EMPOWERING ARCHITECTS FOR SUSTAINABLE HIGH-RISE DEVELOPMENT:

A PARAMETRIC APPROACH FOR SUSTAINABLE TIMBER HIGH-RISE DESIGN.

by

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Abstract
The paper establishes the need for a parametric design tool in contemporary tall timber construction, combining literature studies, expert interviews, and case study analyses. Findings reveal seven key challenges, including economic feasibility and fire safety, and explore techniques from recent tall timber developments. The conclusion highlights the potential of tall timber in reducing carbon footprint, balancing costs and sustainability, and introduces a parametric design tool serving as a decision-support system for architects, promoting the transition to timber as the main construction material in high-rise structures.

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ABSTRACT

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KEYWORDS:
High-rise, Tall Timber, Timber Construction, Hybrid Construction, Parametric Design, Digital Design Tool.

I. TABLE OF CONTENTS

II. INTRODUCTION

The Netherlands is currently facing a severe housing crisis, with increasing housing prices and a shortage of available housing units (Korevaar & van Dijk, 2024). This crisis is exacerbated by rapid urbanization, leading to an explosion in the size of urban populations without a corresponding increase in housing supply (Nabielek & Hamers, 2015). A significant majority of the Dutch population resides in urban areas, constituting about 74% of the total population. Of these urban residents, 44% are located in cities (Nabielek & Hamers, 2015). This high concentration of the population in urban areas puts a strain on the housing resources on these areas, contributing to the housing crisis. The demand for housing is outpacing the supply, leading to skyrocketing housing prices and a shortage of available housing units (Boztas, 2023).

Traditional methods of housing delivery are proving to be insufficient to meet the rising demand, necessitating the need to find a solution for this problem. One such approach is to accelerate urban densification, a strategy that involves maximizing the use of existing urban areas to accommodate more residents. As part of sustainable urban development initiatives, cities in the Netherlands are actively exploring solutions to address the housing crisis. Rotterdam in particular, stands out as a city experimenting with densifying its city center by the means of high-rise (Suurenbroek, 2022). Which is according to industry experts, among Emiel Arends, necessary to be able to densify cities and solving the housing crisis (Suurenbroek, 2022).

However, despite the potential benefits of high-rise development for sustainable urban development, there are also significant challenges and impacts associated with the conventional materials used for high-rise construction. Concrete is the most widely used construction material in the world, and it is particularly dominant in high-rise construction (Bester & Bester, 2013). While concrete has undeniable structural qualities, it also brings a substantial carbon footprint along that poses a significant burden to the environment (Ali et al., 2015).

Concrete production is a highly energy-intensive process and contributes significantly to greenhouse gas emissions, notably through carbon dioxide emissions during cement production, one of the key components of concrete (Ali et al., 2015). According to Kerkhoven (2022), the construction industry in the Netherlands processes approximately 14 million cubic meters of concrete annually, resulting in a CO2 emission of approximately 3.5 million tons per year. Notably, 80% of this emission is related to cement production. Kerkhoven notes that the 3.5 million tons accounts for 1.7% of the total annual CO2 emissions in the Netherlands. The amount of CO2 emissions per cubic meter of concrete is on average 508 kg (Kerkhoven, 2022).

In recent years, the environmental impact of the excessive use of concrete in high-rise construction has raised concerns (Schouten, 2021). In response driven by sustainability and environmental considerations, the modern construction industry is witnessing a growing interest in timber as a construction material (Henry, 2021). While this interest has predominantly manifested in low- and mid-rise buildings, there is a notable shift toward incorporating timber in high-rise construction projects now as well (*Why Timber Is the Environmentally Friendly Building Material of Tomorrow | World Economic Forum*, 2019). While still a challenging alternative to traditional high-rise construction materials, timber offers the potential to significantly reduce the carbon footprint associated in the building sector.

Contemporary architecture has already demonstrated the potential of timber in high-rise buildings, with successful structures reaching up to approximately 86 meters in height (*Tallest Mass Timber Buildings – CTBUH*, 2022). Presently, there are relatively few projects on the horizon aiming to exceed this height. One of the notable exceptions include ‘The Dutch Mountains’, proposed to reach to heights of 100m and 130m (Vermeulen et al., 2021). Globally, other ambitious projects are slowly emerging in other countries as well, underlining timber's upcoming feasibility in high-rise construction, such as plans for structures as tall as 191 meters in Perth (Dumas, 2023), 300 meters in London (Gerst, n.d.), and a towering 350 meters in Tokyo (Forestry & Sekkei, 2018).

Although we see increasing potential for timber in high-rise construction, high-rise designs in contemporary architecture still heavily relies on traditional materials like concrete and steel.

Consequently, relatively few architects have experience with the complexities and requirements related to timber-based construction in high-rise design.
To help architects navigating the uncharted territory of timber as the structural material in high-rise design, this project and research aims to provide them with a digital design tool. Based on rules of thumb, this design tool helps architects navigating the complexities and requirements of timber-based high-rise construction. By doing so, architects can unleash their creativity while ensuring that their designs remain structurally realistic. The objective is to empower architects to create remarkable and efficient high-rise designs with a realistic structural basis early on in their design process.

Ultimately, this research seeks to contribute to the shift towards more sustainable timber-based high-rise architecture by reducing the barrier associated with the complexities and requirements that come with timber-based high-rise design. The aim is to make timber a more accessible choice as the main construction material in high-rise design.

Therefore, the main objective of this research is to develop a parametric design tool for timber-based high-rise construction, based on rules of thumb and performance criteria. This tool will enable architects to explore the potential and the constraints of timber as a structural material for high-rise buildings, and thereby to create sustainable and efficient designs that reduce the environmental impact and carbon footprint of high-rise construction. In order to do this, the aim is to answer the following research question: "*How can a parametric design tool be developed in order to aid architects in the design of sustainable and innovative timber high-rise buildings, guided by fundamental structural principles and performance criteria?*"

In order to answer this research question, I've formulated the following set of sub-questions:

sQ1. "*In contemporary Tall Timber development, what are the key challenges in adopting timber as the main construction material for high-rise buildings (in the Netherlands) and what methods are currently in use in the latest Tall Timber developments?*"

sQ2. "*In what way can the carbon footprint of high-rise structures be reduced effectively by incorporating timber as its main construction material, while also being an economically viable alternative to the conventional high-rise construction materials?*"

sQ3. "*What are the key parameters and (structural) rules of thumb needed for developing the parametric design tool for Tall Timber buildings?*"

III. THEORETICAL FRAMEWORK

This chapter will present an overview of the theoretical framework applied to this research, which consists of the following aspects: the compact city concept, Embodied Carbon Calculation, the Paris Proof initiative, the European Green Deal and Tall Timber.

3.1 Compact City Concept

The compact city concept, as outlined by Bibri et al. (2020), is a strategic urban planning approach, which aims to create sustainable urban environments through dense, diverse, and efficient design. This involves optimizing space use, promoting public transport connectivity to reduce reliance on personal vehicles, and ensuring proximity to essential services, thus minimizing car dependency which is beneficial for the environment. Connected with sustainable urban planning, it addresses challenges posed by population growth and fosters resource efficiency. Notably, the concentration of activities in high-rises, a key element of the compact city concept, contributes significantly to reducing carbon emissions by shortening commute distances (Bibri et al., 2020). This research embraces these principles, serving as a crucial framework that aligns with the goals of sustainable urban planning and contributes to the reduction of carbon emissions.

3.2. Embodied Carbon Calculation

In contrast to traditional metrics like MPG, which focus on operational efficiency, this research prioritizes the Embodied Carbon Calculation. This method offers a comprehensive view of a building's environmental impact, spanning extraction, manufacturing, transportation, and end-of-life considerations (Orr et al., 2020). By emphasizing the entire lifecycle, the goal is to provide a more complete insight of how sustainable timber-based high-rise projects really are, aligning with the broader research objective.

3.3. The Paris Proof Commitment

The Paris Proof Commitment, advocated by the Dutch Green Building Council, aims to realize the global Paris climate accords by shifting the focus from energy labels to actual energy consumption measurements. This aligns seamlessly with the research objective of evaluating the sustainability of timber-based high-rise projects. Emphasizing the significance of actual energy use as a more accurate metric, the commitment contributes to broader climate goals, fostering rapid sustainability in urban environments (*Paris Proof Commitment: "Measuring Actual Energy Use Makes Climate Goals More Achievable" - Dutch Green Building Council*, 2023).

3.4. The European Green Deal

In parallel to The Paris Proof Commitment, the European Green Deal, a ambitious initiative by the European Commission, seeks to transform the EU into a resource-efficient and competitive economy with no net greenhouse gas emissions by 2050. Going beyond the Paris Agreement, the European Green Deal sets more stringent targets, reflecting a comprehensive approach to combat climate change. The research is inherently linked to these transformative agendas, as it explores how timber, with its exceptional carbon storage capacities, can contribute to reducing the carbon footprint of high-rise structures. This aligns with the ambitious goals outlined in both the Paris Proof Commitment and the European Green Deal, collectively shaping the research trajectory towards a more sustainable built environment (*The European Green Deal - European Commission*, 2023).

3.5. Tall Timber

"Tall timber" in the building industry refers to the use of wood as the primary structural material in the construction of taller buildings. This method, known as "mass timber" construction, involves the use of large, solid wood panels, columns, or beams to construct buildings. This term is pushing the boundaries of what is traditionally considered possible with timber construction (Jennen & Koskamp, 2023). Elements used in tall timber are called Engineered Wood Products (EWPs), which include materials like Cross-Laminated Timber (CLT), Laminated Veneer Lumber (LVL), and Glued Laminated Timber (GLT), which are composite wood products with enhanced structural properties (Schreyer et al., 2019). In this research, there will be examined how these EWPs contribute to sustainable building practices by assessing their environmental impact, structural performance, and compliance with regulations. This will involve a life cycle assessment, evaluating their strengths compared to traditional materials, and exploring innovative design applications enabled by these materials.

IV. METHOD

This chapter will describe how the research questions will be answered, and thus which methods will be used to do so. Among others, these include; Literature Study, Case Study Analysis, Interviewing Industry Experts, Data Analysis, Tool Development (and Tool Evaluation and Optimalisation).

4.1. Literature Study

In order to address the above mentioned sub-questions and thereby the research question, a series of literature studies were selected as primary sources to develop a good understanding of the following aspects; contemporary tall timber development challenges and techniques(1), costs and profitability of timber as a structural material (2), lowering CO2 Emissions (3) and identifying structural rules of thumb for Tall Timber structural design (4).

4.2. Case Study Analysis

The case-study analysis will focus on some real-world projects that are at the forefront of Tall Timber development. For this part of the research three case studies were selected, the selection of these projects is based on location, therefore I selected the two tallest completed Tall Timber buildings in Europe (2nd and 3rd tallest in the world) and the tallest timber-based buildings in The Netherlands (4th tallest in the world). The focus of these case studies to bring out key aspects or techniques rather than comparing the same for each project, contributing to get an overall understanding of Tall Timber projects.

4.3. Interviews Industry Experts

The interviews with industry experts will encompass individuals specializing in timber construction, high-rise design and engineering, parametric design, BIM Workflow Optimization, and business development. Selections will be made based on the participants' extensive experience and expertise in their respective fields. To ensure a comprehensive understanding of the diverse perspectives uncovered in the research, the panel of experts includes a structural engineer with expertise in timber construction and high-rise design, two engineering consultants with a focus on timber-based high-rise construction, and two architects, one specializing in Parametric design and the other bringing broad experience in high-rise design.

4.4. Data Analysis

The collected data from the literature review, case studies and expert interviews will be analyzed, documented and synthesized into a comprehensive set of additional data that is added to this research as appendices. Additional data that didn't derive from answering to the research questions needed for developing the parametric design tool, is gathered once more in '5.4. Data Analysis'.

4.5. Tool Development

By utilizing Grasshopper, a visual programming language in Rhinoceros 3D, a parametric design tool for architects aiming to design tall timber buildings will be developed. The goal of the tool is to provide feedback on structural feasibility and sustainability, allowing users to optimize their designs. Additionally, the Grasshopper script is compatible with software such as 'Rhino Inside Revit' and 'Grasshopper – Archicad Live Connection', enabling it to support and facilitate a wide range of architects.

4.6. Tool Evaluation and Optimalisation (Not included, MSc4)

The design study on the Unilever plot in Rotterdam's Central District, where the aim is to incorporate a 150m mixed-use residential tower with a focus on timber construction, will serve as a case study to validate the effectiveness of the parametric design system I aim to develop. During this phase the tool will most likely need to be optimized, since it will be the first time the tool will be tested. The selection of this location aligns with my research objectives and provides an ideal setting for the study.

V. RESULTS

This chapter shows all the results of the conducted research, both the positive outcomes and negative outcomes. The results section is build up in four paragraphs, the first three to answer their specific sub-question, and the fourth to gather additional data needed to ultimately answer the main-research question in the conclusion.

5.1. In contemporary Tall Timber development, what are the key challenges in adopting timber as the main construction material for high-rise buildings (in the Netherlands) and what methods are currently in use in the latest Tall Timber developments?

5.1.1. Biggest Challenges in Contemporary Tall Timber Construction

To understand what the biggest challenges are for using timber as the primary construction material for high-rise buildings (in the Netherlands), extensive interviews were conducted with industry experts [*see Appendix 1*]. The insights gathered in combination literature studies led to the identification of 7 key challenges of adopting timber as the main construction material for high-rise buildings (in the Netherlands), which are; *Economic Feasibility* (1), *Fire Safety* (2), *Structural Robustness Requirement* (3), *Acoustic Challenges* (4), *Limitations in Floor Systems* (5), *Vibrations Due to Wind* (6) and *Natural Characteristics of Timber* (7).

1. *Economic Feasibility*: One of the most significant challenges faced in tall timber projects is ensuring their economic feasibility. Which is commonly perceived as the reason why a lot of projects in contemporary architecture are still build in traditional materials as concrete and steel. Current research supports this notion, showing that timber buildings tend to be economically costly and are only financially viable in certain countries. (Tupenaite et al., 2021).

2. *Fire Safety*: Given that wood is inherently flammable, adhering to fire safety regulations presents a significant challenge. Buildings taller than 70 meters fall into Consequence Class 3 (CC3), necessitating a minimum fire resistance of 120 minutes before potential collapse [*see Appendix 1, Interview 1, 2 and 3*].

3. *Structural Robustness Requirement*: Structurally, tall timber faces a substantial hurdle concerning compliance with the "Robuustheidseis" or robustness requirement. As explained by Siemon Bisschop, this entails constructing a building in a way that enables the structure to withstand the failure of a construction element without overall collapse [*see Appendix 1, Interview 1 and 3*].

4. *Acoustic Challenges*: The relatively light weight of wood introduces challenges in dealing with impact sound. Achieving high-end soundproofing demands, especially in the insulation of apartments constructed solely in timber, proves to be a challenging task [*see Appendix 1, Interview 1 and 3*].

5. *Limitations in Floor Systems*: Solid timber floor systems encounter limitations in seamlessly integrating piping, a feature easily achieved through in situ concrete pouring [*see Appendix 1, Interview 3]*. The intrinsic characteristics of solid timber lack the flexibility needed for the effortless incorporation of piping channels, presenting a challenge in meeting plumbing system and utility requirements. As a result, alternative strategies for routing and installing piping in timber structures become imperative, demanding careful consideration during both design and construction phases.

6. *Vibrations Due to Wind*: The response of tall timber buildings to wind-induced vibrations emerges as a critical consideration for structural integrity and occupant comfort. Timber's inherent lightness and flexibility, advantageous in many aspects, increase vulnerability to wind forces. Effectively addressing and minimizing these vibrations necessitates a detailed examination of timber's dynamic behavior under various wind loads. While admitted to be very difficult to calculate via rules of thumb, this is something that is important to consider when designing Tall Timber [*see Appendix 1, Interview 3*].

7. *Natural Characteristics of Timber*: The way timber products are orientated significantly influences the strength and stability of timber constructions, since timber only has its great resistance along the grain direction. Proper alignment is crucial for optimal structural performance [*see Appendix 1, Interview 1*]. Additionally, natural tendencies such as shrinkage and creep must be carefully managed during material selection and design to ensure the resilience of high-rise timber buildings.

5.1.2. Techniques Behind Most Recent Tall Timber Developments

Due to the development of EWPs like CLT, LVL and GLT, over the last 10 years building in timber picked up momentum, with completion of buildings till 81m and proposals reaching till 350m tall (*Tallest Mass Timber Buildings – CTBUH*, 2022). In order to get a better understanding of the techniques required to build tall with timber, of most recent tall timber developments three case studies were selected. The selection of the case studies is based on; structural system, building height and location. Especially its location was decisive since regulations for building with timber can vary a lot between governments of different countries. Therefore, the following European located projects were chosen: Mjøstårnet (*Brumunddal, Norway*), HOHO (*Viena, Austria*) and HAUT (*Amsterdam, The Netherlands*). Accompanied with information extracted from interviews with industry experts, the most notable specific techniques behind these projects are listed below.

5.1.2.1. Fire Safety Techniques

Insights from industry experts [*see Appendix 1, Interviews 1 and 2*] reveal varied strategies to meet fire safety regulations:

1. *Wrapping in Fire Retardant Material*: A common approach involves wrapping timber structures in fire-resistant materials, such as plasterboard. Case study HAUT implemented this strategy for fire safety and sound insulation, addressing potential interactions between burning surfaces [*see Appendix 2, Case*

Study 2]. However, a downside of this strategy is that, by applying it, the (often perceived as aesthetically pleasing) timber is not visible anymore, as it is enveloped in fire-retardant material.

2. *Over-dimensioning Timber Elements*: Another effective solution is over-dimensioning timber elements, creating larger structural components. Mjøstårnet successfully employed this approach, conducting rigorous burnout tests on large glulam columns for self-extinguishing capability [*see Appendix 2, Casestudy 1*]. Fire retardant paint and plasterboard were selectively used for exposed wood in escape routes and CLT walls. However, a downside of this strategy is that structural elements become rather large, potentially exceeding the economical limits outlined by Dutch regulations [*see Appendix 1, Interview 2*].

Additional measures at timber element joints include; A sprinkler system, as seen in *Appendix 2, Case study 2,* intumescent fire strips to seal gaps and deep embedding of steel plates and dowels, enhancing overall fire resilience.

5.1.2.2. Tall Timber Structural Design Principles

When examining three case studies, distinct construction principles emerge for Tall Timber. Mjøstårnet and HoHo both employ a post and beam system, but with different lateral stability methods. Mjøstårnet utilizes a diagonal truss system [*see Appendix 2, Case Study 1*], while HoHo features a reinforced cast-in-situ core, forming a hybrid system. Robustness has been ensured with horizontal tension connections integrated in its floors vertically this was done by the means of large diameter reinforcing bars integrated in its columns [*see Appendix 2, Case Study 3*]. HAUT adopts a shear-walled system combined with a concrete core and diagonal truss for stability, enabling the design of large vertical windows [*see Appendix 2, Case Study 2*].

5.1.2.3. Floor soundproofing Techniques

Addressing soundproofing challenges in timber construction, various methods for soundproofing floors are employed:

1. *Timber-Concrete Hybrid Floor*: Given the difference in mass between concrete and timber floors, a common approach is to enhance soundproofing by additional concrete on top of timber floors, creating a timber-concrete hybrid floor. Additionally, this gives the opportunity to integrate rebar in the concrete top of the floor to comply with structural demands. This method is implemented across both case studies HAUT and HOHO [*see Appendix 2, Case Studies 2 and 3*].

2. Sand-filled Mass Honeycomb System: An alternative, more sustainable upcoming approach, revealed in an interview with an industry expert [*see Appendix 1, Interview 3*], involves the use of the 'Sand-filled Mass Honeycomb System.' This system, by adding approximately 1,500kg per m3 of extra weight, not only provides sound insulation benefits but also eliminates the need for unsustainable concrete.

5.2. In what way can the carbon footprint of high-rise structures be reduced effectively by incorporating timber as its main construction material, while also being an economically viable alternative to the conventional high-rise construction materials?

In order to answer this sub-question, this section explores the potential of using timber as the main construction material in high-rise structures, aiming to significantly reduce its carbon footprint while assessing its economic viability compared to conventional materials. In order to meet the goals set in the Paris Proof Agreement and the European Green Deal, Tall Timber emerges as a strategic solution. By shifting from concrete and steel towards bio-based materials like timber, with exceptional carbon storage capacities, there is the potential to transform the polluting high-rise construction industry into a man-made carbon sink. Responding to global and even more challenging European sustainability goals (Paris Proof Commitment: “Measuring Actual Energy Use Makes Climate Goals More Achievable” - Dutch Green Building Council, 2023; The European Green Deal - European Commission, 2023).

5.2.1. Lowering CO2 Emissions

Highlighted in the case studies of HoHo and HAUT [*see Appendix 2, Case Studies 2 and 3*], the environmental benefits of timber construction are evident. HoHo, with 75% of its volume in timber, has produced 2800 tons less CO_2 compared to conventional materials. Similarly, HAUT, if built entirely with concrete, would have emitted 45% more CO_2 during construction. What underscores the significant difference timber as a construction material can make to address global environmental concerns.

Also in terms of embodied energy consumption, timber construction proves significantly more sustainable than concrete, which accounts for 8% of global CO_2 emissions (Andrew, 2018). Compared to steel and concrete, timber structures consume 12% and 20% less energy, respectively (CWC, 2007). This way, embracing timber as a primary construction material aligns with Paris Proof and the European Green Deal, offering a substantial reduction in the carbon footprint of future high-rise structures, not only during construction but also throughout their operational lifespan.

5.2.2. Costs of building tall in timber

Recent research shows that one of the main reasons for the reluctance towards Tall Timber is the perception of higher cost (van Helmond, 2022). While front-end costs of mass timber buildings are 26% higher compared to concrete alternatives, analyzing Total Life Cycle Costs (TLCC) over a 60-year period reveals a 2.4% cost advantage for mass timber buildings, despite the initial cost difference due to higher end-of-life salvage value (Gu et al., 2020). Additionally, construction in timber is much quicker than traditional materials, therefore reducing construction time by almost 60%, saving costs (Mallo and Espinoza, 2016). Still, Dutch architect Do Janne Vermeulen who worked on case study HAUT notes that building a timber-based tower like HAUT [*see Appendix 2, Case Study 2*] is more expensive (for now), relative to traditional materials (Comello, 2022).

5.2.3. Profitability of Tall Timber

In order to find out how timber, as the primary material, could be viable as an alternative to traditional materials in high-rise projects, it is crucial to explore ways it could be profitable. Research reveals that a carbon emission tax could be impactful solution. Carbon emission costs, which are determined by multiplying the total CO_2 emissions with a CO_2 price, would significantly stimulate the use of timber(van Helmond, 2022). Additionally, the same research highlights that current regulations don’t include ‘Biogenic carbon’, which is the carbon that is stored in biobased products such as timber (van Helmond, 2022). Advocating for the inclusion of Biogenic Carbon in building regulations is essential to enhance the profitability of tall timber projects. Moreover, including both emitted and stored carbon, provides a more comprehensive understanding of the environmental impact.

Another way that can lead to further cost reductions and increased efficiency, is ongoing research and innovation in timber construction technologies, materials, and design methodologies, making tall timber buildings more financially viable. Architects working on timber-based high-rise projects confirm that this goes also for large scale application of timber. As Architect Brjarne Mastenbroek states "Scale enlargement is extremely important. Otherwise, it [Tall Timber] remains an exclusive product (VPRO, 2019).”

In an interview, Dirk Visser pointed out that for projects that have to comply with Dutch regulations, columns larger than 0.7x0.7m become uneconomical, as they cannot be included in the Rentable Floor Area (RFA) of a building [*see Appendix 1, Interview 2*]. Since structural elements exceeding $0.5m^2$ are excluded from the RFA calculation. For residences, the GFA/NFA (Gross Floor Area/Net Floor Area) ratio is crucial. The choice to overdimension structural elements for fire safety, such as columns, could exceed 0.7x0.7m. Therefore the need for a timber structure of larger dimensions compared to a slimmer structure of traditional materials, could lead to favor traditional materials in terms of profitability, allowing for more square meters of NFA to be considered within the same building. Additionally, as other research points out, timber structures with smaller floor spans tends to increase profitability as well (van Helmond, 2022).

5.2.4. Balancing Sustainability, Costs and Profitability

The decision to embrace timber as the primary construction material in high-rise structures involves delicately balancing sustainability, construction costs, and profitability. While timber construction significantly reduces the carbon footprint and aligns seamlessly with sustainability goals outlined in initiatives like Paris Proof and the European Green Deal, associated costs may present a challenge.

Although building cost advantages might appear to lean towards traditional materials for now, the expectation is that as timber becomes more standard practice, costs will gradually decrease. Therefore ongoing research, innovation and on-site experience are essential.

To accelerate future developments in Tall Timber construction, certain changes have to be made. This include potential changes in CO_2 taxation and including biogenic carbon into regulations. Such initiatives could significantly enhance economic viability, making Tall Timber more attractive as a construction material compared to traditional alternatives [*see Table 1*].

	Tall Timber *present*	*future*	**Traditional High-Rise** *present*	*future*
Sustainability	+	+	-	-
Building Costs	-	=	+	=
Profitability	-	=	+	=
	+	+	+	+
Result:	-	+	+	-

Table 1: Balance between Sustainability, Building Costs and Profitability in Tall Timber and Traditional High-Rises.

5.3. What are the key parameters and rules of thumb needed for developing the parametric design tool for Tall Timber buildings?

To develop an effective parametric design tool for timber-based high-rise buildings, it is crucial to identify key parameters and to structural rules of thumb. Drawing insights from contemporary research and interviews, along with practical considerations, the following aspects are identified;

5.3.1. Key Architectural and Structural Design Considerations

A comprehensive study of 13 international tall residential timber building case studies showed that Core planning (1), building form (2) and Floor-to-Floor height (3) were the most essential architectural parameters to take into account. Additionally, the vertical and horizontal structural system are also important factors to decide on when designing Tall Timber.

1. Core Planning: Core arrangements significantly impact structural stability, space efficiency, fire safety, and circulation. Different core arrangements, such as Central Core (1), Atrium Core (2), External Core (4), and Peripheral Core (5), offer varying advantages and disadvantages in terms of stability and efficiency. In this study came forward that of these different core arrangements, central cores emerge as the most common and preferred type for tall residential timber buildings, providing sufficient stiffness, compactness, and openness.

2. Building Form: The aesthetic, functional, and environmental performance of the building is influenced by its form. Building forms include Prismatic forms (1), Setback forms (2), Tapered forms (3), Twisted forms (4), Leaning/Tilted forms (5), and Free forms (6). Each form category carries unique considerations for stability and efficiency. Prismatic forms with rectilinear plans and regular extrusions are prevalent for their effective use of interior space and ease of workmanship.

3. Floor-to-Floor Height: Determining overall building height, cost, and comfort, the average floor-to-floor height of tall residential timber buildings is found to be 3 meters, meeting or exceeding minimum requirements for residential functions. The floor-to-floor height can vary based on different factors, such as the type of construction material used and the intended function of the space. Designers must adhere to a minimum clearance height of 2.6 meters, ensuring sufficient usable space. In the case of office buildings, an additional space, ranging from 0.5 to sometimes 0.8 to 1 meter, is required above the ceiling for installations, adding complexity to the overall height considerations in office structures [*see Appendix 1, Interview 5*].

4. Structural System: A distinction can be made of various Mass Timber Framing Systems, of which includes; Post & Beam construction (1), Hybrid Post & Two-Way Panel Deck (2) and Hybrid Light-frame & Mass Timber (3). This can be subdivided in to vertical elements like the Glue-lam Columns (1) and Mass Timber Shear Wall Elements (occasionally in combination with light framed walls) (2) and horizontally (Hybrid) Mass Timber Panels (1) or Beams (2). All for which multiple different Mass Timber Products are available with their accompanied advantages and disadvantages.(Jennen & Koskamp, 2023)(Schreyer et al., 2019)

6. Grid size: According to Architect Stephan Verkuijlen, in office design, grid sizes play a crucial role in both planning and structural considerations. Offices commonly follow to specific planning-grids, with variations between 1.2m and 1.5m. This grid guides the arrangement of workspaces, and the trend favors the 1.5m grid for more spacious layouts. For structural design, a structural-grids of 7.5m or 9m are common, aligning with the planning-grid of 1.5m. These structural-grids ensure efficient office space planning while also aligning with a buildings structure [*see Appendix 1, Interview 5*].

5.3.2. Rules of Thumb

In this section, a set of crucial rules of thumb, essential for developing the parametric design tool for Tall Timber buildings, are identified. These rules, outlined in detail in Appendix 3, encapsulate the following:

Formula Sheet 1 | Element Dimensions and Spans: This formula sheet shows the (initial) rules of thumb that can be used to get a global estimation of what the dimensions of certain structural elements will be.

Formula Sheet 2 | Total Load Calculation: This formula sheet shows the formulas needed to calculate the total load of the most critical column, which is needed to recalculate the refined column size, displayed on the following formula sheet [*see Formula Sheet 3*].

Formula Sheet 3 | Refined Column-size Calculation: This formula sheet shows the formulas needed for recalculating the column size based on the total load obtained from the previous formula sheet [see Formula Sheet 2] and the initially calculated column cross section that was based on rules of thumb on Formula Sheet 1.

Formula Sheet 4 | Additional Rules of Thumb: This formula sheet shows additional rules of thumb, such as for calculating the additional timber cladding needed to comply with fire safety requirements, for the minimum core width relative to its height and to calculate a structure's Embodied Carbon.

While the identified rules of thumb in this section form a robust foundation for developing a parametric design tool for Tall Timber buildings, it's essential to note that additional rules may emerge, enhancing the tool's adaptability to address evolving challenges and innovations in timber construction not covered by the listed rules.

5.4. Data Analysis

This chapter is dedicated to collect additional data from the literature study, interviews with industry experts and case studies that is needed for developing the parametric design tool. Some of the data collected will give restrictions on certain parameters already, of which the reasons for them are advocated here as well;

1. Minimum height: From an interview with Structural Engineer Siemon Bisschop of Pieters Bouwtechniek [*see Appendix 1, Interview 1*], it became evident that buildings falling under Consequence Class 3 are subject to a set of stricter regulations, posing a challenge to compliance. The goal of the tool is to provide architects with insights on how to meet such requirements. Therefore, to prevent overlap between different consequence classes, the minimum height is set at 70 meters, derived from Consequence Class 3.

2. Maximum height: A maximum height has been established as well, currently set at 150 meters. This aligns with the high-rise vision of Rotterdam, where 150 meters is a commonly referenced threshold (*Hoogbouwvisie 2019*, 2019). While wooden buildings exceeding 150 meters are not currently the norm (which is more than double the height of the current tallest timber building in the Netherlands), this parameter may be reconsidered in the future if circumstances deemed this necessary.

3. Concrete as a core Material: During the literature study it became evident that for timber buildings between 70 and 150m a concrete core was necessary to handle lateral forces (van Helmond, 2022)(Angelucci et al., 2022). Therefore, a concrete core has been preselected.

VI. DISCUSSION

Despite the diverse perspectives uncovered in the research, including sources both skeptical of and strongly in favor of timber in high-rise construction, it is essential to consider additional viewpoints. In addition to perspectives from architects, structural engineers, consulting engineers, experts in parametric design, experts in BIM Workflow Optimization, and business developers , insights from (sub)contractors (1), real estate developers (2), and policymakers (3) could be valuable as well. Particularly to gain a better understanding of the practical application of installations in Tall Timber or application of timber as a structural material in high-rise projects (1), a real-word perspective on the profitability of timber projects (2) and a view on the possibilities and challenges for implementing policy changes related to CO2 taxation and biogenic carbon (3).

Information gathered from conducting case studies may be limited, as the case study analysis was confined to 3 cases. Certain techniques and methods in contemporary Tall Timber development, due to not examining more case studies, could still remain unidentified. If more case studies had been selected, a greater variety of methods could have been identified and compared to the ones that were found. Despite the selected case studies intentionally focusing on geographic location (due to building regulations varying worldwide), the inclusion of additional case studies from outside Europe could have yielded further valuable insights. Nevertheless, the decision to exclude them was made to manage the overall scope of the research.

For the literature study, I searched mostly for sources related to the research question I wanted to answer. The interpretation of the obtained insights may be influenced by my subjective opinion as a researcher, possibly highlighting more positive aspects from studies and less aspects that might weaken my perspective on Tall Timber. To prevent this, it would be useful to validate the interpretations by discussing them with other researchers or industry experts.

Additionally, considering the fine line between an architect's influence in the design process and subsequent responsibilities of engineers is essential. For instance, sound insulation is a critical aspect to consider, but in the preliminary design phase, architects might primarily deal with broader concepts such as thicker columns and spans rather than intricate details of connections. While this may become relevant later in the process, integrating aspects like connection details is (in general) not something that an architect needs to worry about the preliminary design phase, where this tool is intended for.

Furthermore, the scope of this research has limitations when it comes to integrating certain critical aspects into the parametric design tool. As identified in this research, factors such as vibration calculations due to wind (1), lateral stability calculations due to wind (2), and the exploration of alternative core materials other than concrete (3) are examples of significant challenges in contemporary Tall Timber projects. However, due to the inherent complexity of these aspects, they could not be incorporated into the parametric design tool.

VII. CONCLUSION

The challenges identified in contemporary tall timber construction, including economic feasibility, fire safety, structural robustness, acoustic concerns, floor system limitations, wind-induced vibrations, and the natural characteristics of timber, provide a comprehensive understanding of the obstacles faced in adopting timber as the primary material. These insights form the basis for understanding what is important to keep in mind when setting up design parameters and guidelines within the parametric tool.

Analyzing the carbon footprint reduction and economic viability of tall timber structures reveals its potential as a sustainable alternative. Despite potential initial higher costs, the long-term advantages, including significant CO2 emission reductions, make tall timber an attractive option over a building's life cycle. The results underscores the importance of balancing sustainability, costs, and profitability, setting the stage for the integration of such considerations into the parametric design tool.

The identification of key parameters, rules of thumb, and design considerations for tall timber buildings is crucial for the development of the parametric design tool. Core planning, building form, floor-to-floor height, structural systems, and grid size, along with essential rules of thumb, provide the foundational elements required for the effective implementation of the parametric tool.

The development of a parametric design tool for sustainable and innovative timber high-rise buildings relies on the integration of identified parameters, rules of thumb, and design considerations. To meet this objective, insights from challenges, techniques, and sustainability aspects uncovered in the research above must be leveraged. The envisioned tool aims to facilitate dynamic and flexible design processes, addressing to the unique demands of tall timber structures.

Functioning as a decision-support system, the parametric tool provides architects with real-time feedback on certain design choices. Through the incorporation of sustainability metrics, cost analyses, and structural guidelines, the tool empowers architects to make informed decisions aligned with both environmental goals and economic considerations. This approach not only ensures sustainability but also promotes innovation in design.

Guided by fundamental structural principles encompassing load-bearing capacities and material strengths, the parametric tool maintains a commitment to structural viability. It navigates designs through robustness requirements, fire safety standards, and overall stability considerations. By incorporating identified structural design considerations, the tool guides architects in making decisions among various design options.

In essence, the parametric design tool is designed to guide architects through the complexities of designing tall timber structures in a complete and informed manner. By effectively integrating these elements, the tool becomes a comprehensive resource, paving the way for a future where timber stands as a viable and sustainable primary material for high-rise construction.

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