Drivers, barriers, and strategies to enhance the adoption of cross-laminated timber in multi-storey buildings in the Netherlands

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Figure front page: (Moelven, 2019)

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MSc. Thesis

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Preface

This thesis marks the completion of my master’s studies ‘Construction Management and Engineering’ at the Delft University of Technology. At the start of my bachelor's degree in 2017, I had no idea where I would stand seven years later. During my bachelor’s degree my interest in timber as building material was created which led me to write my bachelor’s thesis on timber office buildings. My interest in timber construction rose and when I completed all the courses in my master’s program, I knew I wanted to do research on timber construction again. I am looking forward to put all the acquired knowledge into practice and would like to continue with timber construction in my working life. I am glad that I had the opportunity to study on the TU Delft and look back on an amazing time.

I would like to thank Yasmine Mosleh as my main supervisor from the Delft University of Technology for her guidance and feedback throughout the process of writing this thesis. Besides her, I would like to thank Hans Ramler and Chris Noteboom, both from the TU Delft as well, for providing significant help and bringing in specialised knowledge. Finally I would like to thank Mike Vernie and Stéphane Lauwerys from Besix for their guidance with my thesis, as well as their guidance during my internship at the construction site of the DPG Media office building. Finally, I would like to thank all participants in my field study who were willing to take part in this research.

M.J. Jansen
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Acknowledgements

Abstract

Climate change is one of the most urgent global issues, with the construction sector contributing nearly 11% of global CO_2 emissions. Traditional materials like concrete and steel dominate the construction of multi-storey buildings due to their structural integrity and cost-effectiveness. However, these materials have high embodied carbon, significantly impacting the environment. Cross-laminated timber (CLT), is proposed as a sustainable alternative that can reduce carbon emissions and promote environmental sustainability.

The primary objectives are to identify the main drivers and barriers to using CLT in multi-storey buildings in the Netherlands and to propose strategies to overcome these barriers. The research employs a qualitative approach consisting of two main components:

1. **Literature Review:** The literature review focuses on CLT's performance as a structural material, design principles for multi-storey timber buildings (MSTBs), the identification of drivers and barriers for the use of CLT in MSTBs, and strategies to overcome the barriers. A total of 17 research papers were systematically reviewed using search engines like Google Scholar and ResearchGate.

2. **Interviews:** Twelve semi-structured interviews were conducted with a diverse range of stakeholders in the Dutch architecture, engineering and construction (AEC) industry, including architects, contractors, structural engineers, project developers, building physics consultants, timber suppliers, policy advisers, and cost specialists. These interviews aimed to validate the literature findings and gather practical insights into the use of CLT.

The data from the literature review and interviews were analysed using thematic coding, categorized according to the PESTE (Political, Economic, Sociocultural, Technological, Environmental) framework. This approach ensured a comprehensive understanding of the factors influencing the adoption of CLT.

The results from the interviews and the literature review both indicate that environmental aspects were the most important driver for using CLT in MSTBs. Timber's natural ability to store captured carbon dioxide throughout its lifespan, combined with a lower-energy production process, gives it a significantly smaller carbon footprint compared to materials like steel and concrete. Construction with CLT can also offer technical benefits: CLT's lightweight nature makes it ideal for prefabrication in controlled factories. This translates to high-precision, modular components that can be quickly assembled on-site, minimizing construction time and hazards. Also, building with CLT can improve the indoor environment by using biophilic design principles, and consumers perceive CLT as aesthetically appealing.

The biggest barriers are related to financial and political aspects, but also to sociocultural and technical aspects. The results of the interviews and the literature review were quite consistent for the barriers. Firstly, some of the regulatory barriers are CLT's unfair representation in the MPG system and its incompatibility with building codes. The MPG system was one of the key barriers according to the interviews. However, since this system is only used in the Netherlands, it was not identified as a barrier in the literature. Additionally, the higher costs associated with CLT, including costs for fire safety measures, design and engineering, and material costs, contribute to its lack of cost-competitiveness compared to traditional materials. Moreover, there is still till some extent a lack of knowledge and experience across the AEC industry regarding CLT, leading to perceptions of risk and reluctance to adopt it. Some of the technical challenges are related to fire-safety, acoustics, moisture, and connections.

A set of strategies is developed to overcome the aforementioned barriers. All the barriers can fit into one of the five identified themes of strategies:

- **Increase Knowledge and Awareness:** This involves raising industry-wide knowledge about the benefits and capabilities of timber construction. Proposed measures include sharing knowledge internationally, developing a case study database, providing information to consumers and clients, and increasing timber knowledge in educational programs and among licensing authorities.
- **Change Industry:** To counteract the conservative nature of the construction industry and improve supply issues, strategies include moving from simple linear relations to collaboration in networks, increasing production facilities, and by using European forests for timber supply.
- **Create New Financial Models:** This theme addresses the higher costs associated with CLT by proposing financial strategies such as leveraging carbon credits, applying biophilic design principles to reduce sick leave costs, leveraging global financial services, and convincing clients of the increased residual value of timber buildings.
- **Technical Advancements:** Enhancements in technology are seen as a way to overcome technical barriers and reduce costs. This includes increasing prefabrication levels, promoting modular construction, conducting full-scale testing of CLT buildings, and fostering research and development.
- **Regulatory Change:** Adjustments in regulations are suggested to support the wider use of CLT. Strategies include revising the MPG system to better account for biogenic carbon storage, expanding the national environmental database to include more timber products, establishing building codes that support timber construction, setting timber building quotas, and encouraging governmental support to stimulate CLT production.

The study concludes that while there are significant drivers for adopting CLT in multi-storey buildings, substantial barriers must be addressed. Political support and economic considerations are crucial for promoting timber construction. Overcoming the industry's path dependency on traditional materials and increasing stakeholder knowledge are vital for the widespread adoption of CLT.

The field study examining the use of CLT in MSTBs faced several limitations, including a small sample size of twelve interviews, which restricts making broad generalizations. The semi-structured nature of the interviews allowed for in-depth exploration of topics familiar to each interviewee but limited comparative analysis across different interviews. Additionally, all interviewees had experience with MSTB projects, potentially introducing bias towards the benefits of CLT. Future research could build on this study by including perspectives from industry professionals with minimal or no experience with MSTBs to reduce bias and increase the validity of the results.

Table of contents

Preface iv

Acknowledgements v

Abstract vi

List of Abbreviations xi

1. Introduction 1

 1.1 Background 1

 1.2 Relevance 4

 1.3 Research definition 4

 1.4 Reading guide 6

2. Methodology 7

 2.1 Research approach 8

 2.2 Data collection 9

 2.3 Data analysis 10

 2.4 Justification of methodological choices 10

3. Cross-laminated timber 12

 3.1 Structural performance 13

 3.2 Fire performance 13

 3.3 Thermal performance 14

 3.4 Acoustic performance 14

 3.5 Moisture 16

4. Multi-storey timber building design 17

 4.1 Structural design 18

 4.2 Construction methods 19

 4.3 Material combinations 20

 4.4 Construction process 22

5. Drivers for the use of cross-laminated timber in multi-storey buildings 23

 5.1 Political drivers 24

 5.2 Economic drivers 24

 5.3 Sociocultural drivers 25

 5.4 Technological drivers 26

 5.5 Environmental drivers 29

 5.5 Overview drivers 31

6. Barriers for the use of cross-laminated timber in multi-storey buildings 32

 6.1 Political barriers 33

6.2 Economic barriers 34
6.3 Sociocultural barriers 35
6.4 Technological barriers 36
6.5 Environmental barriers 37
6.6 Overview barriers 38
7. Proposed strategies to bridge barriers 39
7.1 Increase knowledge and awareness 40
7.2 Change industry 42
7.3 Create new financial models 43
7.4 Technical advancements 46
7.5 Regulatory change 47
7.6 Overview strategies 51
8. Results field study 52
8.1 Drivers 53
8.1.1 Political drivers 54
8.1.2 Economic drivers 55
8.1.3 Sociocultural drivers 55
8.1.4 Technological drivers 55
8.1.5 Environmental drivers 56
8.2 Barriers 57
8.2.1 Political barriers 58
8.2.2 Economic barriers 58
8.2.3 Sociocultural barriers 59
8.2.4 Technological barriers 59
8.2.5 Environmental barriers 60
8.3 Strategies to overcome barriers 61
8.3.1 Increase knowledge and awareness 61
8.3.2 Change industry 63
8.3.3 Create new financial models 64
8.3.4 Technical advancements 65
8.3.5 Regulatory change 66
8.4 Case study: Mediavaert 69
9. Discussion 75
9.1 Evaluation of results 76
9.1.1 Discussion of drivers 76
9.1.2 Discussion of barriers 78

9.1.3 Discussion of strategies 79
9.2 Contribution of research 80
9.3 Limitations of research 80
10. Conclusions 81
11. Recommendations 90
References 93
Appendices 103

List of Abbreviations

An overview of the significance of the abbreviations that are used throughout the report is provided in Table 0.1.

Table 0.1: Demographics of interviewees

Abbreviation	Meaning
AEC industry	Architecture Engineering and construction industry
CLT	Cross-laminated timber
EWP	Engineered wood product
LCA	Life Cycle Assessment
MC	Moisture content
MSTB	Multi-storey timber building
MSTC	Multi-storey timber construction
RQ	Research question
SRQ	Sub-research question

1. Introduction

1.1 Background

1.1.1 Sustainability and the construction sector

Climate change is one of the most critical and urgent issues of our world today (IPCC, 2014). Scientific evidence has linked the rise in global average temperature, currently around 1°C above pre-industrial levels, to human-caused greenhouse gas (GHG) emissions (NASA, 2023). Business-as-usual practices threaten to push temperatures beyond the critical 2°C threshold, with catastrophic consequences for Earth's ecosystems (IPCC, 2014). This challenge is compounded by rapid population growth and urbanization, with estimates suggesting 68% of the global population residing in cities by 2050 and more than three billion people need new housing (Ritchie, Samborska, & Roser, 2024). The construction sector faces a critical challenge. While it plays a vital role in providing sufficient housing to cope with the growing population, it is also a significant contributor to the problem. The construction sector is responsible for nearly 39% of global CO2 emissions: 28% stems from operational energy use to heat, cool and power buildings, and the remaining 11% stems from the production of materials and construction (WGBC, 2024). To mitigate the worst effects of climate change, the industry must embrace innovative solutions that dramatically reduce carbon emissions throughout the construction process. This transformation is essential to ensure the sustainable development of our built environment.

1.1.2 Construction materials

Concrete and steel are the predominant materials employed in the construction of modern multi-storey buildings (MSTBs), because of their structural integrity, cost-effectiveness and durability (Crawford & Cadorel, 2017). However, a growing concern lies in the environmental impact associated with their production processes. These processes are highly energy-intensive, resulting in the substantial release of GHG into the atmosphere. For instance, the production of one tonne of cement or steel is estimated to emit approximately 1 tonne and 1.85 tonnes of CO2, respectively. Consequently, the cement industry is currently responsible for around 8% of global CO2 emissions, with the steel industry for construction contributing an additional 3-4% (Olivier, et al., 2020). By using alternative construction materials with a lower embodied carbon content, global carbon emissions can be reduced. Embodied carbon refers to the total greenhouse gas emissions generated from the materials and processes involved in the production, transportation, installation, maintenance, and disposal of building materials and infrastructure.

Timber and other biobased materials are considered to have a low embodied carbon content, especially when compared to concrete and steel (Sandin, Peters, & Svanström, 2013). Building with timber can reduce carbon emissions in two ways: (1) carbon is stored in buildings and (2) emissions from traditional construction practices are reduced. Trees sequester CO_2 by absorbing it from the atmosphere during their lifetime. Estimates suggest that one cubic meter of wood can store around 1.1 tonnes of CO_2 (Puettmann & Wilson, 2005). Applying wood in a high-value manner within the built environment can therefore contribute to carbon sequestration. Buildings, especially those constructed using circular principles, stand for multiple decades or even centuries, effectively retaining the captured CO_2 for an extended period. In this way, alongside the CO_2 storage in forests, a secondary CO_2 storage is created in the built environment. Even when accounting for energy consumption in the processing of raw materials into building components, timber emerges as a more environmentally favourable choice compared to concrete and steel (Sagheb, Vafaihosseini, & Ramancharla, 2011).

1.1.3 Cross-laminated timber

Mass timber construction (MTC), a term widely used in the construction industry, encompasses a family of engineered wood products (EWP) characterized by their substantial cross-sectional dimensions, offering a compelling alternative to traditional materials such as steel and concrete. While the term primarily applies to thick panel products, it can also encompass large-section components formed through gluing or block-lamination of linear elements. This category of materials has gained significant attention due to its impressive technical capabilities, and environmentally-friendly attributes (Low, Gao, & Ng, 2021).

One specific product within the mass timber category that has gained substantial recognition in recent years is CLT, also known as X-lam. CLT represents a prefabricated, multi-layer engineered wood panel, manufactured by gluing an uneven amount, usually three, five, or seven, of parallel boards together at a 90° angle using adhesive and pressure. This cross-laminated panel is stronger, stiffer and more stable than normal wooden products and can be used for many applications like multi-storey residential or commercial buildings (Ceccotti, Sandhaas, & Yasumura, 2010)

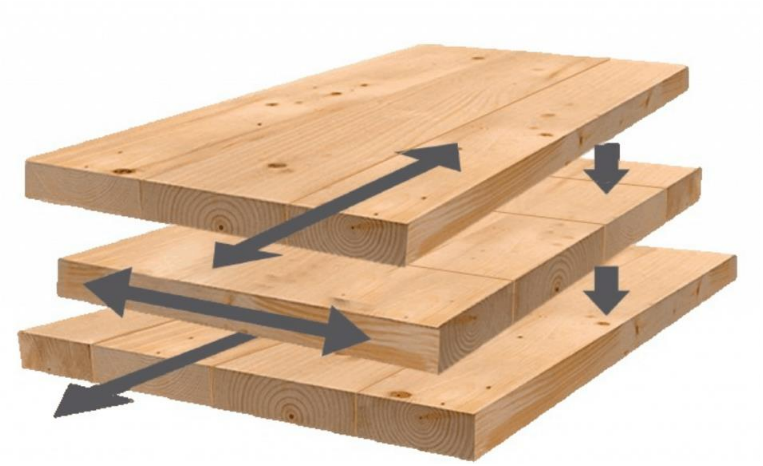

Figure 1: CLT panel lay-up (BY, 2018)

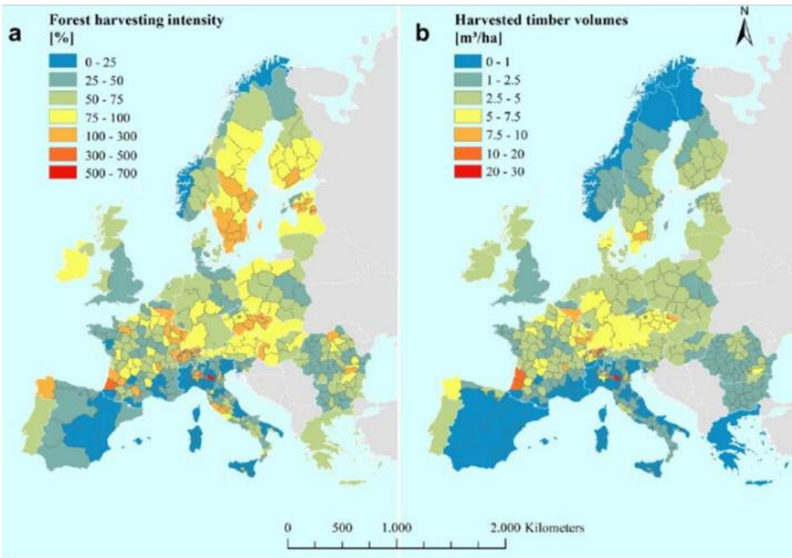

Figure 2: Average timber harvest in percentage (a) and in cubic metres (b) of the total additional growth per year (Thijssen, 2021)

Nowadays, predominantly softwood species are used for the production of CLT. The Norway spruce is the mostly used species, shortly followed by the White fir (Krzosek & Klosinska, 2021). Regulatory bodies such as Program for the Endorsement of Forest Certification (PEFC) and Forest Stewardship Council (FSC) play pivotal roles in overseeing and certifying the sourcing of timber, ensuring that timber production remains entirely sustainable. A significant portion of CLT manufactured in Europe originates from timber harvested and manufactured in Scandinavia, Austria and Germany. Despite ongoing timber harvesting, European forests experience a year-on-year increase in forest coverage (Prem, 2015; Bundeswaltinventur, 2023), see Figure 2.

1.1.4 Multi-storey timber buildings

While the recent developments in multi-storey timber buildings (MSTB) with EWP's are new, multi-storey timber construction (MSTC) is actually not new. Timber was, for centuries, the primary building material due to its abundance and workability. MSTBs existing as early as 7th century Japan, with the five-storey pagoda of Hōryū-ji temple standing as prove to this age-old practice.

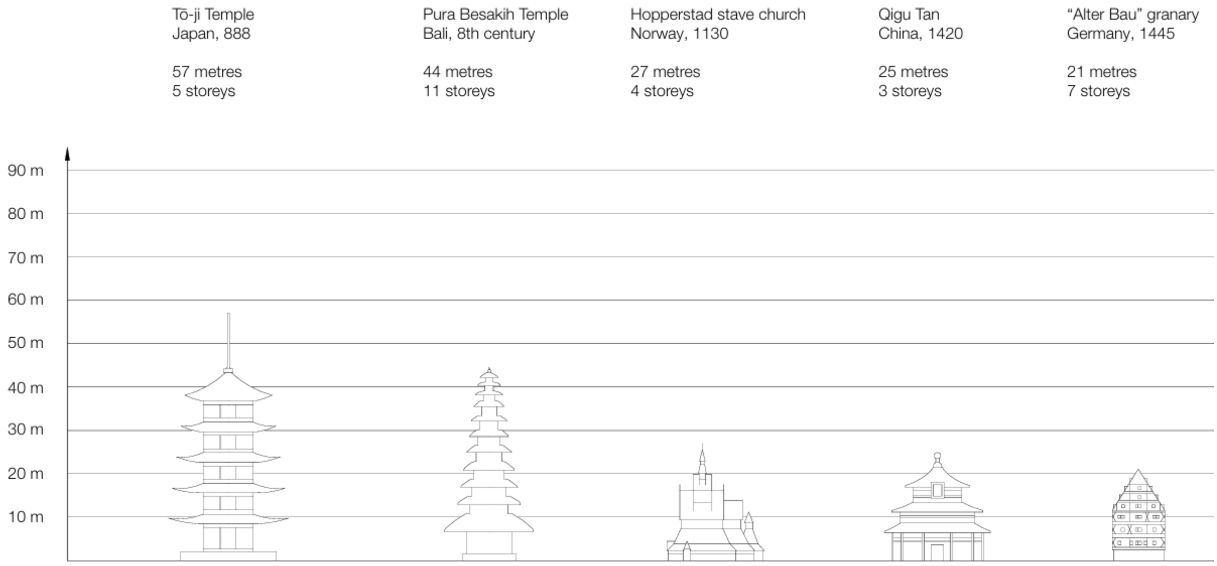

Figure 3: Multi-storey timber buildings in the past (Kaufmann, Krötsch, & Winter, 2018)

However, the rise of alternative materials like steel and concrete in the 20th century, coupled with concerns about fire safety, led to a decline in tall timber structures, particularly in Western countries. The late 20th century saw a resurgence of interest in MSTBs, driven by several factors. Firstly, advancements in wood treatment and engineering techniques led to the development of new, fire-resistant materials like glulam and CLT. Secondly, growing environmental concerns placed a new focus on sustainable construction materials like wood, due to its lower carbon footprint compared to concrete and steel.

The Netherlands has experienced a growing trend towards multi-storey timber construction as well. One such noteworthy project is Haut, in Amsterdam. Haut is a timber-concrete hybrid residential tower, in which CLT is used for both walls and floors. Haut proves the potential of timber as a primary structural material in high-rise structures. The use of timber contributes not only to Haut's striking appearance but also to its environmentally friendly footprint. Another notable timber hybrid building showcasing the feasibility of multi-storey timber buildings is the recently completed Mediavaert office building in Amsterdam, distinguished as one of Europe's largest timber-hybrid constructions. Haut and Mediavaert are true hybrid buildings, integrating timber, concrete, and steel elements. Furthermore, the Netherlands has also seen the realization of true timber multi-storey buildings, like the pioneering Triodos office building. This project points out the potential of CLT as a standalone material, without the use of concrete and steel. All these projects underscore the increasing acceptance and exploration of timber multi-storey construction methodologies within the Netherlands, reflecting a broader trend towards sustainable building practices. Although MSTC is gaining popularity in the Netherlands, the widespread adoption of CLT in MSTBs is lagging behind.

1.2 Relevance

1.2.1 Drivers and barriers for the use of cross-laminated timber in multi-storey buildings

Timber construction is becoming increasingly popular, as can also be seen in the rising number of research publications of timber construction. Publications on multi-storey timber construction also gained traction in the last decade. Nowadays, many research studies have been conducted identifying the drivers and barriers of CLT in construction with varying scopes. Distinctions lay in the region of study, types of structures and types of data gathering methods. There are however only a few studies that researched the application of CLT in MSTBs.

A wide consensus exists on the environmental drivers for the use of CLT in MSTBs. Common arguments for the use of CLT include the carbon storing capacity of CLT, renewability, reusability, and that less energy is required in the production and construction process (Santana-Sosa & Kovacic, 2022). While most literature agrees on these environmental benefits of CLT, the other drivers are up for debate. Other drivers for the use of CLT that occur frequently in literature are among others a faster construction time, aesthetics, design flexibility and a lightweight construction method (Jones, et al., 2016). A faster construction time specifically is not always the case and is very much dependent on the project specifications. Research also highlights government regulations as a driving force increasing timber construction (Low, et al., 2021). However, that is again dependent on the local legislation and is not uniform across the world.

Besides these perceived benefits of CLT, various barriers for the use of CLT in MSTBs exist as well. Frequently occurring themes are related to the cost-competitiveness of CLT, the culture of the construction industry, the lack of knowledge and experience and doubts on material's performance with regard to fire-safety, acoustics and structural integrity (Gosselin, et al., 2017). There is no consensus on the most important barrier that hinders the adoption of CLT, as that is very much dependent on factors such as the region of the study and the scope of the study. Local legislation and local supply chains play a significant role in that regard as well. There are even some aspects identified as drivers as well as barriers, like fire-safety and cost-competitiveness. The conditions under which these aspects act as drivers or barriers remain unclear.

1.2.2 Strategies to enhance the adoption of CLT

The drivers and barriers for the use of CLT in MSTBs are not unambiguous and also depend on local factors. Various studies have researched how the adoption of CLT can be enhanced, upon realising that constructing MSTBs with CLT can offer environmental benefits. The existing literature has different views on how the adoption of CLT can be enhanced. A wide variety of barriers exist, for which there are also a wide variety of strategies to overcome them. Again, no consensus exists on what strategies are best, and the viability of these strategies is dependent on the scope of the study and local characteristics. The practical applicability is also different for all strategies.

1.3 Research definition

1.3.1 Research objectives

This paper aims to address the aforementioned gaps in literature by critically analysing existing literature and doing interviews. The main objective of this research is to study the drivers and barriers for the use of CLT in MSTBs in the Netherlands and to present a set of strategies that should overcome these barriers and that should enhance the adoption of CLT in the Netherlands. In order to achieve this goal, it's also important to understand how CLT is implemented in MSTBs and what the most important design parameters are for CLT.

1.3.2 Research questions

To achieve to goal of this research the following research question is formulated:

RQ: What are the key barriers and potential strategies to overcome these barriers for the widespread adoption of cross-laminated timber in multi-storey buildings in the Netherlands?

Multi-storey buildings are in this thesis defined as buildings of six storeys and higher.

To support the research question, four sub-research questions (SRQ) have been formulated:

SRQ1: What are important design parameters for cross-laminated timber in multi-storey buildings?

SRQ2: How is cross-laminated timber in multi-storey buildings implemented?

SRQ3: What are the drivers and barriers for the use of cross-laminated timber in multi-storey buildings?

SRQ4: Which are the opportunities and strategies to support the further implementation of cross-laminated timber in multi-storey buildings?

1.3.3 Scope

This study concentrates on structural CLT applications within buildings, and it excludes facades and other structural components directly exposed to weather conditions. Additionally, the research does not delve deeply into other EWPs such as glulam and LVL. Section 4.3 Material combinations briefly touches upon hybrid structures that incorporate both glulam and CLT. However, the remainder of the study and interviews prioritize CLT as the primary focus. Moreover, this study focusses on MSTBs of six storeys and higher. This is especially relevant, since some barriers appear more dominant for higher structures compared to low-rise structures. The scope includes all types of actors, ranging from policy makers to market practitioners like contractors, engineers, and architects. Lastly, the focus area of this study is the construction sector in the Netherlands.

1.3.4 Research approach

This study is conducted using a qualitative approach and consists of two parts: (1) an extensive literature review, (2) interviews with stakeholders of the Dutch construction industry. The literature review consists of several parts. First, the available literature CLT's performance as a structural material is studied. Secondly, literature on MSTB design is studied and elaborated on. Thirdly, the drivers and barriers are identified by reviewing a total of 17 research papers. As a last step of the literature review, strategies to overcome the barriers are studied.

The interviews with stakeholders in the Dutch construction industry consist of three parts: (1) the identification of drivers and barriers for the use of CLT in MSTBs in the Netherlands, (2) strategies to overcome these barriers, and (3) a discussion of a case the interviewee worked on. The interviews and literature review serve to validate each other's findings and to draw conclusions and provide recommendations for further research.

1.4 Reading guide

The structure of this paper is as follows. After the introduction in chapter one, the methodology is presented in chapter two. Chapter three elaborates on the performance of CLT followed by the design fundamentals of MSTBs in chapter four. Chapter five and six dive into the drivers and barriers for the use of CLT in MSTBs respectively and chapter seven discovers the potential strategies to bridge the barriers. Chapter eight contains the results of the interviews and covers the drives, barriers, strategies, and the case study, after which the discussion and conclusions follow in chapter nine and ten respectively. Lastly, the recommendations are presented in chapter eleven.

2. Methodology

This chapter discusses the methodology of this research. First, the research approach is discussed, followed by a description of the data collection methods. Next is a description of the data analysis methods. Lastly, the methodological choices made in this study are justified.

2.1 Research approach

The main objective of this study is to research the drivers and barriers for the use of CLT in multi-storey buildings in the Netherlands and to present a set of strategies to overcome these barriers and to enhance the adoption of CLT in the Netherlands. Multi-storey buildings are in this study defined as buildings of six storeys and higher. The focus of this study is the Dutch AEC industry.

In the identification stage, the research questions were formulated based on the problem description and research gap in the introduction. To achieve the objectives of this research and to answer the research question, the project will be carried out in several stages:

- In-depth literature review in chapters 3, 4, 5, and 6.
- Proposal of a set of strategies to overcome barriers, based on literature in chapter 7.
- Field study: twelve semi-structured interviews with various stakeholders in the Dutch construction industry in chapter 8.
- Discussion, conclusions, and recommendations in chapter 9, 10, and 11 respectively.

The first part of this research consists of a literature review, which will be done to gain a better understanding of the topic and to understand what has been researched before. The first part of the literature review elaborates on the performance of CLT as a structural material in chapter 3 and on the design of multi-storey timber buildings in chapter 4. These chapters answer sub-research question 1 and 2 respectively.

Next step in the literature review is the study phase on the drivers and barriers for the use of CLT in MSTBs in chapter 5 and 6 respectively. These chapters answer sub-research question 3. Also, several Dutch MSTBs have been identified in this stage, that will be used in the selection of stakeholders for the interviews.

In the analysis stage of the literature review, the drivers and barriers are analysed and form the basis of the proposed strategies. Chapter 7 presents this set of strategies, which should overcome the previously identified barriers and should enhance the adoption of CLT as structural material. These strategies are based on literature, supplemented with strategies proposed by the author specifically focused on the Dutch construction context. That completes the literature review, and forms the basis for the semi-structured interviews.

The results of the literature review form the basis for the interviews. A total of twelve interviews was conducted with the goal of validating the findings of the literature review and to apply the findings to the Dutch AEC industry. The drivers and barriers were discussed and also the strategies were discussed to check whether the proposed strategies can count on support from practitioners in the Dutch AEC industry. Finally, a specific case was discussed on which the stakeholder had worked. The drivers and barriers for the use of CLT in that project were discussed and also how the barriers were overcome.

2.2 Data collection

This study contains primary and secondary data. The literature review consists of an analysis on existing literature and therefore contains secondary data. Primary data is gathered through the interviews.

2.2.1 Literature review

The first part of the literature review was carried out to gain a better understanding of CLT as a material and how MSTBs are designed. For this part of the literature review, different types of data sources were used. Books were used for in-depth information of CLT and construction methods and research papers were used for recent developments with regards to CLT.

The second part of the literature review investigated the drivers and barriers for the use of CLT in MSTBs. The data used for these chapters all came from research papers online. Search engines like Google Scholar and ResearchGate were used to acquire the right information. For the drivers and barriers chapters, papers were searched using the terms "Cross-laminated timber", "drivers and barriers", "multi-storey", "multi-storey timber construction", and "multi-storey timber buildings". Eventually, a selection of seventeen papers was made on the basis of the applicability to this study.

The next part of the literature review investigated how the barriers could be overcome. The data for this chapter was partially already provided in the studied seventeen research papers. However, more studies that specifically investigated how the adoption of new construction methods could be enhanced were also reviewed. The same search engines were used and the same search terms were used but with some additions like: "adoption" and "implementation".

2.2.2 Interviews

In total, twelve interviews were held with various practitioners in the Dutch AEC industry: two architects, two contractors, two structural engineers, one project developer, one building physics consultant, one timber supplier, one policy adviser of a Dutch political party and one building cost specialist have been interviewed. Interviewees were selected based on the case studies identified in the literature review. After selecting specific cases, stakeholders involved in those projects were approached, often through the author's or supervisors' networks, or through platforms like Google or LinkedIn. The interviewees all represent a company that has sufficient experience with projects in CLT. A diverse range of stakeholders was selected to ensure a comprehensive and varied perspective on the research topic, see Table 1.

The interviews had a semi-structured set-up. This approach was chosen because a diverse range of stakeholders was interviewed, each with their own background and expertise. Conducting interviews with predetermined questions would be suboptimal due to this diversity. Some interviews focused more on costs, while others focused on engineering or building physics aspects. In general, the interview had three themes:

- The drivers and barriers for the use of CLT in MSTBs.
- Strategies to overcome the barriers.
- A specific case they worked on.

The drivers and barriers and strategies that were first identified during the literature review were used as the basis for the interviews. Based on the answers in the interview follow-up questions were asked. The interviews were audio-recorded with the consent of the participants. The interview recordings were then fully transcribed. The transcriptions were then analysed and used to validate the findings of the literature review. An overview of the interview set-up can be found in appendix A.

Table 1: Demographics of interviewees

Characteristics		Number
Type of company	Architect	2
	Builder / main contractor	2
	Building physics consultants	1
	Client / building owner	1
	Cost consultant	1
	Dutch political party	1
	Project developer	1
	Structural engineer	1
	Timber structural engineer	1
	Timber manufacturer	1
Number of employees	Less than 10	0
	11 up to 50	3
	51 up to 200	4
	201 up to 500	4
	501 up to 1000	0
	More than 1000	1
Years of experience	Less than 10 years	0
	Between 11 and 25 years	2
	Between 26 and 50 years	4
	Between 51 and 75 years	4
	75+ years	2
Total		12

2.3 Data analysis

2.3.1 Literature review analysis

The seventeen articles were read thoroughly and the drivers and barriers per paper were analysed by thematic coding. After all drivers and barriers were identified, the drivers and barriers were categorised according to the PESTE analysis: political, economic, sociocultural, technological, and environmental aspects. This categorization ensures a broad view on the topic and helps to analyse the drivers and barriers extensively. The PESTE analysis is a simplification of the PESTEL analysis, which also includes legal aspects. The reason legal issues are left out is for simplicity and clarity, since legal aspects have an overlap with political aspects. An overview of the PESTE analysis can be found in appendix B.

The strategies were analysed were analysed according to a similar approach. After the research papers were reviewed and the strategies had been identified, a categorisation was made. The categorisation was not done according to the PESTE analysis, but specifically based on the findings from literature.

2.3.1 Interview analysis

The interviews were first transcribed and then analysed with the same categorisation as with the literature review. The drivers and barriers were identified using the PESTE analysis. And the analysis of the strategies followed the same categorisation as in the literature review.

2.4 Justification of methodological choices

For this research, a qualitative research approach was chosen by doing a literature review and interviews. While semi-structured interviews often yield results that cannot be generalized beyond the sample group, they offer a deeper understanding of participants' perceptions, motivations, and emotions. It is crucial to assess the reliability and validity of this study.

In qualitative studies, reliability is primarily about conducting research thoroughly, carefully, and honestly (Robson, 2002). However, more important in qualitative studies is their validity, which is often addressed in relation to three common threats: researcher bias, reactivity, and respondent bias (Robson, 2002). Researcher bias is related to the potential negative influence of the researcher's knowledge or assumptions about the study. Reactivity involves the researcher potentially influencing the situation or interviewees. Respondent bias occurs when participants do not provide honest responses, perhaps due to perceiving the topic as threatening or attempting to please the researcher with desirable responses. Robson (2002) suggested six strategies to minimise these risks to validity: (1) prolonged involvement, (2) triangulation, (3) peer debriefing, (4) member checking, (5) negative case analysis, and (6) audit trail.

Prolonged involvement refers to how long the researcher and the participants of the study have been involved in the topic of research. The author has a study background in Civil Engineering and all participant were selected on the basis of their experience with CLT projects. Triangulation of data is done by comparing findings in the literature study with the results of the interviews. Peer debriefing is done throughout the study by people at the University of Technology in Delft, and by people in the Dutch AEC industry. Member checking is done by sending the transcriptions of the interview to the interviewee to check whether the transcription truly reflect the beliefs and opinions of the interviewee. The interviewee may clarify or expand on some answers in the interview to prevent incorrect assumptions or interpretations by the author. Negative case analysis involves examining responses that deviate from the majority of answers, requiring separate analysis to understand the reasons for the deviation. Lastly, an audit trail involves maintaining a comprehensive overview of all research-related data and activities. This is accomplished by organizing all examined research papers on the topic and storing and analysing the interviews. This method ensures that all research data is properly stored and documented.

3. Cross-laminated timber

This section provides a summary of research findings from studies on CLT and answers the following sub-research question: *What are the important design parameters for cross-laminated timber in multi-storey buildings?* It discusses the structural, fire, thermal, and acoustic performance of CLT.

3.1 Structural performance

Mechanical properties of the lamellas used in CLT elements can vary for different manufacturers. The structural properties of a CLT panel are highly dependent on the strength classes of the individual layers, the dimensions of the individual panels, the amount of panels used, the timber species, the adhesive and the compression technique (Brandner, 2014).

The base material for CLT lamellas is in general C24. CLT manufacturers can choose for a different strength class, or for a combination of strength classes. The material properties of CLT have to meet the minimum requirements laid down in NEN-EN 16351, or conform the appropriate ETA.

Table 2 shows the comparison of the characteristic values of timber C24, concrete C25/30, and steel S235. Noteworthy is that the characteristic compressive strength of C24 is close to the compressive strength of concrete C25/30, while the self-weight of timber is less than one fifth of concrete.

Table 2: Comparison of characteristic values of timber C24, concrete C25/30, and steel S235

	C24	Concrete C25/30	Steel S235
Modulus of elasticity	11,6 N/mm^2	31.000 N/mm^2	210.000 N/mm^2
Compressive strength	21,0 N/mm^2	25,0 N/mm^2	235,0 N/mm^2
Tensile strength	14,5 N/mm^2	1,8 N/mm^2	235,0 N/mm^2
Bending strength	24,0 N/mm^2	2,7 N/mm^2	235,0 N/mm^2
Self-weight	420 kg/m^3	2400 kg/m^3	7800 kg/m^3

3.2 Fire performance

When wood is set on fire, a transformative process known as charring occurs. As the flames contact the wood's surface, intense heat causes the timber to decompose. Instead of immediate combustion, a layer of char is formed. This char, a blackened, carbon-rich residue, acts as a protective barrier, insulating the inner layers of wood from the flames. Paradoxically, charring slows down the rate of burning by limiting access to oxygen, which is essential for combustion. This phenomenon not only contributes to the wood's fire resistance but also provides a visual record of the fire's intensity and duration (Friquin, 2011).

3.2.1 Char rates

The char rate is commonly defined as the penetration depth into the wood at a specific temperature, divided by the time taken to achieve this temperature. Initially, when wood undergoes pyrolysis temperatures, the char rate is rapid. Pyrolysis is the chemical decomposition of organic materials through the presence of heat. Subsequently, as this char layer forms, the char rate diminishes, due to the insulating properties of the char layer. This formed char layer decreases the char rate by restricting the movement of gases involved in combustion, serving as thermal insulation protecting the still intact wood. Therefore, the continuity of the combustion cycle gets hindered (Shafizadeh, 1982).

3.2.2 CLT protection methods and limitations

There are three common approaches to make a fire design with CLT: (1) the charring method, (2) encapsulation method, and (3) a sprinkler system. When using the charring method, the cross-sectional area of the CLT members are made bigger than strictly necessary for structural reasons. In case of a fire, the cross section decreases with the known charring rate, while maintaining its structural function. The second method is het encapsulation method, in which the timber elements are partially or fully encapsulated by fire-resistant materials like fire-rated gypsum board or non-combustible fibre insulation (American wood council , 2017). These protective measures must endure for the specified fire duration, ensuring the CLT surface stays below 300°C (Zelinka et al., 2018). The last method is a sprinkler system which should slow down and control the fire.

Figure 4: A slice of a glulam column after a standard fire test showing the reduced cross-section after a standard fire test of 90 minutes (Think Wood , 2023)

3.3 Thermal performance

Effectively managing heat transfer throughout the building is crucial for decreasing energy usage, mitigating condensation risks, and enhancing occupant comfort. When employing CLT in building enclosures, heat flow is regulated by the thermal resistance of the CLT, taking into account factors like panel thickness and wood species, along with supplementary thermal insulation and the thermal resistance of other enclosure components such as finishing materials (Straube & Burnett, 2005).

Timber has a low thermal conductivity, thereby minimizing the risk of thermal bridging (Straube & Burnett, 2005). This characteristic can be beneficial for detailing and structural design. For instance, it enables the extension of an internal floor slab to create a balcony without the need for a separate thermal barrier.

Furthermore, owing to its density, timber exhibits a notable capacity to store heat, which not only insulates against cold during winter but also guards against excessive heat in summer. Its natural regulation of heat and moisture can therefore contribute to comfortable living environments (Mallo & Espinoza, 2014).

3.4 Acoustic performance

CLT is a light material and therefore naturally has low acoustic damping and is susceptible to vibrations. Especially low-frequency sounds are perceived as disturbing in lightweight constructions. Acoustics is therefore a challenge in MSTC, especially for residential buildings due to the stricter regulations on acoustics. Sound can travel in two ways in buildings: either through the air (airborne sound) or through the solid components of a structure (structure-borne sound). To achieve optimal acoustic performance, it is crucial to address both airborne sound and impact sound transmission in the design of wall, floor, or ceiling assemblies.

A CLT wall or floor can meet the acoustic requirements without additional measures, but that would require a very thick panel and that is not economical. Therefore, extra measures are needed to prevent the transmissions of sound and vibrations. This is more complex in timber construction than in concrete construction, where the mass quickly ensures that the acoustic requirements are met. A few

- Acoustically decoupling of structural elements
- Adding sound insulation or cavity
- Adding mass

Walls and floors can be acoustically decoupled, for example by adding acoustic dampers between the elements, see Figure 5. However, this can come at the expense of the overall stability of the structure.

A cavity or insulation material can be installed to absorb some of the airborne sound. Common materials are fibreglass or mineral fibre matting placed in the space between the finish and the mass timber elements.

The last measure involves ensuring that the walls and floors possess adequate mass to reduce vibrations, and thereby lowering noise levels. For walls, this is often (double) gypsum plasterboard (on acoustically insulating brackets), while for floors, this can be sand, gravel, or concrete.

Figure 5: Structurally decoupled wall-floor assembly (Delta, 2024)

3.5 Moisture

Wood is a natural material, and therefore decomposes through natural processes under specific conditions, forming the basis of the biological cycle in forests. A typical moisture content (MC) for structural CLT of ± 12% is lower than required MC of 20% at which biological degradation, and thus destructive fungi, occurs. As long as the MC of the CLT remains below this level, there will be no biological degradation caused by destructive fungi. Buildings from the past have shown that properly dried timber has the potential to endure for several hundred years. The key principle in building with CLT is to shield it from prolonged increases in moisture through suitable protective measures and ensure its long-term dryness. Temporary increases in moisture levels, such as those occurring on timber surfaces in bathrooms, are not problematic as long as the surfaces can dry rapidly.

The risk for the growth of fungi can occur in three variations: (1) short-term wetting that promotes mould development, (2) extended exposure to wetting during construction which enables the establishment of decay fungi capable of surviving for years in dry wood, and (3) long-term of moisture infiltration which provides an environment for decay fungi to gradually degrade the wood.

The likelihood of mould growth during mass timber construction is minimized by several factors. Firstly, the wood is typically dry when it gets prefabricated, with a moisture content of less than 15%. Additionally, it is usually protected with plastic coverings during transportation, and the on-site construction process is fast. However, managing internal moisture post-construction is more challenging. While effective mechanical ventilation systems can reduce the risk of heightened humidity, especially in hot and humid climates, there is a potential issue with these systems operating below the dew point, leading to moisture condensation on cooler surfaces. Furthermore, the risk of moisture-related problems increases due to potential leaks resulting from improperly installed or deteriorated seals around windows and doors, as well as from plumbing issues. While these water sources may theoretically not exist, they frequently occur in reality, causing significant damage that can be particularly problematic in mass timber construction.

4. Multi-storey timber building design

This section explain the design of multi-storey timber buildings and answers the following sub research question: *How is cross-laminated timber in multi-storey buildings implemented?* It discusses the structural design and construction methods of MSTBs, and different material combinations and the construction process.

4.1 Structural design

A structural design should always match the minimum strength, rigidity and stability requirements. Regardless of the materials used, the primary goal is to establish a framework that can withstand various loads and fulfil other operational needs throughout its lifespan, all while avoiding premature decay or breakdown. Loads can be vertical, as with the weight of occupants or furniture, the weight of the structure itself, or the variable load of snow. Loads can also be horizontal like wind loads.

4.1.1 Load paths

External forces, including those exerted by live loads such as occupants and equipment within the building, may subject individual structural components or elements to compression, tension, bending, torsion, or shear. The design of the structure should ensure the absorption and transfer of these forces through both horizontal and vertical elements to the ground.

An essential factor in the design of tall wood buildings is the consideration of shrinkage. This becomes particularly critical when designing vertical elements, since excessive or uneven shrinkage can impact the elevation and alignment of crucial building elements, jeopardizing the integrity of the entire building. Ideally, the vertical wooden elements are loaded parallel to the grain. This can be achieved by either stacking vertical elements directly on top of each other or creating connection details that minimize cross grain loading conditions in the vertical section.

4.1.2 Vertical loads

Ideally, it is recommended to transfer vertical loads efficiently through continuous or superimposed structural elements, which could be CLT panels. If there are significant deviations in the vertical load path, specialized structural features like transfer trusses may be necessary.

Typically, CLT structures are built using a platform system, in which the vertical load-carrying elements, like the panels, have a single-story height, and each floor serves as a platform for constructing the subsequent one. Ideally, most of the vertical loads are transferred directly from the upper to the lower panel. When employing CLT in a platform construction, it is important to create a design that minimizes the risk of shrinkage in the floor panels stressed perpendicular to the grain.

4.1.3 Lateral loads

There are various ways to absorb lateral loads in the vertical plane like rigid (moment) frames, braced frames, or shear walls strategically positioned along the building perimeter. Shear walls may be distributed periodically throughout the structure or concentrated within robust vertical cores like elevator or stair shafts. Alternatively, a combination of these locations may be employed based on the design's feasibility. It is essential for lateral systems to be implemented in both east–west and north–south directions, particularly in buildings aligned with the wind directions, and it is preferable to evenly distribute them across the building.

For effective collaboration, brace frame and shear wall components must be interconnected through rigid horizontal elements such as floors, roofs, or a combination of both. The main objective of the lateral system should be to facilitate the transmission of applied lateral loads to the ground by some kind of an anchor. This anchoring function is commonly fulfilled by stair or elevator shafts or by continuous vertical brace frames extending the full height of the building.

4.2 Construction methods

4.2.1 Platform frame method

The platform frame method stands as one of the most widely adopted construction technique. In this approach, each floor acts as a functional base for the subsequent storey, with wall panels being installed first followed by the placement of floor panels above. As construction progresses, wall panels for the next storey are positioned one top of the preceding floor, continuing in this manner. One disadvantage of this method arises from compression stresses perpendicular to the grain in floor elements clamped between walls. Timber's maximum allowable compression stress perpendicular to the grain is relatively low. Consequently, as building height increases, so does the stress on the lower storey floors, potentially leading to their crushing. To accommodate taller structures, it becomes imperative to reduce the stress perpendicular to the grain of the floor elements, which can be achieved by increasing the load bearing area on the floor panel.

4.2.2 Balloon frame method

In the balloon frame method, load-bearing wall elements extend continuously and span across multiple stories, with floor structures supported internally by these walls. Because floors are supported within the wall panels, there is no stress perpendicular to the grain, eliminating the need for floor panels to bear the maximum weight of the wall elements as seen in the platform method. However, a significant drawback of this approach is the absence of a convenient working platform for upper-floor construction. Unlike platform construction, where workers can easily access the top of the walls being erected, balloon construction necessitates the use of scaffolding to reach the uppermost sections of the walls, which may be two or three stories above the working platform. Hybrid timber solutions with glulam columns and beams and CLT floors is possible for both construction methods.

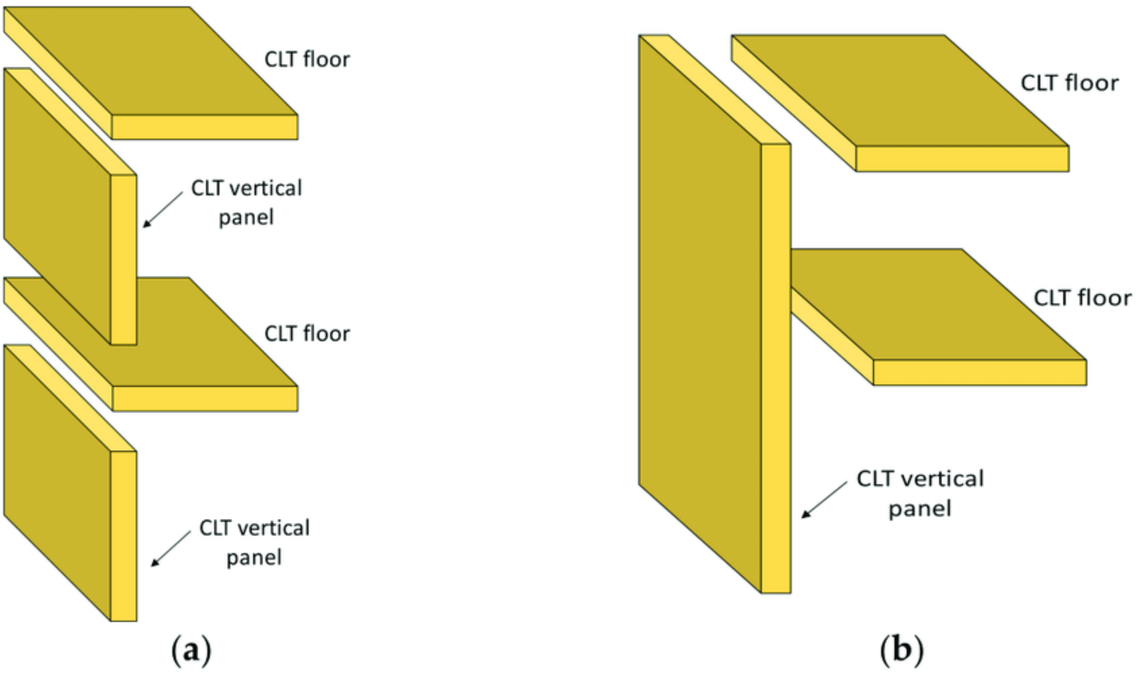

Figure 6: Construction techniques for CLT buildings: (a) platform frame, (b) balloon frame (Sandoli, 2021)

4.2.3 Modular construction

Modular construction thrives on repetition and standardization. This means the number of unique elements in a project is limited, with the building relying on a set of standard units. This constraint is the key to achieving the true benefit of modular construction: a fast assembly (Bhandari, et al., 2023). Timber is a perfect material for both prefabrication and modular building for several reasons. First, it's incredibly easy to process. This allows manufacturers to efficiently pre-cut various features into wooden components off-site, saving valuable time during construction. Second, timber is lightweight compared to other common building materials, making transportation and installation relatively easy (Bhandari, et al., 2023). Lastly, the development of CLT and other EWPs has opened up new possibilities for timber buildings. EWPs offer more predictable engineering properties and can be produced in dimensions not readily available with traditional sawn lumber, further expanding the design potential of CLT in modular construction.

4.3 Material combinations

There are various combinations of materials possible. Sometimes, the limitations of CLT require a hybrid structure. For example, the basement is usually always in concrete due to the presence of ground water. CLT also has limitations with spans. A CLT floor has a maximum span length of ten metres, but is optimal at around six metres (Vos & Jackson, 2024). When the desired span length exceeds this maximum range, a different approach can be used with for example steel beams. Also, timber might not be ideal for large cantilevers, for which steal could be more applicable. The choice for an all timber structure or a steal/concrete-timber hybrid structure is dependent on the design and function of the building. The next paragraphs elaborate on the various material combinations with their limitations.

4.3.1 All timber structures

For a building to be classified as an "all-timber" structure, both its primary vertical and lateral load-bearing components must be made entirely from timber. However, the inclusion of localized non-timber connections between timber elements is permissible within this classification. Even if a timber-built structure incorporates a floor system composed of concrete planks or a concrete slab resting on timber beams, it remains categorized as a "timber" structure, as the concrete elements do not serve as the primary load-bearing structure.

It will be increasingly difficult to ensure the stability in an all timber building of twelve stories or higher and therefore a hybrid solution might be a better option (Vos & Jackson, 2024). Nevertheless, MSTBs have been built with all-timber structures. The tallest all timber structure currently is Mjøstårnet in Norway with 85.4 metres. Stability in Mjøstårnet is achieved by large glulam trusses and CLT lift shafts. Concrete is only used on the top level floors to prevent wind induced acceleration and does not have a structural function.

4.3.2 Steel-timber structures

In constructions featuring timber-steel hybrid frameworks, a significant portion of either the vertical or lateral load-bearing structure is constructed from steel components. Typically, this involves the incorporation of steel elements in lateral force resistance systems, such as steel-framed cores, buckling-restrained braces, or exoskeleton steel bracing systems. Additionally, the vertical load-bearing system comprises columns and beams that interact with timber-based floor or wall systems. This structural categorization highlights a substantial utilization of steel, surpassing the standard use of fasteners and connectors found in typical mass timber and wood-frame constructions.

4.3.3 Concrete-timber structures

These structures feature a notable incorporation of concrete in either the vertical or lateral load-bearing framework, typically manifesting as a concrete core that supports a timber frame. Another viable application involves utilizing concrete for the plinth or the initial few stories, while timber is employed for the remaining levels. Sometimes, only concrete is used as a top layer on the CLT floors in the top level stories to add mass to prevent horizontal displacements, see figure 10 for the various concrete-timber hybrid structures.

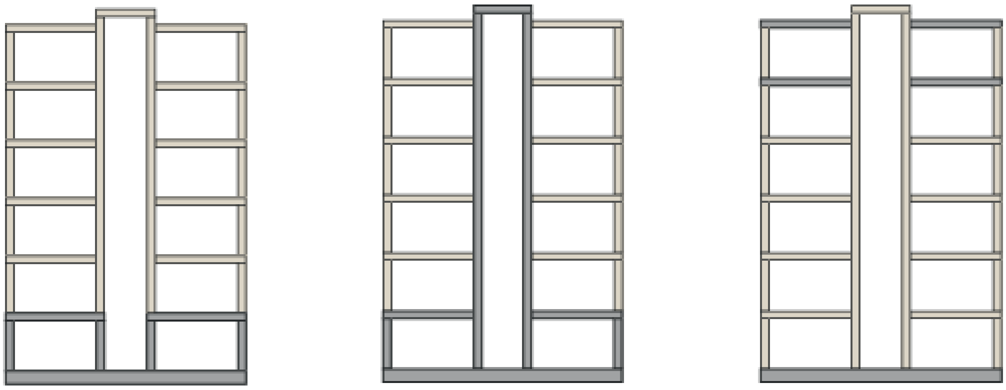

Figure 7: Concrete-timber hybrid structures (Vos & Jackson, 2024)

Another scenario involves buildings utilizing a combination of concrete beams and columns with a CLT floor decking system. Moreover, various prefabricated systems available in the market seamlessly integrate concrete frames with timber inlay panels for walls or flooring, or alternatively, timber-framed modules combined with precast concrete flooring.

Figure 8: Prefab CLT-concrete composite floor (Vos & Jackson, 2024)

4.3.4 Concrete-Steel-Timber Hybrid Structures

These structures employ a blend of all three materials to support primary loads. A common arrangement involves a concrete core complemented by steel beams and columns, alongside timber flooring and partition walls, although numerous configurations are possible.

4.4 Construction process

Timber construction demands more upfront planning compared to traditional methods due to the interconnectedness of design choices with fire safety, prefabrication, building systems, physics, and structural elements (Höfferl, 2021). Early and open communication among all parties involved is essential to ensure everyone is on the same page and that planning is holistic. While this initial phase might take longer, it oftentimes translates to faster construction times later on (Prause & Vadas, 2018).

A core principle in timber construction is maximizing prefabrication. This means a significant portion of the construction work is done in a factory setting, minimizing work on-site (Abed, et al., 2022). This approach is crucial for both cost-effectiveness and quality in timber projects. The preliminary design choices are influenced by the requirements from the individual components, the requirements of the system and the assembly on site (Kaufmann, Krötsch, & Winter, 2018).

The traditional construction model used in many regions separates planning and construction entirely. This allows clients to easily compare prices. However, it limits the ability to integrate specialized knowledge early on to optimize the design and leverage the construction company's specific strengths, often leading to rework. For multi-storey timber buildings, alternative models like general contracting, "bouwteams," and functional tendering can be advantageous (Kaufmann, Krötsch, & Winter, 2018).

The "bouwteam" model, originating in the Netherlands, establishes a single contract between the construction and planning teams, and the client, from the early stages. Here, performance criteria are established, and construction companies can be awarded the project after the planning is finalized, provided they meet budget and deadlines. If not, the bouwteam is compensated, and the client can seek alternative bids. This model promotes collaboration and integrates all planning parties (Kaufmann, Krötsch, & Winter, 2018).

5. Drivers for the use of cross-laminated timber in multi-storey buildings

In this chapter, a comprehensive literature review is conducted to examine the factors driving the use of CLT in MSTBs. The following sub-research question will be answered: *What are the drivers for the use of cross-laminated timber in multi-storey buildings?* A total of seventeen scientific articles have been reviewed and analysed according to the PESTE analysis. This chapter elaborates on the most important drivers per category. An overview of the full PESTE analysis and reviewed articles can be seen in Appendix B.

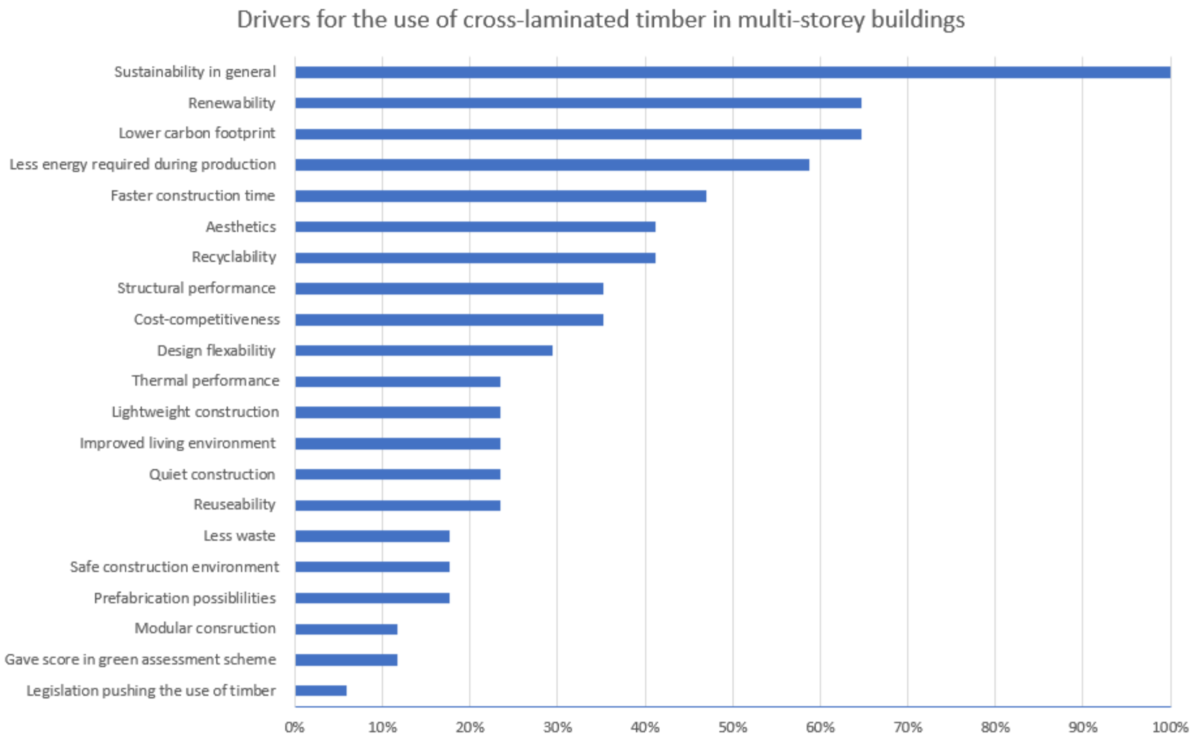

Figure 9: Overview of perceived drivers for the use of CLT in MSTBs based on the results of the literature review

5.1 Political drivers

The first category of drivers for the use of CLT in MSTBs in the Netherlands are political drivers. In the Netherlands, there is a notable legislative and political push towards biobased construction. National policy stimulating biobased constructions is laid down in the Nation Nationale Aanpak Biobased Bouwen (NABB – National Approach Biobased Building). And the metropolitan region of Amsterdam (MRA) also developed a timber building quota.

5.1.1 Nationale Aanpak Biobased Bouwen

A recent development was the announcement by the Dutch government to invest 200 million euros aimed at scaling up biobased construction in a program called the **NABB** (Rijksoverheid, 2023). The ambition of the Dutch Government is to realise at least 30% of newly built homes with at least 30% biobased materials in 2030. 25 million euros are reserved to setup new biobased production facilities and 175 million euros are reserved to expand the markets further. The NABB currently focuses on fibres like flax and hemp and not specifically on timber. Nonetheless, this may change in the future.

5.1.2 Amsterdam Convenant Green Deal

Besides this national policy, the use of timber is also stimulated locally. The MRA developed the **Amsterdam Covenant Green Deal** in 2020 (Metropoolregio Amsterdam, 2020). The aim of this covenant is to have at least 20% of the entire housing production in the Metropolitan region of Amsterdam executed with biobased materials annually starting from 2025. Parties - including the municipalities in the Amsterdam Metropolitan Area, the provinces of North Holland and Flevoland, the national government, developers, institutional investors, housing associations, builders, as well as knowledge institutions and other involved parties - declare a shared goal to promote the expansion of timber construction. However, based on weight, the current market share of wood is 2% and of other biobased materials is 0,1%. Hence, there is still a lot to gain.

5.2 Economic drivers

The next category of drivers that enhances the adoption of CLT has to do with economics. There are however different views on the price competitiveness of timber construction.

5.2.1 Cost-competitiveness

The lack of cost-competitiveness was most often cited as a barrier for the adoption of CLT in MSTBs. Nevertheless, six out of sixteen reviewed studies concluded that MSTBs constructed with CLT can be **cost-competitive** with traditional materials. Franzini et al. (2018) argue that when local production facilities are established, the logistical costs can decrease. And due to the faster construction time the **labour costs and overall project costs can decrease**. While building MSTBs with CLT can in some cases offer **a faster construction time,** it doesn't necessarily mean lower construction costs, but it can bring various cost savings like more rent income due to the faster delivery of the building. Or with demolition and reconstruction, an alternative residence is needed for a shorter period. Furthermore, a higher on-site precision can be achieved due to the high levels of prefabrication, which could result in **lowers fault costs** (Franzini, Toivonen, & Toppinen, 2018). Low et. al (2021) also mention lower labour costs, but not necessarily lower total project costs. That is dependent on the entire supply chain of timber in that specific region. Also **foundation costs** are generally lower due to timber's light self-weight (Wang, Toppinnen, & Juslin, 2014).

While some authors claim that timber construction can be cost-competitive to traditional construction, most studies mention that traditional construction is in most cases the most economical option. Despite it is clear that some costs savings can be realised with the construction of MSTBs using CLT, it does not necessarily result in lower total project costs. The economic barriers regarding construction of MSTBs with CLT is explained in 6.2 Economic barriers

5.3 Sociocultural drivers

Another important category that drives the use of CLT is sociocultural aspects. This chapter addresses the consumer's perceptions, consumer's demand, perceived improved living environment, and improved well-being due to biophilic design principles.

5.3.1 Consumer's perception

Various studies have been conducted to examine the consumer's perception of timber as a building material. Gold & Rubik (2008) conducted a consumer survey among the German population exploring the consumer's perception of timber as a construction material. The study found that structural timber had **a positive image** and was related to **eco-friendliness**, **aesthetics** and **well-being**. Table 3 shows the attitudes towards timber as a construction material.

Table 3: Consumer's perceptions of timber as a building material (Gold & Rubik, 2009)

	I agree fully	I agree somewhat	I disagree somewhat	I fully disagree
Natural	88	11	1	0
Cozy	76	20	3	1
Eco-friendly	70	21	7	2
Aesthetic	68	26	6	1
Healthy	66	27	5	1
Stable	47	37	13	1
Modern	45	40	12	2
Long lasting	37	40	19	3
Stable value	27	43	23	5
Expensive	23	40	24	5
Abundant	9	17	43	30
Fire resistant	7	12	29	51

Question: To what extent do you agree with the following statement: Timber as a construction material is:

5.3.2 Consumer's demand

In 2023, a similar study was undertaken in the Netherlands. The Dutch housing market faces a significant challenge with the ambitious goal of constructing one million houses before 2030 (Rijksoverheid, 2023). Addressing the dual challenge of providing sufficient affordable housing while transitioning to a more sustainable and circular economy presents a remarkable opportunity for timber dwellings. To ensure the successful adoption of mass timber construction, understanding the actual demand for timber houses in the Netherlands is crucial. Consequently, Woertman (2023) conducted a survey involving 1091 Dutch consumers to assess their willingness to move into a timber house. Consumers identified **sustainability**, **the natural aesthetic of timber**, and a **faster construction time** as the primary motivators for choosing timber houses.

7% of respondents with an intention to move state that they would definitely consider a wooden new-build home as their next residence, while 10% say they would consider it, and 18% indicate that they would probably consider it. The estimated market potential for a wooden new-build home thus amounts to 35%. Within the subgroups of 'doubters' and 'rejecters,' the interest in a wooden new-build home can increase in two ways. Firstly, this can be achieved by presenting counterarguments (in the form of factual information) addressing consumers' perceived barriers of wooden homes. The market potential can then increase by a maximum of 15%. Furthermore, lower prices for wooden homes compared to 'traditionally' built homes also lead to greater interest; the market potential can then increase by an additional maximum of 15% (Woertman, 2023).

5.3.3 Improved living environment

Additionally, existing mass timber projects serve as examples of how current homeowners perceive their massive timber homes. The Dutch Ministry of the Interior and Kingdom Relations collected the consumer's perceptions of nine different biobased projects in the Netherlands (De Graaf & Nio, 2023). One of the main drivers was **the improved living environment**. A resident in Stories, Amsterdam mentioned the following: *'I really like the living environment. It feels warmer. Our previous concrete house felt different. And I find the natural tones calming.'* A resident of M'DAM in Monnickendam mentioned a similar feeling of their massive timber home: *'It felt good from the first moment I saw this house. I chose to leave the timber in white wash. I find it very beautiful. It feels very pleasant. It feels different than a concrete house. I cannot really explain why.'*

Figure 10: M'DAM, Monnickendam (Leegwater, 2021)

Figure 11: Stories, Amsterdam (Heutink, 2024)

5.3.4 Biophilic design for increased well-being

Studies reveal a fascinating link between touching wood and positive physiological changes. Unlike other building materials, wood seems to trigger a relaxation response, lowering blood pressure and calming the nervous system. Research by Forest and Wood Products Australia (Knox, et al., 2018) suggests workplaces with wood interiors promote increased focus, better moods, and higher productivity. Similarly, a University of British Columbia study highlights the stress-reducing properties of wood, comparing it to the well-documented benefits of experiencing nature (Fell, 2010).

5.4 Technological drivers

The fourth category of drivers is related to technological aspects. These are partially related to the material characteristics, but also to the construction process.

5.4.1 Faster construction time

Buildings constructed with CLT can, in some cases, offer a faster construction time. Various studies emphasize the faster construction time as one of the biggest drivers for the use of CLT in MSTBs. This has various reasons. Firstly, CLT panels are prefabricated off-site, allowing for simultaneous construction of foundations and site-work, minimizing sequential processes. Secondly, CLT structures are lighter, facilitating easier transportation and installation on-site, reducing construction time. Additionally, the precision engineering of CLT panels ensures accurate and quick assembly, eliminating the need for time-consuming on-site cutting and fitting. Lastly, the simplicity of CLT construction methods and fewer labour requirements contribute to faster project completion, making it an attractive option for efficient and timely construction projects.

A study by Smith et al. (2017) conducted a comparison between multiple MTC projects and its conventional counterpart to evaluate their schedules. The results indicated an average schedule reduction of 20% with MTC, translating to an average duration of 12.7 months for MTC projects compared to 15.4 months for traditional construction. The prefabrication of mass timber panels in a factory enables concurrent construction of site-work and foundations, thereby reducing the sequential construction process typical in traditional on-site building projects, see Figure 32. On average, mass timber panels took 2.9 months to fabricate in the factory and only 60 days to erect on-site.

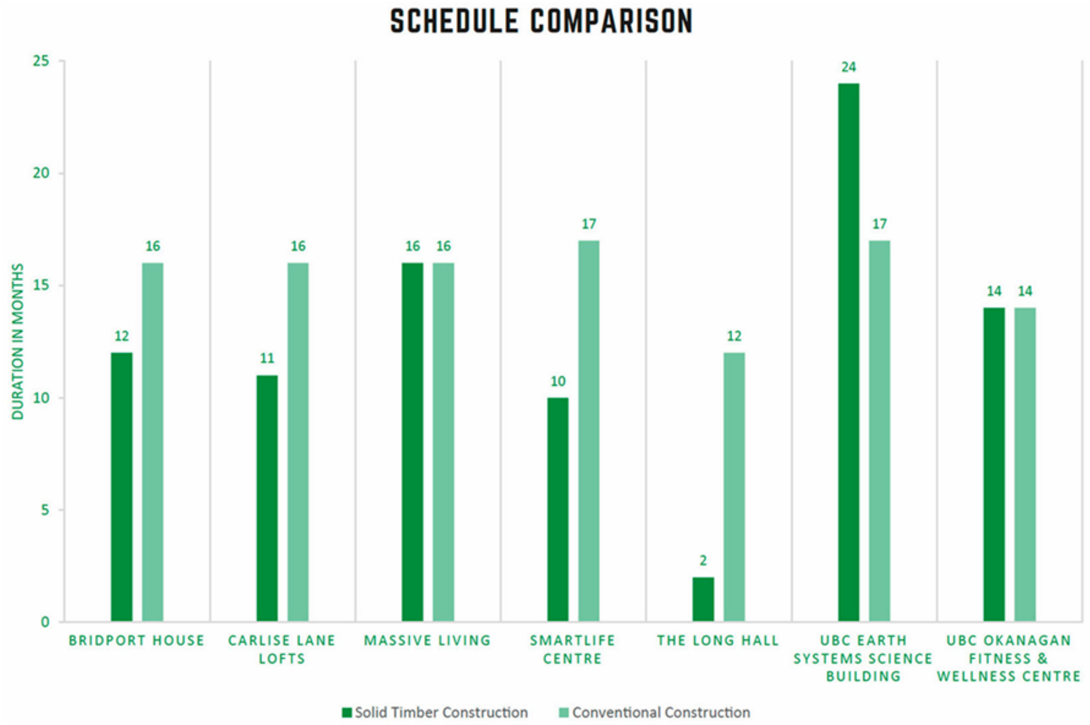

Figure 12: Schedule comparison between mass-timber construction case studies and traditional site built counterparts (Smith, et al., 2017)

Besides this study, also various Dutch studies have been conducted to examine the project time savings of CLT building projects. A study by de Rijksdienst voor Ondernemend Nederland (RVO, 2021) compared the building costs and construction time of four CLT apartment buildings with concrete and steel buildings and found that on average the CLT buildings had a 17% faster construction time compared to its concrete and steel counterparts.

The Gantt chart in Figure 13 shows the approximate time savings of a CLT building and a reinforced concrete building.

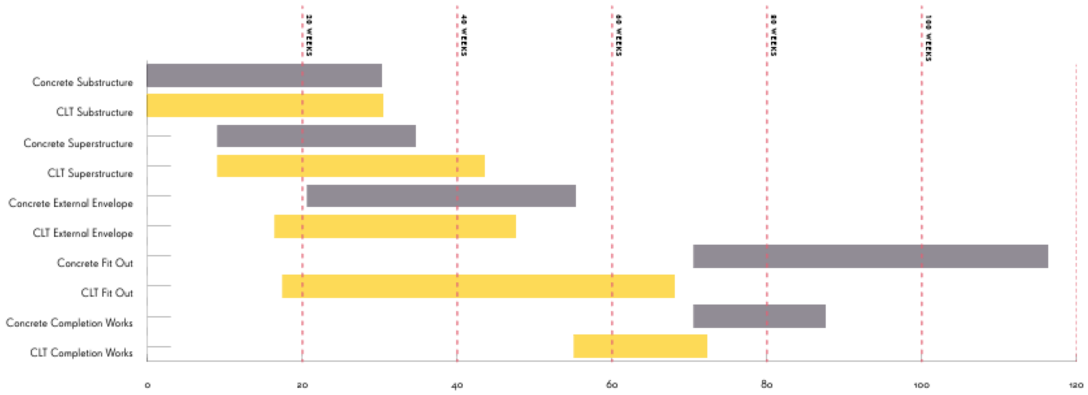

Figure 13: Approximate program adjustments that would be expected for a CLT scheme compared with a traditional reinforced concrete building (Waugh Thistleton Architects, 2018)

5.4.2 Lightweight material

CLT is **light** and has a very good **strength-to-weight ratio** (Santana-Sosa & Kovacic, 2022). This can translate to cost savings on foundations, or even allowing builders to potentially use existing foundations. Additionally, research by Winter et al. (2010) highlights CLT's exceptional resistance to lateral forces due to its inherent ductility. This makes CLT a highly **suitable** choice for construction in **earthquake-prone areas**.

Several authors state that CLT constructions show strong resistance against lateral forces and possess ductility due to various small connections (Winter, et al., 2010). An experiment conducted by the Trees and Timber Research Institute of Italy involved testing a full-scale seven-story CLT building on the world's largest shake table (Popovski, et al., 2010). Despite undergoing a severe earthquake simulation of 7.2 on the Richter scale, the structure experienced no permanent deformation. Researchers concluded that the structural damage was "negligible".

5.4.3 Prefabrication and modular construction

Besides some advantages of CLT's material characteristics, the construction process with CLT can also offer advantages. Its lightweight nature allows for efficient **prefabrication** in controlled off-site facilities. Prefabrication refers to a manufacturing method where materials and parts are fabricated into ready-to-install elements and partially assembled at a specialized facility, often separate from the final assembly location. This process creates components that are later used in the final installation. This translates to **high-precision** components and potentially **faster construction times** at the building site (Santana-Sosa & Kovacic, 2022). Especially with **modular construction**, rapid construction times can be realized. Modular construction is a building method where structures are composed of modular units or modules, which are manufactured off-site in a factory setting. Each module is designed to serve a specific function within the final product it will become a part of. Unlike traditional prefabrication, modular construction emphasizes the repetition of standard units and dimensions, which may restrict the variation of elements within a project and limit the use of unique components. However, these constraints contribute to the consistency of modular units throughout the building and can speed up the construction process. Prefabrication and modular construction also **reduce on-site labour**, potentially leading to **a safer work environment**. Fewer workers on-site combined with controlled factory settings minimizes the risk of accidents and errors, leading to a more efficient and safer construction process overall (Low, et al., 2021).

5.5 Environmental drivers

There is a general agreement regarding the environmental benefits of using CLT in MSTBs. One of the most cited drivers for the use of CLT is **sustainability**. Sustainability is a broad concept and encompasses different aspects. This chapter addresses the climate change effects of the use of CLT and circularity.

5.5.1 Reduction of CO_2

Climate change is primarily related to the concentration of CO_2 in the atmosphere. Building with timber can reduce CO_2 emissions in multiple ways:

1. Fewer CO_2 is emitted during the production and construction phase
2. Emissions from traditional construction practices are avoided
3. CO_2 is stored in buildings

For the production of CLT, **less use of energy** is required than for concrete and steel, leading to less greenhouse gas emissions (Jones, Stegemann, Sykes, & Winslow, 2016). Timber construction also allows **less on-site emissions:** due to timber's lightweight properties, lighter or electric machinery can be used and less transportation is required (Roos, Woxblom, & McCluskey, 2008). Ans lastly, **trees sequester CO_2** by absorbing it from the atmosphere during their lifetime. Additionally, the amount of CO_2 captured by forests can be increased by refraining from burning wood in biomass power plants, where the CO_2 would be released again. Instead, applying wood in a high-value manner within the built environment can contribute to carbon sequestration. The carbon dioxide that is sequestered in CLT is way more than the carbon dioxide emissions to produce it (Bossenmayer, 2018), see Figure 14.

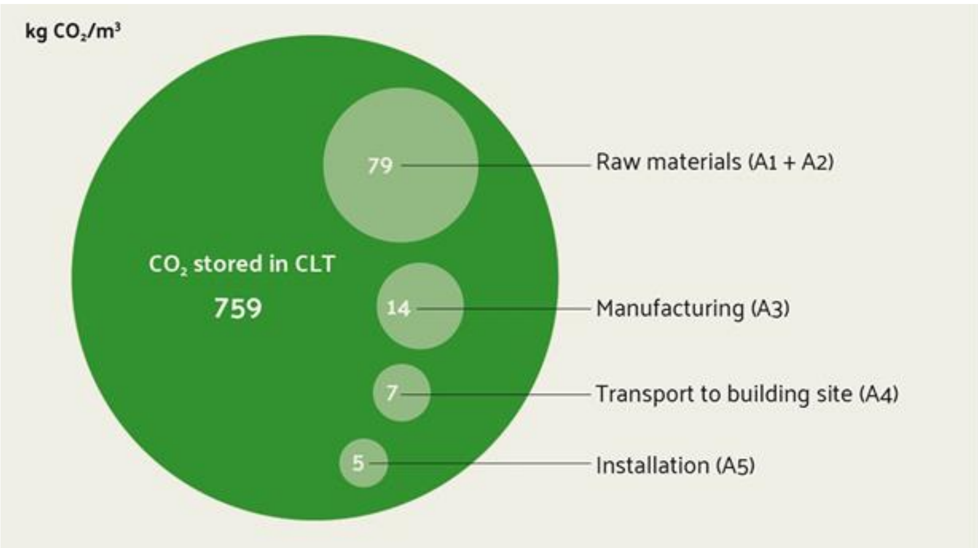

Figure 14: Comparison of carbon storage and carbon emissions of CLT (Van der Lugt, 2023)

5.5.2 Circularity

Another environmental driver of the use of CLT in MSTBs is circularity. It is essential to minimize the use of resources, particularly for finite resources. Building in an environmentally friendly manner means finding a way to reduce the impact on finite resources. Even better is to use renewable resources like timber. Timber is characterised by true renewability, if sustainable forestry practices are utilised. Besides r**enewability, recyclability** was also mentioned oftentimes (Evison, Kremer, & Guiver, 2018). Timber construction allows for a 'dry' assembly with screws and bolts, which is easy to deconstruct once the building reaches its service lifetime. Therefore, CLT can easily be **reused**, without compromising the material performance. A Dutch laminated timber supplier Derix recently decided to take back their laminated timber products after the service-life of the building to improve and prove the circularity of their products (Derix, 2024). This approach proves the circularity of CLT. It also entails that there is **less waste** at the end of the building's service life (Marfella & Winson-Geidemann, 2021).

5.5 Overview drivers

The construction of MSTBs with CLT offers various benefits compared to traditional construction methods using reinforced concrete and steel:

- **Legislation pushing the use of timber**: Local and national governments are pushing the use of timber and other biobased materials by stimulating market developments with subsidies through the Nationale Aanpak Biobased Bouwen and by setting timber building quotes for new construction projects in the Metropolitan Region of Amsterdam.
- **Cost-competitiveness:** While CLT construction is oftentimes more expensive than traditional construction, there are potential cost savings to consider. Faster construction times can lead to lower overall project costs. Prefabrication with CLT reduces the need for on-site labour, which can bring down labour and fault costs. Additionally, the lightweight nature of timber allows for potentially lower foundation costs.
- **Consumers perception:** There's a strong positive perception of structural timber among consumers, who associate it with being environmentally friendly, aesthetically pleasing, and contributing to well-being. In the Netherlands, there's already a 35% demand for timber houses, with potential to grow to 50%.
- **Improved living environment:** Studies show that structural timber elements in sight can lower stress and improve focus, suggesting wood in buildings can promote well-being and productivity.
- **Rapid construction time**: MSTBs constructed with CLT can in some cases achieve a faster construction time of up to 20% compared to conventional approaches using reinforced concrete and steel.
- **Prefabrication and modular construction**: CLT's lightweight nature makes it ideal for prefabrication in controlled factories. This translates to high-precision, modular components that can be quickly assembled on-site, minimizing construction time and hazards.
- **Reduced Carbon Footprint:** Timber's natural ability to store captured carbon dioxide throughout its lifespan, combined with a lower-energy production process, gives it a significantly smaller carbon footprint compared to materials like steel and concrete.
- **Circularity:** Timber, unlike concrete and steel, is a readily renewable resource. Additionally, CLT itself can be reused or recycled at its end of life, further minimizing environmental impact.

6. Barriers for the use of cross-laminated timber in multi-storey buildings

In this chapter, a comprehensive literature review is conducted to examine the factors hindering the use of CLT in MSTBs. The following sub-research question will be answered: *What are the barriers for the use of cross-laminated timber in multi-storey buildings?* A total of seventeen scientific articles have been reviewed. After all barriers were identified, all barriers were categorised according to the PESTE analysis. This chapter follows the same structure and describes per category the barriers for the use of CLT in MSTBs. Figure 15 summarises the most important barriers based on the reviewed articles. An overview of the reviewed articles can be seen in Appendix B.

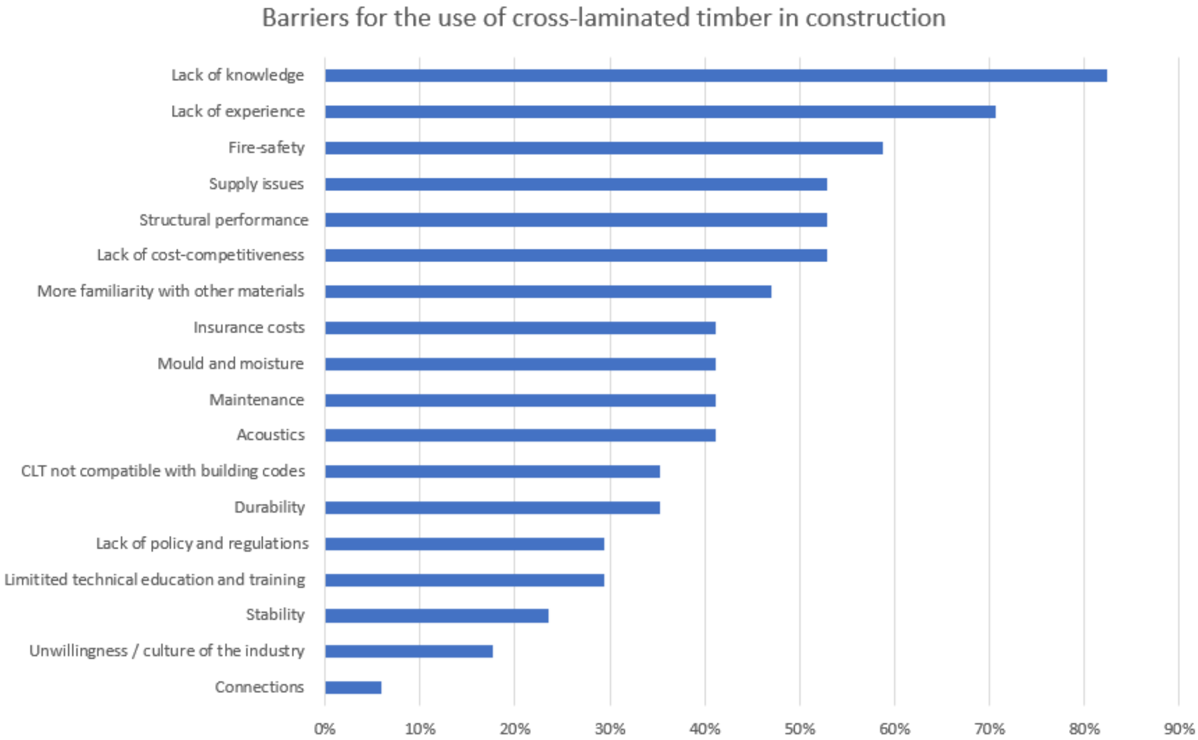

Figure 15: Overview of perceived barriers for the use of CLT in MSTBs based on the results of the literature review

6.1 Political barriers

The first category of barriers that hinder the adoption of CLT in MSTBs in the Netherlands are political aspects. The most impeding aspects are the Mileu Prestatie Gebouw (MPG) system, the lack of available data in the Nationale Milieu Database (NMD) and the lack of available building codes.

6.1.1 Milieu Prestatie Gebouw score

In the Netherlands, the environmental impact of building materials is assessed using the MPG score. However, when it comes to CLT, solely relying on MPG can be misleading and fail to capture the true environmental benefits of CLT. The problems with the MPG are listed below.

The main problem with the MPG score lies in the factor 'land use' and in the factor 'particulate matter'. In the first case, the underlying data appears to assume that construction timber is burned and that this is also done in the open air. This assumption diverges far from reality, considering timber's potential for recycling and reuse, alongside market parties offering warranties to repurchase timber elements after its service-life. In reality, much wooden waste material that is intended for energy generation is pressed into pellets or burned as biomass in closed ovens with numerous soot and particle filters on the chimneys. In the case of the 'land use' factor, the assumption is made of non-sustainable forest management, where logging disrupts soil life and even erosion is possible. In the Netherlands, more than 90 percent of the (soft) wood used is FSC and/or PEFC certified, which means that the trees are managed and harvested with great attention to the preservation and expansion of the forest.

One of the other shortcomings of the MPG Framework is the focus on embodied carbon: The MPG score primarily focuses on the "embodied carbon" of a material, which reflects the greenhouse gas emissions associated with its production, transportation, and installation. While this is important, it ignores other crucial aspects like the carbon storage of timber.

6.1.2 Limited data in the Nationale Milieu Database

Another barrier, linked to the MPG system, is that there is very limited data of timber products is available in the Nationale Milieu Database (NMD – National environmental database). Currently, only a dozen timber products are registered in the NMD, including 15 CLT Environmental Product Declarations (EPDs). If a CLT element from a supplier isn't registered in the NMD, it leads to unfavourable assumptions in MPG calculations, as was mentioned in chapter 6.1.1 Milieu Prestatie Gebouw score. Thus, it's crucial for more suppliers to register their products in the NMD.

6.1.3 Building codes

Another important barrier that hinders the adoption of CLT in MSTBs is that **CLT is not integrated in the Eurocode**. This is the same for other EWP's like glulam and LVL. Many studies mention this as a barrier.

CLT currently still lacks formal inclusion in standards, despite its first production in 1995. Consequently, its adherence to building regulations is governed by national or European technical approvals (ETA). These approvals outline minimum requirements for the product, its raw materials, and the manufacturing process. They also specify verification procedures and, in the case of ETA regulations, guidelines for CE marking.

The International European Technical Assessments (ETA) started the regulation of CLT properties and design in 2006. The push for standardizing CLT across Europe gained momentum in 2008, leading to the approval of the first European product standard for CLT, NEN EN 16351, in 2015. Simultaneously, in 2015, CLT was integrated into the International Building Code, and the National Fire Protection

Association (NFPA) initiated research and code development pertaining to the fire safety of CLT and other engineered wood products.

NEN-EN 16351 outlines regulations concerning the performance attributes of CLT intended for utilization in buildings and bridges. This code establishes guidelines for various factors during the manufacturing process of CLT, encompassing conditions such as moisture content, temperature specifications for the timber to be bonded, and the fabrication of finger joints and bonds between layers.

The current Eurocode 5 lacks calculation rules for CLT, but these are included in the draft versions for the new version of Eurocode 5, of which the publication date is still unknown. In addition to including CLT, the new Eurocode 5 will also include rules for timber-concrete-composite structures. For an overview of all current norms and assessment documents.

6.2 Economic barriers

Economic barriers were among the most frequently mentioned barriers in literature. It is not possible to compare the construction costs of MSTBs and buildings constructed with concrete or other materials based on the price difference of the materials. This is because the quantities of material per construction differ because the properties of the materials are different. Varying factors are weight, spans, insulation values, appearance, and flexibility in design. The labour costs are also different for different building materials. Therefore, this chapter addresses some of the factors related to costs of CLT construction.

Chapter 5.2 Economic drivers identified some possibilities of cost savings for the use of CLT in MSTBs. While some of these cost savings can be realized due to the attributes of timber, the overall costs often still surpass those associated with its traditional material counterpart. The economic benefits must offset the 25% **higher cost of materials**, **additional expenses incurred for fire safety** (approximately +6-7% in Finland) and **acoustics** (Hurmekoski, Jonsson, & Nord, 2015). **An insecure wood supply chain** in combination with a lack of wood-industry developments was also linked to higher material costs for timber (Roos, Woxblom, & McCluskey, 2010). There are few CLT suppliers, which makes the market volatile. This fluctuation in price can have a destructive effect on projects and project owners are therefore oftentimes reluctant to choose for MSTC due to the financial risks (Zaman, et al., 2022). Also due to the relatively new wood developments for MSTBs, the **initial costs are high** (Gosselin, Blanchet, Lehoux, & Cimon, Main Motivations and Barriers for Using Wood in Multi-storey and Non-Residential Construction Projects, 2017) and oftentimes the **financial risks** are hard to estimate. This has a price-raising effect, as contractors and other parties charge a higher risk premium than when they would construct the building with traditional materials (Markstrom, Kitek Kuzman, Bystedt, & Sandberg, 2019).

Some Dutch studies also compared the construction costs of MSTBs with concrete and steel variations. One study found that the CLT variant was 14% more expensive (RVO, 2021), and another study by BBN (2023) found an increase of 10-15% in total project costs for the MSB.

In conclusion, the answer to the question ‘if MSTC is cost-competitive to traditional materials’ is nuanced. However, according to most Dutch studies, MSTC is oftentimes more expensive than their concrete and steel counterparts.

6.3 Sociocultural barriers

Sociocultural barriers that hinder the development of mass timber buildings in the Netherlands are mostly related to the culture of the construction industry. A path-dependent industry and years of specialization in concrete and steel led to a lock-in of construction firms. This, in combination with a lack of knowledge and experience led to a lack of willingness to invest in new construction techniques.

6.3.1 Lack of knowledge and experience

A lack of knowledge and experience among different stakeholders in the building industry was the most frequently mentioned barrier in literature. Contractors that are unfamiliar with timber construction may perceive it as risky, leading them charge premiums (Franzini, et al., 2018). Similarly, consulting firms might lack expertise in fire engineering and acoustics for CLT, resulting in longer design times and higher costs (Xia, et al., 2014). The lack of knowledge and experience can also leads to many different second-opinions to verify the design, which also increases the costs. Lastly, there is a substantial lack of knowledge and experience at licensing authorities, which complicates permit application processes (Marfella & Winson-Geidemann, 2021).

6.3.2 Lack of willingness

Typically, stakeholders such as contractors, developers, and politicians lack sufficient knowledge and experience when it comes to timber construction, especially for high rise timber buildings. At the same time, an abundance of expertise, standards, knowledge, and familiarity concerning traditional building materials exists. This familiarity with conventional approaches makes them predictable and lucrative, discouraging a shift towards timber construction which is perceived as complicated and risky. Construction firms and developers currently have little incentive to deviate from their practices. Additionally, higher initial costs compared to traditional construction processes and uncertainty in cost estimations limits stakeholders' willingness to invest in such practices. Traditional procurement practices with a focus on the lowest price further limits the development of quality projects and the exploration of alternative designs with unconventional materials.

6.3.3 Path-dependency and lock-in

The construction industry has a path-dependant culture (Hurmekoski, et al., 2015; Riala & Ilola, 2014). An example of the Finnish construction industry that showcases this **path-dependency**: *'In Finland we have about five big companies, and they are very old-fashioned. They build concrete buildings, they have their element factories, and their systems. In fact, the systems are quite common, they have been* made *together with Finnish, standardization committee in the 1970's and they all use the same systems.'* (Franzini, Toivonen, & Toppinen, 2018). A similar situation is applicable to the Netherlands, in which 'tunneling' is the predominant construction method. Tunneling is a construction method in which one pour of concrete is used to realise walls and floors using a concrete formwork. The early adoption of concrete and steel in the construction industry created the **path-dependency and lock-in** which hindered the innovation in different construction methods and materials (Cecere, et al., 2014). Hence, although some parties have the ability to propose unconventional construction methods, they might not have the chance from a business standpoint, leading to a **lack of motivation** to incur additional costs or risks associated with unfamiliar building materials (Jones, et al., 2016). The culture of building with other materials and therefore **a lack of familiarity with timber** products hinders the adoption of CLT for MSB's in the Netherlands.

6.3.4 Culture of the industry

Another barrier in the construction industry that hinders the adoption of massive timber is the **culture of the industry**. Some of the characteristics of the construction industry that hinder the adoption of innovative construction methods are:

- **Prioritizing cost over value:** Hemstrom et al. (2017) noted that the construction industry is characterized by robust cognitive norms rooted in a culture centred around concrete-based construction. This mindset can lead to overlooking the long-term benefits that innovative methods offer.
- **Risk-averse and conservative culture:** A conservative approach can hinder exploration of new technologies or construction techniques (Matinaro & Liu, 2017).
- **Fragmented industry:** The fragmented nature of the industry with mostly linear relationships and separate entities for design, construction, and ownership, can hinder collaboration and coordinated implementation of innovative solutions (Gosselin, et al., 2018).

6.4 Technological barriers

Technical aspects also hindered the adoption of CLT in MSTBs according to literature. There are various technical challenges related to MSTBs among others fire safety, acoustics, moisture, stability and connections. This chapter addresses the most important technical barriers in order of importance.

6.4.1 Fire safety

One of the challenges with timber construction is that the Dutch Building Decree does not yet adequately address fire safety for mass timber constructions, as was found in a study by Arup, TNO, and Rise on behalf of NEN (Brandon, et al., 2022). One of the authors mentioned: *"You can currently follow the Building Code to the letter, but that doesn't mean you achieve the same level of safety as for concrete buildings."* This is because the current performance requirements do not take into account the potentially increased permanent fire load. *"If you add wood to a building, you have an extra fire load and the fire behaviour in such a dwelling is then very different from that in a concrete dwelling. In particular, the fire duration is much longer."*

The fact that the presence of wood can cause partitions between dwellings to burn longer is also crucial information for the fire brigade. After all, they have to extinguish taller buildings from the inside. Up to 30 meters, the fire brigade can extinguish from the outside, and from 70 meters onwards, certain high-rise building regulations apply. Everything in between falls into a rather dangerous grey area in the regulations (Brandon, et al., 2022).

Therefore, especially for high-rise timber buildings, fire safety is a challenge. An easy solution to increase the fire-safety of the building is to install a sprinkler system. However, this causes a huge cost increase and is therefore not always possible. It’s also possible to fully encapsulate all timber elements, ensuring that the timber elements are not in direct contact with a potential fire. This is a viable solution, however it cuts of some of the other timber advantages that exposed timber can offer, like a better living environment. The real challenge lays in designing a high rise timber building that is fire safe, while leaving some timber elements exposed.

6.4.2 Acoustics and vibrations

Acoustics and vibrations are two other frequently mentioned technical barriers in literature. This is not a specific high-rise problem, but more a general challenge with timber structures. It poses a specific challenge in residential buildings, as they must meet stricter noise standards than office spaces. Without dedicated acoustic measures, CLT alone fails to meet these requirements. While solutions to acoustic problems exist, it requires complex detailing and specialized expertise. Unfamiliarity with

CLT's properties and design methods can make practitioners perceive it as risky, discouraging its use (Roos, Woxblom, & McCluskey, 2008).

Contractors may encounter difficulties in executing certain connections, while engineers might lack the know-how to design CLT connections that meet acoustic standards. According to Hurmekoski et al. (2015), the negative perception surrounding CLT's acoustic performance stems from stakeholders' limited experience and knowledge. Markström et al. (2018) confirm this and add that some stakeholders indicated that CLT cannot fulfil the acoustic requirements.

6.4.3 Moisture

Maintaining a moisture content (MC) around 12% is crucial for CLT elements. Fluctuations in the MC can cause timber element to swell and shrink, potentially leading to cracks. Furthermore, increased relative humidity within the surrounding environment can create mould on wooden surfaces (Markstrom, et al., 2019). The relative novelty of high-rise CLT construction can introduce challenges that contractors may not have encountered before. Implementing additional measures to keep the MC within the desired range can potentially increase both risk and cost for the contractor (Xia, et al., 2014). Achieving a rapid enclosure of the building envelope is essential to create a dry environment for the timber structure.

6.5 Environmental barriers

Environmental aspects were mostly identified as drivers for the use of CLT in MSTBs, see 5.5 Environmental drivers. However, two possible barriers related to environmental aspects were identified in literature: **durability** and **a shorter service life**.

There is a dissensus on the topic of durability of timber products. Five studies mentioned durability as a driver for the use of CLT and six studies mentioned durability as a barrier. Hurmekoski et al. (2015) state that perceptions on durability vary depending on the level of experience: The less experienced (majority) tend to be more sceptical. Most concerns about durability stem from moisture and weather conditions. But, since this study only focuses on structural CLT indoors, and does not include facades, this barriers is considered to be not relevant.

Next to durability being a barrier, a **shorter service life** was also mentioned (Riala & Ilola, 2014). This has mainly to do with early decay of the material due to, again, moisture effects and other weather influences. The same reasoning applies to this perceived barrier: when structural timber is used inside and is not exposed to weather conditions, it should show no decay in material performance.

6.6 Overview barriers

The widespread adoption of CLT in MSTBs in the Netherlands faces some barriers:

- **Milieu Prestatie Gebouw:** While the MPG score is used in the Netherlands to assess a building material's environmental impact, it can be misleading for CLT. The MPG assumes that the CLT in the building is burnt when the building reaches the end of its service life, unsustainable forestry management is used, and doesn't account for CLT's ability to store carbon, leading to an underestimation of its true environmental benefits.
- **Nationale Milieu Database:** There is limited data on timber products in the national environmental database (NMD) which leads to unbeneficial assumptions in the LCA methods.
- **Incompatibility with building codes:** Incompatibility with building codes poses a major hurdle for CLT adoption in high-rise buildings. The existing codes lack design guides and are oftentimes not economical.
- **Lack of cost-competitiveness:** Constructing MSTBs with CLT typically involves higher initial costs attributed to fire safety measures, extra engineering, and a less established supply chain in contrast to conventional materials. The unfamiliarity with CLT construction and the associated lack of expertise contribute to heightened perceptions of financial risks.
- **Lack of knowledge and experience:** A lack of experience and knowledge across the construction industry is a major hurdle for CLT adoption. Contractors perceive CLT as risky due to unfamiliarity and often opt for traditional materials like steel or concrete. Similarly, architects and engineers may struggle to design with CLT due to limited knowledge and training. A cultural shift towards embracing timber and improved education are needed to address these knowledge gaps.
- **Lack of willingness:** Stakeholders favour familiar materials like steel and concrete due to existing expertise and predictable costs, while the perceived complexity and cost uncertainties of CLT construction discourage a shift. This, combined with traditional procurement practices focused on lowest price, creates a lack of willingness to adopt new construction technologies.
- **Fire safety:** Fire safety is a major hurdle for high-rise CLT construction in the Netherlands. Existing building codes don't fully address the unique fire behaviour of timber, and solutions like sprinklers or full encapsulation can be expensive or nullify secondary benefits like aesthetic or improved well-being.
- **Acoustics:** Acoustics present a significant technical challenge in timber construction. While solutions to acoustic problems exist, it requires complex detailing and specialized expertise. Unfamiliarity with CLT can make practitioners perceive it as risky, discouraging its use.
- **Moisture:** Preventing that CLT elements' moisture content exceeds 20% is crucial throughout construction. To achieve this, designers and planners need to design moisture control measures. Additionally, rapid enclosure of the building envelope is essential to create a dry environment for the timber structure.

7. Proposed strategies to bridge barriers

This chapter presents a set of strategies that should overcome the identified barriers and should enhance the adoption of CLT in MSTBs. The following sub-research question will be answered: *Which are the opportunities and strategies to support the further implementation of cross-laminated timber in multi-storey buildings?* Starting with the barriers, several strategies have been formulated to overcome these barriers. The strategies were partially based on literature, supplemented with ideas of the author. When all strategies were formulated, the strategies were grouped, and five key themes were identified:

- Increase awareness
- Change industry
- Create new financial models
- Technical advancements
- Regulatory change

These strategies should contribute to exploit the benefits of CLT as a construction material, and should overcome the identified barriers. Some of the strategies tackle multiple barriers at once. Per theme, the supposed strategies are elaborated on and it is noted which barriers should be overcome with these strategies.

7.1 Increase knowledge and awareness

The first method to enhance the adoption of CLT in MSTBs is to increase awareness. Increasing awareness should overcome the barriers:

- Lack of knowledge
- Lack of experience
- Perceived risks
- Lack of willingness
- Culture of the industry

It can be concluded from chapter 6 that a lack of knowledge is present industry-wide. Practitioners in the AEC industry oftentimes lack the required expertise to build MSTBs. At the same time, consumers and clients oftentimes are not aware of the benefits of timber construction, and oftentimes have wrong perceptions of the capabilities of timber construction. The lack of knowledge and experience with building MSTBs at governments and licensing institutions also adds to the problem. Lasty, this lack of knowledge in the industry is not fully addressed in education, what could be a part of the solution to tackle this knowledge gap. And due to the novelty of MSTC, only a few companies have gained some experience constructing MSTBs. Companies with little or no experience therefore perceive such building practices as risky which amounts to their lack of willingness to invest in these new innovative construction methods.

This chapter proposes several strategies to overcome the aforementioned barriers. The strategies are mainly focused on increasing industry-wide awareness for MSTC by sharing knowledge and consultation. The proposed strategies are to:

- Share knowledge across countries
- Develop a case study database
- Provide information to consumers and clients
- Establishment of a brand image
- Increase timber knowledge in education
- Increase timber knowledge at licensing authorities
- Think timber from day one

7.1.1 Share knowledge across countries

Dutch companies can participate in study tours across countries where building with timber is more common practice. For example to Sweden, where they are building the world's first timber city, which features 7000 office spaces and 2000 homes (Horn-Muller, 2023). In Australia, such study tours to Europe exist already. The Timber Development Association New South Wales in combination with Wood Products Australia offered various study tours to Sweden and Norway (Woodworks , 2023).

7.1.2 Develop a case study database

Another strategy to close the knowledge gap is to develop a case study database. Sharing documents from completed projects would be highly beneficial as examples, both technically and for initial cost estimations. It's essential to effectively transfer the specific requirements and advantages of timber construction to various stakeholders, particularly clients and developers, to enable informed decision-making. Geier developed such a database; a criteria catalogue (Geier, 2018). The criteria catalogue serves as a strategic tool to support project development. It visually represents projects in their early stages, creating common understanding and transparency in interdisciplinary communications. This catalogue encompasses multiple criteria, covering functionality, technical and design considerations, client preferences, legal aspects, as well as production, logistics, and assembly considerations. The interdependencies between the various criterion are identified and defined. By assessing the complexity associated with each criterion, projects can be systematically defined and compared. Based on these reference projects, potential challenges can be identified in an early stage, making it possible for early adjustments if necessary. Various design approaches can be compared, which helps with cost estimations and managing uncertainties in decision-making. Additionally, it assists developers and designers in addressing issues concerning acoustics and fire safety. By comparing designs from existing case studies, potential cost savings in design and engineering can be realized.

7.1.3 Provide information to consumers and clients

It's very important to include future owners or occupants in the design process. In chapter 4.3 it was identified that the demand for timber houses could increase with 15% if timber home-owners were informed about timbers fire and acoustics related properties. It is also important to overcome other prejudices around timber like durability. Once these fears are taken away, timber can be fairly compared to traditional construction methods. Another important factor is to educate consumers about the sustainability advantages of timber construction. Once the sustainability advantages of timber construction are widely known to the public, it is expected that support for CLT construction will increase.

7.1.4 Establishment of a brand image

Once misconceptions and biases around timber construction are taken away and their advantages are known to the public, it becomes beneficial to publicly highlight buildings constructed with CLT. Establishing a strong brand image could elevate and internationalize the timber industry by promoting timber structures along with their associated sustainability attributes. This robust brand presence would attract and engage customers like well-known consumer brands like Apple or Tesla, focusing on factors such as product and service quality, value, delivery time, reliability, maintenance, and warranties. CREE, an Austrian company, has already initiated a similar approach, marketing its services globally and licensing experienced general contractors for large projects to use their knowledge, technology, and processes. Furthermore, they assist in the procurement of local subcontractors for product production and offer support and consultation throughout all project phases (Rhomberg, 2024).

7.1.5 Increase timber knowledge in education

Necessary to close the knowledge gap is to put more emphasis on timber in education. Universities should adopt the new timber construction methods as mandatory courses in the curriculum of architecture and civil engineering studies. This should combat biases against timber construction and increase awareness of its properties. Besides including CLT construction methods in the mandatory curriculum, this initiative should also include research and doctoral programs and collaborative projects with scientific and industrial partners. Such efforts would enhance research competencies and capabilities, producing a pool of highly skilled young researchers, planners, and practitioners.

7.1.6 Increase timber knowledge at licensing authorities

The lack of knowledge and experience at licensing authorities complicates permit application processes (Marfella & Winson-Geidemann, 2021). In order to speed up this process, it is important that licensing authorities possess enough knowledge on MSTC, especially with regard to fire safety.

7.1.7 Think Timber from Day One

Thinking timber from day one is essential to determine critical design parameters that meet the project specific requirements, thereby preventing the need for redesigns, and avoiding additional costs and delays. The design and construction process of MSTBs is very different than that to traditional buildings, and therefore requires a different approach (Gosselin, et al., 2018). It is therefore also recommended that timber expertise is incorporated into the very first design stages. Santana-Sosa & Kovacic (2022) defined three principles essential for achieving success in the design and construction phases. The initial approach involves ensuring that the design team possesses the requisite knowledge. Only a few companies possess the required expertise of all the different disciplines like architecture, structural engineering, building physics, and technical systems. Therefore, opting for a Bouwteam could be more practical. The second approach involves engaging independent timber experts who can offer guidance throughout the design and implementation phases. The third strategy highlights the importance of involving timber contractors early on, as their practical expertise can offer significant benefits during the design stages.

7.2 Change industry

The second theme to enhance the adoption of CLT in MSTBs is to make changes in the AEC industry. The barriers that should be overcome are:

- Culture of the industry
- Lack of willingness
- Supply issues

Chapter 6 highlights that the construction industry is conservative and fragmented, with path-dependent characteristics and linear relationships, which hinder the adoption of unconventional construction approaches. Overcoming these barriers demands a shift in mindset and collaborative efforts. Additionally, industry barriers related to the supply chain exist. Few timber suppliers are available due to the novelty of timber construction, and timber prices are highly volatile. Addressing these barriers requires a different approach. To tackle these challenges, the chapter proposes several strategies. The strategies are mainly focused on changing the way practitioners in the AEC currently collaborate and on addressing the supply chain of timber products.

The proposed strategies are to:

- From Simple Linear Relations to Collaboration in a Network;
- Local wood production and increased production facilities.

7.2.1 From Simple Linear Relations to Collaboration in a Network

The design and construction of MSTBs are relatively new to the Dutch construction industry, introducing complexities and uncertainties that increase costs for project stakeholders. Collaboration is crucial in this innovative field, where firms specializing in various technologies must foster "loose coupling networks" to share knowledge effectively. Research by Meng (2013) showed a transformation towards collaborative supply chain practices in the UK construction sector, but challenges persist due to the lack of knowledge transfer between projects. Establishing value networks is crucial to sharing insights from past projects and enhancing collective knowledge for future ones.

Engaging stakeholders during early design stages fosters more collaborative relationships within construction projects. For example, Design-Build contracts often enhance collaboration and yield better performance in cost control and frequency of modifications compared to traditional Design-Bid-Build contracts (Rosner et al., 2009). Procurement systems play a key role in influencing innovation; more innovative projects are less reliant on traditional contract procurement methods (Blayse & Karen, 2003).

7.2.2 Local wood production and increased production facilities

The current use of Dutch wood in construction is relatively low (NBVT, 2024). Stimulating the use of wood in high-quality applications from the perspective of circularity and achieving climate benefits will lead to increased demand for wood and consequently more pressure on forests. It is expected that the Dutch demand for sawn timber and sheet materials will increase by at least 215,000 m³ (100% timber frame construction) or up to 430,000 m³ (100% CLT), if the intended increase from 1,500 homes in 2020 to 10,000 homes in 2030 will be met (NBVT, 2024).

These volumes are relatively modest on a European scale and can be easily met through additional imports of sawn timber and sheet materials. However, a much larger demand for wood from the construction sector is anticipated by CE Delft (2020). They expect an almost 90% increase in demand by 2030, reaching over 5 million m³ of roundwood equivalents annually (more than 1.8 million m³ of product). If current Dutch roundwood harvesting levels are increased, Dutch wood could play a role in meeting this growing demand for construction wood. However, due to the limited size of Dutch forests, this role would be modest. It's estimated that Dutch wood could fulfil about 40% of the target of 10,000 timber frame homes in 2030 (Oldenburger, et al., 2020). In order to fulfil that demand, it is necessary to scale up the entire production chain from forests to sawmills to CLT production facilities.

7.3 Create new financial models

The third theme to enhance the adoption of CLT in MSTBs is focused on tackling the cost gap between timber and conventional construction. The barrier that should be overcome is:

- Lack of cost-competitiveness

The lack of cost-competitiveness is a significant barrier to building MSTBs. Construction using CLT typically incurs higher initial costs, costs for fire safety measures, additional engineering requirements, and a less established supply chain compared to conventional materials. The unfamiliarity with CLT construction and associated lack of expertise also contribute to heightened perceptions of financial risks. These factors collectively result in 5-15% higher costs for MSTBs (BBN, 2023). To tackle this cost barrier, various strategies are proposed. The strategies aim to reduce the cost of MSTBs, generate additional income by leveraging their unique features, and focus on added value over costs. The proposed strategies are to:

- Use CLT to reduce carbon costs;
- Use European Union Emission Trading System to sell carbon credits;
- Use biophilic design principles to reduce sick leave costs;
- Leverage financial service premiums by using global organisations;
- Convince client of increased residual value.

7.3.1 Use CLT to reduce carbon costs

The first driver for the use of CLT in MSTBs is related to the introduction of the CO_2 levy in 2021. The CO_2 levy in the Netherlands is a price instrument that aims to reduce greenhouse gas emissions and help the Netherlands achieve its climate targets. It is a tax on the CO_2 emissions of companies in the industry and electricity sectors. The levy encourages companies to invest in sustainable technologies and to reduce their CO_2 emissions. It has been in effect since January 1, 2021.

The CO_2 levy applies to companies with large industrial installations that emit more than 50,000 tonnes of CO_2 per year. These include power plants, refineries, chemical plants and the cement industry. The rate of the CO_2 levy is linked to the European Emissions Trading System (EU ETS). Currently, the rate is

€74.17 per tonne of CO_2. This rate will increase annually to €136.79 per tonne of CO_2 in 2030. The levy must then be paid to the Netherlands Emissions Authority (NEa).

Table 4: Yearly increase in EU ETS price

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Rate [€]	30,48	41,75	55,94	67,49	79,04	90,59	102,14	113,69	125,24	136,79

There are a number of exemptions and reductions from the CO_2 levy. For example companies that invest in innovative technologies to reduce their CO_2 emissions may also be eligible for a reduction. Companies covered by the CO_2 levy must file an annual CO_2 emissions return.

Currently, CLT construction is in most cases still more expensive than construction with concrete and steel. However, with this CO_2 levy, CLT becomes more cost-competitive in the future. Figure 16 shows that with a CO_2 levy of €125 per kg, the price of reinforced concrete will increase by 34% and the price of laminated timber will increase by 4%. It is therefore expected that MSTBs will become more cost effective in the future.

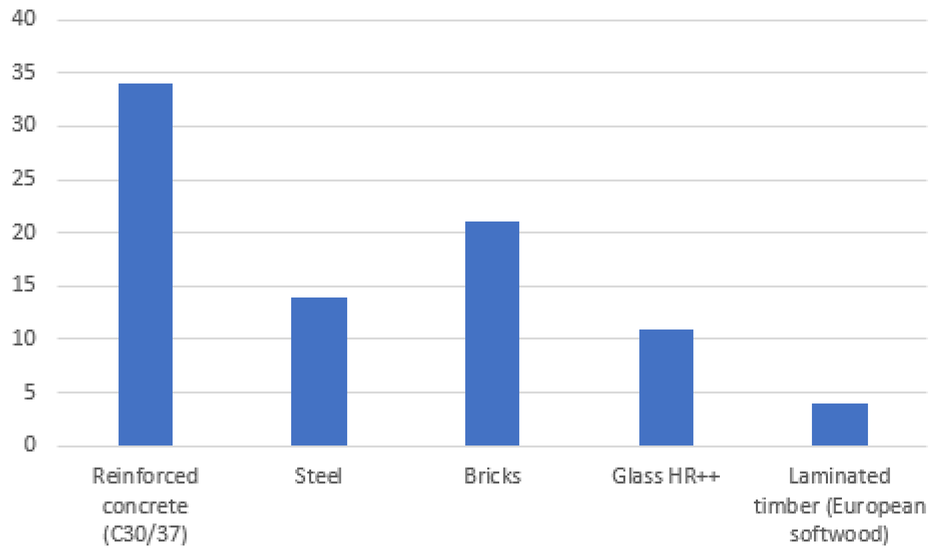

Figure 16: Average increase in cost price of materials caused by the CO_2 levy of €125/tonnes CO_2 in % (Van der Lugt, 2021)

7.3.2 Use European Union Emission Trading System to sell carbon credits

Emissions trading is the trading of emission allowances: the right to emit greenhouse gases. One emission allowance allows a company to emit 1 ton of CO_2. The number of available allowances is limited and decreases annually. The price of an emission allowance, the CO_2 price, is determined by supply and demand. This makes emissions trading a market instrument to combat climate change.

The structure of a true circular MSTB will then store so much carbon that those carbon emission allowances can be sold on the market. There are already platforms on which companies can sell their stored carbon to other companies, like Climate Cleanup (2024). Building MSTBs with CLT with true circular design principles will then allow developers to sell the stored carbon in that building, generating extra income that can compensate for the higher construction costs.

7.3.3 Use biophilic design principles to reduce sick leave costs

Biophilic design principles can contribute to a better work environment, potentially decreasing sick leave rates and subsequently reducing absenteeism costs. By incorporating natural elements like ample sunlight, potted plants, and even exposed timber elements, these buildings secure a connection with nature. Studies have shown that employees in biophilic environments experience less stress, improved cognitive function, and a stronger sense of well-being. This translates to a boost in productivity and a decrease in sick leave, creating a win-win situation for both employees and employers (Heerwagen, et al., 2012) .

In the Netherlands in 2023, the average sick leave was 5,5% and the Dutch gross national product was €1,033 trillion euros (CBS, 2023). It is unclear what the average sick leave is of office workers, as there is no explicit data of that available. However, in financial institutions the average sick leave is 3,3% (CBS, 2023), so that number is used in this calculation. Of the total gross national product, the contribution of work that is produced by people in offices was estimated. The assumption was that workers in finance, real estate, information and communication and business services generally work in office buildings. Those categories of the gross national product add up to €284 billion. This estimate likely underestimates the total contribution of work that is produced by people in Dutch offices. While some salaries within the considered sectors might not represent office-based work, employees from healthcare, government, and other office-heavy sectors are not included. When the average sick rate of 3,3% is applied to the conservative estimate of the Dutch office-based gross national product, a potential loss of €9,4 billion in productivity due to absent employees in Dutch office buildings.

Studies have shown that biophilic work environments can reduce about 10% of workers' absenteeism (Elzeyadi, 2011). Important to note is that biophilia in this study encompassed not only the use of natural materials like timber, but also having enough daylight, being connected to nature and the office being built with natural shapes. Nevertheless, building with CLT and thereby creating biophilic work environments could potentially save €940 million annually in reduced absenteeism in the Netherlands alone.

7.3.4 Leverage financial service premiums by using global organisations.

Another financial barrier is that local financial institutions might load premiums for investments or insurances for timber buildings (Xia, et al., 2014). While Dutch companies might be hesitant, foreign companies might be willing to invest in such sustainable buildings. Yvonne Wattez from Arup states: "Foreign investors are willing to pay more for a wooden version of the building than for the concrete version" (Change , 2023).

While foreign investors already prefer investing in timber construction from a sustainability perspective, Dutch investors and insurers are more cautious. "Fire is still the biggest risk. Although statistically the chance is low. As an insurance company, we notice that moisture and water are the most common damages," says risk engineer Jermaine Muller from Achmea. "With concrete construction, this has a small impact, but if you build with a material that is quite sensitive to moisture, there may be other consequences in terms of damage" (Change , 2023). By sourcing for finance and insurance abroad, this challenge can be tackled.

7.3.5 Convince client of increased residual value

Timber buildings could potentially boast a higher residual value, when circular design principles are applied. This is because timber components can be 'dryly' assembled with bolts and screws and therefore be deconstructed and reused in new projects. CLT floor/wall elements, and glulam beams and columns can be carefully dismantled and find a second life in another structure. This not only reduces construction waste but also allows the inherent value of the timber to be captured even after the building's initial service life. This concept is already gaining traction, with a Dutch timber supplier Derix offering warranties to repurchase their materials at the end of a building's lifespan, as previously mentioned.

7.4 Technical advancements

Technical advancements can be helpful in overcoming some technical and financial challenges. The barriers that can be overcome by technical advancements are:

- Costs
- Fire safety
- Acoustics
- Connections
- Stability
- Vibrations

Multiple barriers to the widespread adoption of CLT in MSTBs find their origin in technical aspects. Problems related to fire-safety, acoustics, connections and stability all have a technical character, and solutions lay partially in increasing knowledge on these topics, and partially in technical advancements. A lack of cost-competitiveness is another hurdle, which can be overcome with innovative solutions. The proposed strategies are to:

- Increase prefabrication levels;
- Increase modular construction possibilities;
- Promotion of research and development;
- Full scale testing.

7.3.1 Increase prefabrication levels

In general, prefabricated systems can offer significant advantages in the construction sector, such as reduced construction times and enhanced quality, as was mentioned in various studies (Höök, 2005). Furthermore, research by Gosselin et al. (2018) suggests that prefabrication in the building sector can foster collaboration. When a company integrates building services into its offerings, it streamlines the supply chain, facilitating optimized collaboration with clients within the same organization. However, prefabrication is not an easy solution to all problems. Cox & Piroozfar (2011) outlined several challenges hindering the adoption of prefabricated systems in construction, including insufficient education on prefabricated practices within the industry, a conservative industry culture, and reluctance to adopt new techniques. To fully leverage the advantages of prefabricated solutions, it's crucial to address the aforementioned obstacles that hinder the adoption. By implementing and scaling up new prefabricated practices and by testing and licensing new prefab modules, these barriers can be overcome, potentially offering a solution to the financial and technical challenges encountered by the timber building industry.

7.3.2 Increase modular construction levels

In the Netherlands, CLT construction is still relatively limited, but examples in Scandinavia and Germany demonstrate the potential of this construction technique. By modularizing solid wood elements, they can be easily replaced or adapted, increasing the flexibility of the building. When a CLT building no longer meets requirements, it can be relatively easily dismantled and the modular elements can be reused in a new building. If the elements are ultimately no longer suitable, they can be recycled into wood products such as veneer, chipboard, and insulation material. Large-scale modular building elements can provide integrated solutions for fire safety and acoustic issues. By using standardized modules, these obstacles can be effectively addressed. Additionally, large-scale modularization has the potential to reduce project costs by minimizing the need for engineering work for each module, as well as allowing for the replication of other modules. This not only saves costs but also accelerates construction times.

7.3.3 Full scale testing

Many technical barriers can be overcome by doing full scale testing. The lack of knowledge and experience with CLT's behaviour in large volumes during a fire was identified as one of the key barriers. By doing full scale fire tests on buildings, this knowledge gap can be closed. Approvals can then be granted to those specific products which are tested in full scale test setups. This should also be helpful with convincing licensing authorities, insurance companies, and financial service providers. The same reasoning accounts for the problems related to acoustics and connections.

7.3.4 Promotion of research and development

The promotion of research and development (R&D) can be helpful in overcoming technical and financial barriers as well. Currently, concrete hollow-core elements are nearly half the cost of comparable timber floor elements (Nesheim, et al., 2021). It requires cost reductions for timber elements to become cost competitive to their concrete counterparts, for which R&D can be an outcome. These solutions are closely linked to the strategy of increasing prefabrication. As new timber elements are researched and validated, expanding prefabrication production capabilities can drive down costs. Reducing design and engineering costs can also be achieved through the promotion of R&D. Once research has validated solutions for specific technical hurdles such as fire safety, acoustics, moisture, and connections, there's no need to start from scratch. These proven solutions can then be implemented across different projects.

7.5 Regulatory change

Some barriers require regulatory change to be overcome. The barriers that require regulatory change to be overcome are:

- MPG system;
- Lack of available data in the Nationale Milieu database;
- CLT not compatible with building codes;
- Costs;
- Lack of willingness.

The MPG system, along with inadequate information in the NMD and the absence of available building codes, presents regulatory barriers. Cost remains a significant obstacle, and regulatory changes could offer potential solutions. And lastly, governmental support for timber construction could incentivize market parties to invest in these practices.

The proposed strategies are to:

- Change the MPG system;
- Expand the NMD with timber products;
- Establish Buildings codes;
- Setting timber building quotas;
  - For the industry;
  - For governments;
- Governmental push to scale up CLT production;

7.4.1 Change MPG system

The three most important problems with the MPG score are the assumptions of 'particulate matter', land-use and that biogenic carbon storage is not accounted for. This chapter presents three recommendations to improve the MPG score. In all variations the condition to change the factors 'particulate matter' and 'land-use' are in place.

The three proposals for a new MPG system are:

1. MPG with a separate declaration of biogenic carbon storage.
2. MPG 'inclusive' in which the biogenic carbon storage is deducted of the total carbon storage.
3. MPG with an additional 'Net Carbon Footprint' of the building

MPG with a separate declaration of biogenic carbon storage

In this scenario, the MPG calculation will not change. Next to the current MPG calculation, a separate declaration of the biogenic carbon storage is presented. By showing the amount of carbon stored in the materials for the building in addition to the MPG, the climate performance is now explicitly valued. The MPG is expressed as a shadow price in euros per square meter gross floor area. The amount of (temporarily) stored CO_2 can be expressed in tons of CO_2 per building per m^2 gross floor area.

An advantage of this new method is that there is no modification of the current MPG system needed, and biogenic carbon storage should be already determined according to EN 15804:A2 with every LCA. With this new method biogenic carbon storage is insightful and can be valued. However, some downsides are that there is no integration with the MPG and that there is no distinction between short and long term carbon storage, as some materials might degrade faster than the buildings lifetime.

MPG 'inclusive' in which the biogenic carbon storage is deducted of the total carbon storage

In this MPG inclusive variant, the amount of CO_2 that is stored during the lifetime of a biobased product in a building is deducted from the total CO_2 emissions from production (phase A1-A3 in the LCA methodology).

In the current methodology, temporary CO_2 storage in biobased materials is not accounted for. For this inclusive MPG variant, a change would be needed in the 'Bepalingsmethode Milieuprestatie Bouwwerken' (Determination Method for Environmental Performance of Buildings) and in the EN15804. In this inclusive MPG variant, the temporary CO_2 storage in biobased products is included. The better CO_2 performance results in a better MPG score. For biobased products, the MPG expressed as a shadow price per m^2 gross floor area will be lower than it is now.

A study by Keijzer (2021) on behalf of TNO showed the results of this MPG inclusive variant and found that the CO_2 emissions of a CLT ground-bound home were negative: more CO_2 emissions are delayed over 100 years than there are emitted during production.

An advantage of this method is that the biogenic carbon storage is included in the MPG, but a downside is that changes in the LCA methodology are needed, which is decided on a European level. Furthermore, further research is needed for this variant to understand the true carbon storing capacities of biobased materials and to change the LCA in the best and fairest way.

MPG with an additional 'Net Carbon Footprint Declaration' of the building

In this variant, the carbon footprint of the production of the building is also shown in addition to the MPG as determined with the current methodology. The carbon footprint shows the total CO_2 emissions from the production of the building (A1-A5) and is expressed in tons of CO_2 for the entire building. This carbon footprint is reduced by the temporary CO_2 storage: the Net Carbon Footprint.

The advantages of this variant are that there is no need to change the methodology and that CO_2 emissions are insightful. Also, it is relatively easy to make policy on the basis of the net carbon footprint of buildings with quotas. A disadvantage of this variant is that there is no integration with the MPG.

Concluding remarks MPG score

To achieve a fairer assessment of timber construction, and especially CLT, the current MPG methodology needs adjustments. Addressing inaccurate assumptions about land-use change and particulate matter emissions is crucial. Additionally, the significant carbon storage capacity of CLT throughout its lifespan should be accounted for. While integrating this directly into the MPG score through changes in the Dutch Determination Method and EN15804 standard offers a holistic approach, it's a lengthy process. Therefore, the more immediate variant one or three is suggested to be most effective on the short term. Ultimately, this two-part strategy advocates for both a separate declaration in the near future and revisions to integrate carbon storage into future versions of MPG and EN15804 standards. These changes should result in a more comprehensive and precise assessment of timber construction, especially concerning CLT.

7.4.2 Expand the NMD with timber products

The problem with the NMD, as was identified in chapter 5.7, is that the NMD covers very few timber products. Currently, only a dozen timber products are registered in the NMD, including 15 CLT EPDs. If a CLT element from a supplier isn't registered in the NMD, it leads to unfavourable assumptions in MPG calculations for CLT. Thus, it's crucial for more suppliers to register their products in the NMD. Derix was the first supplier in obtaining product licensing, setting an important example for other suppliers to follow suit.

7.4.3 Building codes

The current building codes have to be developed further for MSTBs to be easier designed and constructed. The Eurocode 5 is in development for many years and the publication date is still unknown. In the meantime, market parties should use the pre-Eurocodes, the ETA's and EAD's, and foreign codes to design buildings, as there is still no alternative.

There are some design rules in the pre-Eurocode that need to be improved or expanded. Many studies have been conducted in the past on various aspects of the usability and shortcomings of Eurocode. One study by Stepinac et al. (2018) conducted a survey in which they specifically addressed the connections part in the Eurocode 5, as this is often mentioned to be one of the most concerning chapters. Most people surveyed in this study indicated a need for enhancements to the standard. This includes both the technical information itself and how easy it is to use. Some design rules need to be improved and some design rules need to be added according to the survey. A similar study by Dietsch & Winter (2018) presented a list of improvements, summarized in Table 5.

Table 5: List of design rules to be improved and list of desired additional design rules

Design rules to be improved	Additional design rules
Vibration of floors	Design rules for holes in beams
Shear resistance of timber	Design of reinforcements for local timber areas by screws, glued in rods, and punched metal plate fasteners
Element stability	Doweled and bolted connections
Capacity of multiple shear connections	Timber-concrete composites
Timber failure capacity in connections	Notched members
Rules for geometrical imperfections	Design rules for modern carpentry connections
Rules for fire design	Curved, pitched cambered and double tapered beams

7.4.4 Timber Building Quotas

Currently, the MRA agreed on setting a biobased building quota of 20% to increase the use of biobased materials in construction. However, there are no national biobased building quotas yet. National timber building quotas could be helpful to stimulate the use of CLT in construction. France set an example to build 50% of all government building with biobased materials. A starting point could be to set a national timber building quota for government buildings like in France. A national timber building quota could be a next step, building on the policy of the MRA initiative. This policy would require municipalities across the country to dedicate a certain percentage of land sold through tenders specifically for timber construction projects.

7.4.5 Governmental push to scale up CLT production

Another governmental means to enhance the adoption of CLT in construction is to use subsidies to promote the use of CLT. The French government developed such a program in 2013. This program consisted of measures such as tax benefits for the purchase of equipment, government-sponsored training, architecture competitions focused on CLT as a building material, and research into the use of French wood species in CLT.

Researchers at Oregon State University investigated the motivations of CLT production companies to start producing CLT (Albee, et al., 2018). They interviewed French companies about their motivations for entering the CLT market, and all of them mentioned the government program as a major factor. Other reasons such as serving the public interest and growing knowledge and expertise were also frequently mentioned. However, the most important factor was that CLT would be an economically profitable product. France proved that governmental measures can accelerate the adoption of CLT.

In the Netherlands the ‘Nationaal groeifonds’ exist, which is a fund to promote sustainable and innovative projects. Using the funds in this program to stimulate timber construction can help creating sustainable building practices.

7.6 Overview strategies

The chapter explored various strategies aimed at enhancing the adoption of CLT MSTBs. These strategies address the barriers identified previously and are grouped into five key themes:

- **Increase Awareness:** This involves raising industry-wide knowledge about the benefits and capabilities of timber construction. Proposed measures include sharing knowledge internationally, developing a case study database, providing information to consumers and clients, establishing a brand image, and increasing timber knowledge in educational programs and among licensing authorities.
- **Change Industry:** To counteract the conservative nature of the construction industry and improve supply issues, strategies include moving from simple linear relations to collaboration in networks, increasing production facilities, and promoting local wood production.
- **Create New Financial Models**: This theme addresses the higher costs associated with CLT by proposing financial strategies such as leveraging carbon credits, applying biophilic design principles to reduce sick leave costs, leveraging global financial services, and convincing clients of the increased residual value of timber buildings.
- **Technical Advancements:** Enhancements in technology are seen as a way to overcome technical barriers and reduce costs. This includes increasing prefabrication levels, promoting modular construction, conducting full-scale testing of CLT buildings, and fostering research and development.
- **Regulatory Change:** Adjustments in regulations are suggested to support the wider use of CLT. Strategies include revising the MPG system to better account for biogenic carbon storage, expanding the national environmental database to include more timber products, establishing building codes that support timber construction, setting timber building quotas, and encouraging governmental support for scaling up CLT production.

Each strategy directly addresses specific barriers and is designed to promote the broader adoption and acceptance of CLT as a viable construction material in multi-storey buildings.

8. Results field study

The interviews were performed to validate the findings from the in-depth literature study. It is important to be aware of the different backgrounds of all interviewees. While some aspects are more general and may be mentioned more frequently, other aspects may have received fewer mentions due to the specialized knowledge required for those aspects. Consequently, the amount of mentions per driver, barrier, or strategy is no clear indicator of how important that aspect is; it is merely a tool to explore the different potential solutions.

8.1 Drivers

In all interviews, the drivers and barriers for the use of CLT in MSTBs were discussed. Table 6 gives a summarized overview of the interviews and shows how often every category of barriers was mentioned per actor. The table shows that environmental aspects were the main driving factor for the use of CLT in MSTBs.

In general, most answers were in line with each other and no large deviations have been noted. One exemption is the Dutch political party employee. He mentioned no other drivers besides environmental and political drivers, but that mainly had to do with the structure of the interview. That interview briefly touched upon the drivers and barriers for the use of CLT in MSTBs, but the main focus of the interview was how politics can take away some of the barriers and how MSTC can be enhanced or stimulated.

Another notable thing is that almost no actors identified economic factors as drivers. Most interviewees found that costs are the one of the biggest barriers for the use of CLT, however some actors did see some financial opportunities in building MSTBs with CLT.

Table 6: Overview of categories driving the use of CLT in MSTB per actor.

	Political drivers	Economic drivers	Sociocultural drivers	Technical drivers	Environmental drivers
Architect	o	+	++	++	+++
Builder / main contractor	o	o	+	+	++
Building physics consultants	o	o	++	++	+++
Client / building owner	o	o	++	++	++
Cost consultant	o	+	++	++	+++
Dutch political party	++	o	o	o	+++
Project developer	o	o	++	+++	+++
Structural engineer	o	o	++	+	++
Timber structural engineer	o	o	++	++	+++
Timber manufacturer	o	o	o	++	+++

"o" means that no drivers in that category were mentioned by the actors;
"+" means that one driver in that category was mentioned by the actors;
"++" means that multiple drivers in that category were mentioned by the actors;
"+++" means that most drivers in that category were mentioned by the actors.

Figure 17 on the next page shows the various drivers mentioned in the interviews.

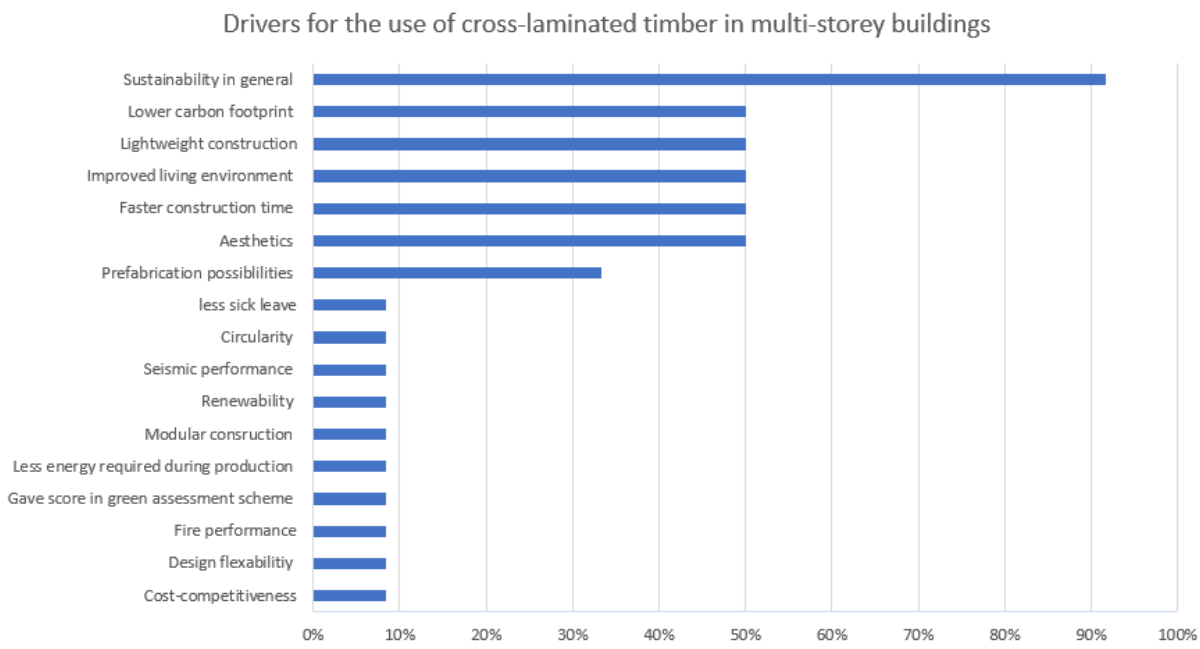

Figure 17: Drivers for the use of CLT in multi-storey buildings

8.1.1 Political drivers

The first category of drivers relates to political factors. While market parties did not directly cite political aspects as drivers for the adoption of CLT in MSTBs, many acknowledged that potential solutions to overcome barriers could be found within the field of politics. These solutions will be explored in

8.3 Strategies to overcome barriers . However, a Dutch political party did highlight some political drivers. The first driver mentioned was the NABB, which promotes the use of biobased insulation materials. The interviewee noted that although the current focus is on insulation materials, there is potential for timber manufacturing facilities to receive funding in the future. Additionally, the interviewee expressed support for the timber building quota in the metropolitan region of Amsterdam as a positive driver, though they advocated for such policies to be implemented on a national scale.

8.1.2 Economic drivers

Most parties did not emphasize economic drivers, yet most interviewees agreed that costs were a barrier. They concluded that, particularly for multi-storey construction, CLT is often not yet economically competitive with concrete and steel. Despite this, there are notable advantages that can promote the use of CLT in MSTBs.

Firstly, the precision of CLT construction stands out as a significant driver. Its prefabricated nature allows for remarkable precision with minimal error margins, potentially reducing faults costs. Additionally, according to an architect, timber construction can lower labour costs during the assembly of load-bearing elements. For instance, he mentioned that only four workers were required for the main load-bearing structure of a fourteen-story apartment building they were involved in. Thanks to prefabrication, all elements seamlessly fit together, requiring minimal labour:

"And the bizarre thing is that four people are working on the main structure until the summer. So that's in four months' time. And of course, that's incredibly fast." – Architect

Another economic driver is the opportunity to monetize the carbon stored in timber as carbon credits, with a value of at least €150 per tonne of stored CO_2 (Climate Cleanup , 2024). Additionally, most interviewees noted that faster construction times could lead to cost savings by reducing rental periods.

8.1.3 Sociocultural drivers

The third category of drivers revolves around sociocultural aspects. The most mentioned driver in this category is aesthetics. Almost all interviewees said that CLT, and timber in general, is aesthetically appealing and that it is therefore desired to leave as much timber exposed as possible. Another frequently mentioned driver was the improved living environment. This strokes with the findings in literature and is also in line with studies related to biophilic design.

8.1.4 Technological drivers

Several drivers were identified within the technical aspects category, with diverse perspectives. Among the twelve interviewees, eight highlighted construction time as a key factor favouring the utilization of CLT in MSTBs, although some remained sceptical about the speed of CLT construction. Nuance is crucial in understanding this aspect. The opponents of this claim all agreed that a MSTBs can generally be constructed faster compared to an in-situ concrete building. But, that is an unfair comparison they conclude:

"I think the comparison should not be timber versus concrete, but prefab versus in-situ. And timber is per definition prefab, since that is the most economic and viable way to build with it. However, prefab concrete buildings can also be very fast." – Structural engineer

Since timber is always prefabricated, the construction of large elements is always fast. A storey a day can be realised according to one contractor, and therefore the construction of the cascade is really fast. But since timber oftentimes requires more work for finishing, the construction time of the entire project is not always faster:

I am not sure if timber construction is so much faster than traditional construction if you consider the entire construction time and not just the construction time of the cascade. And I'm also not so sure if you can assign a value to the claimed faster construction time, like savings on construction and execution costs. – Timber manufacturer

Additionally, the lighter weight of timber compared to traditional materials was cited by seven interviewees as a driving factor, potentially leading to reduced foundation costs. One contractor, however, raised a concern about buoyancy. They cautioned that timber's lighter weight could pose a risk of the building floating due to high groundwater pressure.

Other advantages highlighted included prefabrication capabilities, modular construction, and enhanced on-site precision. Fire safety properties were mentioned as a driver by a project developer, albeit most interviewees considered fire safety a barrier. Lastly, timber's seismic resilience was noted as a driver in earthquake-prone regions.

"I also think that prefabrication can be, or is, another advantage. That you can manufacture conditioned components in factories and deliver them to the construction site. And that way, you can eliminate construction errors. Everything that is done on the construction site now is super precise. The main beam structures are very precise. The beams for the floors fit together perfectly, down to the millimetre." – Architect

8.1.5 Environmental drivers

The last category of drivers is environmental aspects, which emerged as the most frequently mentioned and significant factor among all interviewees. For many, it was the primary motivation behind adopting CLT in MSTBs. Numerous individuals expressed that they only began incorporating CLT and timber into their projects when they become aware of the carbon emissions associated with traditional materials.

"I never knew anything about sustainability scores. The predetermined scores with the corresponding emissions were always so extremely high that it was impossible to fail the criteria. It was therefore not necessary to know anything about it. Only until recently, I started to learn about the MPG system. Really weird, as the structural engineer is responsible for roughly half of the materials in a building." - Timber structural engineer

While some interviewees spoke generally about sustainability without specifying attributes, others highlighted particular aspects such as reduced carbon emissions, recyclability, circularity, and renewability. Furthermore, several individuals emphasized that timber construction is crucial for the construction industry to align with the goals of the Paris Agreement. In conclusion, the interviews underscored that the environmental advantages of CLT in MSTBs are the primary driving force behind its adoption.

8.2 Barriers

In all interviews, the drivers and barriers for the use of CLT in MSTBs were discussed. Table 7 gives a summarized overview of the results of the interviews and shows how often every category of barriers was mentioned per actor.

The table shows that economic and political aspects were the most important barriers for the use of CLT in MSTBs. Technical and sociocultural aspects were topics of debate. A lack of knowledge and experience and a faster construction time were barriers that were perceived differently by various actors. The explanation for this variance is explained in the upcoming paragraphs.

Another notable thing is that, except for one project developer, no actors identified environmental factors as barriers. The reason for his doubts were related to the durability of CLT for the application in social housing. Other than that, no environmental barriers were identified.

Table 7: Overview of categories hindering the use of CLT in MSTB per actor.

	Political barriers	Economic barriers	Sociocultural barriers	Technical barriers	Environmental barriers
Architect	---	--	-	-	o
Builder / main contractor	-	---	o	--	o
Building physics consultants	-	--	-	-	o
Client / building owner	-	---	-	-	o
Cost consultant	--	--	-	-	o
Dutch political party	--	-	o	o	o
Project developer	-	---	-	--	-
Structural engineer	-	--	-	--	o
Timber structural engineer	--	--	--	---	o
Timber manufacturer	--	-	-	--	o

"**o**" means that no barriers in that category were mentioned by the actors;
"-" means that one barrier in that category was mentioned by the actors;
"--" means that multiple barriers in that category were mentioned by the actors;
"---" means that most barriers in that category were mentioned by the actors.

Figure 18 on the next page shows the various barriers mentioned in the interviews.

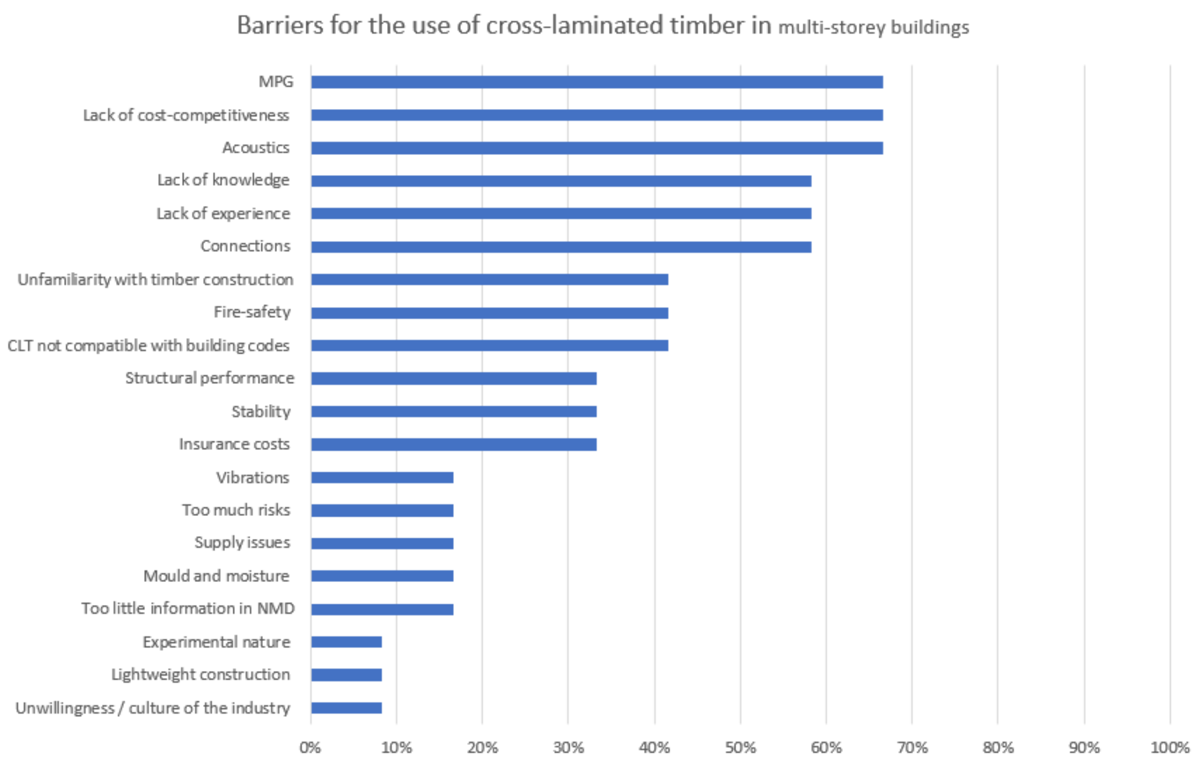

Figure 18: Barriers for the use of CLT in multi-storey buildings

8.2.1 Political barriers

Political factors were a significant obstacle to adopting CLT in MSTBs. Various challenges stem from political issues. The most mentioned obstacle, noted by seven out of twelve participants, was the unfair representation of timber products by the MPG system. All respondents critiqued the MPG's assumption that timber is always burned in open air as unrealistic, pointing out that timber could be effectively reused or recycled if designed according to circular principles. Additionally, the National Environmental Database (NMD) was criticized for its lack of comprehensiveness, failing to list many products and thereby excluding timber data from MPG calculations. Another commonly mentioned barrier was the scarcity of applicable codes, mostly indicated by engineers. While pre-Eurocodes and international codes exist, they don't substantially alleviate the problem. One structural engineer specializing in timber remarked that pre-Eurocodes tend be on the safe side, making them economically disadvantageous. Some projects even required tests due to the absence of necessary design standards in the norms. Furthermore, the reluctance of licensing authorities to grant permits, due to their unfamiliarity with timber and its perceived risks, was highlighted as a barrier. This often resulted in the need for numerous second opinions and additional consultants, increasing project costs.

8.2.2 Economic barriers

All interviewees agreed on the fact that the biggest obstacle for the adoption of CLT in MSTBs was costs. Building with timber often proves more expensive than traditional materials, especially for MSTBs. This price gap arises from several factors. Firstly, fire safety design in MSTBs presents a complex challenge. While encapsulating all timber elements offers a straightforward solution, it's often aesthetically and financially unappealing. Exposing some timber requires extensive engineering to guarantee fire safety, again increasing costs. Secondly, a knowledge gap can hinder approvals. Licensing institutions, municipalities, and fire departments may be unfamiliar with timber construction, leading to hesitation towards these designs. Securing approval often necessitates time-consuming consultations with various firms, adding another layer of costs. Timber prices themselves also significantly impact overall construction costs. MSTBs often require large volumes of load-bearing timber, inherently driving up the overall costs. Also, the lack of timber availability was mentioned multiple times:

“You simply cannot look at the table of products and order the desired strength class in large quantities. Sometimes certain timber members are not available.” – Structural engineer

Finally, some contractors perceive a higher risk associated with timber construction. This perception can translate into budgetary buffers. One contractor mentioned that they budgeted additional costs to mitigate potential risks regarding the timber structure.

8.2.3 Sociocultural barriers

The third major hurdle lies in sociocultural aspects, particularly the lack of knowledge and experience. More than half of the interviewees identified this as a significant barrier to the widespread adoption of CLT in MSTBs. While some people claimed their networks now possess sufficient expertise to handle large MSTB projects, this knowledge remains concentrated in specific firms, not spread across the entire AEC industry. Nationally, a significant knowledge gap persists. The scarcity of specialized professionals is particularly concerning. One interviewee estimated that only twenty fire engineers in the Netherlands possess the expertise for high-rise timber tower fire design. A timber supplier confirmed this concern, highlighting a nationwide shortage across all disciplines. He also mentioned that there are not enough builders with the required timber knowledge to increase timber production by a lot. He emphasized the complexity of timber construction and the importance that no ‘bad buildings’ can be built, since that will undoubtedly harm timbers reputation as a construction material. Another barrier is the reluctance of many stakeholders to invest in timber buildings. Unfamiliarity with the material and a long history of using traditional methods create a risk aversion, limiting companies' willingness to embrace new construction techniques.

8.2.4 Technological barriers

Technical challenges were also mentioned as significant barriers to the widespread adoption of CLT in MSTBs. Among these, acoustics and fire safety emerged as the most frequently mentioned barriers, with fire safety being particularly emphasized. The primary concern regarding tall timber structures is the limited understanding of timber’s behaviour under fire conditions in such large volumes. While numerous tests have been conducted on individual CLT components, comprehensive testing on the scale of entire high-rise buildings remains scarce, forming the basis of this barrier.

Acoustics present another challenge. A structural engineer highlighted the conflicting demands between structural stability and acoustic performance, noting the necessity to balance the desire for a robust structure with the need to prevent sound transmission:

“From a structural perspective, it is desired to make all elements fixed and connected to ensure a robust and stiff structure. However, from an acoustic perspective it is necessary to decouple structural elements to prevent flanking sounds.”

This conflict often leads to complex details and connections. Moreover, the lack of standardized connections and details complicates engineering, especially in all timber or hybrid structures involving multiple materials. Stability is also a concern, particularly for taller buildings where, according to the engineers, a hybrid approach combining timber and concrete is oftentimes economically preferable. Timber elements are typically best suited for transferring vertical loads, while concrete is favoured for horizontal loads.

While material limitations and moisture issues are mentioned less frequently, they remain significant concerns. Some interviewees consider moisture manageable, while others view it as a major risk that requires close monitoring. The issue of material limitations becomes particularly relevant when designing for large spans.

8.2.5 Environmental barriers

None of the interviewees identified environmental concerns as obstacles. Some literature raises doubts about the durability of timber. However, all participants contradicted this opinion, stressing that there are no environmental drawbacks to timber construction as long as sustainable forest management practices are ensured. One exemption was that the project developer addressed his concerns about durability specifically for social housing, since timber elements are more difficult to restore once they are damaged. This had however nothing to do with the structural integrity of CLT structures.

8.3 Strategies to overcome barriers

After analysing the content of the responses, the same categorisation of key themes in chapter 7 was made. These key themes provide solution strategies to increase the use of CLT in MSTBs. By looking at how often each theme appeared in the comments, the author found that people believe wider adoption of timber could be achieved by:

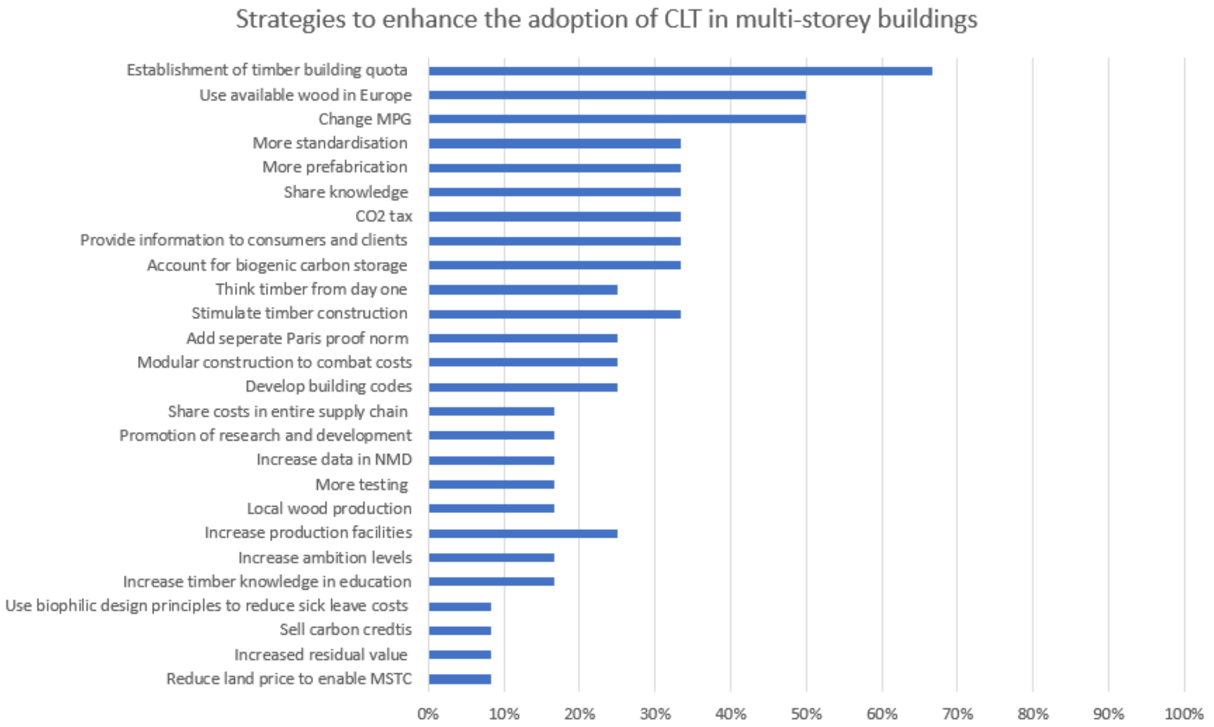

Figure 19: Strategies to enhance the adoption of CLT in multi-storey buildings

Table 8 shows how often each theme of solutions appeared in the interviews.

Table 8: Number of references per theme

Theme	Number of references
Increase knowledge and awareness	13
Change industry	16
Create new financial models	9
Technical advancements	12
Regulatory change	32

8.3.1 Increase knowledge and awareness

The first method to enhance the adoption of CLT in MSTBs is to increase awareness. Increasing awareness should overcome the barriers:

- Lack of knowledge
- Lack of experience
- Unfamiliarity with timber construction
- Perceived risks

The strategies below were presented by the interviewees to bridge the barriers:

- Share knowledge
- Think timber from day one
- Increase timber knowledge in education
- Provide information to consumers and clients
- Increase timber knowledge at licensing authorities

Knowledge sharing was mentioned multiple times to bridge the knowledge gap. Most parties agreed that the lack of knowledge was one of the biggest barriers to the widespread adoption of CLT in MSTBs and that the solution for this problem partially lay in sharing knowledge. A structural engineer said the following about the lack of knowledge on fire-safety and the need to overcome this knowledge gap:

So, I'm basically saying that fire is really the biggest challenge. But we do see that sometimes, especially with fire safety, it is underestimated. Because the required knowledge is not yet fully available. But it is something that you need to invest in. Both in money and in knowledge and attention." – Timber structural engineer

Increasing timber knowledge across the entire AEC industry seemed important. Another frequently mentioned focus point was that it was really important to think timber from day one:

'One of the things we are trying to convey is that when you want to build in wood, you should no longer compare it to traditional construction, because when you build in wood, you need to think in wood from the very first moment. We have done this in the past, where we look at a building and think "what if this had to be made of wood?", but then you're chasing shadows. Wood construction simply requires a different way of thinking.' – Cost consultant

Architects and engineers also emphasized this point. Constructing MSTBs is entirely different than building traditional buildings. Consequently, the decision to use CLT should be made at the very beginning to prevent redesigns, delays, and extra costs.

Creating awareness was not only focused on practitioners in the AEC industry, but also on consumers and clients. Various interviewees mentioned the importance of creating awareness at consumers and clients, since they oftentimes have little knowledge on timber construction. Convincing clients of the societal and environmental benefits of using biobased materials like CLT is crucial in getting enough constituency to realise CLT buildings. Moreover, multiple interviewees mentioned that convincing the client about other benefits like the improved living environment, or the strategies to overcome the cost barriers was necessary to create the required support.

The lack of knowledge and experience on MSTC at licensing authorities remains a knowledge barrier as well, causing lengthy permit processes, particularly regarding fire safety:

"Yes, I think the biggest challenge ultimately was the unfamiliarity at the municipality to be able to assess this [fire]. And there is certainly a lot of expertise there, but of course in concrete and steel." – Architect

Streamlining this process is crucial to avoid delays and cost overruns in MSTB design and construction. Lastly, educational institutions were also identified as a key area to bridge the knowledge gap. Several interviewees, particularly engineers, highlighted that their formal education lacked exposure to timber construction. They only encountered it during their first professional experience with timber projects. Putting more emphasis on timber construction in architecture and engineering curriculums could significantly raise student awareness of timber construction methods.

8.3.2 Change industry

The second category of strategies to enhance the adoption of CLT in MSTBs is to change the industry. This set of strategies should overcome the barriers:

- Costs
- Insecure supply
- Culture of the industry

The strategies below were presented by the interviewees to bridge the barriers:

- Choose contracts that promote collaboration
- Increase production facilities
- Use European timber production facilities

Industry changes were said to be important to overcome some of the barriers rooted in the culture of the industry. The supply chain in the construction sector is traditionally linear, while timber construction requires more value-added stakeholder relationships (Gosselin, et al., 2018). These relationships should be collaborative and focussed on knowledge sharing. Therefore, the first strategy is to choose contracts that promote collaboration:

"Comprehensive systemic changes are necessary, especially in our mindset. What I just mentioned about profit caps, CO_2 sales, and contractors trying to collaborate with timber builders in a different way – that's quite significant. We're currently exploring new project approaches that involve engaging directly with contractors to streamline the coordination of timber structures. This entails fostering a more collaborative relationship with timber builders, similar to a general contractor, to eliminate redundant overhead costs and ensure project feasibility." – Architect

This architect emphasized the importance of collaboration to make timber projects feasible, especially MSTBs.

Besides this mindset change and focus on collaboration, a shift in the supply chain was another topic of debate. An insecure supply chain and fluctuating timber prices was the cause of this problem. Increasing production facilities could be part of the solution, but there was a dissensus on how to do so. Some of the interviewees were convinced that setting up local sawmills, CLT factories and potentially production forests could be part of the solution:

"I strongly support initiatives that promote timber construction, especially while regulations are still lagging behind. Significant investments are required from construction companies, suppliers, clients, and architects to acquire the necessary expertise and, more importantly, to establish production facilities for timber building components. This could include a production line for CLT panels or glulam columns. These factories are essential to enable widespread adoption of timber construction." – Architect

However, most interviewees were convinced that sourcing timber on a European scale is sufficient to fulfil the Dutch timber demand:

"No, I don't believe in that for the short term. There's a massive timber production in Germany, Austria, and Scandinavia. That's where the forests are. Let's not forget that we simply don't have that here. We should simply utilize the timber that's readily available at a relatively low cost from factories located right next to the Dutch border. I don't see any issues with that approach." – Timber structural engineer

While a study by Oldenburger et al. (2020) proved that local timber production can contribute to fulfilling the rising timber demand, it will not be enough to serve the entire market. Therefore focussing on European timber, and maybe a little addition of Dutch timber is probably the most logical approach.

8.3.3 Create new financial models

The third category of strategies to enhance the adoption of CLT in MSTBs is to create new financial models. This set of strategies should overcome the barrier:

- Costs

The strategies below were presented by the interviewees to bridge the barriers:

- Use European Union Emission Trading System to sell carbon credits
- Use CLT to reduce carbon costs due to the CO_2 tax
- Use biophilic design principles to reduce sick leave costs
- Convince client of increased residual value
- Reduction of land price for societal benefits

All previously proposed strategies to overcome the barriers related to costs were underscored by at least one interviewee. The most common suggestion was the CO_2 tax. While this could eventually minimize the cost gap between CLT and traditional materials due to rising carbon costs, it's a long-term solution. Conversely, other strategies, like selling carbon credits from timber construction projects, offer more immediate benefits:

"So, I was wondering, what is your view on the financial feasibility of timber construction?" – Author

"If you say, 'I'm not going for maximum profit; I'm going back to a few percent.' And honestly, you don't need more than that. But that's a mindset, it's a decision. We call that shared value instead of shareholder value. And another thing is that you can sell the CO_2 storage as carbon credits and reinvest that money back into the project." – Architect

This carbon credit strategy is very new, as carbon trading itself is a recent development. Consequently, there are very few examples known. Another interviewee proposed to convince shareholders of the long-term benefits of CLT construction, such as its higher residual value:

And of course, if we ever sell the building, there are a lot of funds that are only interested in highly sustainable buildings. But there are hardly any such wooden buildings. – Client

Using biophilic design principles to reduce sick leave costs also came across to tackle the cost problem:

"Another example is absenteeism, which is a very soft factor. There are plenty of studies on how healthy buildings affect absenteeism in an office. I don't remember the exact numbers anymore, but it's definitely a few percent. Less absenteeism, and especially in long-term absenteeism. So the costs you have for sick staff are much lower. Now, if you calculate that over the entire life cycle of that office building, it adds up. That really adds up." – Cost consultant

High insurance costs were identified as another factor driving up project costs. Involving insurance companies from the project's beginning was seen as particularly beneficial, as their early participation would allow them to gain a deep understanding of the project, including fire safety considerations, ultimately leading to more streamlined process. The interviews did not mention leveraging financial service premiums through global organizations as a potential solution to high insurance costs.

The cost consultant discovered also alternative solutions opting for reductions in land price. He argued that governmental bodies could invest in sustainable building practices themselves, but they can also promote the feasibility of timber construction projects by lowering the price of land. With this strategy, the municipality in question can also contribute to the sustainability of the construction sector without having to invest a lot of time and effort itself. For this strategy to be successful, it is important that the social and environmental benefits are made known to municipalities.

In conclusion, the interviews underscored a clear need to shift the focus within the business case to effectively address cost concerns hindering the widespread adoption of timber construction:

"These are indirect costs, and you need to convert them into direct values now. That is, I think, the biggest puzzle that exists and where I think the difference lies. Because we know that construction costs, material prices, depend on many other things, but unfortunately we cannot influence them that much." – Cost consultant

While the proposed strategies may not provide a single, immediate solution, they collectively illustrate possibilities to tackle the cost problem.

8.3.4 Technical advancements

The fourth category of strategies to enhance the adoption of CLT in MSTBs is technical advancements. This set of strategies should overcome the barriers related to:

- Costs
- Fire safety
- Acoustics
- Connections
- Stability
- Vibrations

The strategies below were presented by the interviewees to bridge the barriers:

- Increase prefabrication levels
- Increase modular construction possibilities
- Increase standardisation
- Full scale testing

Technical advancements were said to be important to overcome most of the technical challenges related to MSTC and costs. Increased prefabrication levels and modular construction were mentioned to as outcomes to scale up timber building practices, as well as to make MSTC more cost effective. A project developer answered the following to the question if MSTC can become feasible for social housing as well:

"Yes, and I think you then have to start thinking much more in terms of modular construction. I think that's really the future. But the problem with wood is of course that once you damage it, it's damaged forever. And how sustainable is it in the long term? So that's a bit of a fear I have with that. But I certainly think that if you want to build houses quickly in a factory-like way, then wood is really the answer of course. There just needs to be a good system and one party that can do it. Before it can really be rolled out on a large scale." – Project developer

While he addressed his concerns about durability specifically for social housing, he thought modular construction could be part of the solution to build timber houses in large volumes for lower costs. A timber supplier added this:

"Yes, absolutely. In fact, I think it (modular construction) is the only way to meet the housing needs. This is also linked to sustainability and the Paris Proof ambitions that we have agreed to. If we do that in the way we do it now, we will never make it." – Timber supplier

Beyond cost concerns, challenges like fire safety and acoustics can also be addressed through technical advancements. Full-scale testing can validate the potential of CLT construction, particularly for MSTBs:

"Fire and acoustics are also barriers. First cost, then fire and acoustics. I think that by making projects, by measuring, and by testing, we can show that the barriers of fire and acoustics can be overcome. And that it increases confidence among testing authorities, contractors, and architects." – Timber supplier

Building confidence at licensing authorities and insurance companies by full-scale testing is crucial. Their current hesitancy likely stems from a knowledge gap regarding MSTC's capabilities. Therefore, the solution lies in demonstrating the viability of MSTC through comprehensive testing and data.

Part of the solution to overcome the technical barriers is to increase standardisation levels. Currently, extensive engineering goes into designing details that meet acoustic, structural, and fire safety requirements. This is because there are almost no standardized details available:

"There are no standard connections. So standardization really needs to improve. Then people use the standards more often. Easier, faster, you don't have to research everything from scratch. And then you can just make standard things." – Structural engineer

Increasing standardisation levels could be achieved by research and development or by knowledge sharing of existing solutions. This is highly requested from the market.

8.3.5 Regulatory change

The last category of strategies to enhance the adoption of CLT in MSTBs is regulatory change. This set of strategies should overcome the barriers related to:

- MPG system
- Lack of available data in the Nationale Milieu database
- CLT not compatible with building codes
- Costs

The strategies below were presented by the interviewees to bridge the barriers:

- Change MPG
- Increase data in NMD
- Establish Buildings codes
- Setting timber building quotas
    - For the industry
    - For governments
- Governmental push to scale up CLT production
- Create national long term targets

Most strategies found their origin in regulatory changes. The strategy that received most support among the interviewees was to set timber building quotas. This strategy finds its origin in the MRA, which set the target to build 20% of buildings with biobased materials from 2025. The MRA established a successful framework by setting clear, long-term goals for sustainable construction. This approach provided predictability for stakeholders within AEC industry, enabling them to strategically invest in acquiring knowledge and expertise in timber building practices. Interviewees expressed strong support for expanding the MRA's goals to a national level, potentially enabling the widespread adoption of MSTB practices. An architect also stressed the importance for long term policies, and can count on support from national policy makers:

"Establishing a clear and consistent long-term strategy is, in my view, very important. The Metropolitan Region Amsterdam's (MRA) timber construction covenant serves as an excellent illustration of this principle. The national government should continue to adopt a similar approach, consistently communicating clear goals for the future." – Architect

"Yes, I believe that approach is quite sound. However, I also think that the national government should take the lead in establishing national standards, ensuring clarity and consistency across the country. We must set ambitious goals, and I agree with Amsterdam on this point. If the national ambition level falls short, then perhaps localized initiatives are necessary." – Dutch political party employee

Multiple interviewees also mentioned a separate timber building quota for governments to set examples for the market, like in France. When the government takes the lead and sets the example, it is likely that market parties will follow suit.

Another widely cited barrier that needed to be addresses was the MPG system. There was a wide consensus on the fact that the MPG should change, and that NMD should be expanded with timber products. The two main proposals for the MPG were to:

- Add a Paris Proof norm to reveal embodied carbon emissions
- Account for biogenic carbon storage in LCA methods

"But yes, I am concerned about the MPG. A while ago there was a lobby to introduce a Global Warming Potential A (GWPa) requirement. So basically the CO_2 emissions up to delivery. And then also to mirror that against those Paris Proof scores. I believe in that very much, as an engineer. Then you'll also be able to steer towards sustainability." – Timber structural engineer

"So basically, I think that almost everyone involved in timber construction agrees that, including the scientists and NIBE, everyone thinks that you should actually account for stored CO_2. And then timber will be represented more positively in those MPGs." – Architect

There is support among Dutch political parties to address the misrepresentation of timber in the MPG, but some of the origins of the problems lay in European laws and are not easy to change. To account for biogenic carbon storage in timber products, the LCA methods have to change, which is determined by the EU. The Dutch political party employee said:

"I believe this is laid down in European laws and is therefore something we cannot fix immediately. It's just a lengthy process. But it is on the agenda." – Dutch political party employee

In the near future, a distinct Paris Proof standard is recommended to manage embodied carbon emissions. In the long term, however, modifications to European LCA methodologies are necessary to account for biogenic carbon storage.

Another barrier that finds its roots in regulations is the lack of available building codes and norms. This was stressed mainly by the engineers, but is a general concern in the AEC industry. New norms are highly requested. Not just the Eurocode 5, but also with regards to fire regulation.

Another strategy is to use governmental funds to scale up CLT construction. Costs remain a barrier for the realisation of MSTBs, and funds can help to get the early adopters starting. The emergence of the NABB marked the beginning of a exploration towards biobased insulation materials. A separate fund could help to set up CLT production facilities.

Finally, it is highly requested that the national government develops a long term strategy. This long-term strategy provides predictability for practitioners in the AEC industry and can take away doubts about the viability of MSTC. This strategy can count on support from Dutch politics:

"I think it would be very helpful if many municipalities did not set excessive requirements above what is legally required. Amsterdam used to do this for a long time. They would say, 'Yes, okay, it has to be sustainable, but we want it to be super sustainable.' And builders get annoyed by this, because they say, 'Yes, in Amsterdam I have to do this, and in other cities I have to do that,' and that's quite frustrating. Therefore, we advocate for the national government to establish high, uniform sustainability standards, ensuring consistency across municipalities." – Dutch political party employee

8.4 Case study: Mediavaert

This chapter provides a comprehensive analysis of a timber hybrid building: Mediavaert in Amsterdam. The goal of this chapter is to provide an example of a realised MSTB and to show how the barriers on this project were overcome. First, an analysis of the project is presented, including an explanation of the structural system. Then the drivers and barriers for the use of CLT in this project are discussed and the strategies that overcome some of the barriers are presented as well. Some proposed strategies from this study that have not been used in this project will be applied to this case to demonstrate the effectiveness of those strategies.

Table 9: Project details Mediavaert

Location	Amsterdam
Sector	Office
Year completed	2024
Number of stories	7
Area of building (GIA)	44.000 m^2
Volume of timber	6500 m^3
Client	DPG Media
Architect	Team V Architecture
Contractor	Besix
Structural engineering	Arup / Ney & Partners
CLT manufacturer	WIEHAG

Mediavaert is one of the biggest office building in Europe constructed with a hybrid timber structure. Sustainability was a core principle throughout the project. The use of timber substantially reduces the building's carbon footprint. In recognition of its sustainable design, Mediavaert has been awarded a BREEAM Excellent certification.

Figure 20: DPG Media office building, Amsterdam

Structural system

The building consists of a trio of interconnected buildings with a continuous facade. The three building blocks are designed as independent structural systems, capable of carrying their own loads. The parking garage and ground level floor are constructed using concrete, while the superstructure embraces a genuine timber-concrete-steel structure. Each floor consists of a 200 mm layer of CLT topped with a 100 mm layer of in-situ concrete, fulfilling both structural and acoustic roles. Due to large spans that create big open spaces, ideal for office spaces, the structural concrete layer was necessary. The concrete cores ensure lateral stability, while glulam columns spanning two stories serve as the primary vertical elements in the design. The cores could have been constructed using CLT, but the client opted for concrete due to concerns about potential squeaking in the structure:

We also checked with the contractor. Can we make the cores from timber instead of concrete? That's possible, but then the building will creak. Is that safe? Yes, that's fine. Do you like that? Actually, I don't think so. – Client

The floors are supported by glulam beams, supplemented by steel beams in some instances. On the building's east side, the cantilever predominantly employs steel to minimize cross sections.

Sustainability

The adoption of CLT in the Mediavaert project had a few driving factors, however, there were also some barriers to overcome. The biggest driver for the use of CLT, and timber in general, was most of all sustainability. The choice for CLT and glulam contributed to a large reduction of carbon emissions.

Faster construction time

The second driver for the use of a timber-hybrid structure was the reduced construction time. Originally, the construction time estimates indicated that construction time of the hybrid variant would be six months faster than the concrete and steel option. This served as an additional incentive for the client to opt for the timber-hybrid structure:

"Ultimately, we made the call and calculated that it would save about six months of construction time." – Client

Improved working environment

The last driver had to do with aesthetics, the improved working environment, and biophilia:

"Everyone becomes happy about it. Wood has a positive effect on people. Everyone who comes in, you see them already smiling because of it, and it's not just the timber construction, but you do see it, so wood is positive for well-being." – Client

Fire safety

Fire safety was not a real problem at Mediavaert. Due to the big open spaces, as was desired by the client, there was no possibility to adhere to the fire regulations by making fire compartments. A sprinkler system was therefore necessary. Timber elements were checked and designed for fire load, but this was not normative for most dimensions of elements. For those elements for which the fire load was normative, cross sections of the timber members were increased to be able to use the charring method.

Lightweight construction

Timber's lightweight properties often allows for lighter foundations, potentially reducing costs. However, under specific conditions, this lightweight structure can become a challenge. For instance, at Mediavaert, during construction, the building's weight was insufficient to counteract groundwater pressure, posing a risk of buoyancy. To address this issue, additional tensile piles were necessary to prevent the building from floating, resulting in extra construction costs.

Connections

Another frequently mentioned barrier with CLT buildings is the connections. This was particularly challenging at Mediavaert. Mediavaert is a true hybrid building, combining timber, concrete and steel. The connections of all the different building elements and joints was already a challenge on its own. A specific challenge was the connection of the CLT floors to the façade:

Wood shrinks, and settles. We calculated the impact of this on the timber construction, especially the connection of the facade to the timber construction. And so, in fact, our facade does not comply with the deformation of wood, which was a serious risk. – Contractor

In this instance specifically, the risk was that a window could break because of the deformation of the CLT floors. The maximum allowed deformation of 9 mm was exceeded with 1,2 mm. The contractor chose to accept this risk instead of taking mitigation measures.

Moisture

Moisture posed another risk for the contractor. The timber supplier mentioned that the timber elements could only be exposed to weather conditions for a maximum of four weeks. That caused a serious risk for the contractor and led to increased expenses:

"The facade needed to be quickly enclosed following the completion of the timber elements. Any delays in closing the facade would have required the installation of temporary facades instead. Ultimately, these temporary facades were indeed necessary."

The contractor allocated additional budgets for the temporary facades to tackle that risk, but the temporary facades were an emergency solution. The primary strategy was to control the moisture content by:

- Wrapping the columns and beams in plastic;
- Adding foil to the CLT edges;
- Draining water puddles on the CLT floors;
- Taping construction joints;
- And by checking the moisture content every two weeks or after a heavy rainfall.

Lack of building codes

A lack of available design guides and building codes was another barrier at Mediavaert. The CLT-hybrid floor was designed according to the pre-standard of the Eurocode 5 and on the supplier's European Technical Assessment (ETA). However, the available codes and norms did not provide sufficient design guides and rules for the openings in the glulam beams. In order to prove the structural integrity of these beams, experimental tests had to be performed. The costs of the teste were €14.000. If the tests would have failed, large delays would have happened. The beams would then have to be reengineered, before a new beam could be produced and then new tests would have to be performed.

Costs

The most important barrier at Mediavaert was costs. The costs were higher in comparison to the traditional variant of the building. Eventually the client was convinced by the sustainability advantages of timber and was willing to pay the cost surplus, which was 4-5% of the total construction costs. The extra costs were mainly determined by the material prices of the timber elements. However, some of the extra costs were related to other aspects like a lack of experience and knowledge at various parties, which led to many second opinions. After some of the financial barriers have been elaborated on, strategies to overcome the financial challenges are presented.

Perceived risks and lack of experience

The novelty of this project and the lack of knowledge and experience might have heightened the total project costs. Engineering costs were higher compared to a traditional building since multiple second opinions have been performed to verify the building's safety:

"Why is it more expensive? I think it's also the fear of the contractor and the structural engineer. We have a wood hybrid structure, so wood where it is possible, but concrete and steel where it is necessary. So the connection of wood to steel, or steel to concrete, or concrete to wood, or wood to concrete and steel, that whole combination caused fear. You see that there is a fear in it, which is why everything, in my opinion, is over-dimensioned, and checked six times, because they are not used to it, you know." – Client

Insurance costs

Another challenge was to prove the fire safety of the building to the insurance company:

"We noticed that the insurance company is hesitant and scared. That is due to the uncertainties. I asked them about their practices in Austria and Switzerland. They build everything in timber there. But somehow they perceive it differently here. It takes time for parties to get used to innovations. We know the risks are not higher compared to a traditional building, but it takes time for other parties to realise this. Currently, the lack of knowledge at those institutions gives them cold feet". – Client

A possible solution is to include potential insurance companies and financial institutions in the very early design stages. However, that does not necessarily mean that it will be easier to insure the building. If the lack of knowledge or experience is the root cause of the financial premiums on timber buildings, overcoming that knowledge gap is essential. Another solution could have been to search for foreign insurance companies with more experience with timber buildings.

Use European Union Emission Trading System to sell carbon credits

When a building is designed with true circular design principles and maximum use of timber, the stored CO_2 can be sold. At Mediavaert, around 6500 m^3 of timber is used. Since it is a true hybrid building, also a substantial part of the structure is made out of concrete and steel. Taking all carbon emissions into account in phase A1 (material extraction) and A2 (production), the entire Mediavaert building is roughly net zero; the stored CO_2 in the timber elements compensates for the emitted CO_2 of the concrete and steel parts. When the use of concrete and steel would have been minimised, the building could have been an actual carbon sink, and then the stored carbon could have been sold.

To clarify the example, a calculation has been made to determine the potential revenue from selling the carbon credits. Table 10 shows that the sale of the stored carbon could have generated €740.000.

Table 10: Potential revenue by selling stored carbon

Volume of timber	6500 m^3
CO_2 storage per m^3	759 kg
Stored CO_2	4,9 million kg
Minimal price per tonne of CO_2	€150 (Climate Cleanup , 2024)
Potential revenue	***€740.000***

Use biophilic design principles to reduce sick leave costs

Biophilic design principles can contribute to a better work environment, potentially decreasing sick leave rates and subsequently reducing absenteeism costs. When this strategy is applied to Mediavaert, potential cost savings of almost 62 million are possible.

The just delivered project Mediavaert is 44.000 m^2 and is home to 2000 employees. The assumptions in this calculation are that employees work 47 weeks per year and that the average costs per employee is €100 per hour. That accumulates to an absenteeism of 62 hours per employee per year and an annual cost of €6211 per employee per year. Over the 50 year service life of the building, these costs add up to 620 million euros. Elzeyadi (2011) found that buildings built with biophilic design principles can reduce sick-leave with 10%. If 10% of these costs can be saved due to a biophilic design of the office space, 62 million euros can be saved. That is enough to compensate for the higher building costs.

Number of employees	2000
Costs per employee per hour	€100
Absenteeism hours per year	62
Absenteeism costs per year	€12,4 million
Absenteeism costs during building service life of 50 years	620 million
Potential cost savings	***62 million***

Increased residual value

The graph below shows a graph in which the building costs of Mediavaert are compared for a traditional variant and a timber-hybrid variant. Variant A is a reinforced concrete structure and variant B is a timber hybrid structure with CLT-concrete floors, and glulam columns and beams. Important to note is that there are some assumptions and some uncertainties in this graph that will determine if this is a real scenario or not. One uncertainty is the material price of timber in the future. The scenario in the graph below is only viable if the material price of new timber is higher than what it would cost to dismantle the building and sell the elements. It is impossible to predict whether that will be the case. Therefore, this graph is meant to give an indication of what could be possible. Data from this graph stems from the interview with the building physics consultant.

With growing awareness on CLT driving the popularity of timber construction, a rising demand for timber can be expected. Over time, this heightened demand could result in rising timber prices, which in turn might elevate the residual value of timber buildings. When a timber structure reaches the end of its service life, it retains value; the individual components can then be sold. The drop at the end of the graph for variant B illustrates this concept.

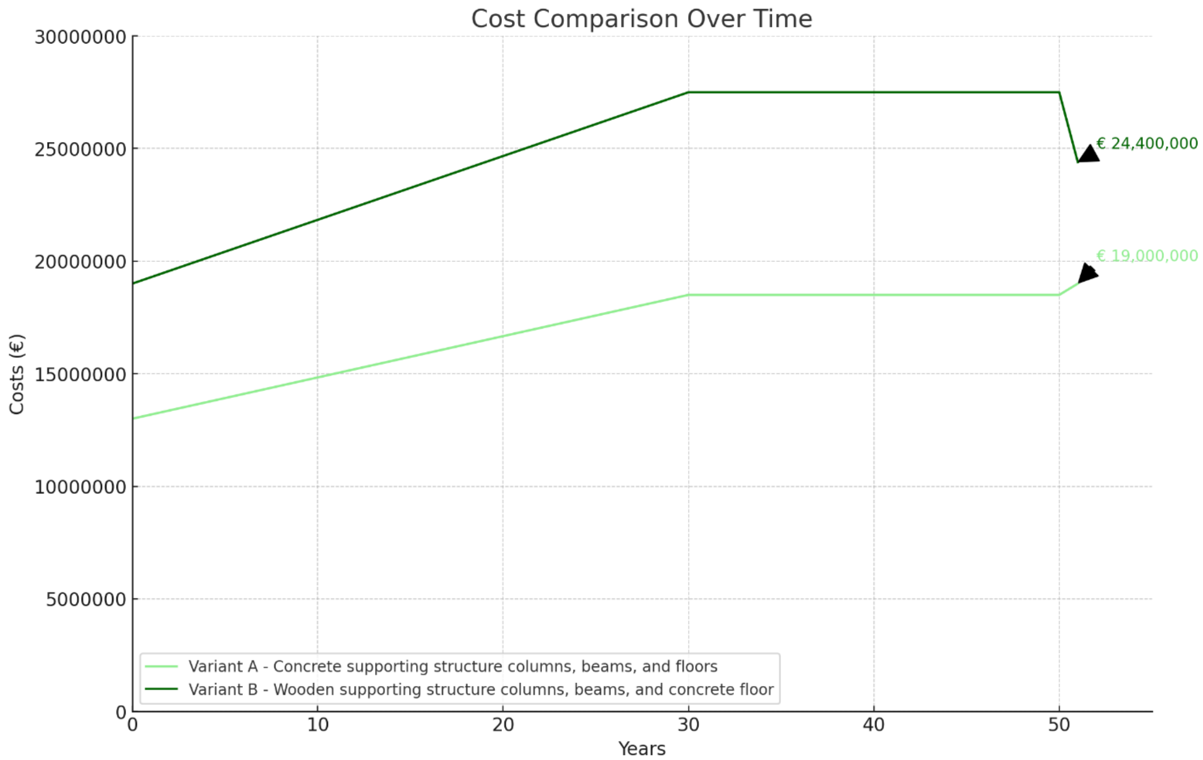

Figure 21: Life cycle costs of a traditional structure versus a timber-hybrid structure

9. Discussion

This chapter covers the discussion of the results obtained in this research. First, an evaluation on the results is provided which discusses the interpretations of this research. Then, the contribution of this research to existing literature is presented Lastly, the limitations of this research are discussed.

9.1 Evaluation of results

The main objective of this research was to study the drivers and barriers for the use of CLT in MSTBs in the Netherlands and to present a set of strategies that should overcome these barriers and that should enhance the adoption of CLT in the Netherlands. First, a critical literature review was carried out after which interviews were done to validate and compare the results. This chapter reflects first on the results of the drivers, then on barriers and lastly on the strategies.

9.1.1 Discussion of drivers

9.1.1.1 Political drivers

One political driver that was mentioned by literature is 'legislation pushing the use of timber'. This driver was mostly mentioned as a general driver in research papers, but not applied to the Dutch construction context. This is understandable, as most of the research papers were executed in other geographical areas. However, this political driver is also applicable to the Dutch context as various initiatives push the use of timber like the NABB and the Amsterdam Covenant Green Deal. While these drivers exist, participants in the interviews did not often explicitly mention these aspects as real drivers for the use of CLT in MSTBs. The reason for this was that other drivers like sustainability were perceived to be more significant. In literature that was quite the same. In conclusion, in the category of political drivers, the results of the interviews and literature review are quite similar and no large deviations were found.

9.1.1.2 Economic drivers

The results in the category of economic drivers were a bit different in literature compared to in the interviews. In literature, more than one third of the studies research papers stated that cost-competitiveness was a driver for the use of CLT in MSTBs. However, in the interviews, with one mention and less than 10% of the total interviewees, cost-competitiveness was perceived to be far les important of a driver. This deviation of results can be explained by various reasons. One important factor is the location of the study. The location of the study and the local characteristics of that construction industry can have a big impact on the economics of building projects. Some aspect that can contribute to this difference in costs are:

- Local construction culture
- Different supply chain
- Local common building practices
- Different legislation

Most of the reviewed papers were focussed on Scandinavia. In Scandinavia, building with timber is much more common and the timber supply chain is far more established than in the Netherlands. Those factors can contribute to lower construction costs for timber buildings in Scandinavia. Furthermore, due to the novelty of building MSTBs in the Netherlands, companies often perceive higher risks which increases total project costs. On the contrary, in Scandinavia building with timber is much more standard, and therefore risks associated with MSTBs are less significant.

9.1.1.3 Sociocultural drivers

The sociocultural drivers found in literature were underscored by most interviewees. Aesthetics was mentioned in 50% of the interviews and in around 40% of the research papers. The improved living environment was mentioned in 50% of the interviews as well, and in 25% of the research papers. This findings are much more similar than the economic drivers. This could be explained by the fact that aesthetics is a general aspect that is not tied to local factors. Despite, since aesthetics is personal and the sample size is twelve, it is therefore not possible to make general claims based on this study. But, it gives an indication of how CLT is perceived among various AEC industry practitioners in the Netherlands. Another notable finding is that the benefits related to biophilia were not often mentioned in literature nor in the interviews. This can be explained by the fact that biophilia is not widely known and encompasses quite specific knowledge that only a few people possess. Biophilia is not related to concrete and steel construction, what is the predominant construction method in the Netherlands. Therefore, many interviewees probably never came across biophilia before.

9.1.1.4 Technological drivers

In the technical driver category one noteworthy difference can be observed: the difference in perceived construction time. While a faster construction time is one of the most cited drivers in literature, the interviewees did not unanimously agree. Especially the contractors and suppliers mentioned that a faster construction time was not necessarily assigned to building with CLT, but more to building with prefabricated systems. In literature this was also said to be true, however, many studies did find that constructing MSTBs with CLT was faster than with traditional materials. This difference could stem from local characteristics, but it can have various other reasons. Further research, including large sample size comparisons and case studies, is needed to determine more precisely which construction methods are faster for different building typologies. The findings on fire safety were also very similar. Most interviewees and most papers identified fire as a barrier, while some mentioned fire-safety as a driver.

9.1.1.5 Environmental drivers

The results in the environmental driver category were very similar for the interviews and papers. Sustainability was mentioned in all interviews and papers as the most important driver. In the interviews, not everyone mentioned the distinctive sustainability aspects of building with CLT. However, all of them did mention at least one sustainability aspect. In literature this was the same.

9.1.2 Discussion of barriers

9.1.2.1 Political barriers

The political barriers category was, according to the results of the interviews, one of the most important category of barriers that hindered the adoption of CLT in MSTBs in the Netherlands. This does not entirely match the results of the literature review. This can be explained by the local factors that play a role in the Netherlands. The MPG system is a Dutch system which is only used in the Netherlands, and not elsewhere in the world. Other countries do have similar sustainability assessment schemes, but all systems work slightly different. So therefore the MPG system was never mentioned in any paper, just like the problems related to the NMD. In literature, some general political barriers were stated like 'a lack of policy and regulations' in 30% of the papers. In the interviewees however, political barriers were mentioned much more frequently.

9.1.2.2 Economic barriers

In literature, economic aspects were mentioned as drivers and barriers, while in the interviews economic aspects were mostly mentioned as barriers. The explanation for this difference is the same for the economic drivers, which can be found in 9.1.1.2 Economic drivers.

9.1.2.3 Sociocultural barriers

The sociocultural barriers found in literature matched the results of the interviews. A lack of knowledge and experience and unfamiliarity with CLT construction received equal mentions in literature and in the interviews. This can be explained by the fact that building MSTBs is not only relatively new in the Netherlands, but also globally. Very few tall timber buildings have been built until now, and therefore only a few practitioners have had the experience to design, construct, and engineer such buildings. Therefore, the lack of knowledge and experience is a broader issue. While in some areas building with timber is much more common practice, like in Scandinavia, building MSTBs of large scales does not occur that often.

9.1.2.4 Technical barriers

The findings on technological barriers were consistent between the interviews and the research papers. Fire-safety and acoustics were identified as the most important technical barriers. Given the diverse backgrounds of the interviewees, not all were able to identify many technical barriers, as this was not their area of expertise. Some of the barriers that received a little bit less citations were connections, stability, and structural performance. Overall, the results of the interviews aligned with those found in the literature.

9.1.2.5 Environmental barriers

Environmental barriers were said to be not relevant in the interviews. In literature some papers had doubts on the durability of CLT, but that had mainly to do with biological degradation. As was mentioned before, in this research only structural CLT not exposed to weather conditions is considered and is therefore not relevant. Besides this one exemptions, the results of the interviews were similar to those found in literature.

9.1.3 Discussion of strategies

9.1.3.1 Increase knowledge and awareness

The strategies in the 'increase knowledge and awareness ' category were mainly addressing the barriers related to the knowledge and experience gap. The lack of knowledge and experience received a similar amount of mentions in both interviews and in literature and naturally strategies were identified to address these barriers. While many interviewees agreed that knowledge sharing should be part of the solution, the practical implementation was still up for debate. Enhancing timber knowledge in academic curricula was one part of the solution, but sharing knowledge among industry partners was not always desired to maintain a competitive advantage. That behaviour can be explained by the culture of the construction industry that is quite fragmented. This strokes with the findings in literature.

9.1.3.2 Change industry

Strategies related to changing the industry addressed barriers related to costs, the supply chain, and the culture of the industry. One key takeaway was that a shift is necessary towards more collaborative relationships. Literature emphasized this as well, stating that collaborative relationships enhance innovation which is necessary for the emergence of new construction technologies. However, verifying the desired setup of the supply chain with existing literature proved challenging due to the distinct nature of the local timber supply chain in the Netherlands compared to other European countries. Some studies suggest that local timber supply should be part of the solution, but this is not applicable to the Netherlands, which lacks significant production forests. Therefore, these findings require consideration of the Dutch context and further research to draw definitive conclusions.

9.1.3.3 Create new financial models

The financial strategies proposed in the interviews received very few mentions. This, however, does not reflect on the credibility of these strategies but rather indicates their niche nature. Many interviewees were designers, engineers, or contractors with extensive knowledge of the technical aspects of building MSTBs, but less familiarity with financial aspects. Conversely, the cost consultant had greater expertise in financial matters but less in technical aspects. Consequently, financial strategies were not frequently mentioned. To determine with greater certainty whether these proposed strategies can count on broad support, larger field studies are needed.

9.1.3.4 Technical advancements

Some of the strategies that were proposed in this chapter were quite general, like increasing prefabrications and modular construction possibilities. Literature also mentioned those as important strategies. Full scale testing was one strategy that received relatively few mentions in interviews, but can be quite important to overcoming some technical barriers like fire-safety and acoustics. Fire-safety and acoustics were the most hindering technical barriers and oftentimes stem from a lack of knowledge and experience. Therefore, more testing to increase the validity of CLT can be part of the solution. This deviation can be explained by

9.1.3.5 Regulatory change

Regulatory changes were the top category of strategies based on the interviews. Various strategies received broad support among the interviewees with the desired change in the MPG system as the most prominent one. This reflects the broad concerns with the MPG system and highlights the importance of addressing this issue. These strategies are also hard to verify with literature, as these strategies strictly apply to the Netherlands. Updating building codes was a strategy that is also mentioned frequently in literature and in the interviews. The issue regarding CLT's compatibility with building codes is not only applicable to the Netherlands, but also to Europe.

9.2 Contribution of research

The results of this study contribute to the existing literature on MSTC. The drivers and barriers in literature were used as the basis for this study and therefore this study expands on the existing literature. The Dutch context seemed especially important for legislative factors and local supply chains. In literature, not many studies have been conducted in the Dutch context. Also, many studies focussed on either the drivers and barriers for the use of CLT in MSTBs, or on strategies to increase its adoption. This study combines these two aspects and presents a holistic view on increasing the use of CLT in MSTBs.

Moreover, this study also distinguishes itself from other studies based on the presented strategies. The proposed financial strategies were new to literature and are therefore an addition to the existing literature. This has various reasons. One reason is because for example trading in carbon credits is relatively new. Therefore, this strategy did not receive mentions in literature. Another example is using biophilic design principles to reduce sick-leave costs. This strategy is not new and was already known in literature, however it was not yet applied in the context of this research. Combining all different kinds of new financial models to make MSTB projects feasible was not done in a research paper before.

The proposed strategies are still of explorative nature and require further research to receive wide acceptance. However, it gives a good indication of possibilities to enhance the adoption of CLT in MSTBs.

9.3 Limitations of research

In the field study, several limitations can be distinguished. The first limitation of this study is the sample size of the interviews. In total, twelve interviews were conducted with a wide variety of industry professionals. Twelve interviewees is not enough to make bold statements and general claims. However, the purpose of this study was to identify the drivers and barriers for the use of CLT in MSTBs and to explore solution strategies to overcome these barriers. Therefore, this constraint does not hinder the purpose of answering the research question.

Another limitation of the field study has to do with the methodological approach. The interviews had a semi-structured approached, which allowed the interviewer to ask follow-up questions based on the answers of the interviewee. This allowed the interviewee to delve deeper into topics he/she had most knowledge on. However, this also means that with all the different interviews, different topics came along. If all the interviewees would have gotten the same questions, more comprehensive comparisons could have been made. But, since the purpose was to identify broad solution strategies, this approach is considered valid.

Another limitation of this research can find its origin in the composition of the interviewees. All interviewees were selected on the basis of having done at least one MSTB project. That requirement ensured that the interviewee had at least some experience with constructing MSTBs. On the contrary, it could also mean that the interviewees were biased by this factor. Since most interviewees have an interest in building with CLT, they could perceive the advantages to be more relevant than they in reality are. Recommendations for further research can be to also include industry professionals with almost no experience.

10. Conclusions

The main objective of this research was to study the drivers and barriers for the use of CLT in MSTBs in the Netherlands and to present a set of strategies that should overcome these barriers and that should enhance the adoption of CLT in the Netherlands. To achieve to goal of this research the following research question was formulated:

What are the key barriers and potential strategies to overcome these barriers for the widespread adoption of cross-laminated timber in multi-storey buildings in the Netherlands?

First, each sub-research question is answered. After that, the main research question will be answered.

SRQ1: What are important design parameters for cross-laminated timber in multi-storey buildings?

Successful implementation of CLT in MSTBs requires considering the following aspects:

- **Mechanical properties**. CLT's mechanical properties are influenced by factors like strength classes of the boards (C24 is common), panel dimensions, and timber species. CLT is a very light material and possesses a good strength-to-weight ratio.
- **Fire safety:** . In case of a fire, CLT undergoes charring, forming a protective layer that insulates the inner layers from flames. Common fire protection methods include increasing cross sectional dimensions to enable charring, encapsulation of timber elements, and installing sprinkler systems.
- **Thermal performance:** CLT's low thermal conductivity reduces the risk of thermal bridging, while its density enables heat storage, providing insulation in winter and preventing overheating in summer.
- **Acoustic performance:** Especially in MSTBs, low-frequency sounds can be an issue. Additional soundproofing measures might be required like acoustically decoupling structural elements, adding sound insulation, or by increasing mass.
- **Moisture management:** Properly dried CLT with a moisture content of around 12% can withstand centuries without biological degradation, but protection from moisture is essential to maintain its durability.

SRQ2: How is cross-laminated timber in multi-storey buildings implemented?

Various construction techniques exist to construct MSTBs. Three common approaches are: the platform frame method, balloon frame method and modular construction.

Platform Frame:

- One of the most widely used construction techniques, where each floor serves as a base for the next wall. Wall panels are installed first, then floor panels.
- This method's disadvantage is the compression stress perpendicular to the grain in floor elements, which can lead to crushing as the building height increases. To accommodate taller structures, the load-bearing area on the floor panels must be increased.

Balloon Frame:

- Load-bearing wall elements span continuously across multiple stories, with floor elements supported internally, avoiding stress perpendicular to the grain.
- Disadvantage: Scaffolding needed for upper floor construction due to lack of working platform.

Modular Construction:

- Modular construction is a building method that involves constructing modules of a structure off-site in a controlled factory environment. Once the modules are completed, they are transported to the construction site and assembled into the final building.
- Modular construction excels at using repetitive, standardized units for a fast assembly.
- Timber is ideal for modular construction due to:
    - It’s easy processing. This allows manufacturers to efficiently pre-cut various features into wooden components off-site, saving valuable time during construction
    - It’s lightweight properties, which simplifies transportation and installation.

There are various combinations of materials possible. Sometimes, the limitations of CLT require a hybrid structure. For example, the basement is usually made in concrete due to the presence of ground water. CLT also has limitations with spans. A CLT floor has a maximum span length of ten metres, but is optimal at around six metres. When the desired span length exceeds this maximum range, a different approach can be used with supporting beams, made from for example glulam or steel. Stability can pose challenges for all timber structures as well. Especially for tall timber structures, a hybrid structure with for example concrete is oftentimes more suitable. Concrete can be used in vertical or lateral load-bearing elements, such as concrete cores supporting timber frames or concrete plinths for the low stories. Concrete can also be used as a top layer on CLT floors to add mass and prevent horizontal displacements. Other configurations include concrete beams and columns with CLT floor decking. In hybrid structures, special attention must be given to the detailing of connections between the various materials. The choice for an all timber structure or a steal/concrete-timber hybrid structure is dependent on the design and function of the building.

SRQ3: What are the drivers and barriers for the use of cross-laminated timber in multi-storey buildings?

Various drivers exist for the use of CLT in MSTC. Environmental aspects are the most important drivers for the use of CLT, but some technical and social aspects were also identified as drivers. The most important drivers are:

- **Reduced Carbon Footprint:** Timber's natural ability to store captured carbon dioxide throughout its lifespan, combined with a lower-energy production process, gives it a significantly smaller carbon footprint compared to materials like steel and concrete.
- **Circularity:** Timber, unlike concrete and steel, is a readily renewable resource. Additionally, CLT itself can be reused or recycled at its end of life, further minimizing environmental impact.
- **Improved living environment:** Studies show that structural timber elements in sight can lower stress and improve focus, suggesting wood in buildings can promote well-being and productivity.
- **Rapid construction time**: MSTBs constructed with CLT can in some cases achieve a faster construction time compared to conventional approaches using reinforced concrete and steel.
- **Prefabrication and modular construction**: CLT's lightweight nature makes it ideal for prefabrication in controlled factories. This translates to high-precision, modular components that can be quickly assembled on-site, minimizing construction time and hazards.
- **Aesthetics**: There's a strong positive perception of structural timber among consumers, who associate it with being environmentally friendly, aesthetically pleasing, and contributing to well-being.

The biggest barriers are related to financial and political aspects, and to a lesser extent to sociocultural and technological aspects. The most important barriers are:

- **Milieu Prestatie Gebouw:** While the MPG score is used in the Netherlands to assess a building material's environmental impact, it can be misleading for CLT. The MPG assumes that the CLT in the building is burnt when the building reaches the end of its service life, unsustainable forestry management is used, and doesn't account for CLT's ability to store carbon, leading to an underestimation of its true environmental benefits.
- **Nationale Milieu Database:** There is limited data on timber products in the national environmental database (NMD) which leads to unbeneficial assumptions in the LCA methods.
- **Incompatibility with building codes:** Incompatibility with building codes poses a major hurdle for CLT adoption in high-rise buildings. The existing codes lack design guides and are oftentimes not economical.
- **Lack of cost-competitiveness:** Constructing MSTBs with CLT typically involves higher initial costs attributed to fire safety measures, extra engineering, and a less established supply chain in contrast to conventional materials. The unfamiliarity with CLT construction and the associated lack of expertise contribute to heightened perceptions of financial risks.
- **Lack of knowledge and experience:** A lack of experience and knowledge across the construction industry is a major hurdle for CLT adoption. Contractors perceive CLT as risky due to unfamiliarity and often opt for traditional materials like steel or concrete. Similarly,

architects and engineers may struggle to design with CLT due to limited knowledge and training. A cultural shift towards embracing timber and improved education are needed to address these knowledge gaps.

- **Lack of willingness:** Stakeholders favour familiar materials like steel and concrete due to existing expertise and predictable costs, while the perceived complexity and cost uncertainties of CLT construction discourage a shift. This, combined with traditional procurement practices focused on lowest price, creates a lack of willingness to adopt new construction technologies.
- **Fire safety:** Fire safety is a major hurdle for high-rise CLT construction in the Netherlands. Existing building codes don't fully address the unique fire behaviour of timber, and solutions like sprinklers or full encapsulation can be expensive or nullify secondary benefits like aesthetic or improved well-being.
- **Acoustics:** Acoustics present a significant technical challenge in timber construction. While solutions to acoustic problems exist, it requires complex detailing and specialized expertise. Unfamiliarity with CLT can make practitioners perceive it as risky, discouraging its use.
- **Connections:** The lack of standardized connections and details complicates engineering, especially in hybrid structures involving multiple materials.

SRQ4: Which are the opportunities and strategies to support the further implementation of cross-laminated timber in multi-storey buildings?

After the drivers and barriers were identified, several strategies were proposed to overcome the barriers and to exploit the benefits of using CLT in MSTBs. When all strategies were formulated, the strategies were grouped, and five key themes were identified, see Figure 22.

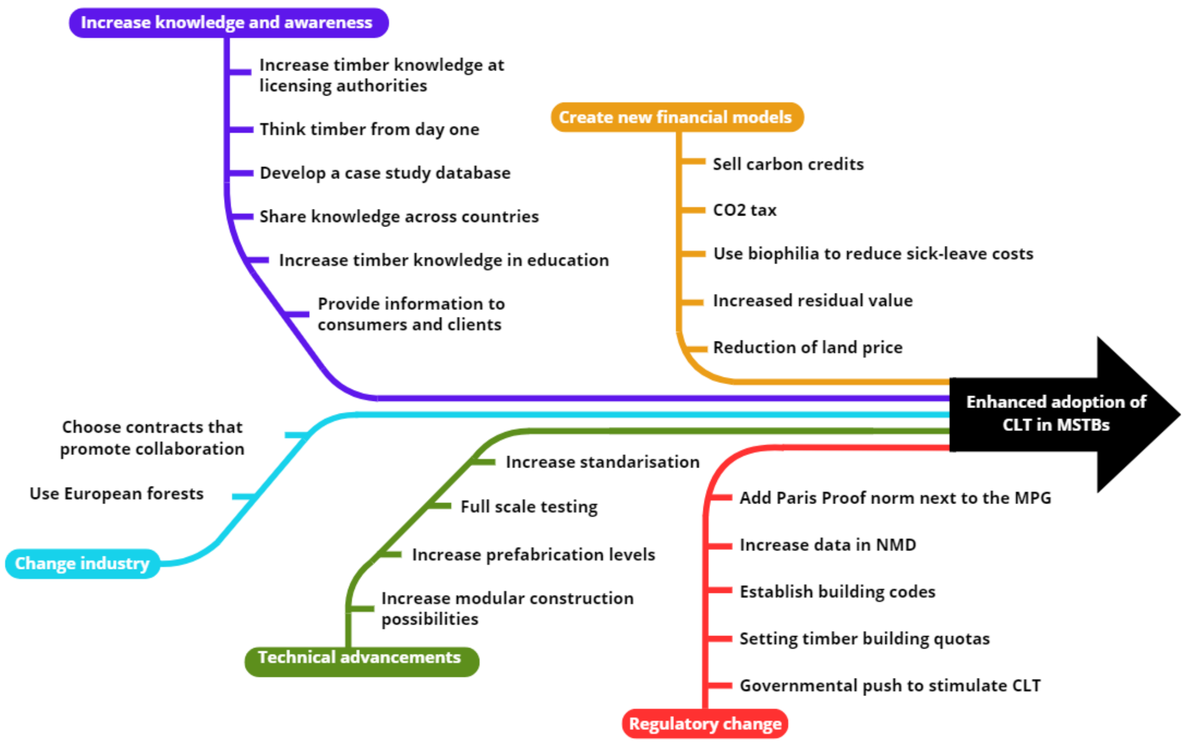

Figure 22: Strategies to enhance the adoption of CLT in multi-storey buildings

Increase Knowledge and awareness : This involves raising industry-wide knowledge and awareness about the benefits and capabilities of timber construction. Proposed measures include sharing knowledge internationally, developing a case study database, providing information to consumers and clients, and increasing timber knowledge in educational programs and among licensing authorities.

- **Share knowledge across countries:** Dutch companies can participate in study tours across countries where building with timber is more common practice. This should help with increasing industry-wide knowledge on MSTC.
- **Develop a case study database:** This database with project documents should improve knowledge sharing in timber construction. A case study database is introduced as a tool to analyse projects systematically. By comparing projects in the database, stakeholders can make better decisions on design, cost, and potential challenges.
- **Think timber from day one:** Building MSTBs requires a different approach from the very beginning. To avoid costly redesigns, timber expertise should be included in the design team from day one.
- **Increase timber knowledge in education:** Current academic curricula have a strong focus on traditional building materials. Increasing mandatory courses on modern timber construction techniques in architecture and engineering programs is desired. Extended programs with

research and industry collaboration would create a new generation of skilled timber professionals.

- **Provide information to consumers and clients:** Involving future owners in the design process and educating them about fire safety, acoustics, durability, and sustainability of timber houses could significantly increase the demand for CLT construction. Overcoming these knowledge gaps at consumers and clients would allow for a fair comparison with traditional methods and highlight the environmental benefits of timber.
- **Increase timber knowledge at licensing authorities:** The lack of knowledge and experience at licensing authorities complicates permit application processes. In order to speed up this process, it is important that licensing authorities possess enough knowledge on MSTC, especially with regard to fire safety.

Change Industry: To counteract the conservative nature of the construction industry and to improve the supply chain, strategies include moving from simple linear relations to collaboration in networks, and to use European forests for timber supply.

- **Choose contracts that promote collaboration:** Bouwteam or Design-Build contracts often enhance collaboration and yield better performance in cost control and frequency of modifications compared to traditional Design-Bid-Build contracts. Besides, engaging stakeholders during early design stages fosters more collaborative relationships within construction projects as well. Especially when value networks are created, insights from past projects can be shared which increases collective knowledge for future projects.
- **Use European timber production forests:** In Europe, more than enough timber is available to fulfil the future demand for MSTC. While increasing local Dutch timber supply can contribute somewhat, it should not be the main focus.

Create New Financial Models: This theme addresses the higher costs associated with CLT by proposing financial strategies such as leveraging carbon credits, applying biophilic design principles to reduce sick leave costs, and convincing clients of the increased residual value of timber buildings.

- **Use European Union Emission Trading System to sell carbon credits:** Companies can fight climate change and potentially earn money through emissions trading. By building with carbon-storing materials like CLT, buildings can become carbon sinks. These stored emissions can be converted into tradable allowances and sold, offsetting the higher costs of MSTC.
- **Use CLT to reduce carbon costs due to the CO2 tax:** The CO_2 levy in the Netherlands is a price instrument that aims to reduce greenhouse gas emissions. The rate of this levy increases yearly and leads to huge price increase for concrete and steel, and to a far lesser extent to CLT. Building with CLT can then save costs.
- **Use biophilic design principles to reduce sick leave costs:** Biophilic design principles can contribute to a better work environment, potentially decreasing sick leave rates and subsequently reducing absenteeism costs. Studies have shown that employees in biophilic environments experience less stress, improved cognitive function, and a stronger sense of well-being. This translates to a boost in productivity and a decrease in sick leave, creating a win-win situation for both employees and employers.
- **Convince client of increased residual value:** Timber buildings could potentially boast a higher residual value, when circular design principles are applied. This is because timber components

can be ‘dryly’ assembled with bolts and screws and therefore be deconstructed and reused in new projects. CLT floor/wall elements, and glulam beams and columns can be carefully dismantled and find a second life in another structure. This not only reduces construction waste but also allows the inherent value of the timber to be captured even after the building's initial service life.

- **Reduction of land price for societal benefits:** Governmental bodies could invest in sustainable building practices themselves, but they can also enable the feasibility of timber construction projects by lowering the price of land, specifically for MSTC. With this strategy, the municipality in question can contribute to making the construction sector more sustainable without having to invest a lot of time and effort itself.

Technical Advancements: Technical advancements are seen as a way to overcome some of the technical barriers and reduce costs. This includes increasing prefabrication levels, promoting modular construction, and conducting full-scale testing of CLT buildings.

- **Increase prefabrication levels:** Prefabricated building systems can shorten construction times, improve quality, and enhance collaboration within the construction industry, as shown by several studies. Manufacturers and distributors can develop pre-engineered solutions that address complex on-site challenges. Examples could be entire lift shafts or ready-to-install timber-concrete-composite floor systems.
- **Increase modular construction possibilities:** Large-scale modularization has the potential to reduce project costs by minimizing the need for engineering work for each module, as well as allowing for the replication of other modules. This not only saves costs but also accelerates construction times. Scaling up modular construction and ensuring that there are enough variations in modules can tackle multiple barriers at once.
- **Increase standardisation:** With CLT construction, very few standardised connections or details exist, leading to long design and preparation times and increased costs. Increasing standardisation through designs, increased prefabricated systems, and standardised details for material combinations should speed up the design process and reduce costs.
- **Full scale testing:** Large-scale testing conducted by independent organizations could validate product applications, for example to ensure fire safety. This independent verification would likely satisfy the requirements of insurance companies and financial institutions, enabling wider adoption of CLT in MSTBs.

Regulatory Change: Adjustments in regulations are suggested to support the wider use of CLT. Strategies include revising the MPG system to better account for biogenic carbon storage, expanding the national environmental database to include more timber products, establishing building codes that support timber construction, setting timber building quotas, and encouraging governmental support for scaling up CLT production.

- **Change the MPG system:** CLT is currently unjustly represented in the MPG system due to the fact that biogenic carbon storage is not accounted for and due to unjust assumptions for the end-of-life scenarios of CLT. Two adjustments are proposed:
    - A short-term solution can be a separate ‘Paris proof norm’ revealing a building’s embodied carbon footprint.

    - A long-term solution is to change the MPG standards (Dutch Determination Method & EN15804) to directly account for carbon storage.

- **Expand the NMD with timber products:** Currently, only a dozen timber products are registered in the NMD, including 15 CLT EPDs. If a CLT element from a supplier isn't registered in the NMD, it leads to unfavourable assumptions in MPG calculations for CLT. Thus, it's crucial for more suppliers to register their products in the NMD.

- **Establish Buildings codes:** Building codes lack design guides, and solutions proposed by pre-norms are oftentimes not economical, or don’t exist at all. Establishing building codes for CLT and other EWP’s is crucial to enable a smooth and rapid design process.

- **Setting timber building quotas:** To encourage the use of CLT in MSTC, the Dutch government could implement timber building quotas for public buildings, as well as for private buildings. This approach could build on existing initiatives like the MRA. Such quotas would promote and incentivize the use of CLT.

- **Governmental push to scale up CLT production:** Potential measures could be tax benefits for the purchase of equipment, government-sponsored training, architecture competitions focused on CLT as a building material, and research into the use of different wood species in CLT. The ‘Nationaal groeifonds’ can be used as funding to creating sustainable building practices.

What are the key barriers and potential strategies to overcome these barriers for the widespread adoption of cross-laminated timber in multi-storey buildings in the Netherlands?

This research aimed to identify the most important barriers for the widespread adoption of CLT in MSTBs and to present a set of strategies to overcome these barriers. Based on a qualitative analysis, it can be concluded the biggest barriers are related to financial and political aspects, and to a lesser extent to sociocultural and technological aspects. Firstly, the Milieu Prestatie Gebouw (MPG) score in the Netherlands may underestimate CLT's benefits due to assumptions about its end-of-life scenarios and forestry practices. Limited data on timber products in the Nationale Milieu Database (NMD) leads to inaccurate life cycle assessment (LCA) results. Both of these factors lead to an unfavourable outcome for CLT in the MPG score. Incompatibility with existing building codes, particularly in high-rise constructions, poses a major regulatory barrier as well. Furthermore, building codes lack design guides, and solutions proposed by pre-norms are oftentimes not economical, or don’t exist at all. Additionally, the higher costs associated with CLT, including costs for fire safety measures and engineering, contribute to its lack of cost-competitiveness compared to traditional construction, further amplified by a less established supply chain. Moreover, there is still till some extent a lack of knowledge and experience across the AEC industry regarding CLT, leading to perceptions of risk and reluctance to adopt it. The prevailing procurement practices focused on lowest price also hinder CLT’s adoption. Technical challenges encompasses fire-safety, acoustics, moisture, and connections.

A set of strategies has been developed, to overcome the aforementioned barriers. The first set of strategies is aimed at increasing industry-wide knowledge and awareness on CLT. The strategies are aimed at increasing knowledge at practitioners in the AEC industry, as well at consumers and clients to consulate them on the benefits of CLT as a building material. The second set of strategies is focussed on changing the industry by promoting collaboration and reorganising the timber supply chain. The third set of strategies addresses the cost barriers by offering new financial models to overcome the cost surplus of CLT construction. Costs were identified as one of the main barriers and offering alternative financial solutions is therefore important to ensure the viability of MSTC. The fourth category is focused on overcoming technical barriers by making technical advancements like improvements and innovations in prefabricated systems and increased standardisation. The last set of strategies is aimed at addressing regulatory barriers. Strategies include revising the MPG system to better account for biogenic carbon storage, expanding the national environmental database to include more timber products, establishing building codes that support timber construction, setting timber building quotas, and encouraging governmental support for scaling up CLT production.

11. Recommendations

This chapter contains recommendations for further research, as well as for the practical implementation of the strategies.

11.1 Recommendations for the practical application of the strategies

The previous chapters explored the drivers, barriers, and strategies to overcome the barriers for the use of CLT in MSTBs. While most of the barriers can be tackled with the proposed solutions, it requires many changes for the current AEC industry and a shift in thinking. The successful implementation of the proposed strategies is dependent on all parties involved; governments, architects, engineers, contractors, suppliers, consultants, and even consumers and clients. If standard building practices are continued like they have be done in the past, the likelihood of increasing the use of CLT in the Dutch construction sector is low. Therefore, to be able to accelerate the adoption of MSTC in the Netherlands, systemic changes are necessary. Below, each of the set of strategies will be provided with some practical recommendations. While some strategies are relatively easy to implement, other strategies require more effort. Especially strategies that require knowledge sharing and collaboration are expected to be more difficult to establish due to the nature of the AEC industry. Therefore, it is suggested to develop a timber building network in which collaboration and knowledge sharing is more common. After exploring the possibilities of developing a timber building network, the other strategies are further elaborated on.

Development of timber building network

It is recommended to discover the possibilities of developing a timber building network. This network can contribute to increasing knowledge industry-wide and fostering collaboration, which were one of the key strategies. Experts and stakeholders can use the timber building network to share knowledge about construction techniques, building physics, financing, business models, and all other aspects related to MSTC. Within this network, a case study database can be introduced which can give examples of finished MSTBs. This network should be accessible to all relevant stakeholders, including designers, engineers, contractors, but also governmental bodies such as municipalities and fire departments. Besides a case study database, this network can organise meetings where different stakeholders can give presentations on their projects. By incorporating educational institutions into this network, knowledge within these institutions can be enhanced, while practical problems faced by industry practitioners can serve as the foundation for research topics. This allows students and researchers to tackle real-world issues faced by the industry.

Increase knowledge and awareness

General knowledge sharing seemed to be important for an enhanced adoption of CLT in MSTBs. However, how this would be established is not unambiguous. One part of the solution is to create awareness at consumers and clients by providing sufficient information. This can be done in various ways, but one suggestion is to organise consultation meetings. It is quite common for new construction projects to organise such meetings to discuss the project details and the construction process. These meetings can also be used for to consulate interested parties about the safety and viability of CLT construction and take away possible fears.

Increasing knowledge at licensing authorities was another strategy to overcome the barrier of long permit application processes. Licensing authorities like municipalities and fire departments can increase their knowledge on MSTBs by joining the timber building network. During informative sessions, knowledge can be shared on fire safety and thereby increase the knowledge at these institutions. By partnering with countries where MSTC is more commonly practiced, issues perceived as problems can be addressed and resolved.

Create new financial models

The strategies to overcome the financial barriers are relatively unorthodox and not widely known in the industry. Therefore, the timber building network can be used to spread awareness on these financial strategies. Informative sessions can be used to explain how these strategies should be implemented and under what conditions these strategies can be successful. Some of these strategies can readily be applied if people are aware of them, like the strategy to sell carbon credits or the strategy that accounts for an increased residual value. Creating awareness on these strategies is most important for those to be successful.

Change industry

The strategy in the industry changes category that require most effort is the strategy to choose contracts that promote collaboration. It is suggested that the successful implementation of CLT in MSTBs is more likely with collaborative relationships. Especially collaboration within a network is desired, since knowledge in previous projects will not be lost, but kept inside the network. Therefore the timber building network can be used for parties to collaborate frequently and share the knowledge of previous projects.

Regulatory change

Increasing data in the NMD is dependent on multiple factors. The certification authorities state that the industry should prove the validity of their timber products, while industry professionals blame the certification authorities that their products cannot be licensed. While some timber suppliers have their products registered, most of the products are not yet registered in the NMD. It is recommended that timber suppliers continue to develop true circular timber buildings that satisfy the Dutch building decree to prove that building parts can actually be taken out of the building at the end of a building's service life. And it is recommended that the certification authorities will do further research on these CLT products and finished projects and smoothen the product certification process.

It is recommended for the MPG system to add a 'Paris proof norm' which accounts for all embodied CO_2 emissions. The national government can then use this norm to steer on carbon emissions. It is recommended to establish a path towards a circular building industry in which the Paris Proof Norm can play a role. When the national government sets these long term goals, it is clear for all industry practitioners what to expect.

Timber building quotas are another instrument to enhance the adoption of CLT in MSTBs. Building projects have generally long start-up period, especially with innovative construction practices. Therefore, it is not expected that when timber building quotas are set, immediately many MSTBs will be built. A project can take up to ten years from start to finish. It is therefore important to be quick with the implementation of this kind of policies for the strategy to be successful.

Technical advancements

Technical advancements can accelerate the adoption of CLT in MSTC. When innovative solutions are found for technical problems, barriers can be overcome. Educational institutions can play a huge role in this. Close collaboration between educational institutions and industry practitioners is important to tackle the most problematic issues with CLT construction. The timber building network can facilitate these collaborations.

11.2 Recommendations for further research

This section provides recommendations for further research. The first suggestion is to test the strategies on more case studies. This means that more studies on different types of buildings have to be conducted, including residential and office buildings, as well as buildings of various dimensions. For example the strategy to sell carbon credits is dependent on the volumes of timber in the building. It could be the case that the volumes of timber vary for different building typologies or structural systems, which would result in differences in potential revenues. Therefore, more case studies have to be conducted to test whether this is the case or not.

Moreover, some strategies, like the strategy to reduce sick-leave costs, are dependent on certain unknown variables. The sick-leave rates that were used in the calculations were based on national sick-leave rates, which could be very different per specific company. The best way to check whether sick-leave costs can actually decrease is by measuring the sick-leave rates in the new Mediavaert office building and comparing those with the previous office building. The Mediavaert office building can be used to check whether these theories apply to the reality. Next to the Mediavaert office building, other office buildings can be studied as well and then validity of this strategy can be tested.

Research to overcome technical barriers

Research can help to overcome some of the technical barriers. Fire safety remains a technical barrier for many reasons. More research is necessary, especially on full scale building test setups to study CLT's fire behaviour in large volumes. Fire departments can also learn from these experiments and develop a deeper understanding of CLT's fire behaviour. Besides, research in acoustic detailing is also recommended, as acoustics can be a bottleneck for MSTBs, especially for residential buildings. And lastly, connections were another problematic barrier. Further research can overcome this barrier as well. But besides just finding solutions to some of the technical barriers, it is also important that the findings will be shared in the market, so that all parties can benefit from these innovative solutions. The timber building network can facilitate that knowledge transfer.

Research on installations

One potential barrier that has not been studied in this research is the integration of installations in MSTBs. With traditional construction, installations can milled in the concrete. However, with CLT other solutions have to be sought. This could mean that the floor height must increase in order to implement the installations on top of the CLT floor, which would mean that the total building height must increase as well, leading to increased costs. Hence, it is suggested to further research the effects of installations in MSTBs.

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Appendices

Appendix A	Interview set-up
Appendix B	PESTE analysis

A. Interview Setup

The interviews will be held on the basis of semi-structured interviews. The interview consist of five parts.

1. Intro + their experience with CLT
2. Suitability for multistorey buildings → Drivers / barriers
3. How to bridge barriers → strategies
4. Case study in depth interview → What were the challenges and how did they overcome them?

1. Intro + experience with CLT

- What is your role in your organisation? How long have you been working in the industry?
- What is your experience with CLT for multistorey buildings? (number of projects, what kinds of projects)
- How would you describe your knowledge on CLT?

2. Suitability for multi-storey construction

- What are drivers for the use of CLT in multi-storey buildings? *And elaborate*
- What are barriers for the use of CLT in multi-storey buildings? *And elaborate*
- What limits the widespread adoption of CLT for multistorey buildings?

3. Proposed strategies to bridge barriers:

- How do you think the aforementioned barriers can be overcome?
- What strategies do you propose to enhance the adoption of CLT as a primary building material for multistorey buildings?
- What is your perception of the following strategies? *Ask specifically per role of interviewee*
    - A CO_2 tax as a regulatory driver
    - Promotion of Research and development
    - Develop standardized CLT building systems and design guidelines to reduce engineering and design costs.
    - Increase products standardization through specialisation in multi-storey buildings
    - Increase prefabrication levels
    - Put more emphasis on CLT and timber in general in education.
    - Increase CLT production facilities in the Netherlands
    - Increase local production of timber

4. Case study

- What was the reason to choose CLT for this project?
- What challenges did you face due to the selection of CLT as the structural material? How did you overcome these challenges?
- What were the advantages of using CLT?
- What did you learn from this project with regard to CLT construction?

B. PESTE Analysis

The tables below show the PESTE analysis in which a D indicates that an aspect was mentioned as a driver and a B as a barrier.

Table 11: Political drivers and barriers per paper

Authors	Year	Legislation pushing the use of timber	Limited legislative support from state government and municipalities	Lack of regulatory driver	Standardisation and regulation	Lack of design guides and tools	Lack of policy and regulations
Santana-Sosa et al	2022						
Jones et al.	2022			B			
Roos	2021						
B. Xia	2021		B				
Hurmekoski et al.	2021						
Zaman et al.	2019			B			B
Markström et al.	2018				B	B	
Franzini et al.	2018		B				B
Karjalainen et al.	2018						B
Gosselin et al	2017						
Marfella	2017					B	B
Riala, Iola	2016						
Markstrom et al.	2015						
Low et al.	2014	D					
Toppinen	2014						
Roos et al.	2010						
Kremer, Symmons	2008						

Table 12: Economic drivers and barriers per paper

Authors	Year	Cost-competitiveness	Labour costs	Maintenance costs	(Lack of) standardization	Promotes innovation	Initial costs	Costs for fire protection	Insurance costs	Too much risk / Financial uncertainty	Investment already done in existing technology	Supply issues
Santana-Sosa et al	2022				B							
Jones et al.	2022	B		B					B			B
Roos	2021	B										B
B. Xia	2021	D/B	D	B			B	B				B
Hurmekoski et al.	2021								B			B
Zaman et al.	2019	D						B	B	B	B	B
Markström et al.	2018	D/B				D				B		
Franzini et al.	2018	D/B	D						B	B		
Karjalainen et al.	2018									B		
Gosselin et al	2017	D/B	D/B	D/B	B		B	B	B	B		B
Marfella	2017											
Riala, Iola	2016	B		B					B			B
Markstrom et al.	2015	B		D/B								
Low et al.	2014			B					B			
Toppinen	2014											
Roos et al.	2010	B										B
Kremer, Symmons	2008	D								B		B

Table 13: Sociocultural drivers and barriers per paper

Authors	Year	Aesthetics	(Lack of) Demand from client	May suit local building traditions	Lack of experience	Lack of knowledge	Limited technical education and training	Bad experiences	Lack of available professionals	More familiarity with other materials	Unwillingness and culture of industry	Experimental nature	Construction preconceptions
Santana-Sosa et al.	2022		B		B	B							B
Zaman et al.	2022		B		B	B				B	B		
Karjalainen et al.	2021		B		B	B				B		B	B
Marfella	2021									B			
Low et al.	2021	D			B	B				B			
Markström et al.	2019	D		D		B	B	B			B		
Franzini et al.	2018	D	B		B	B						B	
Markstrom et al.	2018				B	B				B			
Kremer, Symmons	2018	D				B							
Gosselin et al	2017	D			B	B	B			B		B	B
Toppinen	2017												
Jones et al.	2016		B		B	B							B
Hurmekoski et al.	2015	D		D	B	B	B			B			
B. Xia	2014				B	B	B			B		B	
Riala, Iola	2014				B	B							
Roos et al.	2010			D	B	B	B						B
Roos	2008	D		D							B		

Table 14: Technical drivers and barriers per paper

Authors	Year	Construction time	Better work environment	Quiet construction	Prefabrication possibilities	Constructability	Design flexibility	Structural performance	Improved living environment	Lightweight construction	Fire properties	Thermal performance	Safety during construction	Maintenance	Modular construction possibilities	Acoustic performance	Stability	Seismic performance	Mould and moisture	Interfaces with other materials	Many different building elements and joints
Santana-Sosa et al.	2022	D	D		D			B							D					B	B
Zaman et al.	2022	D					D	D/B			D/B	D		D		D/B			B		
Karjalainen et al.	2021					B															
Marfella	2021			D																	
Low et al.	2021	D	D					D/B	D		B		D			D	B	D	B		
Markström et al.	2019	D		D				B			B			B		B			B		
Franzini et al.	2018					D	D	B	D				D								
Markstrom et al.	2018	D						B			B			B		B			B		
Kremer, Symmons	2018	D		D	D			D			B				D				B		
Gosselin et al	2017	D		D			D	D/B		D	D/B	D		B		D/B	D/B		B		
Toppinen	2017																				
Jones et al.	2016	D						D/B		D		D							B		
Hurmekoski et al.	2015				D			D			B		D	D/B	D	B	B				
B. Xia	2014										B			B							
Riala, Iola	2014													B							
Roos et al.	2010					D	D		D	D	B					B					
Roos	2008						D	B	D	D	B	D		D		B	B		B		

Table 15: Environmental drivers and barriers per paper

Franzini et al.	Year	Renewability	Recyclability	Use of energy during production	Carbon footprint	Waste	Impact on environment	Reusability	Sustainability general	Points in green assessment scheme	Durability
Santana-Sosa et al.	2022		D						D		D
Zaman et al.	2022			D			D		D		D/B
Karjalainen et al.	2021										
Low et al.	2021	D	D	D	D	D					
Marfella	2021			D	D	D	D				
Markström et al.	2019						D			D	
Franzini et al.	2018						D		D		B
Kremer, Symmons	2018	D		D	D	D			D		D
Markstrom et al.	2018						D			D	B
Gosselin et al	2017			D	D				D		D/B
Toppinen	2017										
Jones et al.	2016	D		D	D						B
Hurmekoski et al.	2015						D		D		D/B
B. Xia	2014										
Riala, Iola	2014										B
Roos et al.	2010			D					D		B
Roos	2008			D	D						