) for wood is generally positive, indicating that it expands when heated and contracts when cooled. However, the magnitude of this expansion is significantly influenced by both temperature and moisture content. For example, dry wood displays a marked increase in CLTE at temperatures below 0 °C, a notable decline around 50 °C and another drop beyond 130 °C (Miki et al., 2014).

Water-saturated wood exhibits more pronounced dimensional changes and higher CLTE values compared to air-dried or oven-dried wood, making moisture control essential in maintaining dimensional stability. Thermal expansion can also affect the mechanical performance of timber, particularly at low temperatures, where changes in stiffness and strength may occur (Zhao et al., 2016).

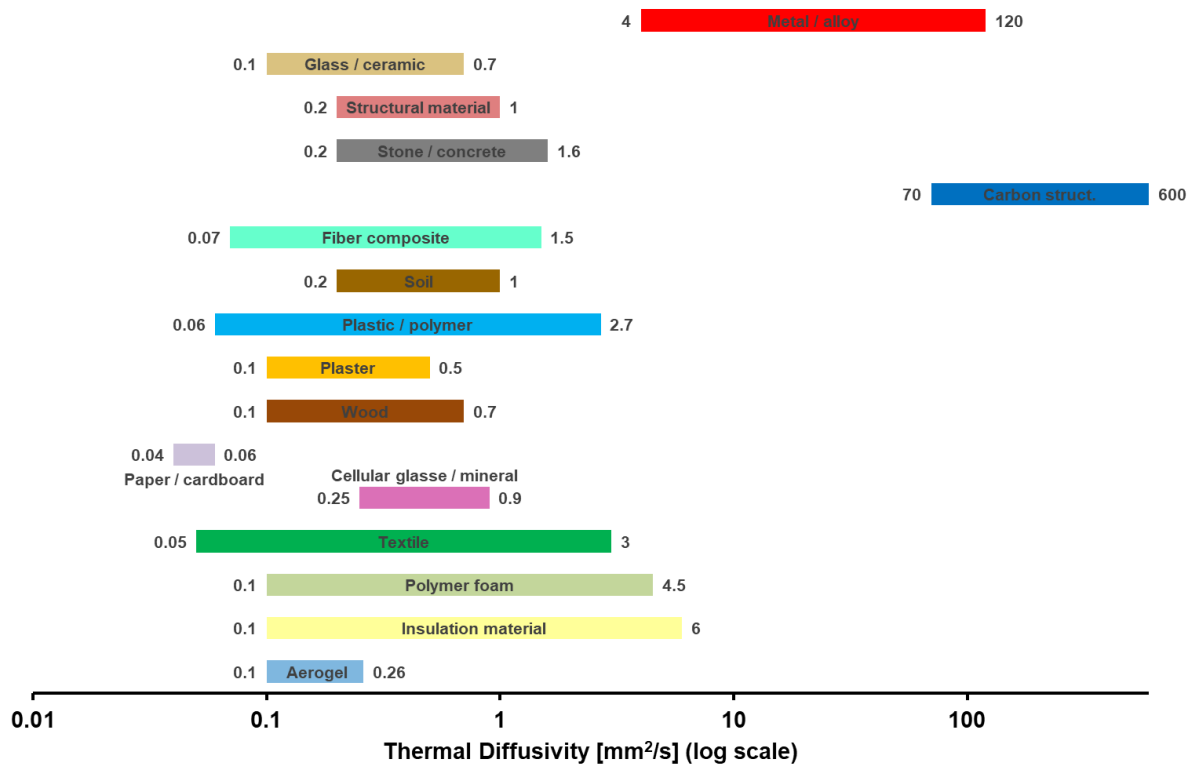


Figure 51. Thermal diffusivity of building materials (log scale) (Johra, 2021)

To mitigate these effects, thermal modification, a process involving controlled heating of wood at elevated temperatures, is commonly employed. This treatment enhances dimensional stability and reduces moisture-induced shrinkage, thereby improving long-term durability in construction applications (Hasanagić et al., 2023). However, it may also lead to a reduction in certain mechanical properties, requiring careful consideration in structural design. Overall, maintaining a stable indoor temperature and selecting appropriately treated wood products are critical strategies for ensuring the performance, dimensional stability and longevity of timber elements in buildings.

6.4.2. Thermal design

Designing a thermally efficient mass timber high-rise building requires careful consideration of multiple interrelated factors, including thermal mass, insulation, airtightness and hygrothermal behaviour. Achieving optimal occupant thermal comfort and enhanced energy efficiency depends on a well-balanced integration of design strategies that are responsive to the climatic context, accounting for both seasonal and diurnal variations in temperature and humidity. In this regard, the application of bioclimatic design principles, which emphasize the incorporation of natural environmental conditions into architectural planning, is essential for promoting sustainability and reducing operational energy demand in buildings (Hall, 2010; Vakharia & Joshi, 2024; Wille & Woolf, 2015).

It is important to recognize that numerous assemblies, construction details and materials commonly used in low-rise wood-frame buildings may be inappropriate for taller structures, primarily due to the heightened environmental exposure and the more stringent durability requirements associated with high-rise applications (Finch, 2016).

6.4.2.1. Enclosure - Control of heat, air and moisture

The incorporation of mass timber in building construction does not fundamentally alter conventional thermal design principles, rather, it can benefit from enhanced thermal envelope strategies aimed at improving energy efficiency. However, it requires particular attention to the hygroscopic nature of wood, which influences its thermal and hygrothermal behaviour. A thorough understanding of these material-specific properties is essential to ensure the long-term performance, dimensional stability and durability of mass timber elements within the building envelope. The careful selection of high-performance, compatible insulation materials in combination with mass timber, high-efficiency glazing and airtight sealing is essential to minimize heat transfer and enhance overall thermal resistance (Morales-Vera et al., 2021).

The building enclosure serves as a critical environmental barrier that regulates thermal, acoustic and visual conditions, ensuring indoor comfort and long-term durability. In high-rise timber structures, enclosure design must account for wood's sensitivity to moisture and its anisotropic dimensional changes due to temperature and humidity fluctuations. A successful strategy for managing the dimensional changes of wood in tall buildings requires a holistic approach that combines material science, building physics and practical construction measures. In tall wood buildings, a cumulative vertical movement (due to shrinkage, compression and seasonal expansion/contraction) must be anticipated and accommodated. For example, at the Wood Innovation and Design Centre, flexible air and watertight joints were designed to absorb up to 1 inch of differential movement between curtain wall systems and CLT floors. The structure used continuous glulam columns to minimize "shrinkable" elements, limiting differential movement across floors (Castro, 2021; Finch, 2016; Wood Innovation and Design Centre, n.d.). The described solution is represented in Figure 52. Additionally, movement joints, such as cross-cavity flashings and silicone transition strips were used at every floor level to accommodate vertical and horizontal movement in walls and cladding systems. These are essential in preventing cracking, deformation, or rupture of cladding or air/vapour barrier systems due to differential movement between materials (Finch, 2016).



Figure 52. Wood structure and building enclosure elements of Wood Innovation and Design Centre (Wood Innovation and Design Centre, n.d.)

Additionally, the use of prefabricated components can significantly improve the thermal efficiency of a building (Finch, 2016). Fabrication in controlled manufacturing environments facilitates greater dimensional precision, consistent material quality and accurate implementation of thermal detailing. In addition, the use of just-in-time delivery and dry construction techniques significantly reduces on-site variability and limits the exposure of building components to moisture, thereby improving the overall durability, airtightness and thermal performance of the building envelope. These benefits are maximized when integrated with a rigorously developed and systematically implemented moisture management and quality control plan throughout all phases of the construction process.

Optimizing thermal performance in buildings requires the implementation of high-performance insulation systems combined with strategies to minimize thermal bridging. Continuous insulation across all elements of the building envelope is critical to reducing heat loss and enhancing energy efficiency. In mass timber construction, the use of interior insulation should be avoided wherever possible in order to maintain the timber elements within the warm side of the thermal envelope. Condensation within exterior wall assemblies during cold weather represents a common performance challenge, particularly in climates with significant temperature differentials. This phenomenon arises from large differences in water vapour partial pressure across the building envelope, which drive vapour migration toward cooler interior layers. While the implementation of air barriers and vapour control layers can effectively reduce the extent and frequency of interstitial condensation, the most effective strategy for mitigating this risk is the application of thermal insulation on the exterior side of the wall assembly. By maintaining the temperature of internal components above the dew point, exterior insulation minimizes the likelihood of condensation forming within moisture-sensitive layers, thereby preserving the thermal integrity and durability of the envelope (McClung et al., 2014). Thus, prioritizing exterior insulation not only supports the long-term durability of timber but also enhances the hygrothermal stability of the building envelope. Therefore, designers should avoid placing more than one-third of the insulation value on the interior side unless a detailed hygrothermal analysis is performed (Finch, 2016). Keeping the wood warm facilitates inward drying, allowing any incidental moisture within the assembly to be released toward the interior environment, reducing the risk of condensation and associated moisture-related deterioration. It is essential, however, that the insulation contribution of each material within the assembly is accurately detailed and properly installed to guarantee optimal performance. This must be complemented by carefully designed airtight construction and appropriately positioned vapour control layers, tailored to the specific climate and wall assembly type (Green & Taggart, 2017). To promote drying and accommodate dimensional movement in mass timber assemblies, the use of vapour-permeable membranes and materials is strongly recommended. These components support the safe evacuation of moisture from within the building envelope. For instance, applying vapour-permeable air and water barriers to the exterior side of CLT walls enables trapped moisture to escape, without compromising either structural integrity or thermal performance. In contrast, the use of rigid or vapour-impermeable membranes directly on the surface of dimensionally active wood elements should be avoided, as they can inhibit drying and exacerbate moisture accumulation, leading to long-term durability concerns (Finch, 2016). The simplified idea of the airtightness and water protection layers placement is represented by Figure 53 and different moisture and vapour solutions by Figure 54.

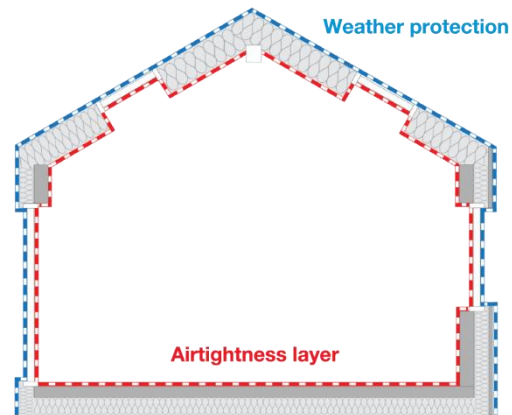


Figure 53. Airtightness layer and weather protection layers (SIGA, 2023)

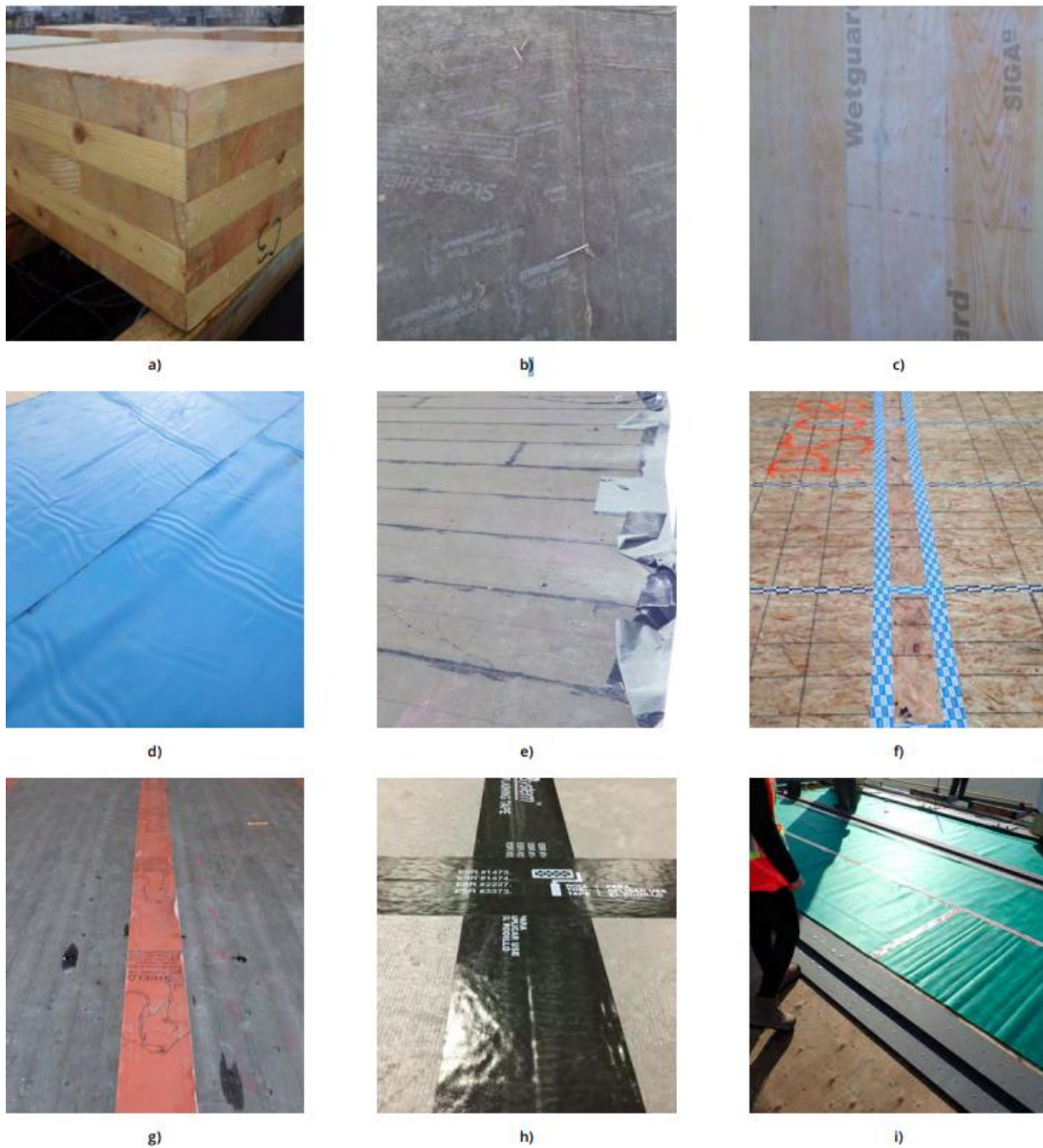


Figure 54. Moisture and vapour protection: a) hydrophobic coating; b) vapour-permeable self-adhered membrane; c) vapour-semipermeable self-adhered membrane; d) vapour-impermeable self-adhered membrane; e) vapour-impermeable self-adhered SBS roofing base sheet; f) vapour-impermeable tape installed at sheathing joints; g) vapour-permeable tape installed at panel joints; h) coated sheathing with taped joints; i) vapour-impermeable loose-laid acoustic mat with taped laps (RDH Building Science Inc., 2022)

An illustrative example underscoring the importance of robust envelope design in mass timber construction is the case of the “Zero Carbon School” in Dartington, UK. Despite receiving multiple awards and being constructed in massive wood at a cost of £6.5 million, the building was demolished in 2017, just seven years after completion. A report by the Building Research Establishment (BRE) attributed the failure primarily to critical design deficiencies, specifically the omission of a vapour control layer on the warm side of the insulation and the use of inadequate waterproofing materials (Braidwood, 2017). These shortcomings led to uncontrolled water vapour movement and persistent condensation within the building envelope, ultimately compromising the integrity of the timber structure. The BRE further cited a fundamental lack of understanding regarding moisture transport mechanisms and the absence of a fully watertight roofing system. This case highlights the essential role of integrated hygrothermal design and moisture control strategies in ensuring the durability and performance of timber buildings, particularly in climates prone to high humidity and precipitation.

In addition, effective air sealing, achieved through the use of thermal break materials around critical junctions such as wall to floor or roof, windows, doors and service penetrations, is vital to eliminating unintended air leakage, which can significantly undermine both the thermal efficiency of the building envelope and the overall quality of the indoor environment (Finch, 2016; Morales-Vera et al., 2021). The example of simple sealing solution is shown in Figure 55. This can be achieved through the implementation of air tightness testing protocols conducted both during and after the construction phase, ensuring compliance with rigorous performance standards for building envelope integrity.

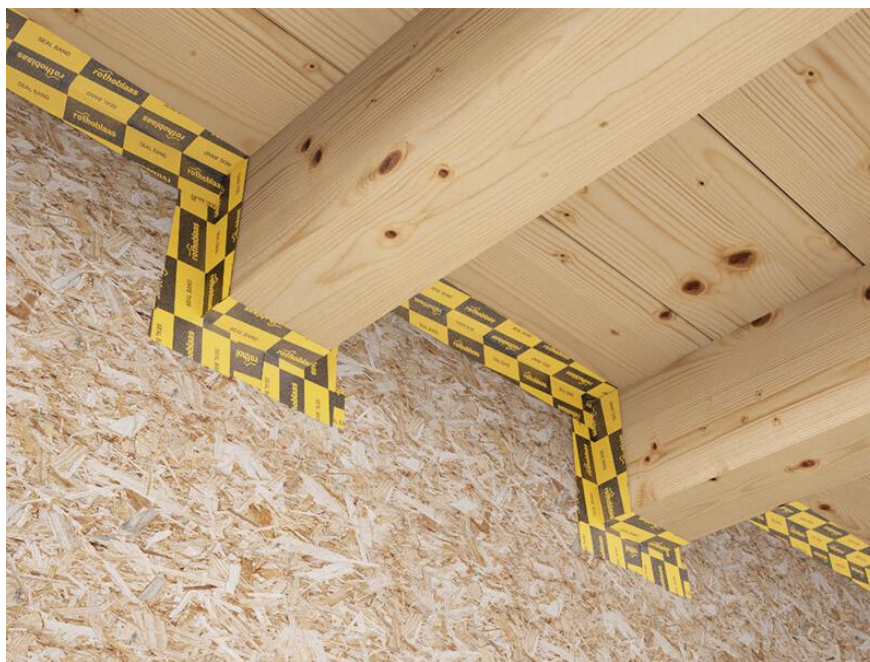


Figure 55. Sealing single-sided tape (rothoblaas, 2025)

6.4.2.2. Thermal mass

The performance of thermal mass in mass timber buildings is a nuanced topic with several factors influencing its effectiveness. The lightweight nature of timber, which does not store and release heat as effectively as heavier materials like concrete, can lead to higher cooling demands and poorer energy

performance in hot climates (Ratajczak et al., 2016). However, mass timber structures encompass a spectrum of thermal storage capacity, as a result, they can no longer be classified solely as lightweight construction systems (Kaufmann et al., 2018). The integration of hybrid systems, such as timber–concrete composite floors, can significantly increase the thermal mass of timber buildings. By enhancing heat storage capacity, these systems contribute to the mitigation of indoor overheating and promote energy efficiency, particularly in climates with pronounced temperature fluctuations. (Liu & Chang, 2018). Nevertheless, timber structures with well-designed insulation can effectively prevent excessive heat gain during summer, as a highly insulated timber envelope resists external heat transfer just as efficiently as it insulates against cold in winter, offering year-round thermal protection comparable to that of other building types (Finch, 2016; Kaufmann et al., 2018; Lancashire, 2010).

6.4.2.3. Ventilation

Thermal comfort is strongly influenced by the effective integration of passive solar design strategies, which should be incorporated from the earliest stages of architectural planning. Key elements such as building orientation, external shading and natural ventilation can significantly reduce dependence on active heating and cooling systems, thereby aligning with the sustainability objectives of mass timber construction. In particular, well-designed ventilation systems that leverage the building's orientation and window placement can enhance natural airflow and contribute to lower energy consumption and operational costs (Asfour, 2015). This approach is especially advantageous in mass timber buildings, which prioritize energy efficiency and environmental performance. Ensuring that the thermal design also supports high indoor environmental quality, including effective temperature regulation, air quality and humidity control, is essential to achieving occupant comfort and overall building sustainability.

Advanced energy modelling and simulation tools should be employed during the design phase to accurately predict the building's thermal performance and inform the selection and optimization of passive and active design strategies. In parallel, post occupancy monitoring systems are essential for tracking actual thermal behaviour, enabling adaptive building management and operational fine tuning. When properly designed and operated, low energy buildings characterized by high-performance insulation and airtight exterior envelopes can reliably ensure thermal comfort for occupants. By integrating these principles and technologies, high rise mass timber buildings can achieve superior thermal performance, contributing to both energy efficiency and occupant well-being, while reinforcing broader sustainability objectives. Such strategies not only harness the inherent thermal advantages of timber but also address the specific design challenges associated with vertical timber construction.

6.4.3. *Project team handout summary: Thermal performance in high-rise timber buildings*

Objective: To design and deliver thermally efficient, comfortable and durable mass timber high-rise buildings by optimizing thermal properties, material selection, moisture control and enclosure design.

What must be done:

- ✓ Understand and optimize timber's thermal properties;
- ✓ Prioritize exterior insulation and airtight design;
- ✓ Choose vapour-permeable and airtight membranes accordingly;
- ✓ Design for moisture management and dimensional stability;
- ✓ Use prefabrication and quality control strategies;
- ✓ Integrate passive and bioclimatic design principles;
- ✓ Consider hybrid systems for thermal mass;
- ✓ Verify thermal performance.

Why it matters:

Mass timber exhibits low thermal conductivity, high specific heat capacity and strong thermal buffering, making it ideal for energy-efficient buildings. However, to fully harness these advantages, especially in high-rise applications, projects must address challenges related to moisture sensitivity, dimensional changes and detailing complexity.

A thermally efficient envelope enhances occupant comfort, reduces operational energy demand and prolongs building durability. Improper insulation detailing or lack of vapour control can result in condensation, structural damage and costly repairs, as exemplified by failures like the Zero Carbon School case.

By following these guidelines, stakeholders ensure that mass timber buildings meet modern sustainability standards, reduce carbon emissions and perform reliably across varying climatic conditions.

6.5. Acoustic performance

Acoustic comfort is a critical parameter in the design of high-rise buildings, regardless of whether the structural system is composed of timber, concrete, or steel. It significantly influences occupant well-being and productivity, as inadequate acoustic performance can lead to reduced privacy, increased stress, compromised security and adverse health effects (Jensen et al., 2008; WHO, 2011). In high-rise timber buildings, achieving acoustic performance comparable to that of traditional systems remains a key challenge, mainly for inter-tenancy floors, where effective sound insulation must be ensured to meet building regulations and occupant comfort requirements (Yeoh et al., 2015). These buildings are particularly susceptible to issues such as low-frequency airborne sound transmission, impact noise and structural vibrations, which are more difficult to mitigate due to the lighter and more flexible nature of timber (Di Bella & Mitrovic, 2020; Finch, 2016). Addressing these complexities requires the integration of advanced acoustic modelling, the use of innovative materials and the application of carefully optimized design strategies that maintain a balance between acoustic performance, structural efficiency and environmental sustainability. Hybrid construction systems and novel sound-dampening solutions can be effective, though they often involve trade-offs related to cost, weight and material sustainability (Balmori et al., 2025; Caniato et al., 2017; Lin et al., 2021; Morandi et al., 2020). Additionally, acoustic requirements may conflict with other building performance goals, needing an integrated design approach. For example, while resilient floor finishes such as carpet or rubber reduce impact sound and enhance thermal insulation, they can hinder the effectiveness of radiant floor heating systems. Therefore, the early involvement of an acoustical engineer in the project is essential to optimize performance across disciplines, particularly in mass timber buildings (Green & Taggart, 2017).

6.5.1. *Regulatory limits*

Noise control has emerged as a critical concern in high rise buildings, driven by increasing occupant expectations for acoustic comfort. In particular, inadequate sound insulation is among the most frequently reported issues in multi-family residential buildings (Green & Taggart, 2017). This widespread concern has driven the development of regulatory limits on noise levels, which are now embedded in national and international standards as well as local building codes to ensure minimum acoustic performance requirements are met (Palmer, 2013).

Various measurement methods and corresponding acoustic performance indicators are used to evaluate sound insulation:

- Sound transmission class (STC). This is a single-number rating that quantifies a partition's sound isolation value, derived from laboratory measurements of sound transmission loss (STL). It is commonly used in the United States and Canada and is specified in ASTM E413-16 (ASTM International, 2016). The rating is based on a frequency range of 125 Hz to 4000 Hz and may not be directly comparable to the weighted sound reduction index (R_w), as the two systems use different frequency weighting criteria;
- Apparent sound transmission class (ASTC). This is a single-number rating of a partition's sound isolation value based on laboratory measurements, which also considers flanking transmission paths, such as shared floors or ceilings, to provide a more realistic assessment of acoustic performance (National Research Council Canada, 2017). It is increasingly being adopted as a replacement for the traditional STC rating;
- Weighted sound reduction index (R_w). Widely used internationally, this single-number rating quantifies the reduction of airborne sound transmitted through a partition, as defined in ISO 10140-2:2010 (International Organization for Standardization, 2010). It is determined under controlled laboratory conditions and is based on sound transmission measurements across a frequency range of 100 Hz to 3150 Hz;
- Weighted apparent sound reduction index (R'_w). This single-number rating assesses the reduction of airborne sound transmission through a partition, as specified in ISO 16283-3 (International Organization for Standardization, 2016). It is determined under field conditions and accounts for the influence of flanking transmission paths and reverberation, providing a more representative measure of in-situ acoustic performance;
- Weighted standardised level difference dB (D_nT_w). This field-based assessment of airborne sound transmission through a partition is used to evaluate the acoustic performance of buildings and of building elements, in accordance with ISO 717-1:2020 (International Organization for Standardization, 2020a). The measurement incorporates the effects of reverberation within the receiving room, offering a realistic representation of in-use sound insulation performance.

A major challenge in specifying acoustic materials and construction systems lies in the regional variation of rating systems, with different parts of the world and consequently, different manufacturers, relying predominantly on either STC or R_w values. These metrics are not directly interchangeable, as they differ not only in geographic adoption but also in measurement methodology and the frequency ranges considered (LoVerde & Dong, 2018). STC ratings are generally determined under controlled laboratory conditions, reflecting idealized performance scenarios (Conroy & Roland, 2003). In contrast,

Rw values can be influenced by real-world factors and may incorporate adjustments for specific noise profiles, such as traffic noise, which tends to be more prominent at lower frequencies (Arana et al., 2005). As a result, careful interpretation and contextual understanding of these ratings are essential when comparing or specifying acoustic solutions across different regions.

To prevent occupants from being unduly disturbed by noise generated from adjacent spaces, building regulations in many jurisdictions establish minimum sound insulation requirements, some of which are illustrated in Table 15. However, there is considerable international variation in these standards, both in terms of performance thresholds and the measurement methodologies employed. While some codes specify laboratory-based metrics such as Rw or STC, others rely on field-derived values such as R'_w, D_{nT,w} or ASTC. These differences reflect regional preferences and complicate direct comparisons between regulatory frameworks.

Table 15. Examples of specified airborne sound attenuation requirements between dwellings for new buildings

	Minimum performance	Acceptable performance	Preferred performance
Laboratory rating for walls separating dwellings			
International Building Code (US)	STC 50	STC 55	60
Australia (Alonso, et al., 2020)	R _w + C _{tr} 50	N/A	N/A
Canada. (National Research Council Canada, 2015)	STC 55	N/A	N/A
Field rating for walls separating dwellings			
Denmark (Rasmussen, 2011)	55 dB R' _w	58 dB R' _w + C ₅₀₋₃₁₅₀	63 dB R' _w + C ₅₀₋₃₁₅₀
International Building Code (US)	ASTC 45	ASTC 52	ASTC 57
Canada (National Research Council Canada, 2015)	ASTC 47		
England and Wales (HM Government, 2010)	45 dB D _{nT,w} + C _{tr}	N/A	N/A
Portugal (Portuguesa, 2008)	50 dB D _{nT,w}	N/A	N/A
Lithuania (Alonso, et al., 2020)	D _{nT,w} /R' _w ≥ 55	N/A	N/A

As noted earlier, floor assemblies are rated for airborne sound insulation using indices such as STC or Rw. In addition, they are further classified based on their ability to attenuate impact noise, particularly footfall, using the following metrics:

- The weighted standardised level difference of impact noise through a floor dB (L'_{nTW}). Used in on-site tests to check the performance of a build. Defined in ISO 717-2: 2020 (International Organization for Standardization, 2020b);
- Weighted normalized impact sound pressure level (L'_{nW}). Laboratory measurement of sound performance of a floor. Based on laboratory tests. Defined in ISO 717-2: 2020 (International Organization for Standardization, 2020b);
- Impact insulation class (IIC). A single-number laboratory rating, which describes how much noise is created in a space below by footfalls/impact on a floor through a ceiling. Defined in ASTM E989-18 (ASTM, 2018). The International Building Code defines values for minimum performance IIC 50, acceptable performance (grade B) IIC 55 and preferred performance (grade A) IIC 60 (International Code Council, 2024);

- Field impact insulation class (FIIC). Field measured rating of impact noise transmission through a floor. Defined in ASTM 1007-19 (ASTM, 2019);
- Normalized impact sound rating (NISR). A single number rating quantifies the level of impact sound transmission through a floor and ceiling assembly. It indicates the assembly's effectiveness in attenuating structure borne noise generated by impacts, such as footsteps, from being transmitted between adjacent spaces. In the International Building Code, the minimum value of NISR for field rating for floors separating dwellings is 45, acceptable performance (grade B) is 52 and preferred performance (grade A) is 57 (International Code Council, 2024).

6.5.2. Noise in high-rise buildings

Effective acoustic design must address both airborne and impact noise (Balmori et al., 2025). The lightweight nature of timber affects sound insulation and vibration control. Although noise generated by internal sources is not inherently a construction defect, its transmission between adjacent spaces is significantly influenced by the building's structural configuration and material properties. In particular, the degree of sound transmission is determined by the effectiveness of airborne sound insulation and the level of isolation from structure borne noise, such as impact sound (Barlow, 2021). Additionally, flanking transmission occurs when sound waves bypass intended insulation elements by travelling through neighbouring structural components, which can further reduce overall acoustic performance if not properly addressed during the design and construction phases.

Furthermore, inherent complexity of timber structural systems, characterized by features such as multiple cavities, stiffeners and layered assemblies poses significant challenges for acoustic performance modelling. Reliable prediction of airborne sound insulation and impact noise transmission in these systems demands the use of advanced computational methods, including finite element analysis and wave-based modelling techniques, to capture the nuanced vibrational and acoustic behaviours of the assemblies (Guigou-Carter & Coguenanff, 2017).

6.5.2.1. Airborne sound

In high rise buildings, airborne noise refers to sound transmitted through the air that can affect the acoustic comfort of indoor environments (Palmer, 2013). This includes both external sources such as road traffic, aircraft and weather-related noise, as well as internal sources like speech, televisions, music, telephones and mechanical building services. Effective control of airborne noise is essential to ensuring occupant comfort and maintaining acceptable acoustic conditions within residential and commercial spaces (Chintapalli, 2024; Palmer, 2013).

In addition to direct transmission, sound can also travel through indirect paths, known as flanking transmission. It is when a sound wave encounters the surface of a partition and portion of its energy is transmitted through the structure and re-emitted on the opposite side as shown in Figure 56 (Quirt et al., 2006). The sound bypasses the main partition by propagating through adjacent structural elements such as floors, ceilings and connecting walls (Nightingale et al., 2009). Flanking is especially prevalent where discontinuities or air gaps exist, including ceiling voids, electrical conduits, ventilation ducts and poorly sealed junctions between walls, floors, or ceilings. Even minor openings, such as ill-fitting window or door

seals, can significantly reduce acoustic performance. Since flanking transmission is present to some extent in all buildings, its impact on overall sound insulation is heavily influenced by the effectiveness of the acoustic detailing and construction quality, such as the orientation of joists, the framing of wall assemblies and the mounting of gypsum boards (Edwards et al., 2017; Palmer, 2013). Addressing these pathways through proper sealing and design integration is essential for achieving reliable sound isolation.

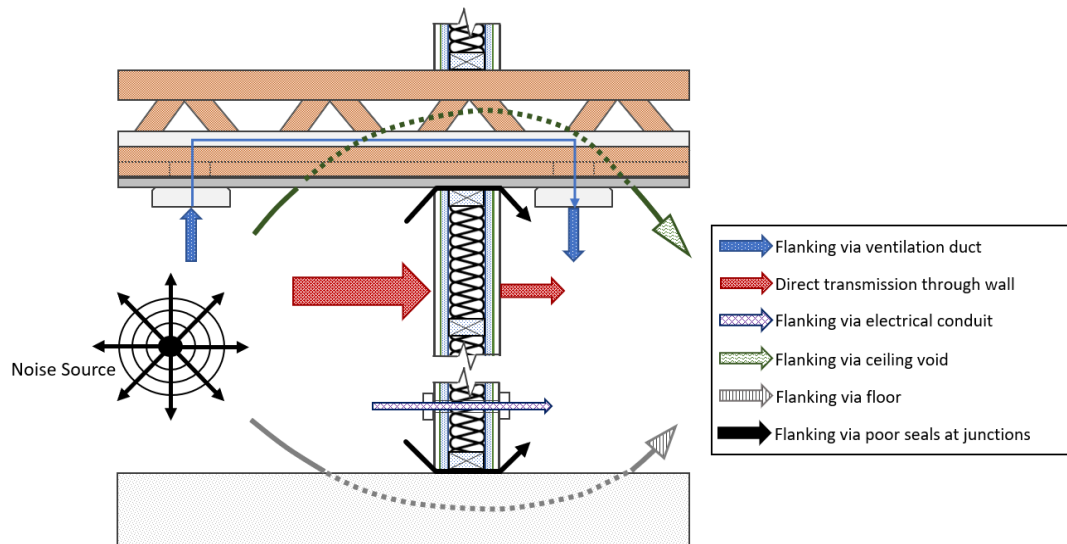


Figure 56. Transmission paths for airborne noise (Barlow, 2021)

6.5.2.2. Impact sound

Impact sound refers to noise generated by physical contact or mechanical disturbance that propagates through the structural elements of a building. It is a common source of acoustic discomfort in multi storey buildings and is particularly pronounced in timber structures due to their lower mass and higher flexibility compared to materials like concrete (Rodrigues et al., 2023). This type of sound transmission typically originates from activities such as walking, falling objects, or vibrations from mechanical equipment that is directly connected to the building structure. Floor deflection can also contribute to this phenomenon (Guigou-Carter & Coguenanff, 2017). When the floor vibrates, it induces motion in adjacent structural components, creating indirect transmission paths known as flanking routes, as illustrated in Figure 57. These vibrations are re-emitted as sound in other areas of the building, including spaces beneath the source room through the ceiling and laterally into adjoining rooms via connected floors and walls.

6.5.3. Noise mitigation techniques

Acoustic performance in high-rise buildings is achieved through the careful detailing of building elements that provide high levels of sound isolation, including façades, internal walls and floor assemblies. Particular attention is given to the specification of façade glazing systems, the acoustic separation of mechanical services and the incorporation of impact isolation treatments (Palmer, 2013). Acoustic design considerations can be broadly categorized into two complementary strategies: the implementation of sound-mitigating materials and technical systems and architectural design decisions that support acoustic

performance. While the use of materials with high sound absorption properties or engineered acoustic solutions, such as soundproofing layers, decoupling systems or resilient connections is essential in achieving targeted levels of sound insulation, architectural strategies play a critical auxiliary role in enhancing overall acoustic outcomes (Chintapalli, 2024; Palmer, 2013). For instance, spatial planning decisions, such as locating noise-generating mechanical systems away from acoustically sensitive areas, can significantly reduce sound transmission and contribute to a quieter indoor environment. An integrated approach that combines technical and architectural measures is therefore vital for optimizing acoustic performance in buildings, particularly those constructed from mass timber (Palmer, 2013).

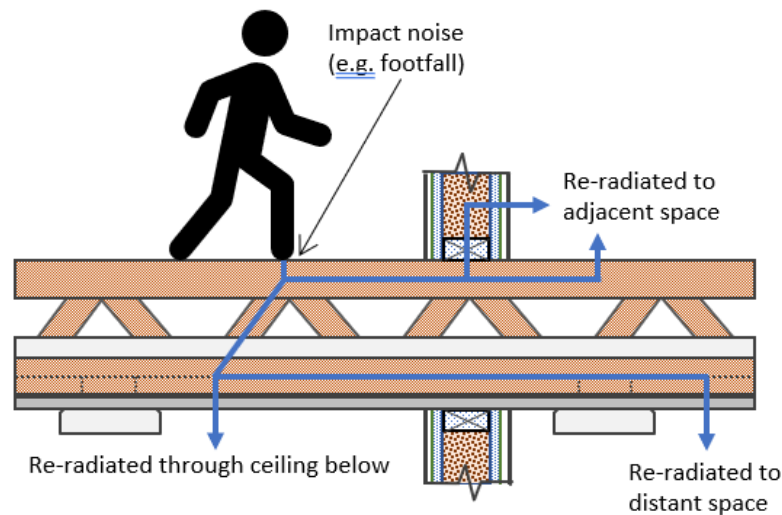


Figure 57. Structural transmission of impact and vibration (Barlow, 2021)

6.5.3.1. Architectural design strategies

Apart from specific material induced challenge associated to timber, in the architectural design of tall buildings, acoustic performance requires special attention due to the increased complexity and variety of noise sources compared to low-rise structures. High-rise environments are exposed to a broader range of internal and external acoustic challenges, including mechanical plant noise, high-speed elevator systems, wastewater downpipes and wind-induced noise from building components or adjacent structures (Swift & Stead, 2008). Architectural strategies must focus on the detailed specification of façade systems, floor and wall assemblies and the strategic placement of mechanical equipment and services. However, the levels of sound insulation across façades are often compromised by sustainable features such as natural ventilation or shading strategies. Repetitive external architectural features, such as louvres or sunshades, can pose a risk of generating aeroacoustic resonance, potentially leading to unwanted tonal noise under certain wind conditions (Yeoh et al., 2015). Aerodynamic noise originates primarily from dipole sources on building surfaces (when wind hits sharp edges, protruding elements, or repetitive structures) driven by fluctuations in wind pressure acting upon those surfaces. Reducing wind-induced noise can be achieved through the aerodynamic optimization of the building form, which minimizes pressure differentials and associated sound generation (Zhu & Deng, 2019). Advanced façade systems, including acoustic glazing, ventilated cavities and noise-attenuated air inlets, must be incorporated to mitigate airborne noise without compromising energy

efficiency. Internally, the design must account for structure-borne noise transmission through careful separation of noise-generating elements from occupied spaces, using vibration isolation techniques and damping materials (Oguc et al., 2016).

6.5.3.2. Materials and technical solutions

The design of building façades plays a critical role in managing external noise exposure. Reflective surfaces such as glass, metal and stone can intensify ambient sound levels. Therefore, the use of fragmented or textured surfaces, as well as vegetation, is recommended to mitigate this effect (Yang & Jeon, 2020). Acoustic and thermal insulation requirements share similar principles, particularly the need for increased mass per unit area to reduce sound transmission across partitions. In high rise timber buildings, CLT and glulam are commonly used for their structural efficiency and sustainability. However, due to their relatively low density, they require supplementary acoustic treatments such as adding fibre insulation slabs within cavities, increasing the thickness of gypsum wallboards, or incorporating concrete boards (Balmori et al., 2025; Di Bella & Mitrovic, 2020; Gaudry et al., 2019). While conventional buildings can replace lightweight walls with denser materials like brick or concrete, such an approach is less compatible with timber buildings due to sustainability concerns and structural limitations. Bare wood wall and floor assemblies inherently offer lower airborne sound insulation when compared to masonry or concrete systems. According to mass law, doubling the mass of a partition increases insulation by approximately 6 decibels. For instance, the performance of a lightweight stud wall with single gypsum board (STC 32) can be enhanced to STC 38 by incorporating fibre insulation, using acoustic-grade boards, or applying double layers of gypsum. In CLT structures, upgrading from a three ply CLT panel of 78 mm to a five-ply panel of 175 mm improves STC from 33 to 41 (Schoenwald et al., 2013).

Floor assemblies must also be designed to reduce impact sound, which is achievable through targeted treatments and material layering. Adding concrete toppings improves both acoustic and structural performance by forming effective horizontal diaphragms and reducing the depth of the floor system (Balmori et al., 2025; Gaudry et al., 2019). The integration of concrete in timber concrete composite (TCC) systems significantly enhances floor acoustics by increasing mass and damping capacity, thereby reducing both airborne and impact sound transmission. Semi prefabricated LVL and concrete composite floors further improve acoustic separation compared to timber only systems, while also addressing structural stiffness, vibration control and fire resistance, making them suitable for acoustically demanding applications (Yeoh et al., 2015). Nonetheless, while concrete toppings are effective, their use should be critically assessed in relation to the building's carbon footprint, as they may not align with sustainability goals (Rodrigues et al., 2023).

To further address sound transmission, especially flanking, design strategies such as resilient channels, additional gypsum board layers and damping treatments can be employed to increase internal energy losses (Quirt et al., 2006). Structural details such as adding a concrete nib along the wall line can help reduce flanking between floors in lightweight assemblies (Nilsson et al., 2023). The use of resilient interlayers at junctions in tall buildings is particularly beneficial, as it mitigates the transmission of increased loads through lower floors, thereby improving the vibration reduction index and overall sound insulation (Nilsson et al., 2023). Furthermore, the design and mechanical behaviour of shear connectors, not only influence structural performance but also play a key role in acoustic

comfort. Effective connector design can reduce interlayer slip, enhance floor stiffness and limit the propagation of noise and vibration between structural components (Yeoh et al., 2015).

6.5.3.3. Decouplers and resilient mats

In building structures where one surface is directly connected to another, sound is readily transmitted through the assembly. This occurs because the mechanical coupling allows vibrations to propagate with minimal resistance. Additionally, single-panel constructions often exhibit a resonant frequency at which their ability to attenuate sound is significantly diminished. To mitigate this, an effective strategy involves the decoupling of wall or floor components. Decoupling introduces a flexible or resilient layer between surfaces, allowing for a degree of independent movement between them (Rodrigues et al., 2023). This mechanism reduces the transmission of vibrational energy, similar to how suspension systems in vehicles isolate vibrations from the road.

When a sound wave strikes the first element of a decoupled assembly, the energy is partially absorbed and its transmission to the opposing surface is significantly diminished due to the physical separation. In timber construction, this technique is particularly valuable, as it improves sound insulation without adding substantial mass, thereby preserving the lightweight advantages of wood-based systems (Rodrigues et al., 2023).

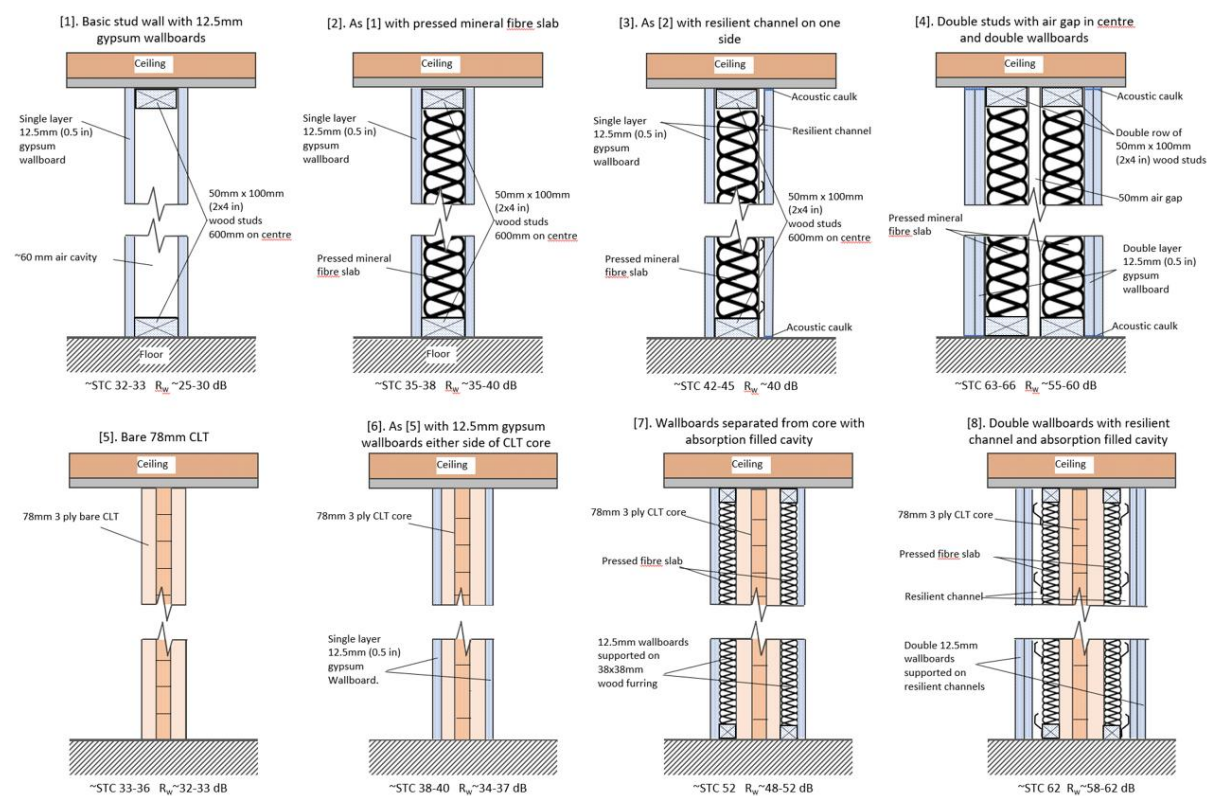


Figure 58. Increasing sound insulation in wood framed wall structures, derived from (Thorburn, 2014; Pirm & Fullerton, 2010; Quirt et al., 2006; Wood Products Council, 2020; Rockwool Ltd, 2018)

Various technical methods have been developed to implement decoupling. These include the use of acoustic adhesives between layers of wallboard, which add both resilience and minimal mass. The insertion of fibreboard between wallboards to interrupt direct screw coupling and the installation of resilient

channels. Resilient channels employ metal brackets to create air gaps between the wall finish and the structural core, whether composed of studs or laminated timber, thereby limiting transmission primarily to the points of connection. The most effective configuration combines two independent structural elements with an air cavity and integrated insulation slabs, enhancing both mass and sound absorption. Figure 58 illustrates the variation in insulation performance resulting from different structural design configurations. Experimental studies confirm that these approaches effectively reduce both the apparent sound reduction index and normalized impact sound pressure levels in timber assemblies (Kraler & Brugnara, 2022).

Decoupling techniques are also essential in mitigating flanking sound transmission. This is achieved through the use of resilient materials such as isolation strips at junctions between horizontal and vertical structural elements (Figure 59), floating floors and resilient ceiling hangers to reduce vertical transmission paths. Introducing breaks into the subfloor can also prevent a single continuous slab from acting as a conduit for vibration.

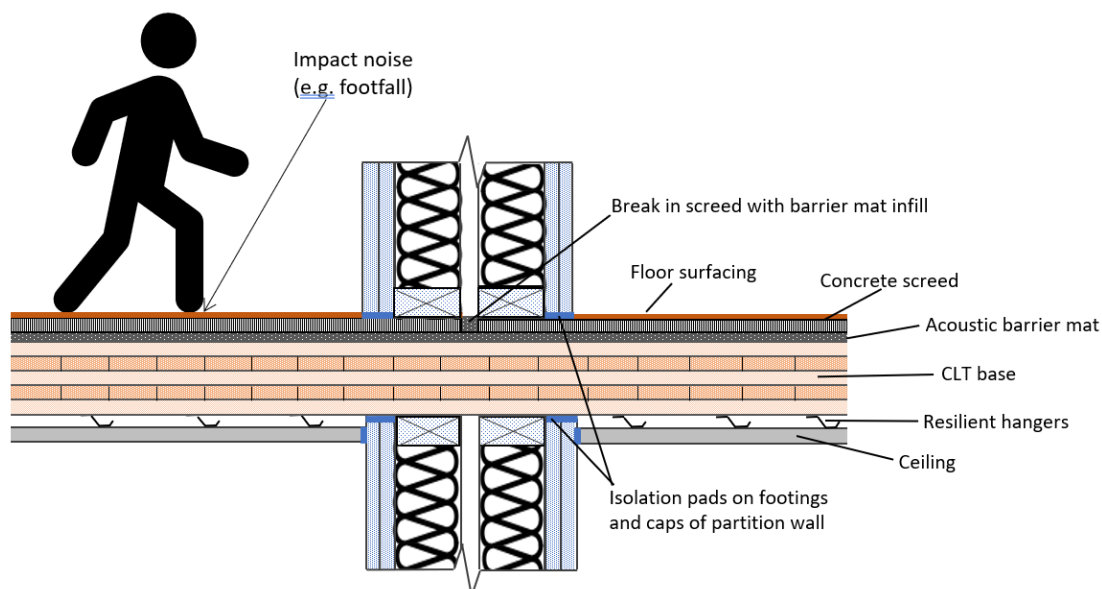


Figure 59. Use of increased mass and resilient materials to reduce structural transmission (Barlow, 2021)

Manufacturers have developed joint solutions that integrate decoupling technologies specifically tailored for timber structures. For instance, the Straviwood product line by CDM Stavitec offers decoupling systems for walls, floors and ceilings in CLT and modular wooden buildings, addressing the distinct acoustic challenges posed by these systems (Figure 60).

As illustrated in Table 16, substantial improvements in airborne and impact sound insulation can be achieved in glulam and cross laminated timber floor systems through strategic combinations of mass enhancement and decoupling layers. Notable improvements are achieved through the use of dry screed acoustic overlays, which raise STC values to 47 and 48 (from 35 and 39 base values) and IIC values to 37 and 41 (from 20 and 22 base values) for glulam and CLT systems, respectively. The performance further increases when precast concrete slabs are introduced with acoustic underlay. The highest insulation values are reached when combining both mass (through precast concrete topping) and decoupling (via acoustic underlay and intermediate OSB wood raft layers) reaching 65 and 66 STC values and 59 and 60 IIC rating values for glulam and CLT respectively. This demonstrates that

combining layered acoustic treatments with structural decoupling is highly effective in enhancing the acoustic performance of mass timber floor systems.

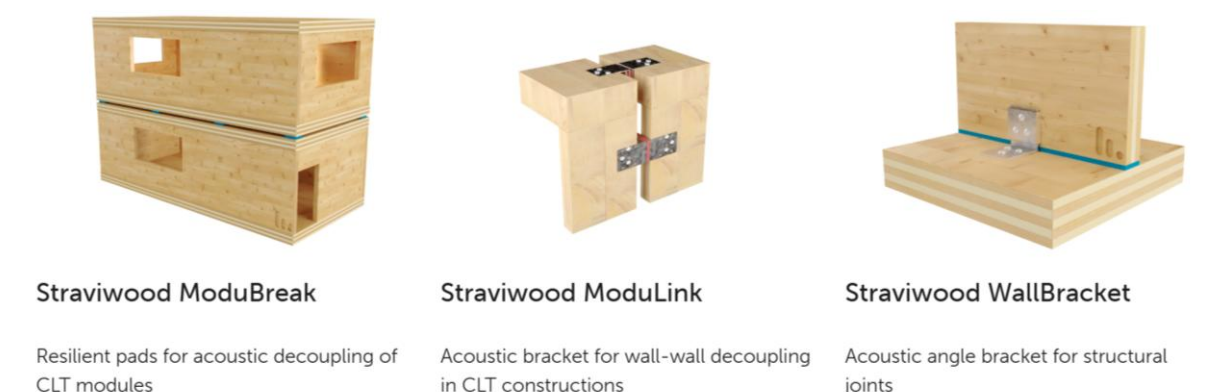


Figure 60. Straviwood acoustic isolation solutions (CDM Stravitec, 2025)

Table 16. Effect of adding mass and decoupling on STC and IIC of CLT and Glulam flooring, derived from (Wood Products Council, 2020; National Research Council of Canada, 2016)

Material	STC rating	IIC rating
Bare 89 mm glulam decking	35	20
Bare 131 mm 5-ply CLT	39	22
Dry screed acoustic overlay on 89 mm glulam decking	47	37
Dry screed acoustic overlay on 131 mm 5 ply CLT	48	41
70 mm precast concrete slab on 25 mm acoustic underlay placed on top of a glulam decking (89 mm)	54	45
38 mm precast concrete slab on 25 mm acoustic underlay placed on top of a 131 mm 5 ply CLT	56	49
38 mm precast concrete slab on 17 mm acoustic underlay placed on an OSB wood raft on top of 89 mm glulam decking	65	59
38 mm precast concrete slab on 17 mm acoustic underlay placed on an OSB wood raft with sand on top of a 131 mm 5 ply CLT	66	60

Decoupling techniques are fundamental to improving acoustic performance in timber structures, particularly in lightweight and modular construction. These strategies reduce both direct and flanking sound transmission by introducing mechanical separation and resilient layers. Combined with appropriate material layering and increased mass, these solutions enable timber buildings to achieve sound insulation levels comparable to heavier construction systems, without compromising structural efficiency or sustainability.

6.5.3.4. Reverberation in indoor spaces

A common architectural characteristic of many timber high-rise buildings, whether residential or commercial, is the use of exposed timber beams and ceilings along with wooden or laminated flooring. Although visually appealing and consistent with biophilic design principles, these surfaces, particularly when polished or varnished (Figure 61), exhibit low acoustic absorption, especially at low frequencies, in contrast to porous materials which are more effective in absorbing sound energy (Di Bella & Mitrovic, 2020; Jang & Kang, 2022). In such environments, sound generated within the space reflects repeatedly off hard surfaces before being attenuated. This accumulation of reflections increases the reverberation

time, which can substantially amplify background and user-generated noise, including that from domestic appliances, televisions, music and general activity (Peters et al., 2013). While controlled reverberation may enhance acoustic performance in specific contexts such as concert halls, in residential, office, or commercial applications this effect diminishes acoustic comfort and contributes to elevated sound levels. Moreover, prolonged reverberation increases the likelihood of noise transmission to adjacent spaces, potentially disturbing other occupants and undermining overall acoustic performance within the building.



Figure 61. Reflective wooden surfaces in Carbon 12 (Carbon12, 2022)

Excessive reverberation within a space can degrade sound clarity, impairing the intelligibility of speech from sources such as televisions and audio systems. This results in a blurred auditory experience, where distinct sounds overlap and lose definition (Fuchs, 2013).

To mitigate excessive reverberation and sound reflection, particularly in spaces where these phenomena negatively affect acoustic comfort, it is essential to incorporate sound absorptive materials into the environment (Sueyoshi et al., 2013) or interior design strategies that have the acoustic comfort in consideration, that include the shape and the material distribution within the space (Nguyen et al., 2023; Wang et al., 2005). These materials absorb energy from incident sound waves, which reduces the reverberation time. As a result, the amplifying effect of the room is diminished and the clarity of auditory signals is enhanced, leading to improved speech intelligibility and better overall acoustic quality for sounds as shown in Figure 62.

In residential and office buildings, most sound absorbers consist of dense and porous materials such as compressed mineral fibre, melamine foam (Figure 63), or expanded polyethylene. These materials are typically manufactured into panels and either surface mounted on walls or suspended from ceilings (Ikpekha & Simms, 2025). Their sound-absorbing effectiveness is based on the principle of porous absorption. When a sound wave encounters the surface of such a material, it penetrates into the interconnected pores. As the air particles within the wave oscillate inside these narrow channels,

friction is generated against the internal surfaces. This friction converts a portion of the acoustic energy into heat, thereby dissipating the energy of the sound wave and significantly reducing its intensity (Liu et al., 2022). As a result, the reverberation time within the space is reduced, contributing to improved acoustic comfort and speech intelligibility.

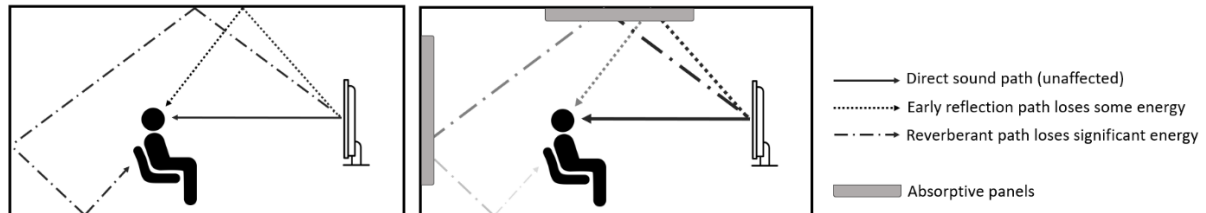


Figure 62. Sound reflection paths in a space and the effect of absorption panels on reflected sound (Barlow, 2021)

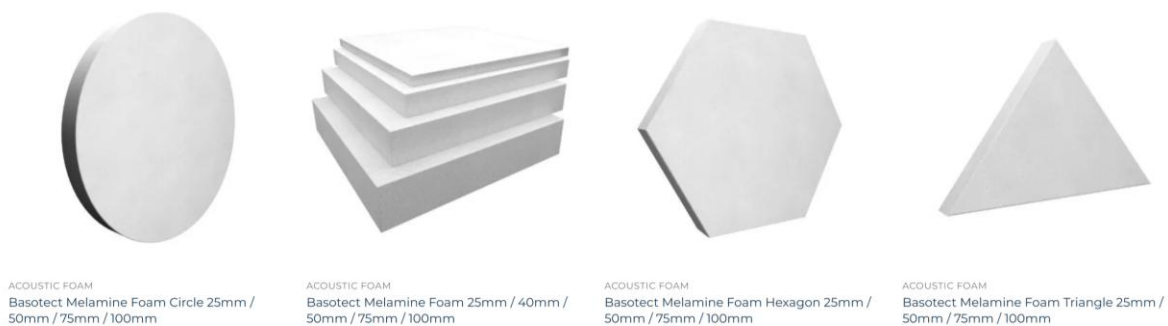


Figure 63. Melamine foam acoustic solution (AcousticPanels.co.uk, 2025)

Porous sound absorbers are widely available and frequently used in residential and commercial applications due to their effectiveness and ease of installation. A typical example is illustrated in Figure 64, which shows wall and ceiling-mounted fabric-wrapped absorbers with a high-density glass wool core.

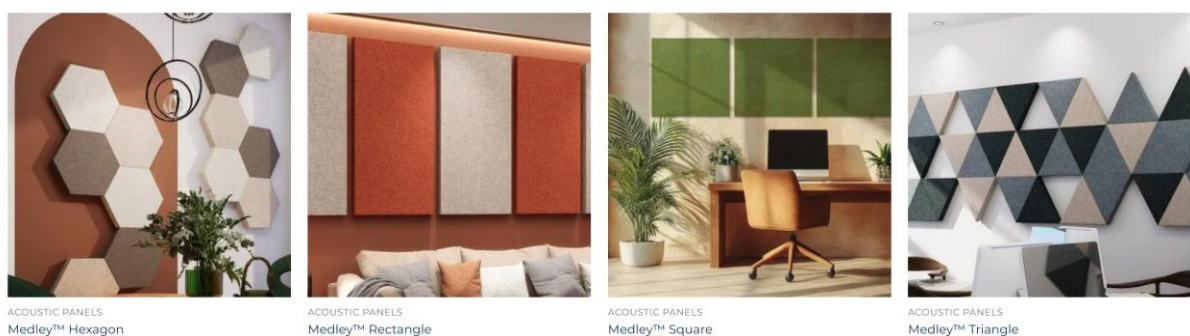


Figure 64. Fabric wrapped acoustic panels (AcousticPanels.co.uk, 2025)

However, many conventional materials, such as mineral wool or glass wool, are derived from non-renewable mineral extraction processes and raise concerns regarding sustainability. In response, there is a growing market for environmentally sustainable alternatives that offer comparable acoustic performance. These include absorbers composed of natural fibrous materials such as bamboo fibre, oil palm fibre, sheep's wool and coconut fibre, which are densely compacted into panel form. In addition

to their acoustic function (Desarnaulds et al., 2005). Many of these materials also provide thermal insulation (Green & Taggart, 2017).

To effectively address reverberation at low frequencies, particularly below approximately 200 Hz, more specialized absorbing structures are required. In this context, slit panel absorbers have demonstrated promising results. For example, Sueyoshi et al. (2013) investigated the acoustic performance of wood-based slit panels, showing that sound absorption could be significantly influenced by the panel dimensions and the configuration of absorptive materials placed within the cavity behind the slits. Additionally, naturally porous and renewable materials such as cork matting have been shown to provide effective surface-level absorption while also offering a sustainable material profile. The market is also witnessing the emergence of absorbers made from recycled content, including fibres derived from recycled plastic bottles, reclaimed rubber and recycled glass. These alternatives not only contribute to circular economy goals but also provide acoustically effective and visually adaptable solutions for a range of building typologies (Sueyoshi et al., 2013). The creative 3D acoustic wall panels from recycled cork are presented in Figure 65.

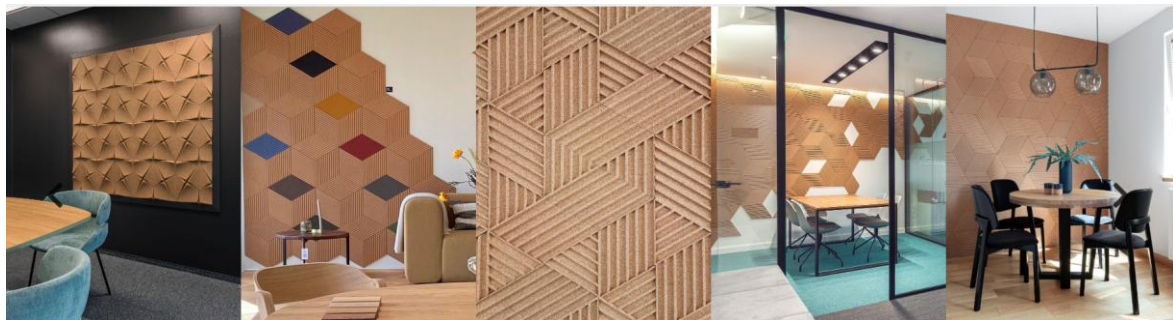


Figure 65. Examples of 3D wall panels made of recycled cork (Corkbee, 2018)

6.5.3.5. Challenges and insights

Balancing the inherently low embodied carbon of timber with the acoustic performance requirements of modern buildings presents a notable challenge. Selecting construction materials and strategies that yield favourable ratios between environmental impact and acoustic insulation is essential (Bligh, 2022). Prefabrication plays a key role in this process by allowing for more efficient material use, reducing waste and minimizing on-site exposure to moisture. This not only lowers the carbon footprint but also supports the long-term acoustic integrity of wood assemblies by preventing moisture-related degradation (Schmid, 2005).

The acoustic performance of timber buildings often exhibits significant variability due to differences in construction techniques and the inherent properties of timber-based materials (Jayalath et al., 2021). As a result, achieving consistent acoustic outcomes across multiple projects remains a complex task. To mitigate this and to achieve optimal results, it is essential to involve acoustic engineers early in the architectural design process. Acoustic modelling, numerical simulations and predictive tools are widely used to evaluate potential design configurations and materials. These tools aid in identifying effective acoustic solutions and serve to validate theoretical predictions through experimental testing (Lin et al., 2021). Early collaboration is particularly valuable in addressing both direct and less predictable sources of noise and in adapting construction techniques initially selected to meet structural, aesthetic, thermal

or economic criteria to also satisfy acoustic performance requirements. This underlines the importance of defining and prioritizing acoustic expectations for individual spaces early in the design phase to avoid costly modifications later (Wetherill, 2009). Furthermore, the design of tall timber buildings must integrate architectural decisions with technical solutions to meet rising standards for acoustic and environmental performance. The quality of both the initial design and the on-site execution has a profound impact on the final acoustic outcome. Proper planning, detailing and construction practices are essential to ensure compliance with regulatory requirements and occupant comfort (Schmid, 2005). Additionally, real-world assessments of airborne and impact sound insulation are critical. Post-occupancy evaluations provide valuable data that can help identify acoustic deficiencies not evident during design, ensuring that corrective measures can be implemented and that all building systems contribute to satisfactory acoustic quality (Mahbub et al., 2010).

Although acoustics was once viewed as a potential limitation for tall timber buildings, recent research and practical experience from completed projects have shown otherwise. For example, the Limnologen residential development reported only one acoustic complaint since occupancy began in 2009, underscoring the effectiveness of modern acoustic strategies in mass timber buildings (Green & Taggart, 2017).

In conclusion, acoustic design in high-rise timber buildings must address noise as a critical factor influencing user comfort and well-being. It requires a combination of careful material selection, early-stage acoustic modelling, real-world performance validation and construction quality control. By meeting these demands, designers can ensure that mass timber buildings are not only environmentally sustainable but also acoustically comfortable for occupants.

6.5.4. Project team handout summary: Acoustic performance in high-rise timber buildings

Objective: To deliver high acoustic performance in tall mass timber buildings by controlling airborne and impact noise, minimizing flanking transmission and ensuring interior acoustic comfort, while balancing sustainability, construction efficiency and regulatory compliance.

What must be done:

- ✓ Engage an acoustic engineer at the early design stage;
- ✓ Perform acoustic modelling for airborne and impact sound;
- ✓ Position noisy services away from sensitive spaces;
- ✓ Use layered walls with insulation and acoustic wallboards;
- ✓ Apply decoupling techniques at walls, floors and junctions;
- ✓ Install floating floors or timber–concrete composite systems;
- ✓ Seal all joints with resilient materials to block flanking paths;
- ✓ Use certified acoustic products for isolation;
- ✓ Include acoustic-rated glazing and ventilated façades;
- ✓ Add sound-absorbing panels in reverberant or open areas;
- ✓ Use sustainable absorbers;
- ✓ Validate acoustic performance with on-site testing.

Why it matters:

Acoustic performance is one of the most common sources of occupant dissatisfaction in multi-storey buildings. Due to timber's lower mass and stiffness compared to concrete or steel, mass timber systems are more prone to transmitting airborne and impact noise, as well as flanking sound through connected structural elements. Without early integration of acoustic strategies, such as mass layering, decoupling and sound-absorbing finishes, projects risk failing to meet regulatory requirements and user expectations.

Effective acoustic planning improves occupant comfort, productivity and privacy while reducing complaints and post-occupancy interventions. It also ensures compliance with increasingly strict building codes and performance standards. Integrating acoustic performance with sustainability goals is achievable through careful material selection and detailing, especially when validated through simulation and field testing.

6.6. Seismic performance

As timber becomes an increasingly popular material in high-rise construction due to its sustainability and structural capabilities, understanding its seismic performance is critical. Timber structures, particularly mass timber, can perform well under seismic loads due to several inherent properties of the material. Timber is much lighter than concrete or steel, which helps reduce seismic forces, as they are directly related to a structure's mass (Ceccotti et al., 2006; Ramage et al., 2017). During an earthquake, heavier buildings endure stronger inertial forces, increasing the risk of structural damage or collapse. By contrast, timber's lightweight nature reduces the overall seismic load, making structures more resilient to ground shaking, enabling its wider use even in zones with the risk of seismic activity. Additionally, timber has a favourable energy-absorbing capacity, enabling it to withstand dynamic movements, further enhancing its earthquake performance. Besides, advancements in modern timber engineering, particularly the development of CLT and other engineered wood products, have significantly improved the seismic performance of these structures by providing additional strength and stability.

Nonetheless, the international codes and standards do not accompany the developments in mass timber industry at the same rate. By 2018, the Canadian code CSA O86-14 was the first standard to provide guidelines for the seismic design of CLT buildings (Izzi et al., 2018). Contemporary seismic design methodologies adopted by building codes worldwide, such as Eurocode 8 (EC8) (CEN, 2004b), the National Building Code of Canada (NBCC) (National Research Council of Canada, 2015) and ASCE 7 in the United States (American Society of Civil Engineers, 2021) have traditionally relied on force-based design (FBD) approaches (Loss et al., 2018). These frameworks incorporate provisions that reflect the current state of the art in seismic engineering. However, despite the increasing adoption of timber as a structural material, its representation in current seismic design standards remains limited. For instance, Eurocode 8 dedicates only four pages to the seismic design of timber structures, offering minimal guidance. Section 8 of Eurocode 8 "Specific rules for timber buildings" lacks provisions for many widely used systems. Moreover, the code does not address essential aspects of seismic design, including capacity design principles tailored to different timber structural systems, elements that are critical for ensuring adequate seismic performance. Additionally, there is an absence of guidance on the design of transfer zones necessary for maintaining the continuity of shear walls in multi-storey timber buildings, further limiting the applicability of current standards to modern timber construction practices (Stepinac et

al., 2020). Yet, in the context of timber structures, research into their seismic performance is still developing. Therefore, standards and codes are continuously being updated to incorporate new insights and technological advancements in timber engineering and construction (Loss et al., 2018).

Even though the Eurocodes do not provide specific recommendations regarding the seismic resistance, construction details, or design factors applicable to this structural systems in seismic conditions, timber's natural flexibility allows structures to dissipate seismic energy and while used together with steel connections, guarantees appropriate ductile behaviour, reducing the risk of catastrophic failure (Asdrubali et al., 2017; Loss et al., 2018).

Over the past two decades, seismic design philosophy has undergone a significant transformation, evolving from prescriptive FBD methodologies toward more advanced, multi-level performance-based design (PBD) approaches (Benoy et al., 2023). This paradigm shift underscores a growing emphasis on achieving targeted performance objectives under various levels of seismic intensity, allowing for more precise evaluation and control of structural behaviour. This evolution is particularly relevant for timber structures, where the integration of performance-based strategies offers greater flexibility and robustness in addressing the unique dynamic characteristics and material properties of engineered wood systems.

PBDs are rigorously evaluated through advanced numerical simulations and full-scale experimental investigations, including shake table testing. These methodologies have demonstrated that mass timber structures are capable of achieving and in some cases surpassing, the seismic performance criteria established by current safety standards. As a matter of fact, several full-scale tests have been conducted on timber buildings using shaking tables to evaluate their performance during extreme seismic events, particularly focusing on CLT structures. Multi-storey timber buildings have demonstrated high levels of resilience, exhibiting no significant structural damage even after being subjected to a series of simulated high-magnitude seismic events (Ceccotti et al., 2006; SERIES 227887, 2013; SERIS, 2013).

One of the most notable studies in this area is the SOFIE project, led by the Trees and Timber Institute of Italy in collaboration with the National Research Institute for Earth Science and Disaster Resilience (NIED), Shizuoka University and the Building Research Institute (BRI) in Japan. The SOFIE project focused on the seismic performance of both three-story and seven-story CLT buildings (Ceccotti et al., 2006). In the first phase of the project, a three-story CLT building was subjected to 15 destructive earthquakes, with a peak ground acceleration (PGA) reaching 1.2 g. Despite the intensity of these seismic forces, the building remained intact without severe damage, showcasing the robustness of CLT in withstanding significant earthquakes. The second phase involved testing a seven-story CLT building, which was exposed to forces equivalent to the Kobe earthquake, a magnitude 7.3 event on the Richter scale. This test simulated one of the most devastating earthquakes in modern history, yet the CLT structure survived without any significant damage, further proving its durability and seismic resilience (Ceccotti et al., 2013).

The most recent experimental campaign involved the dynamic testing of a full-scale, 10-storey (34.4 m) mass timber building incorporating two pairs of post-tensioned rocking shear walls (Figure 66). A total of 88 seismic tests were conducted across a range of ground motion intensities, including multiple tests at the Maximum Considered Earthquake (MCE) level corresponding to the building's design location—Seattle, Washington. Throughout the campaign, the structure exhibited no significant residual drift, nor any damage to primary structural members or connections. Only moderate, repairable damage was observed in non-structural components (Pei et al., 2023, 2024). These tests have been crucial in

demonstrating the resilience of timber, especially in the context of high seismic forces, providing empirical evidence that supports the continued integration of timber technologies in earthquake-resistant design (Sandhaas & Ceccotti, 2012).



Figure 66. Structural construction sequence of the test building of NHERI Tall Wood project (Pei et al., 2024)

Research has highlighted the importance of ensuring a complete and continuous transfer of vertical and lateral loads from the superstructure to the foundation (Loss et al., 2018). A well-defined load path not only guarantees structural integrity under gravity loads but is also fundamental for the reliable performance of the structure under seismic and wind actions, which are particularly significant in tall and high-rise buildings. Ductility in building systems is used to dissipate energy and reduce the maximum force-demand on buildings. Timber, as a structural material, exhibits brittle behaviour in bending, tension and shear parallel to the grain. Consequently, in timber structures, the necessary ductility for energy dissipation during seismic events must be provided primarily through the design and performance of connections (Loss et al., 2018; Rothoblaas, 2020). Subsequently, a key to the seismic performance of high-rise timber buildings is the design and engineering of connections, as they are the main elements that transfer forces between members (e.g. beams to columns, walls to diaphragms, walls to foundations) and their behaviour under seismic loading is a major factor in determining overall building performance (Izzi et al., 2018; Loss et al., 2018). Various timber construction systems, such as CLT, glulam and LVL, offer unique seismic advantages. CLT, for example, has demonstrated good performance in seismic testing due to its rigidity and the way it distributes forces across panels (Popovski & Karacabeyli, 2012). However, detailing and integrity at connections, shear walls and diaphragm action in the floor systems are critical in certifying that vertical loads (dead + live) are safely transferred down to the foundation and lateral loads (wind + seismic) are properly resisted and redistributed through the structural system to guarantee its resilience. If any connection fails or degrades, the load path is

interrupted, potentially leading to disproportionate damage or collapse under extreme loading.

Mass timber buildings often incorporate steel connections or hybrid systems that combine timber with concrete or steel to improve lateral stiffness and ductility, key factors in resisting seismic forces. Among these, shear and tensile connectors play a critical role in ensuring that both in-plane and out-of-plane actions are effectively resisted and transferred through the load path. Special devices such as energy-dissipating fuses, yielding hold-downs and hybrid steel-timber systems are being developed to improve response under cyclic loads (Daneshvar et al., 2023; Marchisella & Muciaccia, 2024).

Shear connectors

Shear connectors are primarily responsible for transferring horizontal shear forces between elements such as floors and walls or wall-to-wall interfaces. These connectors are essential in resisting racking during seismic or wind loading. Common shear connectors include fully threaded screws, dowel-type fasteners, notched connections and steel plates embedded in timber panels. Quasi-static testing of CLT wall panels has demonstrated that these structures can achieve satisfactory seismic performance when steel brackets are fastened using nails or screws. The incorporation of hold-downs with nails at both ends of the wall further enhances seismic resistance. However, the use of diagonally placed long screws to anchor CLT walls to the underlying floor is not advisable in seismically active regions, as it tends to result in less ductile wall behaviour (Popovski & Karacabeyli, 2012). Figure 67 illustrates typical shear connectors configurations in CLT wall-floor assemblies, highlighting the placement of angle brackets and hold-downs.

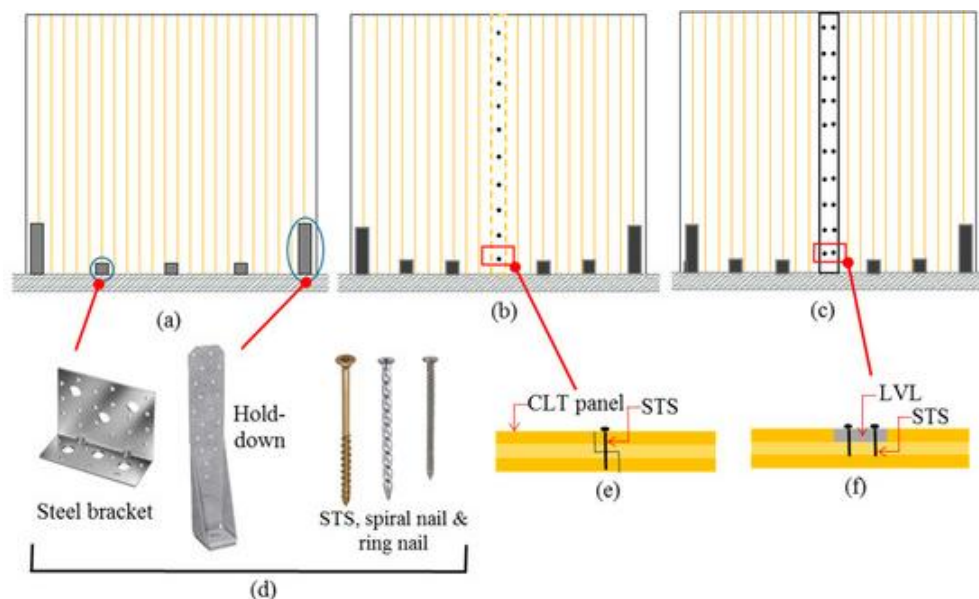


Figure 67. CLT shear walls: (a) single, (b) coupled wall with lap joint, (c) coupled wall with spline joint, (d) connectors and fasteners, (e) half-lap joint, (f) spline joint (Shahnewaz et al., 2018)

Tensile connectors

Tensile connectors are crucial for resisting uplift forces, such as wind suction or overturning moments during earthquakes and for maintaining the vertical continuity of structural systems such as post-and-beam or wall assemblies. These may consist of steel rods, post-tensioning tendons, or custom-fabricated brackets and hold-downs designed to transfer tensile forces across floor levels. As an example, Figure 68 showcases a post-tensioned rocking shear wall system with self-centring capability, demonstrating the use of unbonded

post-tensioning tendons and energy-dissipating devices of NHERI Tall Wood project.

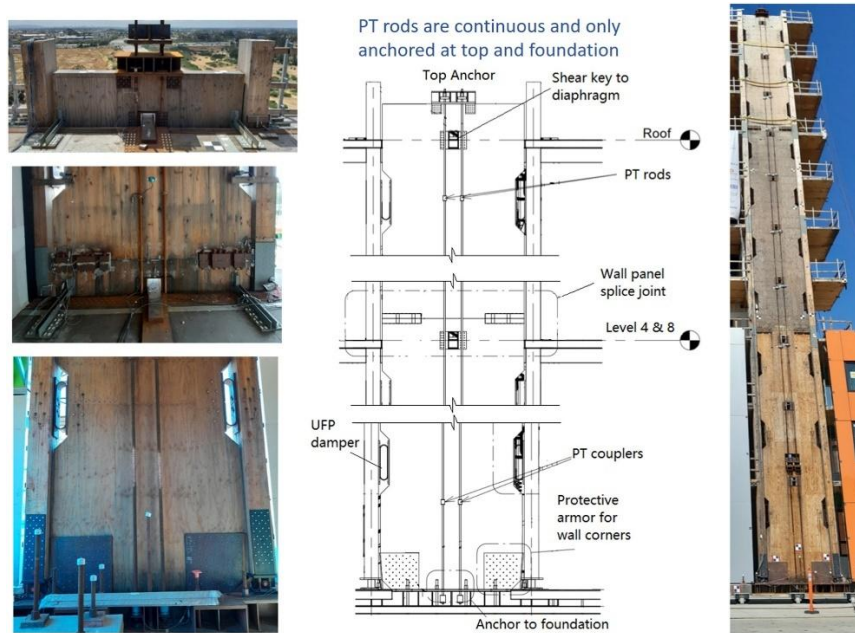


Figure 68. Details of rocking shear wall of NHERI Tall Wood project (Pei et al., 2024)

6.6.1. Seismic design details for connections of mass timber structures

6.6.1.1. Traditional connections

As mentioned previously, in mass timber structures, the performance of connections is critical to ensure seismic resilience. As structural elements are subjected to dynamic and cyclic loading during seismic events, connections in timber buildings must exhibit ductile behaviour to dissipate energy effectively, allowing the structure to undergo large deformations without sudden failure. However, conventional solutions such as steel hold-downs, angle brackets and other metal fastener-based systems, frequently exhibit brittle failure modes, which are inherently unfavourable in seismic conditions (Casagrande et al., 2016; Li & Tsavdaridis, 2023). These brittle modes may include sudden fracture of steel components or splitting of timber members, both of which compromise structural safety. To achieve the required ductility, these systems typically depend on inelastic deformation mechanisms, primarily the plastic deformation of fasteners (e.g. nails, screws, or bolts) and localized crushing of wood fibres around the fastener zones (Sarkisian, Garai, et al., 2019). While these mechanisms can provide a measure of energy dissipation, they are limited by the anisotropic properties of timber and its brittle behaviour under some stress orientations (Breijinck et al., 2024; Mowafy et al., 2023). Consequently, there is growing interest in the development of innovative connection systems specifically designed for seismic performance, including systems that enhance energy dissipation, delay failure onset and promote more favourable hysteretic behaviour under cyclic loading.

6.6.1.2. Innovative connections

Therefore, recent advances in connection design for mass timber structures have focused on improving ductility, energy dissipation and post-earthquake reparability. These new approaches intend to overcome the limitations of conventional systems by incorporating mechanisms that concentrate

damage in sacrificial or replaceable components, thereby protecting the primary structural elements and enhancing the building's overall resilience (Sarkisian, Garai, et al., 2019).

Innovative strategies include self-centring techniques, friction energy dissipating devices, engineered yielding elements and hybrid timber–steel systems (Chen et al., 2024; Mowafy et al., 2023; Sarkisian et al., 2019). They are designed not only to withstand seismic demands but also to provide predictable hysteretic behaviour, enabling structures to return to their original position after deformation and reducing residual drift. One particularly promising class of solutions is friction energy dissipating devices, such as Pin-Fuse and Link-Fuse joints (Figure 69). These devices harness controlled sliding friction to dissipate seismic energy, allowing the timber members to remain predominantly elastic throughout the event. By decoupling energy dissipation from the timber components themselves, these systems significantly enhance the ductility, damage tolerance and reusability of the structural system (Sarkisian et al., 2019; Sarkisian et al., 2019).

Another notable innovation involves the use of perforated steel plates as engineered yield mechanisms. These plates can be strategically designed to yield under cyclic loading in a predictable and controlled manner, offering both strength and displacement capacity while minimizing stress concentrations in timber. When paired with capacity-protected fasteners, these systems help ensure that yielding occurs in the steel plate rather than in the timber elements, preserving the integrity of the primary structure and facilitating post-event repair or replacement (Daneshvar et al., 2022).

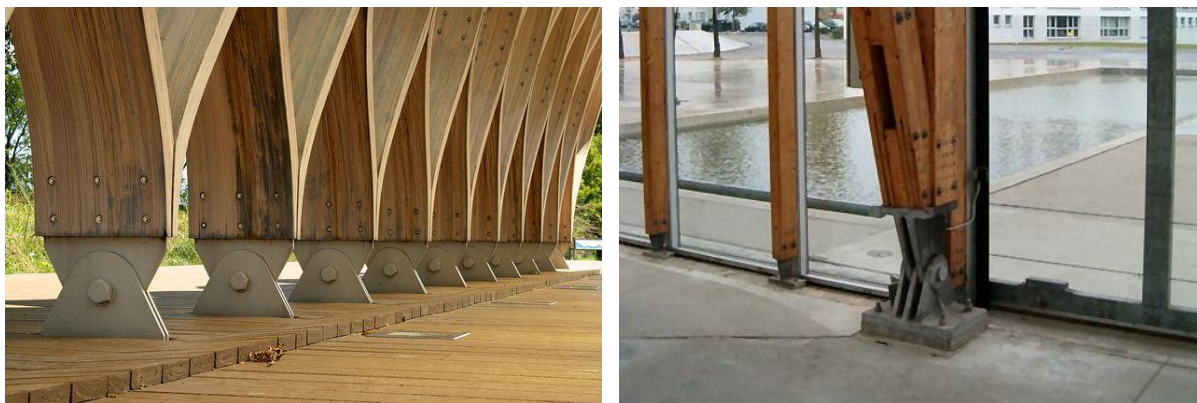


Figure 69. Pin dissipating devices: left (Jones, 2012); right (AITIM, n.d.)

Self-centring (SC) connection systems have emerged as a pivotal innovation in enhancing the seismic performance of mass timber structures. First introduced around 2005, these techniques are designed to enable structures to return to their original position following seismic events, thereby minimizing residual deformations and improving reparability (Chen et al., 2024; Mowafy et al., 2023). Unlike conventional systems that often undergo permanent displacements due to deformation, self-centring connections rely on reversible deformation mechanisms, significantly enhancing the post-earthquake functionality of buildings. These systems typically employ U-shaped flexural plates, post-tensioned rods or cables and friction-based sliding interfaces to achieve their restorative effect. For example, U-shaped steel plates can flex during seismic loading and then return to their original configuration upon unloading, while friction devices dissipate energy through controlled sliding, preventing excessive damage to the timber elements (Mowafy et al., 2023; Sarkisian et al., 2019). These systems are increasingly being explored in conjunction with previously mentioned energy-dissipating mechanisms, creating hybrid solutions that combine the benefits of energy dissipation and re-centring capacity.

Hybrid systems that combine mass timber with strategically placed steel elements have shown substantial promise in improving the seismic performance of timber structures. They leverage the high ductility, strength and predictable yielding behaviour of steel to compensate for the more brittle failure modes commonly observed in conventional timber connections (Iovane & Faggiano, 2021; Mowafy et al., 2023). By integrating steel links, plates and frames within timber assemblies, it is possible to localize inelastic deformations in steel components, thereby protecting the integrity of the timber and reducing the risk of irreversible damage during seismic events (Shulman & Loss, 2023). This approach also allows for the development of capacity-designed systems, where energy dissipation is concentrated in steel yielding zones or sacrificial elements, while timber remains within elastic limits. Such hybridization enhances both global ductility and structural robustness, making these solutions increasingly attractive in performance-based seismic design of timber buildings.

In addition to hybrid steel-timber systems, reinforcing timber connections themselves has emerged as a key strategy for improving seismic resilience. Techniques such as embedding self-tapping screws, fully threaded rods, or using carbon fibre-reinforced polymer (CFRP) wraps can significantly increase the load-bearing capacity, stiffness and ductility of timber joints and prevent premature shear failure (Bellini et al., 2020; Breijinck et al., 2024; Daneshvar et al., 2022). These reinforcements alter the failure mechanisms of joints, shifting them away from brittle, sudden failures toward more ductile and controlled responses. For instance, reinforcing zones of stress concentration can delay or prevent the crushing of wood fibres and splitting failures, while also allowing for better distribution of stresses across connection interfaces (Daneshvar et al., 2022). These strategies are particularly useful in retrofitting existing structures or optimizing newly designed joints, ensuring both safety and sustainability in seismic-prone regions.

Innovative connection designs are promising approaches to enhance the seismic performance of engineered timber structures. Experimental validation remains a critical step in safeguarding the reliability of these designs. The overstrength and ductility are fundamental components of the capacity-based design concept, which ensures that ductile failure mechanisms govern the structural response by deliberately overdesigning brittle components through the application of appropriate overstrength factors, thereby promoting controlled energy dissipation and preventing premature brittle failure (Breijinck et al., 2024; Chen et al., 2024; Ottenhaus et al., 2022). This can be achieved through experimental validation or analytical methods (Iovane & Faggiano, 2021; Ottenhaus et al., 2022). Analytical methods to estimate the overstrength factor of connections based on material properties can reduce the need for extensive experimental testing (Ottenhaus et al., 2022).

On the other hand, to ensure the seismic reliability of emerging timber connection technologies, comprehensive experimental testing plays an important role. This includes both monotonic tests, which assess the ultimate strength and deformation capacity of connections under gradually increasing loads and cyclic tests, which simulate the repeated load reversals experienced during an earthquake (Iovane & Faggiano, 2021; Williamson et al., 2023). Such testing protocols are essential for understanding the hysteretic behaviour, energy dissipation capacity and failure modes of different joint typologies and provide critical data that inform analytical models, such as the ultimate resistance, stiffness and rotation capacity - essential for implementing connections into seismic-resistant building systems and that enable accurate performance-based design (Breijinck et al., 2024; Daneshvar et al., 2022; Krauss et al., 2023).

In parallel with testing, the adaptation and development of design guidelines are necessary to facilitate the integration of these novel connections into practice. Since steel construction has a longer tradition of seismic design, many principles from steel design—such as capacity design, ductility hierarchies and detailing rules—can be adapted to timber systems with suitable modifications (Faggiano & Iovane, 2016; Huber et al., 2018). These evolving guidelines serve not only as a reference for engineers and architects, but also as a foundation for updating building codes and standards, thus supporting the broader adoption of mass timber in seismically active regions. Establishing clear criteria for connection detailing, allowable deformations and failure mechanisms enhances design reliability and structural safety, bridging the gap between research and real-world implementation.

The remarks above are critical for ensuring the seismic resilience of mass timber structures, allowing them to withstand and recover from seismic events effectively. Together, these emerging technologies represent a significant step forward in the development of seismic-resilient timber buildings, aligning with broader goals of sustainability, modularity and long-term performance.

6.6.2. Seismic design remarks for mass timber structures vs. traditional steel or concrete structures

Mass timber structures present unique seismic design challenges and opportunities compared to traditional steel or concrete structures. In the following section, the key differences are presented in terms of weight, ductility, energy dissipation, hybridization, seismic design parameters, performance, resilience and challenges.

6.6.2.1. Weight and ductility

Mass timber: One of the key advantages of mass timber structures is their significantly lower weight compared to conventional steel or concrete buildings. This reduced mass translates into lower seismic inertial forces during an earthquake, which can be beneficial in minimizing structural demands and foundation loads (Sarkisian et al., 2019; Timmers & Tsay Jacobs, 2018b). However, timber's mechanical properties present a trade-off. While its strength-to-weight ratio is favourable, timber inherently exhibits lower ductility than steel or reinforced concrete. This limited ductility reduces its ability to undergo plastic deformation and absorb energy during seismic events, potentially leading to more brittle failure modes if not adequately addressed through connection design and system integration (Gilbert & Erochko, 2016; Sarkisian et al., 2019; Timmers & Tsay Jacobs, 2018b).

Steel/concrete: In contrast, steel and reinforced concrete structures are considerably heavier, resulting in higher seismic forces due to their greater mass. Despite this, these materials possess excellent ductility and energy dissipation capabilities. Steel, in particular, can undergo significant plastic deformation without losing strength, making it highly effective for resisting seismic loads. Concrete, when properly reinforced, also demonstrates robust energy absorption through cracking and yielding mechanisms. These properties contribute to the overall seismic resilience of steel and concrete structures, allowing them to maintain stability and prevent collapse under severe earthquake conditions (Gilbert & Erochko, 2016; Timmers & Tsay Jacobs, 2018).

6.6.2.2. Energy dissipation and ductility enhancement

Mass timber: Due to its inherently lower ductility, mass timber alone lacks the capacity to undergo significant plastic deformation during seismic events. To overcome this limitation and improve seismic performance, advanced connection technologies have been developed. These include friction-based energy dissipation devices (e.g. Pin-Fuse Joint and Link-Fuse Joint), which allow controlled sliding or yielding under cyclic loads (Gilbert & Erochko, 2016; Li & Tsavdaridis, 2023; Sarkisian et al., 2019). Additionally, hybrid timber-steel systems integrate steel components (e.g. yielding plates, tension rods, or dampers) within the timber structure, that leverage the high ductility of steel to absorb seismic energy and localize inelastic deformations within replaceable or non-structural components. As a result, these innovations not only enhance ductility and resilience but also contribute to the long-term sustainability of timber buildings by reducing the need for complete structural replacement after an earthquake (Sarkisian et al., 2019).

Steel/concrete: In contrast, traditional materials like steel and reinforced concrete possess inherent ductile properties that make them naturally suited for seismic energy dissipation. Under dynamic loading, steel yields and undergoes large plastic deformations without fracturing, while reinforced concrete dissipates energy through mechanisms like cracking of the concrete and yielding of embedded steel reinforcement. These characteristics allow steel and concrete structures to effectively manage and survive significant seismic loading with predictable, code-compliant performance (Gilbert & Erochko, 2016; Timmers & Tsay Jacobs, 2018).

6.6.3. Hybridization

Mass timber: Mass timber often benefits significantly from hybridization. The strategic combination of timber with other materials, particularly steel or advanced alloys, helps to overcome the seismic performance limitations of timber as these elements enhance stiffness, damping and deformation capacity. One common strategy is the integration of buckling restrained braces (BRBs) into mass timber frames. BRBs provide stable hysteretic behaviour and prevent buckling under compressive loads, enabling the system to absorb and dissipate a large amount of seismic energy while maintaining its integrity. Another innovative approach involves the use of shape memory alloy (SMA) devices, which can undergo substantial strain and then return to their original shape, providing both energy dissipation and self-centring capabilities (Rubio et al., 2024). As mentioned previously, these hybrid designs not only improve structural resilience but also allow damage to be concentrated in non-timber components, preserving the primary timber structure and reducing post-earthquake repair costs. Additionally, hybridization expands the design potential of timber by aligning its performance more closely with seismic safety standards, enabling its application in mid- to high-rise buildings and in regions with high seismic risk.

Steel/concrete: In contrast, steel and reinforced concrete structures typically do not require hybridization for the purpose of seismic performance. These materials inherently possess the properties needed to handle seismic demands, including high ductility, energy dissipation through yielding and material toughness. Their widespread use in seismic zones is largely due to their predictable and robust inelastic behaviour under dynamic loading. While hybrid strategies may still be employed in steel or concrete structures for other purposes, such as improving constructability or reducing weight, they are generally not essential to achieving seismic resilience (Rubio et al., 2024).

6.6.3.1. Seismic design parameters

Mass timber: Seismic design for mass timber structures presents unique challenges that require tailored approaches distinct from those used for steel or concrete. Seismic performance in timber structures heavily depends on the behaviour of connections and energy-dissipating devices, rather than on the material itself. This places greater emphasis on the calibration of seismic design parameters such as force reduction factors (R-factors), overstrength and displacement limits based on component-level performance rather than system-level material properties.

To ensure safety and serviceability under seismic loading, designers must accurately define and characterize the dissipative zones - the parts of the structure (typically connection regions) that are intended to yield or absorb energy. The reliability of seismic response depends on ensuring these zones behave in a controlled and ductile manner, using engineered solutions (Faggiano & Iovane, 2016; Li & Tsavdaridis, 2023). Because mass timber systems are relatively new and design codes are still evolving, calling for a combination of experimental validation, numerical modelling and adaptation of methodologies from other structural systems.

Steel/concrete: In contrast, steel and reinforced concrete structures benefit from decades of development and extensive research, leading to well-established seismic design parameters. These include predefined ductility classes, standardized detailing requirements for plastic hinge zones and codified procedures for capacity design. These materials possess intrinsic ductility and energy dissipation capacity, allowing engineers to rely on conventional design strategies that concentrate energy dissipation in predefined zones, such as yielding regions in beams or ductile shear walls, while maintaining elastic behaviour elsewhere. The predictability of their seismic response allows for more streamlined design processes and fewer uncertainties compared to emerging mass timber (Faggiano & Iovane, 2016).

6.6.3.2. Performance and resilience

Mass timber: Contemporary mass timber systems are increasingly designed with a focus on low-damage seismic performance. By integrating self-centring mechanisms, resilient energy-dissipating braces and engineered yielding components, these structures intend to limit permanent deformations and reduce the need for extensive post-earthquake repairs. A key strategy involves localizing inelastic behaviour in replaceable or repairable elements, allowing the primary structural system to remain largely undamaged. This approach not only enhances structural resilience, but also minimizes downtime and facilitates rapid reoccupation, which is particularly valuable in high-risk seismic regions (Chen et al., 2024).

Steel/concrete: Traditional steel and reinforced concrete structures are inherently well-suited for seismic applications, relying on the material's ductility and energy dissipation capabilities. These systems are typically designed according to established seismic codes that ensure controlled yielding in specific components and elastic behaviour of the remaining structure. This approach enables them to absorb and dissipate energy effectively during seismic events, thus limiting structural damage and ensuring life safety, even under strong ground motions (Chen et al., 2024).

6.6.3.3. Challenges and remarks

Mass timber: Despite the growing interest in mass timber construction, several technical and performance-

related challenges must be addressed, particularly in the context of high-rise and seismic applications. Key issues include lateral drift control (timber's lower stiffness can lead to excessive deformations during seismic events), deformation compatibility (particularly at connections and interfaces with non-structural elements) and fire resistance (requires careful detailing and often protective measures to comply with building codes and ensure structural integrity). These challenges often limit the feasibility of using entirely timber-based solutions in demanding structural contexts, thus prompting the development of hybrid systems that combine timber with steel or concrete elements to compensate for its limitations (Kasal et al., 2013).

Steel/concrete: In contrast, steel and concrete materials benefit from decades of empirical data, code development and construction experience. Their inherent high stiffness, ductility and fire resistance, as well as well-established detailing practices, reduce the complexity of addressing structural demands such as drift control, deformation capacity and load resistance. Therefore, they do not face the same degree of material-specific constraints as mass timber systems in these applications (Kasal et al., 2013).

This section synthesizes the comparative findings between mass timber and traditional materials (steel and concrete) across several key performance dimensions relevant to seismic design. Mass timber, while offering advantages such as reduced structural weight and sustainability, typically exhibits lower inherent ductility and energy dissipation capacity. To overcome these limitations, recent innovations focus on enhanced connection systems, hybridization with steel components and the integration of self-centring and energy-dissipating devices. However, challenges remain, particularly in drift control, deformation behaviour and fire resistance, which can limit its applicability in high-rise or high-seismic zones without supplemental systems. In contrast, steel and concrete benefit from well-established seismic design parameters, inherent material ductility and superior performance in demanding structural contexts. These materials require fewer modifications to meet seismic resilience targets and are less affected by the limitations seen in mass timber systems. Table 17 provides a structured summary of these findings across analysed categories.

The tests highlight the impressive seismic performance of CLT buildings, demonstrating their potential to withstand extreme earthquake conditions while maintaining structural integrity. This level of performance positions timber as a viable material for construction in earthquake-prone regions, particularly in the context of sustainable, high-performance building design.

Table 17. Summary of seismic design remarks for mass timber structures vs. traditional steel or concrete structures

ASPECT	MASS TIMBER STRUCTURES	STEEL/CONCRETE STRUCTURES
Weight	Lighter, lower seismic forces	Heavier, higher seismic forces
Ductility	Lower, enhanced with special connections	Higher, inherent in material
Energy dissipation	Relies on innovative connections	Inherent in material
Hybridization	Common, improves performance	Rarely needed
Seismic design parameters	Requires careful calibration	Well-established
Performance and resilience	Low-damage, self-centering techniques	Minimal damage, high resilience
Challenges	Drift, deformation capacity, fire resistance	Fewer specific challenges

6.6.4. Tall and high-rise mass timber buildings and geographical seismic risk characterization

This section intends to contextualize tall and high-rise mass timber buildings within the framework of global seismic risk. The global seismic hazard map is then presented to illustrate the worldwide distribution

of PGA, providing a geographical basis for assessing seismic exposure. Following this, an overview of selected tall and high-rise mass timber buildings is provided, categorized by their geographic location and corresponding PGA values. Special focus is given to buildings situated in areas with moderate to high seismic hazard, with the aim of summarizing key structural characteristics and, where applicable, outline the seismic strategies employed in their design. This analysis offers insight into how seismic remarks are addressed in the growing field of tall timber construction.

6.6.4.1. Seismic risk

Seismic risk is conventionally conceptualized as a function of three interrelated components: (1) seismic hazard, referring to the probability of occurrence and the intensity of ground shaking associated with potential earthquake events; (2) seismic vulnerability, which denotes the susceptibility of buildings, infrastructure and systems to sustain damage under given seismic conditions; and (3) expected consequences or losses, encompassing the anticipated social, economic and functional impacts resulting from the damage incurred (Fema, 2004).

PGA maps are integral to evaluating seismic risk and help identify areas with higher seismic hazard, guiding the design of structures to withstand expected ground motions (Agrawal & Chawla, 2006). They are used to develop design spectra for buildings and infrastructure, ensuring that structures can withstand the expected ground motions and thus, these maps are essential for updating building codes and improving construction practices in seismic regions (Dervishaj et al., 2014).

Probabilistic seismic hazard analysis (PSHA) estimates the probability of exceeding a certain PGA level over a specified period, providing a probabilistic framework for seismic hazard assessment (Puteri et al., 2019). The Global Earthquake Model (GEM) global seismic hazard map (version 2023.1) in Figure 70 depicts the geographic distribution of the PGA with a 10% probability of being exceeded in 50 years, computed for reference rock conditions (shear wave velocity, V_{s30} , of 760-800 m/s). The map was created by collating maps computed using national and regional probabilistic seismic hazard models developed by various institutions and projects, in collaboration with GEM Foundation scientists (Johnson et al., 2023).

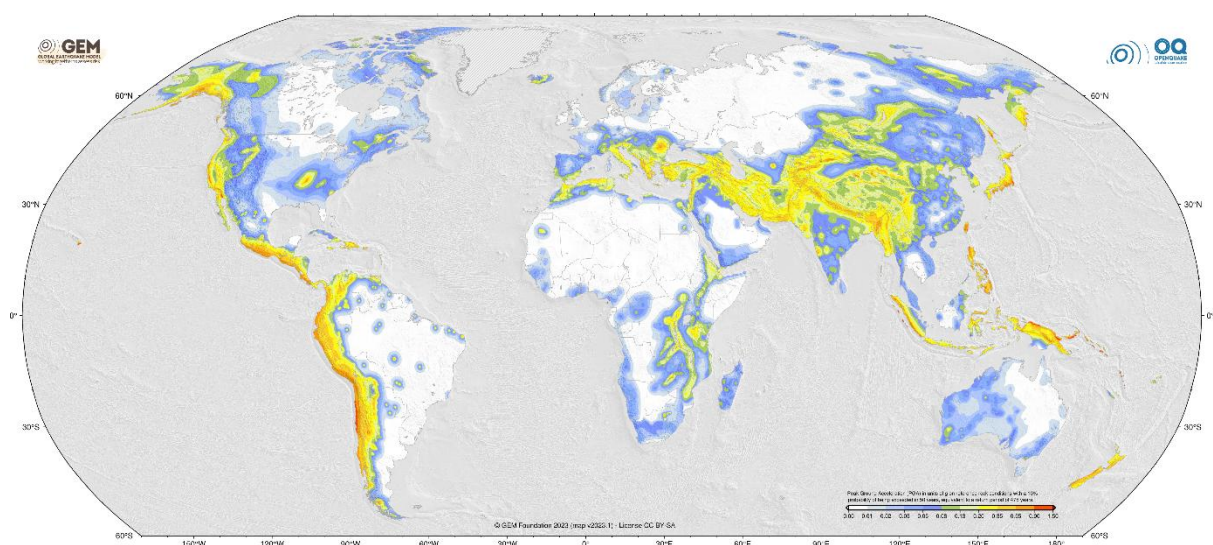


Figure 70. Global seismic hazard map (version 2023.1) (Johnson et al., 2023)

After the geographical check of the location of the list of 198 buildings considered in this study, they were divided according to PGA (g) scale and the results are presented in Figure 71. It can be observed that most of the cases are in the zone with no risk or very low risk of seismic event and only 14 buildings were constructed in the areas of moderate to high seismic activity.

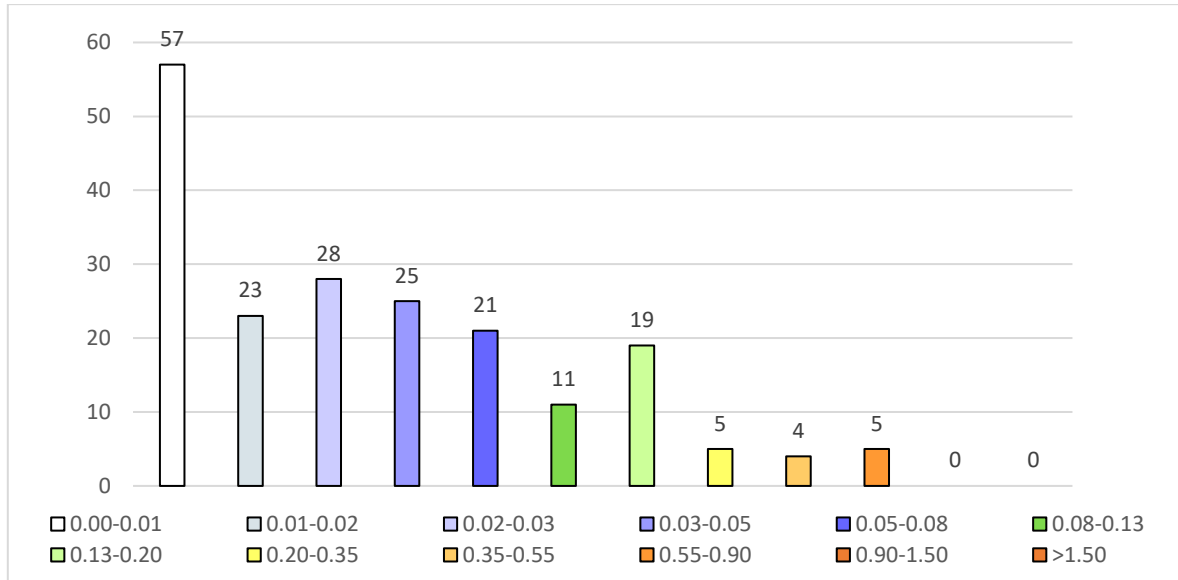


Figure 71. Distribution of the case studies according to their geographical location and corresponding PGA

The nine buildings located in regions with a PGA greater than 0.35 g are presented in Tables 18 and 19. Analysis of their geographic distribution reveals that the majority (five) are situated in Japan, with two in the United States, one in Europe and one in Chile. The tallest structure among them reaches a height of 48 m. While a few of these examples represent purely timber structural systems, the majority incorporate timber-based hybrid load-bearing systems. This trend is consistent with prior research, which indicates that hybrid configurations, combining timber with materials such as concrete or steel, can enhance seismic performance by improving ductility, stiffness and energy dissipation.

The examined cases demonstrate a diverse spectrum of seismic design strategies, reflecting both the complexity of structural systems and the regional seismic demands to which they are adapted. These strategies are specifically engineered to mitigate the dynamic forces induced by seismic events, ensuring structural integrity and occupant safety. Despite the diversity in design, several recurring approaches can be identified, mostly, the use of hybrid material systems, the implementation of base isolation technologies and the incorporation of advanced connection detailing. Such measures are indicative of an evolving design paradigm, in which mass timber and hybrid structures are increasingly optimized for seismic resilience. This evolution combines traditional engineering principles with innovative technologies to enhance energy dissipation, ductility and structural continuity under cyclic loading.

A recurring theme is the use of additional or hybrid earthquake-resistant wall systems, such as LVL, CLT and XLAM panels. These walls are strategically distributed throughout the structural core or lower floors, contributing to global stiffness, lateral resistance and controlled energy dissipation. In some cases, such as the use of additional walls on the 1st to 5th floors, the intent is clearly to enhance base stability and resist soft-storey mechanisms.

Table 18. List of case studies in the areas with PGA (g) 0.55-0.90

Name	No of floors	Year	City	Country	Height	Use	Structure**	Seismic remarks
Park Wood Takamori	10	2019	Izumi-ku	Japan	33.7 m	R	Timber-steel and timber-concrete (sound insulation)	Additional earthquake-resistant walls on the 1 st to 5 th floors (Hanai et al., 2020)
Jack London Square - Site F2	8	2020	Oakland	USA	26 m*	M	Timber-steel over 3 concrete floors	-
FLATS WOOD Kiba	12	2020	Tokyo	Japan	40.8 m	R	Timber-concrete and steel	Seismic-isolation devices at the bottom, reinforced concrete seismic walls arranged in a parallel cross shape, shear walls fastened with mega beams installed on the 12 th floor (<i>FLATS WOODS KIBA</i> , n.d.)
Proud Kanda Surugadai	14	2021	Tokyo	Japan	48 m*	R	Timber-concrete	LVL hybrid earthquake-resistant walls, CLT earthquake-resistant walls (Takenaka Design Department, 2021)
Port Plus	11	2022	Yokohama	Japan	44 m	O	All-timber	Pillars and beams comprise cross-shaped units connected, seismic-isolation structure (Wood Central, 2023)

R- Residential, O- Office, M- Mixed uses.

* Google Earth.

** All-timber: Both the main vertical/lateral structural elements and the floor spanning systems above the ground are made of timber; it may include the use of localized non-timber connections between timber elements as well as concrete/steel elements that are not acting as the primary structure.

Table 19. List of case studies in the areas with PGA (g) 0.35- 0.55

Name	No of floors	Year	City	Country	Height	Use	Structure	Seismic remarks
Kasukabe Convention Hall	6	2011	Saitama Prefecture	Japan	27.1 m	O	All timber over steel (4 levels)	-
Residence Alexander	6	2012	Acquila	Italy	-	R	Timber with concrete core	XLAM earthquake resistance structure (<i>Alexander Residence</i> , n.d.)
Stella	6	2013	Marina del Rey	USA	21 m*	M	All-timber over concrete (1 st level)	Continuous rod tie-down system, 6-inch seismic joints at the intersection of each of L'shape configuration (WoodWorks, 2013)
Los Bronces	6	2019	Los Andes	Chile	-	R	All timber	Wind and seismic metal certified connections (<i>Hotel Pérez Caldera En Los Bronces: Construcción Modular En Madera</i> , 2020)

R- Residential, O- Office, M- Mixed uses, E-Educational.

* Google Earth.

** All-timber: Both the main vertical/lateral structural elements and the floor spanning systems above the ground are made of timber; it may include the use of localized non-timber connections between timber elements as well as concrete/steel elements that are not acting as the primary structure.

Base isolation systems are another key element in some cases. Seismic isolation devices are placed at the foundation level to decouple the superstructure from ground motion. In the case of FLATS WOOD Kiba, this strategy is combined with reinforced concrete shear walls arranged in a cross pattern and with mega beams at higher levels (e.g. the 12th floor), demonstrating a multi-layered seismic approach that distributes forces and prevents excessive inter-storey drift.

In terms of connection technology, multiple cases highlight the use of engineered connection systems. Stella implements a continuous rod tie-down system and seismic joints, which are essential in dissipating energy and accommodating building movement, particularly at junctions of complex building geometries (e.g. L-shaped configurations). Los Bronces reports the use of metal connections certified for wind and seismic loads, emphasizing the role of mechanical fasteners in transferring loads while preventing brittle failure, an essential consideration in timber structures, which rely heavily on connection behaviour for ductility.

Port Plus also presents an innovative cross-shaped beam-pillar modular unit, which, when paired with base isolation, likely serves both structural and prefabrication purposes while enhancing redundancy and load redistribution in the event of a seismic event.

In summary, the most frequently applied seismic strategies across these buildings include:

- The use of hybrid or reinforced wall systems to provide shear resistance;
- The implementation of base isolation for reducing seismic force transmission;
- The optimization of connections through continuous rods, seismic joints and certified metal connectors;
- The integration of concrete or steel elements in hybrid assemblies for added ductility and robustness.

These approaches collectively reflect a shift towards performance-based design in mass timber and hybrid buildings, where localized damage control, redundancy and energy dissipation mechanisms are prioritized to ensure post-earthquake functionality and occupant safety.

6.6.5. Seismic design insights

High-rise mass timber buildings present a promising, sustainable alternative to conventional concrete and steel structures. However, their seismic performance requires careful attention due to timber's material characteristics and the evolving nature of relevant design codes. Compared to traditional materials, timber is lighter, resulting in lower seismic forces, but also more brittle in bending, tension and shear parallel to the grain. Consequently, energy dissipation and ductility must be engineered primarily through innovative connection systems rather than the material itself.

To overcome these challenges, a range of advanced seismic strategies has been developed. These include friction energy-dissipating devices, mechanisms and hybrid systems that combine the ductility of steel with the sustainability of timber, improve strength and stiffness and prevent brittle failure.

Performance has been validated through cyclic and monotonic testing, which remains critical for assessing rotation capacity, energy dissipation and connection integrity. Several experimental studies demonstrate that damage can be localized in replaceable components, significantly enhancing the resilience and reducing downtime after seismic events. Additionally, design adaptations, such as capacity-based design and detailing for transfer zones in multi-story shear walls, are still under development, highlighting a need for more comprehensive design standards.

Globally, high-rise timber buildings are being developed in regions with varying seismic risks and employ diverse seismic mitigation measures. The use of hybrid systems, involving timber, concrete and steel, emerges as a dominant strategy in high-risk seismic zones, offering improved stiffness, ductility and energy dissipation.

Despite progress, several challenges persist: ensuring sufficient drift control, preserving load-bearing capacity and provide fire resistance, particularly for taller structures. Moreover, current building codes, such as Eurocode 8, provide limited guidance on timber seismic design, especially for newer systems. This regulatory gap underscores the need for future research and codification.

In summary, while mass timber offers environmental and aesthetic benefits, achieving seismic resilience in high-rise applications demands hybridization, engineered connections and tailored design strategies. Continued innovation and code development will be essential to fully realize the potential of timber in seismically active regions.

6.6.6. Project team handout summary: Seismic performance for high-rise timber buildings

Objective: To guide project teams in designing and delivering high-rise mass timber buildings that are seismically resilient, code-compliant and functionally recoverable following an earthquake, through effective risk assessment, material selection, connection detailing and interdisciplinary coordination.

What must be done:

- ✓ Understand seismic risk;
- ✓ Design an appropriate structural system;
- ✓ Ensure ductility through connections;
- ✓ Rely on experimental validation;
- ✓ Address construction quality and detailing;
- ✓ Collaborate early and often.

Why it matters:

Seismic resilience is a critical performance requirement for tall timber buildings in moderate to high-risk zones. Due to the material's limited inherent ductility, the safety and functionality of the building under earthquake loads depend almost entirely on the performance of the structural system and its connections. Using well-tested, ductile and replaceable systems ensures that damage remains localized and repairable, reducing downtime and economic loss after an event. Careful coordination during design and construction improves building safety and functionality while demonstrating compliance with evolving codes and standards. A well-executed seismic strategy also supports the broader goals of sustainable design, enabling mass timber to expand into regions where resilience is non-negotiable.

Part 3. Development of guidelines

7. Guidelines for the sustainable design and construction of tall and high-rise timber buildings

The growing relevance of high-rise mass timber buildings as sustainable architectural solutions demands clear, actionable and cross-disciplinary guidance. As the use of engineered wood continues to expand into more complex, tall and high-rise building typologies, architects, engineers, contractors, regulators and owners must navigate a new set of challenges that are fundamentally different from those encountered with traditional materials like steel and concrete. These challenges relate not only to material properties but also to planning processes, construction logistics, building performance and long-term environmental responsibility.

To address this complexity, this chapter presents a comprehensive framework of design and construction guidelines. The objective is to support high-performance outcomes by ensuring that timber's unique advantages as renewability, prefabrication compatibility and natural qualities are fully realized through integrated, well-informed decision-making at every stage of the building life cycle.

The guidelines are organized according to the major phases of a project's life cycle (Figure 72), from early planning and digital design integration through to construction, use and end-of-life remarks. In addition, some strategies are identified at the administrative and governmental level. This structure helps to ensure that every design and technical decision is rooted in lifecycle thinking, technical precision and performance-based evaluation.



Figure 72. Project life cycle stages adopted for these studies

To further support implementation, each guideline is accompanied by a clear indication of the stakeholders most directly responsible or involved in its execution. These include actors across the entire timber value chain such as forest owners, loggers and sawmills, manufacturers, architects, engineers, general contractors, specialty consultants, managing bodies, regulatory authorities and maintenance professionals (Table 20). By explicitly linking each recommendation to its relevant actors, the guidelines foster collaboration, accountability and specialization.

Ultimately, by adhering to these guidelines, professionals and industry participants can effectively contribute to:

- The conservation and sustainable management of forests, enhancing their ecological, economic and social benefits while addressing the pressing challenges of climate change and deforestation;
- The sustainable management and conservation of forest resources, contributing to ecological balance, economic viability and social well-being;
- Manage moisture levels in wood construction, ensuring the structural integrity, longevity and aesthetic quality of wood products, resulting in mass timber products that are structurally robust, dimensionally stable and visually appealing;

- The optimal use of this renewable resource for sustainable and durable building projects;
- The quality, safety and suitability of timber products for construction, supporting informed decision-making and adherence to regulatory standards;
- The durability, structural integrity and longevity of timber structures;
- To create fire-safe buildings, including high-rise structures, while also addressing and overcoming regulatory challenges.

The list of actors in the mass timber construction value chain (Allan et al., n.d.; Orozco et al., 2025) is presented in Table 20.

Table 20. Main actors in the mass timber construction value chain

No.	Name	Description	Icon
1	Forest owners & timber growers	Sustainably manage stands, determine harvest regimes and secure fibre supply	
2	Loggers & harvesting contractors	Fell, extract and transport roundwood to primary processors	
3	Primary processors (sawmills)	Convert logs into dimension lumber and residues for engineered products	
4	Engineered wood manufacturers	Produce engineered timber products	
5	Prefabrication & CNC producers	Translate BIM/CAD models into precision-cut panels, modules and connection details	
6	Transport & logistics providers	Coordinate oversized-load trucking, JIT delivery, site staging and moisture-protected handling	
7	Architects & design professionals	Develop mass timber concepts, BIM coordination and aesthetic integration	
8	Structural engineers	Engineer gravity and lateral systems, perform load-path analyses and size members	
9	Specialty consultants	Fire protection engineers	
10		Acoustical consultants	
11		Building envelope & moisture control experts	
12		Sustainability & life-cycle assessment (LCA) specialists	
13		Vibration & dynamic performance analysts	
14		Connection design specialists	
15		Special inspection providers	
16	MEP & façade consultants	Integrate services, curtain walls and interface details with timber structure	
17	General contractors	Oversee site management, sequencing, quality assurance and safety compliance	
18	Erection & installation subcontractors	Assemble panels, install connectors and tension hold-downs or tie-downs	
19	Developers & owners	Define project objectives, secure funding and set sustainability/occupancy targets	
20	Lenders, insurers & certifiers	Underwrite project risk, certify forest/chain-of-custody (e.g. FSC/SFI) and verify code compliance	
21	Regulatory authorities & code officials	Approve building permits, review fire-safety and structural submissions and enforce inspections	
22	Project managers & BIM coordinators	Align multidisciplinary teams, manage digital models and control change processes	
23	Research institutions & academia	Conduct experimental testing, refine design standards and advance mass timber technology	
24	Facility managers & operation teams	Monitor in-service performance, moisture levels and plan maintenance or end-of-life reuse	
25	Deconstruction and recycling companies	Coordinate and execute the replacement or demolition of a building or its parts	

7.1. Strategies stage

Before design decisions and building processes unfold, the environmental integrity and social responsibility of timber use must be firmly established. The strategies stage sets the long-term vision that shapes how timber is sourced, processed and integrated into the built environment. It connects forest-level decisions with global climate goals, circular economy principles and informed material use through certification and documentation.

This early-phase strategic framework ensures that timber high-rise construction is not only technically and economically viable but also ecologically sound and socially responsible. By adopting these strategies, stakeholders create the foundation for sustainable forestry, carbon-smart construction and a resilient, transparent timber supply chain.

The strategies stage guidelines presented in Table 21 address the upstream sustainability of timber, from forest ecology and management to circular economy alignment and carbon accounting. They shift focus from the building to the biosphere, positioning mass timber architecture as a climate-positive, ethically grounded and resource-conscious practice.

These strategies also serve as ethical and operational filters for later design, procurement and construction decisions. They empower all stakeholders - developers, designers, manufacturers and regulators, to ensure that timber used in tall buildings contributes not just to vertical growth but to ecological renewal, global climate solutions and sustainable development.

Table 21. Guidelines for high-rise timber building strategies stage

Key guideline	Sub-guidelines	Key actors
Recognize the importance of forests	Acknowledge the ecological benefits of forests as habitats for diverse species and regulators of climate	  
	Recognize economic and social benefits of forests and their roles in providing raw materials and recreational opportunities	  
Implement Sustainable Forest Management (SFM)	Adopt forestry and harvesting methods that safeguard forests' long-term health and biodiversity	  
	Through comprehensive management, include timber harvesting, wildlife habitat conservation, watershed protection, fire management and recreation planning.	  
	Utilize selective logging, reforestation and habitat restoration to maintain forest ecosystems	  
	Engage communities, businesses and policymakers in sustainable forest management practices	  
	Promote sustainably managed forests for their economic and carbon sequestration benefits	  
	Address threats such as climate change, wildfires, pests and urban development	  
	Protect forest biodiversity essential for climate regulation and ecological resilience	 
	Emphasize natural regeneration to maintain ecosystem integrity	 
	Apply criteria and indicators representing conditions for SLM and select suitable monitoring tools	  
	Advocate for policies supporting SFM at local, national and global levels	  

Key guideline	Sub-guidelines	Key actors
Promote and expand forest certification	Implement forest and chain of custody certification programs to ensure compliance with environmental standards	  
	Support certification schemes like PEFC and FSC, covering most certified forests worldwide	 
	Foster consumer confidence through certification proving environmental remarks in harvesting	  
	Address the regional differences and low percentage of certified forests in areas like Africa, Asia and South and Central America	  
Support reforestation and afforestation initiatives	Support global efforts to restore degraded forests and establish new ones	  
	Practice sustainable harvesting with careful tree removal, replanting and species diversification to ensure long-term forest viability	 
Use timber to support climate change mitigation	Utilize forests' ability to store carbon in climate change strategies	 
	Promote reforestation to reduce surface and air temperatures	 
	Manage species selection and harvesting intervals based on growth rates to optimize CO ₂ absorption	 
	Promote research on optimal harvesting to increase carbon sequestration	
	Encourage the use of wood products for long-term carbon storage	 
	Quantify emissions throughout the life cycle of timber products using LCA and carbon footprint metrics	
	Use carbon footprint data to guide climate-friendly decision-making and policy development	 
	Promote mass timber construction for reduced emissions, carbon storage and lower environmental impact	  
	Provide education and training to contractors, designers and engineers to support timber construction	  
	Monitor and improve practices for reducing the carbon footprint of timber buildings	  
	Stay informed about innovations in forestry, processing and assessment methods	  
Aim for circular economy and wood cascading practices	Focus on producing durable timber products with long lifespans to extend carbon storage	 
	Implement reduction, reuse, recycling and remanufacture principles	 
	Develop and enforce regulations for timber reuse and recycling	 
	Employ innovative strategies for treating composites to enable recycling	 
	Use high-quality timber in multiple life stages before energy recovery	 
	Maximize timber's functional utility at each life stage	 
	Invest in training for architects, engineers and construction workers in timber cascading	  
	Address knowledge gaps through research for integrating timber into circular economy models	 
	Develop viable business models for circular economy implementation in construction	  
Promote the use of Environmental Product Declarations (EPDs)	Use standardized EPD labels to communicate life cycle impacts of timber products	 
	Enhance EPDs with insights from sustainable forest management certifications	 

Key guideline	Sub-guidelines	Key actors
	Apply Eurocode 5 adjustments for timber strength class based on moisture, temperature and aging	
	Grade by defect size, location, shape, grain slope and stress type; scale criteria to member dimensions	
	Provide standardized grade labels to inform users	
Season, store and treat to control moisture	Kiln-dry to ~12 % equilibrium moisture, follow Eurocode 5 for strength adjustments and manage MC in humid sites	
	Handle excessively dry wood with care to avoid brittleness during machining and shaping.	
	Utilize wood with adequate moisture content level for manipulation and shaping tasks	
	Store panels elevated (≥15 cm over pavement, ≥30 cm over soil) on clean, level, well-drained, ventilated sleepers	
	Apply chemical/physical treatments and factory hydrophobic coatings to enhance durability	
	Cover window/door openings with breathable, double-layer sheeting, avoid plastic wraps, slit factory wrap for drainage	
Employ quality control measures	Implement strict quality control measures during manufacturing to ensure consistent grain orientation across all components, maintaining structural integrity and aesthetic quality	
	Account for natural characteristics like knots, pitch pockets, fissures and grain deviations in sawn timber, as these significantly influence timber's properties	
	Conduct thorough inspections of each piece of timber to identify and quantify the sizes and frequency of defects	
	Ensure adherence to building codes and standards through accurate timber grading	
Produce durable, carbon-neutral products and use EPDs	Employ EPDs to assess, aggregate and communicate cradle-to-gate impacts, enhanced by sustainable-forest data	
	Use standardized labels - EPDs to communicate product life cycle information and environmental impacts	
	Enhance EPDs with insights from sustainable forest management certifications to provide a comprehensive environmental perspective	
	Utilize EPDs to aggregate environmental impacts across a product's supply chain for better decision-making	
Achieve target moisture content	Aim for a target moisture content of 12% (equilibrium moisture content) by kiln drying (seasoning) harvested trees, that reduces the wood's volume and enhances its strength	
	Follow design codes, such as Eurocode 5, which adjust strength values for timber based on specific moisture content levels	
	Carefully manage the moisture content of wood in high-humidity environments	
Aim for the carbon-neutral production	Continuously monitor and improve practices to reduce the carbon footprint of timber products	
	Utilize renewable energy sources in processing facilities to reduce emissions	
	Implement energy-efficient technologies, especially in energy-intensive processes like kiln drying	
Foster innovation in timber construction technologies for CE applications	Encourage innovation in timber connections, protection and sustainable material integration for coatings and insulation	
	Integrate robotic disassembly and automated fastener removal systems to enhance efficiency in timber recovery and reuse	

Key guideline	Sub-guidelines	Key actors
Integrate and enhance digital design and manufacturing technologies	Adopt BIM, high level of prefabrication and JIT manufacturing to ensure more controlled and efficient production, improve interdisciplinary coordination and minimize construction time and waste	  
	Use parametric design, CNC production and prefabricated elements to achieve precise fabrication, optimize material consumption, enhance quality control and streamline construction processes	  

7.3. Design stage

The design stage of high-rise mass timber construction is a pivotal phase where the foundation for structural performance, architectural expression, environmental resilience and construction efficiency is established. The complexity and multidisciplinary nature of mass timber systems require a shift from conventional design practices toward collaborative, performance-driven and digitally integrated processes. Early decisions during this stage significantly impact prefabrication potential, material efficiency, moisture safety, fire resistance and the feasibility of innovative structural solutions.

To support a consistent and optimized approach, this section presents a structured set of design guidelines (Table 23), developed to aid all stakeholders in navigating the technical, environmental and regulatory demands of designing mass timber buildings at height. These guidelines address the unique opportunities and constraints of wood, emphasizing timber's biophilic appeal, strength-to-weight advantages and its role in carbon sequestration. At the same time, they advocate for integrated planning, accurate modelling and proactive engagement with moisture, acoustic, fire and seismic performance parameters.

The guidelines are organized into thematic categories, each focusing on a critical design dimension, from early planning and collaboration, through digital and fabrication workflows, to core structural strategies, performance integration and architectural detailing. This structure allows for clarity and ease of application across different project phases and team roles.

Each guideline is paired with the key stakeholder groups involved in its implementation, recognizing that a high-rise mass timber building is the product of deeply interdependent efforts among architects, engineers, fabricators, developers, consultants, contractors and regulators. By clearly mapping stakeholder responsibilities, the framework enhances project coordination and accountability.

By embedding these design guidelines into the early phases of high-rise timber projects, teams can maximize quality, minimize rework and fully leverage timber's potential as a renewable, high-performance construction material.

Table 23. Guidelines for high-rise timber building design stage

Key guideline	Sub-guidelines	Key actors
Assemble and engage the full team	Include every stakeholder from project inception to balance structural efficiency, required performance and economic feasibility with architectural ambition	   
	Ensure architects, structural/fire/acoustic engineers and fabricators collaborate on requirements and sequencing	     
Adopt an Integrated Design Process (IDP)	Use IDP workshops to optimize decisions across disciplines in the conceptual phase	     

Key guideline	Sub-guidelines	Key actors
	Align architectural, structural and construction sequencing for maximum build efficiency	
	Prototype components and run simulations early to validate cost, environmental impact and performance targets	
Create a comprehensive project roadmap	Define performance, cost and constructability goals in a detailed master schedule	
	Anticipate timber-specific tolerances and multifunctional roles	 
Use digital tools and integrated processes	Employ BIM and 3D software for clash detection and coordination	
	Maintain a unified, coordinated model for all disciplines	
	Ensure software compatibility through common export formats	
Front-load the design	Integrate service cut-outs and openings into prefabricated components	
	Detail all trade intersections to mitigate cumulative errors	
	Finalize electrical and service requirements early	
	Avoid late-stage revisions that disrupt prefabrication	
Embrace timber's natural qualities	Highlight biophilic appeal and tactile warmth in design	
	Avoid mimicking steel/concrete forms	
	Consider cultural context and acceptance	
	Respect local traditions, regulations and climate adaptability	
	Explore beyond timber's structural role	
	Use wood as an expressive material in space making and symbolism	
Design for timber's unique characteristics and advantages	Account for anisotropy, grain direction, moisture movement and joint complexity	
	Select species and finishes suited to exposure and service conditions	
	Optimize panel orientation, layer sequencing and design tolerances for stability and performance	
	Maximize prefabrication, on-site assembly speed and carbon storage potential	
	Exploit inherent thermal mass	
Adapt timber strength class to the environment and use	Adjust design strategies for increased height, loads and building services	
	Match products, assembly selection and connection details to structural loads and service demands	
	Scale strategies for high-rise: address increased gravity, lateral loads, building services and erection methods	
Commit to rigorous engineering strategies	Address wind, seismic, sway, moisture, creep and shrinkage control	
Pursue holistic structural design	Align load paths, stiffness and fire/acoustic/thermal requirements	
Design for various load types	Account for dead/live loads, climate, aging and load duration classes	
Ensure continuous load paths	Align all structural members and joints to ensure uninterrupted force transfer	
Prioritize connection design	Integrate creep/shrinkage allowances and select budget-appropriate solutions	
	Use full-scale physical tests and digital modelling to optimize connections	
Design for adaptability, disassembly and reuse	Integrate circular principles from the design stage by applying strategies such as DfA, DfD and DfR	

Key guideline	Sub-guidelines	Key actors
	Prioritize demountable and standardized timber components to enhance reversibility and enable higher reuse potential	 
	Prioritize the use of modular, prefabricated components and adjustable connections	  
Understand core structural configurations	Choose adequate structural system for functional need	 
	Apply hybrid systems where necessary	  
Understand panelised systems	Maximize prefabrication, limit internal reconfiguration.	  
	Use hybrid panels for performance boosts	  
Understand post-and-beam systems	Regular column-beam grids with engineered wood	  
	Stabilize using cores, bracing, or shear walls	 
Understand 3D modular systems	Prefabricate volumetric units for fast on-site installation	  
	Plan for transport, pod stacking and bracing	  
Address lateral loads (wind & seismic)	Model creep and shrinkage; integrate gravity ties	 
Design for seismic performance	Use ductility, capacity design and dissipative devices	 
	Follow international standards if local ones lack clarity	 
Ensure regulatory compliance	Meet structural safety, durability and code requirements	 
Comply with fire safety standards and regulations	Use charring behaviour, REI ratings and protected assemblies	 
Design fire detection and suppression systems	Include sprinklers, alarms and safe escape routes	  
Adopt humidity responsive design	Prevent water infiltration and plan for vapour control	  
Integrate dimensional stability strategies	Minimize swelling/shrinkage through design detailing	  
Design an effective, high-performance envelope	Prioritize exterior insulation and avoid interior-only vapour barriers	  
Ensure airtightness and vapour control	Match vapour barriers to climate zones and structural joints	  
Take advantage of timber's low thermal conductivity	Integrate into envelope strategies to optimize energy efficiency	  
Engage acoustic experts early	Guide design with simulations and material choices	  
Understand key acoustic concepts	STC, IIC, flanking, impact and airborne noise	  
Design for airborne and impact sound insulation	Apply mass layers, resilient mounts, floating floors	   
Prevent flanking transmission	Detail joints and interfaces with isolation materials	  
Comply with regional regulations	Match rating systems and local performance metrics	   
Prioritize building forms for efficiency	Prefer prismatic forms for modular and cost-efficient execution	 
Introduce complexity thoughtfully	Use façade or volume variation selectively	 
Optimize core configuration	Favour central cores; use hybrid materials for stability	 
Integrate daylighting and solar control	Orient façades, use glazing and shading devices	  
Use timber partitions strategically	For fire, acoustic and structural zoning	   
Enhance shared spaces	Showcase exposed timber in communal zones	 

Key guideline	Sub-guidelines	Key actors
Promote proactive service integration	Coordinate penetrations and risers without disrupting structure	
Leverage economic and environmental gains	Cut waste, support circular economy, improve site safety	
Utilize EPDs and carbon metrics	Communicate life cycle data and integrate into decisions	

7.4. Construction stage

The construction stage in high-rise mass timber projects marks the transition from detailed planning and off-site precision to the real-world assembly of structural and architectural components. Given timber's hygroscopic nature, fire performance characteristics and prefabrication-centric approach, the construction phase demands rigorous attention to sequencing, moisture protection, tolerances and coordination between trades.

Unlike conventional building materials, mass timber components are often pre-cut and finished off-site, leaving minimal room for on-site adjustments. This amplifies the need for accurate design execution, robust logistics and integrated quality assurance. The guidelines under this stage presented in Table 24 support the realization of a durable, safe and high-performance timber structure through effective project management, protection measures and stakeholder collaboration.

The construction stage for high-rise mass timber buildings is more than just putting pieces together, it is a high-stakes orchestration of pre-planned precision, environmental safeguards and stakeholder coordination. Timber demands anticipatory action, from protecting materials in transit to sequencing assemblies around weather windows and fire protocols. Thus, these guidelines collectively emphasize collaboration, control and continuity, ensuring that the design excellence and environmental performance intended in earlier stages are preserved and delivered in the built form.

Table 24. Guidelines for high-rise timber building construction stage

Key guideline	Sub-guidelines	Key actors
Prefabricate to improve performance and minimize risk	Off-site fabricate walls and envelope panels for airtightness and accuracy	
	Use CNC and automated workflows for precise fabrication	
	Protect assemblies with tents or covers during transport and install	
Use a formal project plan	Pre-inspect sealants, membranes, insulation and joints before shipping	
	Single approved document for roles, schedule, QA, risks and communications	
	Keeps every stakeholder aligned and accountable	
Employ advanced scheduling	Critical path method for task dependencies and minimum duration	
	Gantt charts to visualize dates, durations and links	
Follow specific planning phases	Preliminary design: set fire, acoustic, structural and prefab targets	
	Design development: finalize systems, materials, joints and prefab levels	
	Construction planning: sequence erection, hoisting, tolerances, access	

Key guideline	Sub-guidelines	Key actors
	Implementation: detail moisture barriers, fire stops, secure approvals	
Choose cooperative delivery models	Engage fabricators and constructors in design to spur innovation	
	Minimizes change orders and boosts quality	
	Balance technical and economic choices from the outset	
Secure legal mass-timber transport and solve logistic issues	Confirm route permits and legal restrictions	
	Obtain oversize permits, respect width/length and axle-load limits	
	Segment large panels for bridges and tight turns	
	Schedule just-in-time deliveries, brace and rig loads to avoid damage	
	Right size and frequency of shipments to cut time, cost and emissions	
Prepare and follow an optimal transport schedule	Coordinate among manufacturers, architects, engineers and site teams	
	Deliver in install order to minimize laydown	
	Avoid double handling and on-site re-sorting	
	Verify dimensions, condition and compliance certificates on arrival	
Enforce storage and moisture control	Follow manufacturer's transport, storage and assembly specifications	
	Implement moisture-management plan with membranes, sensors and shelters	
	Choose proper storage sites	
Consider off-Site timber yards	Keep areas clean, level, well drained and ventilated to deter decay	
Prevent handling damage	Leverage off-site yards for staging and pre-installation flexibility, balancing against added management costs	
	Lean on just-in-time deliveries to minimize laydown and double-handling	
	Use forklifts with extended attachments, combi-lifts, tie-off beams and thick dunnage	
Use appropriate storage protection	Store panels off the ground on sleepers (≥15 cm over pavement; ≥ 30 cm over soil) for airflow	
	Wrap with breathable paper or canvas, strap securely and vent the bottom	
	Slit factory wraps for drainage, avoid plastic/clear sheeting and vent after rain event	
	Shade from direct/indirect sun to prevent "sun-tanning"	
	When heating is required, raise temperatures gradually	
	Use sealers to buffer moisture shifts	
	Guard cut ends and exposed faces from weather	
	Maintain dynamic coordination	
	Update project plans, BIM models and shop drawings continuously as the works evolve	
Define Quality Assurance (QA)/Quality Control (QC) framework	Coordinate layered systems—floor slabs, partitions, façades, services—through unified planning reviews	
	Set clear performance criteria and inspection protocols for materials, processes and workmanship	
	Document thoroughly	
	Maintain a central log of specifications, approvals, inspections and meeting minutes	

Key guideline	Sub-guidelines	Key actors
Integrate oversight across disciplines	Track moisture-control and QA metrics digitally for transparency	
	Embed QC checkpoints into schedule, cost, safety, environmental and technical workflows	
	Appoint cross-discipline QA leads to monitor interdependencies and resolve issues	
Enforce contractor quality measures	Standardize handling and installation procedures	
	Train crews on timber-specific protocols (moisture, connections, tolerances)	
	Conduct daily audits with checklists and immediate corrective actions	
Pursue a zero-defect policy	Require strict adherence to approved drawings and specifications	
	Employ skilled labour under continuous supervisory oversight	
	Log, track and close out every defect to prevent recurrence	
Perform enclosure & moisture protection QC	Inspect membrane placement, window/door interfaces and air-barrier continuity	
	Verify moisture content ($\leq 19\%$) before closing in structural elements	
	Ensure subcontractors follow detailed envelope-detailing standards	
Verify construction quality & moisture control	Prevent water ingress at connections and protect fasteners from corrosion or swelling	
	Confirm all temporary and permanent bracing is installed as specified	
	Sequence framing and enclosure in drier seasons when feasible	
Develop a weather protection plan	Adopt just-in-time deliveries and plan floor-by-floor tarping for rain events	
	Weigh benefits and logistics of mobile enclosures or retractable roofs	
	Cover exposed slabs each night or before storms with large waterproof tarps	
Appoint a moisture-management team	Assign dedicated supervisors, establish monitoring and documentation procedures and enforce protocols	
	Deploy specialists to oversee moisture control from transport through erection	
Control moisture on-site	Delay moisture-sensitive installations until the envelope is fully closed	
	Maintain relative humidity below 75%, then 45–55% after insulation, at temperatures above 10 °C	
	Use temporary heating in sealed spaces for controlled drying	
Inspect and validate performance	Before finishes, use calibrated moisture meters to check hygrothermal performance and replace any damp or damaged components	
Prevent ignition on construction site	Enforce no-smoking and no-hot-work policies	
	Restrict unattended heat sources	
	Provide fire-safety training to workers and occupants	
Plan for fire safety during construction	Appoint on-site fire-safety manager; install temporary standpipes and hoses early	
	Progressively enclose timber surfaces, document and inspect fire systems	

Key guideline	Sub-guidelines	Key actors
Install and inspect fire detection and suppression	Equip with alarms, smoke detectors, extinguishers and sprinklers per design	  
	Ensure proper water-supply routing and system commissioning	  

7.5. Use and end of service stage

The use and end-of-service stage encompasses the building's operational life, its ongoing performance and its eventual disassembly or reuse. For high-rise mass timber buildings, where material performance is closely tied to environmental conditions and long-term maintenance, this phase is critical to ensuring durability, indoor quality and a responsible end-of-life strategy.

Timber's natural aging, moisture sensitivity and biogenic carbon storage present both opportunities and challenges. While timber can offer stable performance for decades or even centuries, improper maintenance or design oversight can lead to premature degradation. Similarly, embracing circular economy principles requires careful planning at the design stage but must be enacted through responsible management, repair and reuse practices during and after use.

The following guidelines intend to support durability, sustainability and adaptability by establishing protocols for maintenance, performance monitoring and future disassembly.

This stage highlights a long-term stewardship approach to mass timber buildings, where operational strategies are just as critical as design decisions. Timber's biological nature requires that users and facility managers remain proactive in monitoring conditions, maintaining protective strategies and planning for responsible end-of-life scenarios.

The guidelines presented in the Table 25 and Table 26 reinforce the idea that designing for disassembly, adaptability and inspection not only preserves structural integrity but unlocks new value in timber's reuse. In doing so, they align timber construction with the goals of durability, circularity and climate-positive architecture.

Table 25. Guidelines for high-rise timber building use stage

Key guideline	Sub-guidelines	Key actors
Monitor environment continuously	Deploy sensors for humidity and temperature; log weekly and adjust protection strategies	   
	Establish inspection and maintenance protocols to ensure efficient follow-up	   
	Maintain record of repair events in MPs and in BIM to enable reliable material tracking	   
Validate performance post-occupancy	Conduct field testing to verify airborne and impact sound insulation	   
	Perform follow-up acoustic assessments to resolve unforeseen issues	   
Control moisture	Carefully manage the moisture content of wood in high-humidity environments	  
	Maintain timber moisture content at $u \leq 20\%$ to prevent fungal infestation and other moisture-related issues	  
	Implement comprehensive operation and maintenance guidelines for moisture safety	  
	Instruct all parties involved about moisture management protocols and the importance of moisture control	   

Table 26. Guidelines for high-rise timber building end of service stage

Key guideline	Sub-guidelines	Key actors
Enhance end-of-life management	Promote recycling and re-use of timber products to extend their carbon storage potential	
	Integrate timber into cascading schemes, chip for fuel or mulch, or consider landfill as a last resort, offering a sustainable end-of-life solutions for timber products	
	Prioritize uses in construction and furniture for long-term carbon sequestration	
Use technological advancement to keep the information about product available for different end of life scenarios	Update and validate the information in material passports and BIM for the decision on product's end of life	
	Promote upcycling and structural repurposing of reclaimed timber by remanufacturing it into engineered wood products and prioritize reuse over down-cycling or energy recovery*	

This chapter assembles a comprehensive set of actionable guidelines spanning every phase of a mass-timber project - forest management, product fabrication, design, construction, in-use operation and end-of-service. Each stage is framed around core objectives such as sustainability, performance, moisture and risk control, quality assurance, carbon-neutrality, fire safety and circular-economy thinking and assigns clear roles to the stakeholders best placed to deliver them.

In crafting a truly resilient and low-impact mass-timber workflow, the heart of success lies in weaving together continuous collaboration, integrated decision-making and rigorous oversight from forest to end-of-service. From the earliest concept sessions through delivery and beyond, every actor, whether sourcing timber, engineering connections, coordinating logistics or certifying building performance, operates within a shared process, driving alignment on cost, schedule, safety and environmental targets. This unified approach embeds moisture control and quality assurance at every handoff, ensures fire-safety and structural integrity through proactive planning and leverages prefabrication to minimize on-site risk while maximizing precision and speed.

Layered atop these operational foundations is a steadfast commitment to sustainability and circularity. By prioritizing locally certified wood, optimizing carbon storage in durable building elements and publishing transparent life-cycle data, the value chain not only meets rigorous ecological benchmarks but continually refines its carbon footprint through energy-efficient manufacturing and renewable power. At project handover and throughout occupancy, real-time environmental monitoring and post-occupancy performance validation close the feedback loop, equipping facility teams to maintain humidity, acoustic comfort and structural health. Finally, by designing every component with end-of-life reuse, recycling and cascading in mind, timber construction transcends its primary structural role to become a dynamic, regenerative force in the built environment.

Part 4. Synthesis and evaluation

8. Discussion of the results

The emergence of high-rise mass timber construction constitutes one of the most profound paradigm shifts in the built environment of the twenty-first century. Driven by increasingly stringent climate targets and continuing urban densification, engineered timber systems offer a unique combination of carbon sequestration, reduced embodied greenhouse-gas emissions and rapid, prefabrication-enabled assembly, all while conferring distinctive architectural warmth. Nonetheless, the widescale adoption of MET in taller buildings remains constrained by a complex interplay of technical hurdles, regulatory uncertainty and cultural perceptions of timber's performance. This thesis systematically investigates MET's potential contributions to sustainable urban development, rigorously evaluating its environmental, economic and operational advantages alongside the principal barriers to implementation. The results underscore the imperative for a coherent, interdisciplinary framework to steer the planning, design, construction and long-term operation of high-rise mass timber buildings.

8.1. Discussion

The integration of mass timber into the vertical urban fabric holds the potential to radically decarbonize construction, revitalize local forestry economies and create healthier, biophilic environments. However, the path is neither linear nor simple. The complexity of the material, the precision of the processes and the necessity of coordinated expertise make high-rise timber construction a frontier of modern architecture and engineering.

The guidelines presented here intend to demystify and support this evolution. They help stakeholders anticipate challenges, reduce risk and unlock the full potential of timber as a modern structural material. Looking ahead, mass timber can become a cornerstone of sustainable cities, a material of innovation, responsibility and resilience, aligned with the world's urgent goals for climate action and human well-being.

Across the global construction industry, several interconnected educational, technical and policy-related factors influence the adoption of MET construction.

8.1.1. Key findings

8.1.1.1. Environmental benefits

MET construction offers significant environmental benefits, positioning it as a sustainable alternative to conventional materials like concrete and steel globally. A primary advantage stems from timber's nature as a renewable resource. One of the most compelling environmental benefits is carbon sequestration. Forests play a crucial role in mitigating climate change by absorbing vast quantities of carbon dioxide from the atmosphere through photosynthesis, converting it into biomass and storing it within the wood. This stored carbon remains locked in the timber throughout its operational life in buildings, delaying its release until the wood decays or is burned. Sustainable forestry practices, including responsible management, harvesting, reforestation and biodiversity conservation, ensure that forests continue to act as vital carbon sinks while providing a sustainable supply of wood products. Certifications like the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC) further guarantee

that timber is sourced from sustainably managed woodlands. Optimizing harvesting intervals based on annual growth rates can even maximize carbon sequestration.

Furthermore, timber construction boasts a significantly lower total embodied energy compared to concrete and steel. The production and processing of wood into construction material require considerably less energy. Even though concrete blocks have a lower embodied energy per kilogram, the sheer volume of concrete typically required for a building often results in a higher total embodied energy for concrete structures compared to wood. This reduced energy consumption directly translates to less fossil fuel consumption and consequently, reduced CO₂ emissions into the atmosphere during the material production phase.

Mass timber also aligns strongly with circular economy principles. Its components can be designed for disassembly, facilitating their reuse and recycling at the end of a building's lifecycle. This concept of "wood cascading" maximizes the utility of timber by sequentially using it in various applications before it is eventually used for energy production, minimizing waste and conserving resources. Even when reuse or recycling is not feasible, timber naturally biodegrades, returning valuable nutrients to the ecosystem and minimizing landfill waste. Utilizing EPDs helps to assess and communicate the environmental impacts across a product's supply chain.

The lightweight nature of mass timber further contributes to its environmental profile. This property enables rapid modular assembly and efficient transportation of prefabricated elements, which not only reduces CO₂ emissions associated with logistics but also maintains a low embodied energy throughout the construction process. The prefabrication process itself, often leveraging technologies like CNC, enhances material efficiency and significantly reduces on-site waste. This systematic approach leads to optimized material usage and improved working conditions, supporting overall sustainable practices. Overall, timber buildings offer a rapid, environmentally friendly solution that aligns with the three pillars of sustainability: environmental, financial and social.

8.1.1.2. Global trends

Global trends in mass timber high-rise construction reflect a significant and growing interest in sustainable building practices, with a notable geographical distribution and evolving patterns of development.

A key finding is that the great majority of tall and high-rise timber buildings, almost three-quarters, are located in Europe, followed by North America (16%), Australia (6%) and Asia (4%). This leading position for Europe stems from its rich history of building with timber and extensive mature forest areas, alongside a strong focus on sustainability and stringent environmental standards. European countries, particularly those in Scandinavia, have a history of efficient sustainable forest management, ensuring timber availability and long-term resource sustainability. The European Union's strong stance on climate change has further fuelled innovations in the bioengineering industry, driving demand for materials with strong renewable credentials.

Within Europe, Sweden takes a significant lead with 12% (24 buildings) of the identified cases, followed by Great Britain and France, each with 10% (19 buildings). The United States accounts for 9% (17 buildings), Germany 8% (16 buildings) and Switzerland and Canada each have 15 buildings. While Germany, Switzerland and Austria have a higher number of smaller timber buildings (three or more stories), Sweden, France and Great Britain have seen a greater prevalence of tall and high-rise wooden

buildings in recent years. In North America, the United States and Canada also possess extensive forest resources and established timber industries, providing ample wood supply for mass timber construction. In Asia, countries have been increasingly exploiting wood in architectural projects since 2019. South America currently has only one registered case in the study, though the region is seeing growing popularity for mass timber, with a certified CLT manufacturing plant in Uruguay and an expectation of 40 mass timber building projects between 2024 and 2025.

Looking at the timeline, the completion of mass timber buildings has shown a fluctuating but generally increasing trend from 2005 to 2023. After initial years with only single completions annually until 2012, there was a remarkable surge in 2013, followed by a consistent increase from 2015 to 2018, peaking in 2019 with 41 buildings completed. This surge is attributed to a combination of increased awareness, regulatory support, technological advancements, successful demonstration projects and environmental remarks. However, the peak in 2019 was followed by a decline in 2020 and 2021, stabilizing in 2022 and decreasing in 2023.

In terms of building height, the majority of high-rise mass timber structures are relatively smaller, with slightly more than 80% of the dataset consisting of buildings with fewer than ten floors. Specifically, 6-story constructions are the most common, accounting for 31% (61 cases), followed by 7-story and 8-story buildings at 25% and 18% respectively. The average height observed in the study is eight floors. Despite this, the global trend shows an ambition for taller structures. The tallest mass timber building in the world, ASCENT, was completed in Milwaukee, USA in 2022, reaching 25 floors and 86.6 meters. It comprises 19 residential levels of mass timber supported by a six-level concrete podium structure, utilizing glulam beams and columns for CLT floors and reinforced concrete cores for lateral stability. The second tallest building by height is Mjøstårnet in Norway (85.4 meters, 18 floors), which held the global title until 2022. Vienna, Austria, boasts HoHo Wien with 24 floors, the second with the highest number of floors. These three structures are the only ones exceeding 80 meters in height, with only five mass timber buildings identified globally that have twenty or more floors.

The growth of the mass timber market is significantly driven by sustainability initiatives, regulatory support and collaborative industry efforts. As a renewable resource, wood offers environmental benefits such as carbon sequestration and lower embodied energy. Mass timber components also integrate well into the circular economy due to their reusability and recyclability, minimizing waste and resource consumption. From a regulatory standpoint, modern building codes are increasingly accommodating and promoting mass timber, recognizing its environmental and structural benefits. This includes updating building standards to facilitate mass timber construction and offering subsidies, grants and tax incentives for green building practices. For example, the Canadian National Building Code introduced provisions for structures up to twelve stories in 2020 and the California Building Code was updated in 2021 to permit buildings up to 18 floors. European standards (Eurocodes), particularly EN 1995 Eurocode 5, have provided a comprehensive framework that has facilitated taller wood buildings across most European countries.

While mass timber construction offers numerous advantages, challenges remain, including the need for specialized knowledge among general contractors, designers and engineers, which can be a barrier to wider adoption. Additionally, logistical organization for transport and erection is often more complex and timber structures are more susceptible to weather conditions during construction, requiring extra precautions. Despite these challenges, the use of hybrid systems, combining timber with concrete

and steel, is common to enhance performance and achieve higher levels of resilience and sustainability. These innovations and evolving regulatory frameworks continue to propel mass timber high-rise construction forward as a competitive and environmentally conscious alternative.

8.1.1.3. Structural performance

MET construction presents a unique set of structural performance characteristics for high-rise buildings, distinguishing it from traditional materials like concrete and steel. While timber offers significant advantages, its application at height requires rigorous engineering strategies and innovative solutions to address various structural demands.

A primary structural advantage of mass timber is its impressive strength-to-weight ratio. Mass timber buildings can weigh significantly less, typically 35-50% less than conventional structures. This reduced weight leads to lower seismic inertial forces during an earthquake, minimizing structural demands and foundation loads, which can also reduce overall costs and enable construction in areas with challenging soil conditions. While timber can match reinforced concrete in strength, it generally exhibits less stiffness and falls short in compression resistance compared to concrete and steel. However, its lower density makes it efficient for long span or tall structures. The inherent anisotropic nature (direction-dependent properties) of wood can be mitigated through engineered wood products, allowing for greater flexibility in shaping and sizing building elements where limitations depend primarily on manufacturing and transport capabilities.

A fundamental shift in timber structures for high-rise applications is the transition from linear members to planar structural elements. While traditional timber systems primarily bear loads in one direction, panelised systems integrate elements that provide multidirectional load-bearing capacity, significantly enhancing stiffness and load distribution for complex forces. This has led to the widespread adoption of hybrid structural systems. Relying solely on a single, uniform construction system for high-rise buildings is often limited in terms of efficiency and cost-effectiveness, making the intelligent integration of complementary materials a standard practice. These hybrid solutions, combining timber with materials like concrete or steel, are critical for meeting the multifaceted performance requirements of a building system.

Common structural configurations include:

- Panelised systems: These systems predominantly use engineered timber panels, such as CLT or LVL, for both walls and floor diaphragms. They are highly suited for modular designs due to their prefabrication potential and are often combined with concrete podiums or cores, or steel elements for enhanced rigidity;
- Post-and-beam systems: Characterized by a grid of columns and beams, typically with pinned connections, these systems gain stability from additional elements like diagonal bracing, shear walls, or central cores. Engineered wood products like glulam and LVL enable larger spans and heavier loads. They are often paired with composite timber-concrete floor systems for improved structural and acoustic performance;
- Modular systems: These involve off-site prefabrication of complete volumetric units (including floors, walls, ceilings, finishes and services) that are transported and assembled on-site. While offering rapid assembly and quality control, they are limited by road transport dimensions and generally do not exceed 5 to 8 stories in height for mass high-rise applications.

A continuous load path is fundamental to structural integrity, ensuring that forces from gravity, wind and seismic action flow uninterrupted from the roof and envelope through floors, walls, connections and into the foundation. For vertical (gravity) loads, prefabricated floor solutions are preferred, with meticulous detailing required to accommodate timber shrinkage and ensure continuity between elements. Lateral loads (wind and seismic) introduce horizontal forces that demand robust resisting systems. The three principal lateral-load-resisting systems include shear walls (typically CLT panels), braced frames (timber or hybrid frames with diagonal members) and moment-resisting frames (glulam beam-column connections designed for rotational stiffness).

Connection design is central to a truly integrated structural strategy. Connections govern load transfer continuity, stiffness, ductility and long-term behaviour (creep and shrinkage) and must align with local practices and budget. Advanced fabrication processes and digital design tools play a crucial role in ensuring dimensional accuracy and optimizing load paths.

Despite timber's light weight reducing seismic forces, timber itself exhibits brittle behaviour in bending, tension and shear parallel to the grain. Therefore, the necessary ductility for energy dissipation during seismic events must be provided primarily through the design and performance of connections.

Key aspects of seismic performance in mass timber high-rise construction include:

- Innovative connection systems: Recent advances focus on improving ductility, energy dissipation and post-earthquake reparability. This includes self-centring techniques, friction energy dissipating devices (e.g. pin-fuse and link-fuse joints) and engineered yielding elements (like perforated steel plates) that concentrate damage in sacrificial or replaceable components, protecting the primary timber structure;
- Hybridization: The strategic combination of timber with other materials, particularly steel, is common and significantly improves seismic performance by enhancing stiffness, damping and deformation capacity. Steel elements can absorb seismic energy and localize inelastic deformations;
- Experimental validation: Rigorous numerical simulations and full-scale experimental investigations, including shake table testing, have been crucial in demonstrating the resilience of mass timber structures. Projects like SOFIE and the NHERI Tall Wood project have shown that multi-story CLT buildings can withstand significant seismic events with minimal damage;
- Regulatory challenges: While modern building codes are evolving to accommodate mass timber, seismic design standards, such as Eurocode 8, still offer limited specific guidance for timber structures, highlighting a need for further research and codification.

In summary, the structural performance of mass timber in high-rise construction is driven by its lightweight nature and renewability, offering environmental benefits and reduced seismic loads. However, to compensate for its inherent brittle behaviour, particularly under seismic conditions, sophisticated engineering, meticulous connection design focusing on ductility and energy dissipation and the widespread use of hybrid structural systems are critical. Ongoing research and evolving building codes continue to enhance the viability and safety of high-rise mass timber structures globally.

8.1.1.4. Specific performance

Mass timber high-rise construction, while celebrated for its sustainability and aesthetic appeal, necessitates particular attention to specific performance remarks beyond its global prevalence and

structural capacity. A comprehensive and integrated design approach is fundamental to addressing these critical aspects throughout the building's lifecycle.

A primary and paramount concern is moisture management and its influence on timber durability. Wood, being a hygroscopic material, readily absorbs moisture from the air and is highly susceptible to humidity and temperature fluctuations, which directly impact its mechanical properties. High moisture content significantly weakens wood, reducing its load-bearing capacity and structural integrity. Exceeding the fibre saturation point (around 30%) can lead to dimensional instability, resulting in warping, twisting, or cracking. Elevated moisture levels also create favourable conditions for biological degradation agents. To mitigate these risks, careful design and construction practices are essential, including kiln drying harvested trees to a low moisture content (e.g. 12%), proper storage on elevated surfaces with good drainage and airflow and the application of hydrophobic coatings or other treatments. The notorious case of the "Zero Carbon School" in the UK, which was demolished after only seven years due to critical design deficiencies in moisture control (e.g. omission of a vapour control layer and inadequate waterproofing), underscores the severe consequences of neglecting hygrothermal design and moisture management. Therefore, a project-specific moisture-management plan is crucial, requiring rigorous documentation, monitoring and a collaborative approach involving all stakeholders from early planning to post-construction maintenance.

Fire performance in mass timber high-rise buildings has been a common concern, but modern engineered timber constructions are designed to meet stringent fire safety standards. Unlike traditional timber, mass timber possesses inherent fire resistance due to its ability to form a protective char layer when exposed to fire. This char acts as a thermal insulator, shielding the inner wood and preserving structural integrity for a required time. Wood's low thermal conductivity also significantly slows heat transmission. Key fire safety measures include compartmentalization to contain fire spread within a designated area, using fire-rated walls, ceilings and floors. Automatic sprinkler systems are essential, proving highly effective at reducing temperatures and preventing flashover and may even allow for increased building heights and areas. Water mist systems are particularly efficient, using significantly less water than traditional sprinklers. Encapsulation, typically achieved with layers of gypsum board, is an effective method to delay or prevent mass timber's involvement in a fire. Connections, often made of steel, are critical vulnerabilities as steel rapidly loses strength at high temperatures and conducts heat, accelerating charring in surrounding wood. Therefore, connections and fasteners must be protected by wood or other fire-rated materials and all construction joints and penetrations thoroughly sealed to prevent fire propagation. During construction, fire risks are heightened due to incomplete safety systems; thus, a comprehensive fire safety program, including a dedicated fire safety manager, worker training and immediate protection of exposed timber, is crucial. Practical examples like HoHo Wien and Forté showcase diverse strategies, from eliminating wood in vertical shafts to implementing double shaft systems and continuous monitoring during construction.

Thermal performance is another advantageous characteristic of mass timber, contributing significantly to a building's energy efficiency and occupant comfort. Timber exhibits low thermal conductivity (0.12 to 0.19 W/mK) compared to concrete or steel, making it an excellent insulator and reducing heating and cooling demands. Its relatively high specific heat capacity (1000 to 2700 J/kg·K)

allows it to store and release thermal energy, contributing to thermal stability and delayed heat transfer. While wood's lower density and thermal mass can pose limitations in cold climates, these can be overcome through hybrid systems like timber-concrete composite floors that enhance thermal mass. High-performance envelope design is critical, prioritizing exterior insulation to keep timber elements on the warm side of the thermal envelope and prevent condensation. The use of vapour-permeable membranes is recommended to facilitate moisture evacuation from the building envelope, avoiding rigid or vapour-impermeable membranes that could trap moisture. Effective air sealing at junctions and penetrations is also vital for thermal efficiency and indoor air quality. Prefabrication contributes to improved thermal efficiency through greater dimensional precision and reduced on-site moisture exposure. Integrating passive solar design strategies like building orientation and natural ventilation can further reduce reliance on active heating and cooling systems.

Acoustic performance is a critical parameter for occupant well-being in high-rise buildings, posing unique challenges for mass timber due to its lighter and more flexible nature compared to concrete or steel. Timber structures are particularly susceptible to low-frequency airborne sound transmission, impact noise (e.g. footfall) and structural vibrations, which are more difficult to mitigate. Regulatory limits, such as Sound Transmission Class (STC) and Impact Insulation Class (IIC) values, vary internationally but set minimum acoustic performance requirements. A significant challenge is flanking transmission, where sound bypasses intended insulation by traveling through adjacent structural components. To address these issues, a combination of sound-mitigating materials and technical solutions is employed. These include adding mass with fibre insulation slabs, increasing gypsum wallboard thickness, or incorporating concrete boards/toppings. Decoupling techniques are fundamental, using acoustic adhesives, resilient channels, floating floors and resilient mats at junctions to reduce vibrational energy transmission and improve sound insulation without adding substantial mass. For reverberation control in exposed timber spaces, sound-absorptive materials like mineral fibre, melamine foam and fabric-wrapped panels are incorporated. Architectural design strategies, such as spatial planning to locate noisy services away from sensitive areas, are also crucial. The industry faces challenges in balancing timber's low embodied carbon with acoustic requirements and overcoming variability in acoustic performance. Early involvement of acoustic engineers, coupled with digital modelling and simulations, is essential to optimize performance, validate designs and address potential issues proactively. Despite these challenges, successful projects like the Limnologen residential development demonstrate that high acoustic performance is achievable in mass timber buildings.

8.1.1.5. Integrated building design and construction

The successful delivery of mass timber high-rise buildings hinges upon an integrated and highly detailed approach to both building design and construction processes, which significantly diverges from conventional methods utilizing steel or concrete. This demands a high level of coordination across all disciplines from the initial concept through to the building's operational life.

In terms of building design, mass timber offers a distinctive warm, tactile and biophilic aesthetic that sets it apart from traditional materials. Architects are encouraged to embrace timber's natural qualities, such as exposed surfaces, modular repetition and clear articulation of structure, rather than attempting

to mimic concrete or steel forms. The prevalence of rectilinear and orthogonal geometries is a key finding, with the vast majority of high-rise timber projects adopting these forms due to their inherent geometric simplicity, efficiency for modular construction and cost-effectiveness. Design complexity tends to be introduced through façade articulation, indented volumes, or programmatic variations rather than dramatic spatial transformations. Central core layouts are dominant in high-rise mass timber buildings, primarily because they efficiently integrate vertical services, allow for symmetrical apartment layouts and aid in acoustic and fire compartmentalization.

Façade and envelope design is critical, balancing architectural expression with thermal performance, weather durability and paramount moisture control. Key performance concerns for timber façades include combustibility, dimensional non-uniformity and moisture sensitivity. To mitigate moisture risks, vertical rainscreen cladding systems paired with robust backing structures and moisture-resistant membranes are commonly employed, facilitating drainage and ventilation. Furthermore, prioritizing exterior insulation is crucial to keep timber elements on the warm side of the thermal envelope and prevent condensation, complemented by vapour-permeable membranes for moisture evacuation and effective air sealing at all junctions and penetrations. Functional layouts are largely shaped by fabrication constraints and the need for standardized modularity, typically using repetitive structural grids of 3 to 5 meters. Load-bearing internal walls made of mass timber products are common, but their rigidity can limit post-occupancy adaptability. A significant architectural challenge is service integration, as routing ducts and conduits through mass timber elements requires precise coordination and prefabrication due to limited on-site modification capacity. Digital modelling, specifically BIM, is indispensable for managing this coordination and reducing detailing errors.

The Construction Process is characterized by an exceptionally high degree of precision and planning. Effective planning is indispensable, acting as the bridge from conceptual ideas to physical realization, setting the stage for cost-efficiency, sustainability and constructability. This phase must be a dynamic, inclusive process engaging all stakeholders from the outset due to timber's integrated prefabrication, tight tolerances and material-specific detailing. BIM is foundational for coordination and optimization, allowing for early clash detection and performance simulations, which is critical given the need for early design finalization in prefabricated timber projects. CNC technologies are closely tied to BIM, enabling high-precision fabrication with millimetric tolerances for cutting, drilling and milling timber components, including embedding service openings. Prefabrication is arguably the most transformative aspect, moving most of the construction process off-site to ensure better quality control, faster installation, reduced on-site waste and improved weather protection, a critical factor for moisture-sensitive timber. While prefabrication significantly reduces on-site construction durations and improves quality, it demands a more intensive and front-loaded design process, with all material selections, service coordination and structural detailing finalized much earlier than in conventional construction.

Quality control during construction is paramount, especially concerning moisture management, which is identified as the most critical factor for timber durability. Therefore, a project-specific moisture-management plan is essential from planning through maintenance, requiring rigorous documentation, monitoring and proactive measures like proper storage and factory-applied hydrophobic coatings on load-bearing elements.

In essence, while mass timber construction offers significant sustainability benefits and prefabrication advantages leading to faster, more efficient construction, its successful implementation in high-rise buildings critically depends on proactive, integrated design and rigorous construction practices. Overcoming challenges related to moisture management, fire safety, thermal performance, acoustic comfort and seismic resilience requires close collaboration among all stakeholders, advanced digital tools and a deep understanding of timber's unique material characteristics.

8.1.2. Challenges beyond building performance

8.1.2.1. Knowledge, experience and educational needs

A widespread challenge for the adoption of MET globally is a general lack of knowledge and experience among building industry practitioners (Wong et al., 2024). Surveys indicate that professionals often have insufficient knowledge of timber, with many noting that their education was predominantly focused on conventional materials like concrete (Roos et al., 2010). This knowledge gap often forces self-education and on-the-job training for those working with timber.

This deficit in familiarity and skills is a significant barrier across regions (Wong et al., 2024). The "poor knowledge of timber among designers and construction companies," coupled with a "lack of wood culture among designers and clients," are identified as major impediments (O'Ceallaigh et al., 2021).

To address these issues, there is a strong call for improved education for future practitioners, along with the provision of specific training courses or detailed guides. Learning through observation and the initiation of demonstration projects are considered crucial for knowledge transfer (Wong et al., 2024). Professionals also express a preference for accessing information through technical databases or websites (being the preferable), Continuous professional development courses, newsletters, informative videos and seminars (O'Ceallaigh et al., 2021). Thus, the structured list of guidelines fit the possible source of information to address the procurement within the professional community.

8.1.2.2. Skilled workforce and industry inertia

The transition to MET construction highlights issues with the existing workforce. The majority of general contractors, designers and engineers are not yet familiar with engineered timber construction methods, often requiring the recruitment of specialized construction crews (Smith et al., 2018). The "inertia in building industry using conventional building materials" is a significant obstacle globally, as new innovations face resistance due to established practices and path dependency. This means that education and knowledge transfer are vital for overcoming these entrenched industry habits (Wong et al., 2024).

8.1.2.3. Technological and policy barriers

The evolution of building codes and government policies plays a critical role in MET adoption. Current codes and policies are often perceived as significant obstacles, particularly in regions like South-East Asia and parts of Europe, such as the UK where statutory restrictions followed the Grenfell fire. The growth of tall mass timber construction, for instance, is closely tied to the advancement and adoption of codes that explicitly permit its use. Therefore, a review of existing building codes is called

for to align with technological advancements, especially for taller and hybrid timber buildings (Kılınç, 2025; Wong et al., 2024).

Conversely, policies can also act as powerful drivers. In Europe, there is an emergence of policies that not only permit but actively promote MET, such as France's regulations limiting embodied carbon and mandating wood or biomaterials in public buildings. Incentives to the building industry are widely recognized as a major driver for MET adoption across all regions, pointing to a need for financial encouragement to switch from conventional materials (Wong et al., 2024).

Beyond codes, the fragmented nature of the timber industry and its supply chain poses a barrier. Concerns include insufficient support from suppliers, fluctuating prices and a global supply chain not yet fully developed for widespread MET adoption (Roos et al., 2010).

Ultimately, while the perceived advantages of MET include its environmental benefits (low embodied carbon, carbon storage), strength-to-weight ratio and suitability for industrialized building methods, the industry's ingrained preference for concrete, perceived risks and a lack of comprehensive knowledge and supportive policies remain significant hurdles (Wong et al., 2024). Despite architects expressing curiosity and interest in timber, their influence over material selection is often limited, with developers and contractors holding the most sway, often prioritizing cost control and familiarity with conventional materials (Roos et al., 2010).

8.1.3. Knowledge gaps

Despite growing interest in MET as a sustainable alternative to conventional building materials, significant knowledge gaps remain that slow down its widespread adoption, particularly for high-rise applications. These gaps reflect a lack of region-specific research, practical implementation insights and technical standardization across critical domains of MET construction. As the industry advances, addressing these issues is essential to ensure safe, durable and scalable deployment of timber technologies in diverse global contexts.

The following key knowledge gaps have been identified through this research:

- Limited cross-country comparisons: There is a notable absence of comparative studies evaluating stakeholder perceptions, regulatory environments and adoption trends across different global regions. This is especially true for underrepresented regions such as South-East Asia and Africa, where MET adoption remains limited compared to more mature markets in Europe and North America. Context-sensitive research is needed to tailor solutions to specific socio-economic, climatic and regulatory conditions;
- Suitability for specific climates and building typologies: Existing research has not sufficiently addressed the performance of MET in high-density urban environments and humid or tropical climates. Questions remain regarding long-term durability, moisture resilience and maintenance requirements for tall timber structures in such conditions, critical factors for risk assessment and material specification;
- Detailed design and specification guidance: While general design strategies exist, there is a lack of practical, detailed guidance on protecting MET structures from moisture during construction and post-occupancy. Integrated guidance on water infiltration protection, joint detailing and repairability is especially scarce, limiting designers' and contractors' ability to ensure performance and longevity in real-

world conditions;

- Perceived property value: The market perception of MET buildings, especially in terms of resale value and long-term financial returns remains underexplored. This gap hampers investor confidence and limits broader market acceptance, particularly in speculative or cost-sensitive developments where economic predictability is essential;
- End-of-life documentation and circular economy integration: Despite the theoretical alignment of MET with circular economy principles, there is a lack of empirical evidence on how mass timber buildings perform at end-of-life. Few projects have reached this stage and documentation on disassembly, reuse, or material cascading remains limited. This absence of data restricts the scalability of sustainable reuse models and hinders the development of regulatory and technical frameworks to support material recovery at building retirement;
- Seismic design in international codes: Seismic performance remains one of the most complex and under-regulated aspects of MET design. While timber's lightweight and energy-dissipating properties offer benefits in seismic zones, current international design codes, such as Eurocode 8, provide insufficient, non-specific guidance for mass timber systems. This leaves engineers without robust, codified procedures for critical aspects such as capacity design, connection detailing and hybridization in seismically active regions.

By addressing these knowledge gaps, researchers, policymakers and industry professionals can help unlock the full potential of MET construction, particularly in high-rise and high-performance applications. These areas represent urgent opportunities for further investigation, pilot testing and code development, ensuring that future timber buildings meet the highest standards of resilience, safety and sustainability.

8.2. Conclusions

The conducted research on high-rise timber buildings presents compelling evidence that these structures hold significant potential in addressing climate change and promoting sustainable urban development. The increasing demand for mass timber high-rise buildings calls for a coordinated, multidisciplinary effort. Architects and engineers bear a substantial responsibility to balance sustainability with safety, performance and regulatory compliance. The process is inherently complex and requires:

- Deep material knowledge, especially given wood's anisotropic, hygroscopic and combustible nature;
- Cross-disciplinary coordination, particularly for integrating structure, services, acoustics, fire protection and moisture control;
- Precision in planning, as prefabrication and digital modelling require early decision-making and minimize tolerance for late-stage revisions;
- Given this complexity, a structured guideline framework becomes essential. It enables clarity, predictability and alignment among diverse actors throughout the project, from concept to completion.

The development of a comprehensive set of guidelines spanning all life cycle stages, from forest management and material sourcing to design, construction, use and end-of-life, emerges as a necessary response to the growing interest in high-rise timber buildings and the complexity involved in their realization.

8.2.1. Key areas of concern and challenges

Despite the promise of timber, professionals continue to raise concerns in several performance domains:

- Seismic design, due to timber's light weight and lack of established ductility models in many regions;
- Moisture control, essential to prevent decay, deformation and loss of strength;
- Thermal and acoustic performance, particularly in multi-storey and multi-occupant buildings;
- Fire safety, which requires a deep understanding of charring behaviour, fire protection detailing and code compliance.

These concerns are compounded by:

- Engineering and technical challenges, such as ensuring continuous load paths, precise connections and hybrid system integration;
- Policy and regulatory barriers, especially in countries where timber codes are underdeveloped or absent;
- Lack of skilled workforce and professional knowledge, highlighting an urgent need for education and training across the construction sector;
- Technological readiness, including the need for better interoperability of digital tools and refinement of prefabrication methods.

The extensive research presented on these areas of concern demonstrates a strong and growing interest within the scientific community to address the increasing global demand for high-rise MET buildings. The findings indicate that, despite the technical and regulatory complexities involved, each challenge, whether related to seismic performance, fire safety, acoustic control, moisture protection, or structural optimization, can be effectively addressed through a well-informed, multidisciplinary approach. With the application of appropriate design strategies, technological innovations and collaborative efforts across all stakeholders, high-performance and code-compliant solutions are attainable, paving the way for broader, responsible adoption of MET in vertical urban development.

8.2.2. Guidelines as a bridge between ambition and execution

The proposed guidelines are structured across the full building life cycle, with specific strategies identified at the pre-design stage, followed by detailed guidance at the design, construction, use and end-of-service phases. Each guideline is accompanied by a mapping of the relevant stakeholders, supporting collaboration and clarity in responsibilities.

They serve as a roadmap through complexity. By offering structured direction across disciplines and life cycle phases, they intend to:

- Support multidisciplinary coordination through clear stakeholder roles;
- Guide early-stage decisions on layout, material choices, structural logic and integration of services;
- Facilitate compliance with existing codes while anticipating future regulatory shifts;
- Enable quality control from digital models to on-site assembly;
- Promote circular practices, long-term reuse and carbon accounting.

The structured guidelines developed in the thesis are crucial for addressing the identified

challenges and knowledge gaps, providing a robust framework for the sustainable design and construction of high-rise timber buildings. Their importance is justified by several benefits and their relevance to current industry needs:

- Bridging the knowledge and experience gap: The guidelines offer practical, actionable guidance that is directly supported by research findings, helping professionals navigate the complexities of mass timber construction where first-hand experience and detailed knowledge might be lacking. They serve as a conscious decision-making tool;
- Promoting holistic sustainability: They emphasize sustainable sourcing (FSC/PEFC certification), responsible forest management (SFM), carbon sequestration, waste reduction and the principles of the circular economy and wood cascading. This ensures that timber's comprehensive environmental benefits are maximized throughout the building's lifecycle, from forest to end-of-service;
- Enhancing performance and safety: The guidelines detail strategies for optimizing fire (e.g. charring, encapsulation, sprinklers), acoustic (e.g. decoupling, mass layers, sound-absorbing materials), thermal (e.g. exterior insulation, airtightness, moisture control) and seismic performance (e.g. innovative connections, hybrid systems). They provide specific measures for material selection, detailing and system integration to meet stringent safety and comfort standards, directly addressing key concerns such as fire and water damage;
- Fostering collaboration and accountability: By explicitly linking recommendations to specific stakeholders across the entire mass timber value chain (forest owners, manufacturers, architects, engineers, contractors, regulators, etc.), the guidelines promote early and continuous collaboration, integrated decision-making and clear accountability, which are vital for complex high-rise projects. This integrated approach is emphasized by the framework's organization across the entire building life cycle, from strategy to end-of-service;
- Addressing technical and logistical challenges: The guidelines provide solutions for managing timber's unique material characteristics, such as moisture sensitivity, dimensional changes and the integration of prefabricated components, ensuring precision and quality control from factory to site. This includes detailed procedures for transport, storage and erection.

8.2.3. Critical remarks

Mass timber high-rise construction, while rapidly gaining prominence for its sustainable attributes, still faces a number of critical remarks and knowledge gaps that block its wider adoption and require further investigation across its entire lifecycle. Many doubts persist concerning high-rise buildings designed and constructed with timber, primarily stemming from the relatively small number of completed projects compared to traditional concrete and steel systems. This lack of extensive experience creates a learning curve for many general contractors, designers and engineers who are currently unfamiliar with MET construction methods, ultimately contributing to lower popularity of the system.

While the findings of this thesis strongly support the viability and sustainability of MET for high-rise applications, several unresolved issues underscore the need for caution and further inquiry. The lack of region-specific research raises concerns about the universal applicability of current design and performance assumptions. Inadequate guidance on moisture protection, repairability and long-term

performance weakens confidence in both construction-phase decision-making and lifecycle durability. Additionally, the absence of comprehensive seismic design standards in international codes and the under-documentation of end-of-life scenarios limit both safety assurance and circular economy integration. These shortcomings must be addressed through targeted research, code development and cross-disciplinary collaboration. Until such gaps are closed, the broader adoption of MET in tall building typologies will remain constrained by uncertainty and technical risk, despite its substantial environmental and economic promise.

Furthermore, whilst the guidelines aim to facilitate and standardize best practices, they do not replace the need for structural reforms. Widespread adaptation of mass timber requires:

- Government-backed incentives for sustainable materials, green building and circular economy models;
- Accelerated code development and harmonization;
- Investment in training, testing and open-source knowledge platforms;
- Greater public awareness and demand for low-carbon, renewable buildings.

In conclusion, this thesis emphasizes the importance of a systematic, informed and collaborative approach to high-rise timber construction. The guidelines developed here serve as a foundational tool for navigating the intricate landscape of mass timber projects. They bridge existing knowledge gaps, support informed decision-making and offer pathways to greater sustainability and innovation. However, to fully realize the potential of high-rise timber buildings, a paradigm shift is required, one that unites design intelligence, technical excellence and policy support toward a shared vision of a sustainable urban future.

8.3. Future developments of the research

The increasing relevance of MET in the global construction sector presents a clear imperative for continued research and development across multiple domains. While this thesis provides a comprehensive framework of guidelines and identifies critical barriers to MET adoption, it also highlights areas where knowledge remains insufficient and technical challenges persist. Future research should focus on advancing both the performance and implementation strategies for high-rise mass timber construction, ensuring it can be widely adopted with confidence, safety and sustainability. Ten potential areas for future developments were identified:

1. Advanced connection systems

Seismic resilience remains a primary technical concern for mass timber, particularly in mid- to high-rise typologies. Future work should prioritize the development and testing of high-performance, energy-dissipating and self-centring connection systems capable of withstanding cyclic loading and dissipating energy during seismic events. These systems must also accommodate timber's anisotropic and hygroscopic nature to ensure long-term reliability and dimensional stability under stress.

2. Fire safety innovation

Although mass timber's charring behaviour is predictable, enhanced fire performance is essential to meet evolving building codes and public safety expectations. Research into advanced encapsulation methods, fire-resistant coatings and non-combustible hybrid solutions is crucial. Future efforts should include performance-based design approaches validated by full-scale fire tests, enabling more nuanced integration of exposed timber elements without compromising safety.

3. Acoustic optimization

Mass timber's lightweight nature often results in suboptimal acoustic performance, particularly in multi-unit residential and mixed-use buildings. Further research is needed to develop cost-effective, prefabrication-compatible acoustic systems, including resilient underlays, hybrid floor systems and decoupling techniques that align with the modular nature of MET construction. Simultaneously, work on quantifying and standardizing in-situ acoustic performance metrics will aid in compliance and design predictability.

4. Material innovation

The development of next generation engineered wood products with enhanced durability, acoustic insulation and inherent fire resistance could expand the applicability of MET across diverse climates and building types. Research into thermally modified wood, new adhesives and bio-based composites can unlock new performance thresholds, while ensuring environmental responsibility.

5. Circular economy integration

The environmental promise of timber construction must be reinforced by circular economy strategies. Future research should explore scalable wood cascading models, reuse pathways for large-format panels and modular design principles that support disassembly and component recovery. This includes the development of design-for-deconstruction standards and material traceability tools to enable reuse at scale and support low-carbon transitions.

6. Hybrid structural systems

Hybridization offers a pragmatic pathway for extending the structural and regulatory viability of mass timber in taller and more complex buildings. Continued study is needed on the integration of timber with steel, concrete and innovative composites, balancing environmental performance with structural optimization, seismic safety and fire resistance. Emphasis should also be placed on connection interfaces and long-term behaviour of hybrid systems.

7. Digital tools and prefabrication

BIM, Digital Twins and CNC technology are indispensable for reducing construction errors and ensuring dimensional accuracy. Research should focus on automating clash detection, improving data interoperability between platforms and stakeholders and enhancing the feedback loop between design and fabrication. Integrating digital material passports and life-cycle tracking will also support sustainability goals.

8. Harmonization of global standards

The disparity in building codes and technical standards continues to hinder MET adoption, especially in seismically active or fire-regulated regions. There is an urgent need for globally harmonized performance-based standards for structural, fire, acoustic and environmental behaviour of timber buildings. International collaborations and consensus-building platforms should be developed to support this effort, ensuring safe and uniform implementation across contexts.

9. Longitudinal case studies and performance monitoring

Empirical data on long-term performance of high-rise mass timber buildings is still sparse. Future work should include post-occupancy evaluations, structural health monitoring and environmental performance tracking to validate current assumptions and refine best practices. Such longitudinal studies will also provide critical insights into lifecycle costs, user comfort, maintenance requirements and

durability, factors crucial for both investor confidence and public acceptance and CE viable applications.

10. Education and workforce development

Finally, addressing the skills gap remains an essential task. Future efforts must include the development of comprehensive educational programs for architects, engineers, contractors and regulatory bodies. These should include curriculum updates in universities, specialized training modules, digital resources and on-site apprenticeship opportunities to ensure the growing demand for mass timber is matched by qualified expertise.

Pursuing these research directions will help bridge current knowledge gaps, improve regulatory clarity and address technical complexities, ensuring that high-rise MET construction can be adopted at scale without compromising safety, performance, or sustainability. The successful integration of MET into mainstream practice will depend not only on innovation but also on collaboration, education and supportive policy environments. Mass timber construction holds the potential to redefine urban sustainability. By leveraging renewable resources, integrating digital fabrication and adopting a life-cycle approach, it can significantly reduce the carbon footprint of cities. The structured guidelines developed in this thesis offer a roadmap to navigate this complex yet promising territory. While technical challenges remain and policy and perception barriers must be addressed, the coordinated efforts of stakeholders across sectors can unlock timber's full potential. As urban areas expand and the need for climate-conscious infrastructure grows, mass timber can become a cornerstone of resilient, low-carbon cities, aligning with the global sustainable development goals.

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