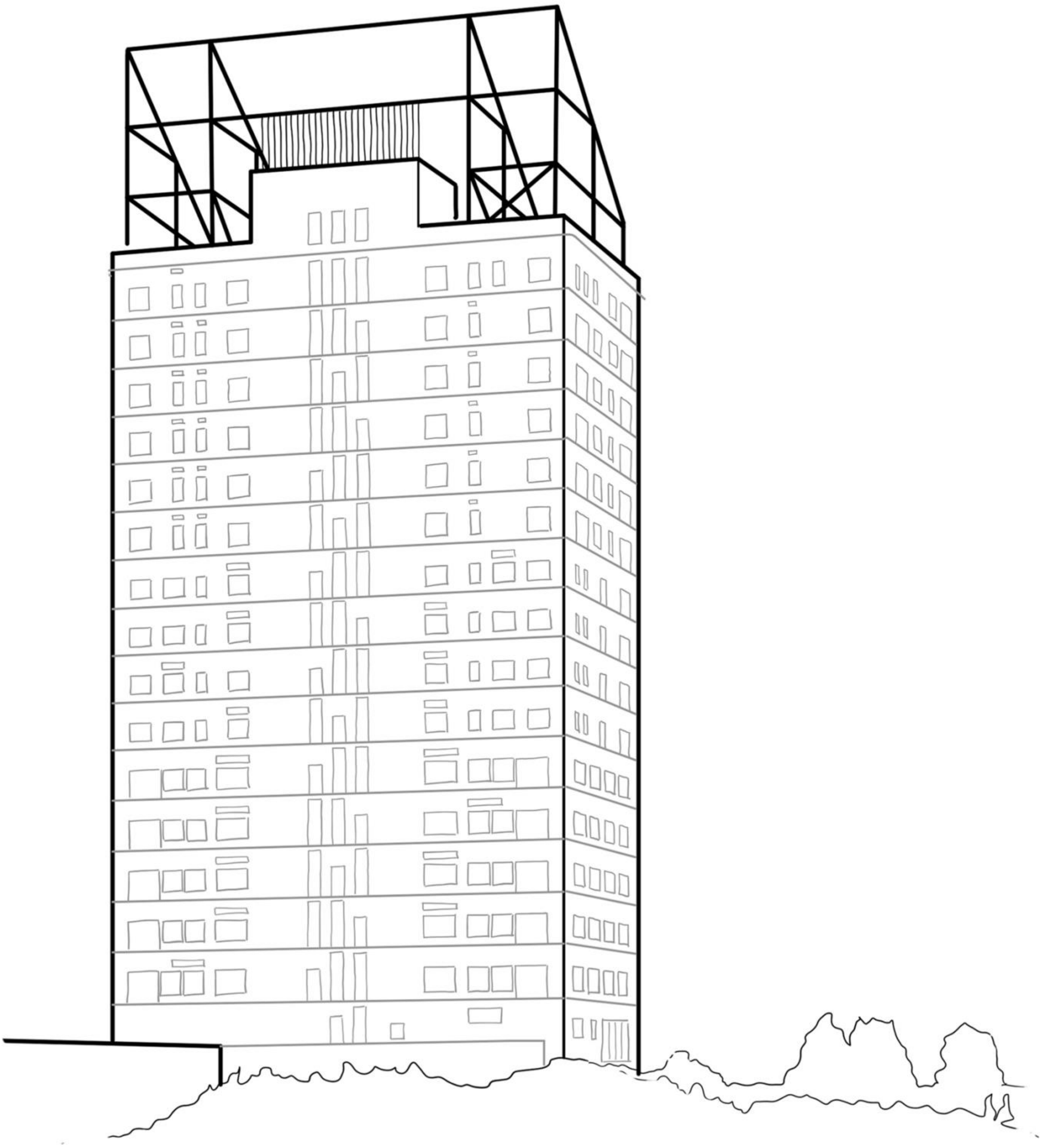
# ARCHITECTURAL LANGUAGE OF TALL WOOD BUILDINGS

## Structural Solutions for Architectural Language of Tall Wood Buildings



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# ARCHITECTURAL LANGUAGE OF TALL WOOD BUILDINGS

## Structural Solutions for Architectural Language of Tall Wood Buildings

Master's thesis
Faculty of Built Environment
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WOOD
HOTEL
VEIDEKKE
HENT

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# ABSTRACT

Marharyta Rämäkkö: Architectural language of tall wood buildings
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This study investigates tall wood buildings through the lens of architectural language as a concept. The aim is to acquire knowledge on the effect of structural solutions on the expression of this architectural language. The tall wood building is an extensively developing architectural phenomenon, which utilizes innovative wood-based products. The performance of these non-traditional wood-based products can be predicted with better accuracy, which makes them suitable for the demanding structures of tall wood buildings. As such, the development of tall wood buildings is parallel to the research and development of these wood-based products, which are more dimensionally stable than solid wood products could be.

Chapter two presents factors that affect the architectural language of tall wood buildings. It is assumed that building regulations, such as fire regulations and acoustic regulations; current material's diversity; and structural solutions affect the expression of tall wood buildings. The architectural language concept is presented to the extent, which allows its' utilization for the analysis of tall wood building's characteristics. Chapter three justifies the use of qualitative case study research, explains data collection methods, and presents Gioia methodology as a data analyzing method. The practical implementation of theoretical knowledge has been explored through two main studies in chapter four. In the first study, five sample buildings of different typologies have been investigated to understand the tall wood buildings' capability to express unambiguous architectural language. This investigation was strengthened by interviews with professionals in the field. The findings, which emerged from the interviews, are discussed in the second study. The conclusion of this study is presented at the end of the work.

Based on literature review and case studies, the architectural language of tall wood buildings is unambiguous but does not have a stereotypical expression yet. The tall wood building remains an exception even on the global scale. Therefore, its' structural solutions have not been standardized yet, which affects the relatively higher cost of the structures. Each structural solution remains unique and creates a characteristic architectural language for each case building. The distinguishable nature of tall wood buildings has consequently made it appropriate for a landmark or for symbolic purposes. It has also turned out as an excellent identity tool for city development.

This study reveals the need for further research of structural solutions for tall wood buildings and their fire performance. Even up to the present day, tall wood buildings have been implemented as experimental constructions. But because the evolution of this architectural phenomenon has been substantial, the number of tall wood buildings will undoubtedly increase.

**Keywords:** *tall wood building, engineered wood products, architecture as a language*

# TIIVISTELMÄ

Marharyta Rämäkkö: Korkean puurakentamisen arkkitehtoninen kieli
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Tämä työ tutkii korkeaa puurakentamista arkkitehtonisen kielen kautta. Tämän tutkimuksen tarkoituksena oli kerätä tietoa rakenteellisten ratkaisujen vaikutuksesta korkean puurakentamisen arkkitehtonisen ilmaisuun. Korkea puurakentaminen on laajasti kehittyvä arkkitehtoninen ilmiö, jossa hyödynnetään innovatiivisia puupohjaisia tuotteita. Korkean puurakentamisen kehitys on riippuvainen puupohjaisten tuotteiden kehityksestä ja tutkimuksesta. Puupohjaiset tuotteet ovat mittasuhteiltaan vakaampia kuin massiivipuutuotteet, jonka takia niiden suorituskyky voidaan ennustaa paremmalla tarkkuudella. Tämä tekee puupohjaisista tuotteista sopivia korkean puurakentamisen vaativiin rakenteisiin.

Luvussa kaksi on esitetty tekijöitä, jotka vaikuttavat korkean puurakentamisen arkkitehtuurin kieleen. Oletetaan, että rakennusmääräykset, kuten palomääräykset ja akustiset määräykset, nykyisen materiaalin monimuotoisuus ja rakenneratkaisut vaikuttavat korkeiden puurakennusten ilmaisuun. Arkkitehtuurin kieleen liittyvä teoria käsitellään vain siltä osin kuin se tulee tietää ja ymmärtää voidakseen hyödyntää sitä korkean puurakennuksen ominaisuuksien analysointiin. Luvussa kolme on perusteltu kvalitatiivisen tapaustutkimuksen käyttäminen, selitetty tiedonkeruumenetelmät ja esitetty Gioia-metodologia, jota käytettiin tietojen analysointimenetelmänä. Teoreettisen tiedon soveltaminen on esitetty neljännessä luvussa kahden päätutkielman kautta. Ensimmäisessä tutkielmassa tutkittiin viisi erilaista rakennustypologiaa, jotka auttavat ymmärtämään korkean puurakennuksen kykyä ilmaista yksiselitteistä arkkitehtuurin kieltä. Tutkimusta vahvistettiin alan ammattilaisten haastatteluilla. Haastatteluista saatuja havaintoja hyödynnetään toisessa tutkielmassa. Tämän tutkimuksen johtopäätökset esitetään työn lopussa.

Kirjallisuuskatsauksen ja tapaustutkimusten perusteella korkeiden puurakennusten arkkitehtuurin kieli on yksiselitteinen, muttei ainakaan toistaiseksi stereotyyppinen. Korkea puurakennus on poikkeus jopa maailmanlaajuisesti, joten rakenneratkaisut eivät ole vielä standardisoituneet, mikä vaikuttaa rakenteiden suhteellisen korkeaan hintaan. Jokainen rakenneratkaisu on ainutlaatuinen ja luo tyypillisen arkkitehtonisen kielen kullekin tapausrakennukselle. Korkeiden puurakennusten erottuva luonne tekee niistä sopivia maamerkki- tai symbolitarkoituksiin. Ne ovat osoittautuneet myös erinomaisiksi kaupunkikehityksen identiteettityökaluiksi.

Tämä tutkimus toi esille tarpeen tutkia tarkemmin korkean puurakentamisen rakenneratkaisuja sekä rakenteiden palokäyttäytymistä. Tähän asti korkeita puurakennuksia on toteutettu kokeellisina rakenteina. Korkea puurakentaminen on ilmiönä kasvanut voimakkaasti ja tulee korkeiden puurakennusten määrä lisääntymään tulevaisuudessa.

**Avainsanat:** *korkea puurakentaminen, puupohjaisia tuotteita, arkkitehtoninen kieli*

# TERMS

**Tall wood building**

Building over six-storeys in height that utilizes wood materials as a primarily material of its structural systems. This definition includes “all-timber” tall building, composite timber building, and mixed-structure timber building.

**“All-timber” tall building**

Building where the main vertical and lateral structural elements and floor systems are constructed from timber. Non-timber connections are allowed between the elements.

**Composite timber building**

Building where the main vertical and lateral structural elements and floor systems are constructed from combination of timber, concrete or steel acting compositely.

**Mixed-structure tall building**

Building that utilizes distinct timber, concrete or steel systems above or below each other.

**Engineered wood products**

Manufactured timber products that have been processed for increased quality.

# TABLE OF CONTENTS

# 1

# 1. INTRODUCTION

This chapter introduces the research topic by, firstly, providing the reader with background and motivation for this thesis. Secondly, it defines the objectives and research questions. Thirdly, the scope of the thesis is defined. And lastly, the structure of the thesis is presented.

## 1.1 Background and motivation

Even though architecture in its physical appearance has a very static nature, the forces behind the architectural development represent anything but a static character. Architectural development is shaped by dynamically mutable forces, which enhance the architectural diversity in all its shapes. This development wave coupled with technological innovations has created and enlivened the phenomena of tall wood buildings. The world of superlatively high buildings has recently opened a new chapter in its development with several over 80m high tall wood buildings now completed.

Tall wood building development however wasn't rapid. The main impediment for the tall wood buildings has been prescribed limits for the height of buildings with wood structure. This kind of impediment was affected mainly by fire regulations due to concerns about wood structures' performance if exposed to fire. The first positive signs for multistorey wood building development in Finland appeared when fire regulations were updated in 2011 (Ministry of the Environment 2011). This revision enables wood construction up to 28 meters high. This is a huge step for wood building development because concerns related to fire safety are deep-rooted and therefore resistant to change. These concerns are, however, well-reasoned and based mostly on catastrophic fire events from the past.

The development of fire regulations is influenced by many reasons. One of them is connected to government policies, which have sought to increase the number of wood buildings in the urban picture for more than 30 years. In Finland, this kind of tendency is motivated by the goal to diversify and increase the use of wood for construction and to promote internationally competitive wood construction know-how and industrial manufacturing business (Ministry of the Environment 2021). Another reason is the development of advanced wood-based products, which are dimensionally more stable than solid wood products. Based on this, the performance of "engineered" wood-based products can be predicted with better accuracy, which makes them suitable for demanding structures of tall wood buildings. Combined together, these reasons, such as the update of fire regulations, government policies, and developed wood-based products, have initiated the first tall wood building projects.

The development of tall wood buildings is in parallel with the development and research of wood-based products. Interest toward "engineered" wood-based solutions has emerged globally, which has affected a significant amount of studies, working on sorting, strength properties, bonding, and the development of new wood building products (Kaufmann et al. 2018). The development of these more advanced wood-based products has allowed the creation of all-timber structures, which transfer all the forces in the structures to the ground level and have significantly better fire performance than structures from solid wood products.

A significant step in the development of tall wood buildings has been the recognition of all-timber structures by the Council on Tall Buildings and Urban Habitat in 2019 (CTBUH 2021). Since then, the official guidelines upon which tall buildings are measured have included timber as a recognized structural system. The update of official guidelines is based on tall wood building discussions in the "Proposal for defining a tall, timber building" by Foster et al. (2016). This proposal defines single material tall buildings as "one where the main vertical and lateral structural elements and floor systems are constructed from a single material". However, these kinds of examples are rare even in global practice. Therefore, to provide a comprehensive analysis of tall wood buildings, hybrid timber structures will also be covered in this thesis.

One of the main benefits of tall wood buildings is their sustainable features. Wood has a low carbon dioxide footprint and often can be produced regionally (Green and Taggart 2017). Therefore, tall wood buildings can utilize local resources, which reduces the carbon dioxide footprint affected by logistics. The decrease in CO2 footprint of tall wood building is significant compared to the same building implemented in steel or concrete. However, the sustainable aspect is not the only benefit of tall wood buildings. Another essential feature is that tall wood buildings provided diversity to the architecture of tall buildings. Now architects have an option other than steel or concrete as the primary structural material of tall buildings.

## 1.2 Objectives and research question

The tall wood building is an emerging phenomenon in architecture. Therefore, there are no established architectural expressions or design guides for this kind of building. This thesis seeks to shed light on the possible architectural appearance of tall wood buildings through the concept of architectural language and define the aspects, which influence the characteristic signs of tall wood buildings. The case studies, interviews, and extensive literature review are used for these reasons. The aim of this thesis is to facilitate the challenging process of design by defining the critical characteristics of tall wood building structures and defining the direction of development for their expressive architectural appearance. Through this research, the author intends to encourage and enhance such development, and these issues and the opportunities for further research will be explored through the next research questions:

RQ1: Are tall wood buildings able to express an unambiguous architectural language?

RQ2: What kind of message/significance does the design of tall wood buildings have or should it have?

RQ3: What are the main limitations for tall wood buildings?

## 1.3 Scope of the thesis

As presented earlier, this thesis focuses on the effect of structural systems and features of used wood-based materials on the architectural appearance of tall wood buildings. This thesis investigates the possibilities of modern wood-based materials and the specification of their use for the structures of tall wood buildings. The specifications of these materials and structures will be covered to the extent, which allows for estimating their impact on the architectural language of tall wood buildings. The design process is explored in this research to understand the design solutions developed during the project's design stage. This doesn't include the evaluation and investigation of different forms of construction project implementation. Also, sustainability aspects will be presented in this research only briefly as an inherent part of wood architecture, which affects the architectural methods for tall wood buildings.

This thesis defines a tall wood building as a building over six-storeys in height. The empirical part of this thesis will include tall wood buildings, which are at least eight-storeys in height. Three of the case study buildings are constructed in Finland, one is constructed in Norway, and one is constructed in Austria. They have been chosen to provide diversity of use-purposes and structural systems for this research and to allow for research of architectural language expressions of tall wood buildings in different contexts.

## 1.4 Structure of the thesis

This study consists of five chapters. The first chapter, Introduction, presents the background and motivation for this thesis. This chapter also describes the objectives and sets three research questions, which guide this research. Furthermore, this chapter outlines the scope of this research. The second chapter, Theoretical Background, presents the structural concept of tall wood buildings briefly as an inherent part of wood architecture, which affects the design solutions for them. The second chapter also presents the building regulations for tall wood buildings, which are discussed on the basis of Finnish building regulations. In addition to this, the Theoretical background chapter describes currently available wood materials and related matters, such as critical characteristics and bonding agents, and current structural solutions. The third chapter provides the research methodology of the empirical research and presents three main aggregated dimensions of collected data. The empirical part, presented in the fourth chapter, is organized according to the three aggregated dimensions of collected data. The empirical part is divided into the two main studies, which are Conceptual Studies and Empirical Understanding of Architectural language of Tall Wood Buildings. Finally, the fifth chapter summarizes the finding of the empirical research, presents its limitations and the directions for possible future research.

2

# 2. THEORETICAL BACKGROUND

This chapter will present the theoretical background of this master's thesis, which is used to explore in depth the findings of the empirical research. The first part of this chapter briefly presents the sustainability aspects of tall wood buildings, as it is an inherent part of wood architecture. After this building regulations for tall wood buildings in Finland are covered, because they have a significant effect on architectural language. In the third part of this chapter the current and developing possibilities of the materials are extensively studied. In the fourth part the current structural solutions for tall wood buildings will be presented and analyzed. And lastly the concept of an architectural language is covered.

## 2.1 Sustainability aspect

The sustainability aspect of tall wood buildings will be presented via key concepts representing the inherent part of wood plays in buildings. When sustainable architecture is discussed wooden buildings are often the first thing which comes to mind. Wood's capability to absorb $CO_2$ has made it a guardian against climate change. However, it is important to understand that while trees capture carbon emission during their growth phase, they start to release the captured $CO_2$ when they die and start to decay (Green and Taggart 2017). In other words, if the forestry and timber industry stops continuous regeneration of forests and tree plantations, they can become net emitters of $CO_2$.

The transformation of trees to engineered wood products or any other enduring items can capture the $CO_2$ for a long-lasting period of time. In this case, sawn wood (felled trees) will keep the $CO_2$ captured during its growth period, but there also needs be new trees planted to replace the felled one and bind more new carbon. The trees' ability to capture the carbon is specie-dependent (Green and Taggart 2017).

Wood materials utilized in the constructions both captures the carbon for a longer period, and reduces the use of other materials, for example, steel and concrete, the use of which and production cause high carbon emissions. To understand the overall carbon emission of using any material for construction, designers need to discover the carbon emissions of all the processes required for the utilizing of the materials in the building. As carbon emissions are usually linked to the amount of energy required for a certain process, then it is relevant to evaluate the amount of "embodied energy", while evaluating the sustainability aspect of the building. Embodied energy includes energy calculations required to extract, process, fabricate, transport and install particular material or product and nowadays consider also usage and demolition phases of the building's lifecycle (Green and Taggart 2017). Therefore, the recycling, reuse and reduction possibilities of the material should be taken into account.

By discovering these beneficial capabilities of wood, it would superficially seem to be advisable to use wood for building whenever possible, but this kind of solution should be considered far more formally. The choice and use of wood as a construction material, should be conducted in a way, which ensures the continuous remaining of raw materials available (Kaufmann et al. 2018). The use of wood for construction should be optimized, and considered individually for every case, without generalizing of wood use in the building. Aspects such as fire safety, energy use, economic and interior climatic criteria will always affect the entirety of the building design, and result in the individualized optimal solution (Kaufmann et al. 2018).

However, sustainability is not only about carbon capture or emissions of the building, but also about the effect both on humans' mental and physical health. Wood is a natural and authentic material, which is highly appreciated, especially in urban living. Especially a wood surface creates positive feelings for the people contacting with it (Kaufmann et al. 2018). Wood is also able to create a healthy indoor climate by regulating the moisture level for human comfort and not emitting particles in the form of dust, fibres, or gases (Kaufmann et al. 2018). These kinds of qualities positions the wood as an attractive building material for public buildings, such as schools, kindergarten, offices, and residential buildings.

## 2.2 Building regulation in Finland

This chapter discusses the building regulations for tall wood buildings in Finland. While technology and engineered wood products (EWP) development are considered to be some of the main restrictors of tall wood building development, another restriction generator for the tall wood buildings is government building regulations. Therefore, it is essential to understand the site's country regulation system opportunities and limitations.

Building regulations in Finland for wood buildings aren't that different from any other buildings if the height of wood buildings is up to 28 meters. The main exception in the

Finnish building regulation system for all types of wood buildings is fire regulations. According to the Decree of the Ministry of the Environment (2017) on fire safety in buildings, wood buildings should be constructed according to the fire class P2. This fire class limits the height of the building to 28 meters. Therefore, wood buildings that are higher than 28 meters should be constructed according to the P0 fire class, which requires case-specific functional fire measurement.

According to part E1 in the Decree of the Ministry of the Environment (2017), the maximum allowed height of the wood buildings, both residential and office, is the height of eight timber-structured floors. This means that all the tall wood buildings constructed in Finland, with heights more than eight-storeys, are made on the basis of exception, requiring special permits and procedures. For the design of wood buildings having storeys numbering up to eight, the structural engineer is required to have qualifications for "demanding" constructions.

In the Decree of the Ministry of the Environment (ibid.) load-bearing and stiffening structures should use wood, which belongs to the class Ds2-d0. Under certain conditions wood of this class can be used also for exterior and interior cladding of residential apartments. In load-bearing structures protective cladding is required to be in the fire class of 10 to 30 minutes, and the inner layer of the cladding, which is against the load-bearing structure, should be of non-combustible material. Particular attention should be paid to preventing the fire spread through the facades and eaves structures and the surface materials of the emergence exits.

### 2.2.1 Fire regulations

Fire regulations for tall wood buildings should be approached on a case-by-case basis. The Ministry of the Environment has assigned the multistorey wood buildings to the fire class P2, which allows only buildings which are maximum of 28 meters high. Therefore, tall wood buildings in Finland are assigned to the fire class P0, which requires case-specific functional fire measurement. The implementation of case-specific functional fire measurement includes wood structures comparing to the performance of concrete buildings assigned to fire class P1 in case of fire. By considering these factors, it would be recommended to collaborate with fire safety consultant from the very beginning of the tall wood building project.

All spaces in the building should be equipped with the automatic fire extinguishing equipment. This kind of system can help to keep the fire under control until the fire department would arrive. This is also an efficient method to prevent the fire spread within the construction and possibly extinguish it at the beginning (Puuinfo 2020). It is recommended to use a high-pressure water mist system instead of traditional water extinguishing to prevent the structures from becoming wet and therefore damaging.

The fire regulations on multistorey wood budlings, which are higher than 28 meters, include at least the requirements to the load-bearing structures fire resistance, which is supposed to be at least 120 minutes. The main requirements relate to the structural performance in the case of the complete absence of firefighting measures. The structural solution should also consider the malfunction of automatic fire extinguishing equipment. Therefore, structures should be able to withstand both fire and cooling phases without significant damages, which can lead to the collapse of tall wood buildings. Designers should envisage safe exits for building users and safe work conditions for rescue service.

Fire regulations also instruct to cover wood constructions in the building with protective cladding, which is most often done with gypsum board. However, it is possible to protect the structure with the wood surface remaining visible if the inner layer toward the constructions is non-combustible material of class A (Weckman 2001). Wood surfaces for the exterior cladding could stay visible, if requirements presented in Table 1 are met:

Table 1. Requirements for the wood surface on the facades.

| Requirement | Definition |
|---|---|
| Floor boundary requirement | The fire spread is limited effectively between the floors |
| Attic and upper floor requirement | The spread of fire from the façade to the attic and the upper floor is prevented. |
| Facade requirements | Falling large parts of the façade structure in the event of a fire are sufficiently prevented. |
| Distance requirements | Buildings or structures shall not be placed less than 8 m from the façade |
| Emergency exit requirements | Buildings, which are over 2-storey height, should be provided with the emergency exist roads on the walls with windows or opening. |

However, the last update of fire regulations in Finland has restricted wood for the facades even from the concrete-structured buildings, which are higher than 28 meters and assigned to the fire class P1. Façades of the buildings, which are higher than 28 meters, should be implemented from the material assigned to class A2. There is no wood material, which could be assigned to the class A2 at the moment.

The possibility to leave the wood surfaces visible is the most desired feature by architects for tall wood buildings. However, this design solution requires more research on fire performance in tall buildings with visible mass timber. Significant research on the fire-safe implementation of visible mass timber in tall buildings has been conducted in Sweden recently (Brandon et al. 2020).

### 2.2.2 Sound insulation

Other regulations for tall wood buildings are sound insulation, long-term durability and energy efficiency (Puuinfo 2020). In this thesis only the requirements for the sound insulation is presented, as long-term durability and energy efficiency are part of the sustainability aspect of tall wood buildings. As previously noted, sustainability aspects are presented only shortly in this thesis to give a background for understanding its relevance for this case.

Sound insulation should be considered properly in the case of tall wood buildings, because one of the main disadvantages of massive wood products is low sound insulation capabilities. The central intention for sound insulation is prevention of airborne and impact noise (e.g. footsteps) through layers and noise transmission through the wood structure. To avoid the sound transmissions through the floor boundaries, a thin layer of concrete on the floor structure is recommended. For the same reasons, the floor structures are usually oversized (Puuinfo 2020).

To prevent the sound transmission between the floors through the structure it is recommended to construct horizontally overlapping compartments in the way, where the horizontal structures are interrupted. Vertical sound transmission in frame structures is prevented by vibration dampers for load-bearing wall lines (Puuinfo 2020).

The sound insulation for the wood buildings is usually oversized, to ensure the comfort sound insulation is achieved. The residents of the wood buildings have given the feedback, according to which, their apartments have been very quiet. The normal for other forms of constructions' buildings noises, such as music or baby crying is almost impossible to hear in the wood buildings, however footstep sound or drilling noise heard through the structure is still present.

## 2.3 Material possibilities

This chapter elaborates different wood and wood-based materials and their most important features. Wood has a long history as a construction material. Starting from simple finger jointing and with the application of industrialization has developed to become cross-laminated timber elements. The development of wood-based materials has allowed its more diverse use in the construction industry.  Therefore, the knowledge of the modern materials' properties is needed to understand its possibilities and limitations in high-rise wood building constructions.

Wood materials can be divided into solid wood and wood-based materials. Solid wood has a wide range of use of possibilities as a construction material. By jointing and gluing, timber's limited individual lengths can be extended to form a larger entity that improves on solid wood spans and load-bearing capacities. Wood's inherent features to shrink and have fungal infestation can be reduced or even eliminated by timber drying.

Nonetheless, despite solid sawn woods benefits it is not a material of high-rise wood building. Barriers are both legislative and perceptual. Concerns and beliefs related to the wood's durability and strength as construction material are fact-based. Solid sawn wood is soft, organic material, which remain wet for a notably long period (Green and Taggart 2017). These features have catalyzed the wood-based materials development in form of planks, sheets, chips, or fibres. Wood-based materials are created through wet or dry processes, mostly with the help of adhesives. It allows to significantly increase the wood beneficial properties. New wood-based materials are stronger, more consistent, and more dimensionally stable in comparison with traditional wood materials (Green and Taggart 2017). The innovations in wood industry enhanced and inspired the development of the high-rise wood buildings.

In any case the one and only right word to explain wood is "organic". This needs to be considered during the whole process of any research or design project. The most characteristic variables of wood material are grain and moisture content (Green and Taggart 2017). To create materials and, therefore, structures which are exact, dimensionally stable, and strong these two variables need to be controlled.

### 2.3.1 Critical characteristics

Critical characteristics of any wood material are moisture movement and strength. These two variables need to be considered already in the design process to understand the material's construction possibilities. The strength parameter is also strongly dependent on wood moisture measurements, and therefore it could be wise to understand first the moisture features of the wood.

#### 2.3.1.1 Moisture movement and its control

As it was noted before wood is an organic and "alive" material with hygroscopic features. One of its main capabilities is the possibility to absorb and release moisture from the environment. A living tree is transporting water and nutrients around the tree through the sapwood in the outer part of the stem, while the inner part, heartwood, stays passive. This kind of structure explains the differences in the moisture content in the wood's different parts. Newly sawn timber's sapwood can have up to 160% of water content, while same timber's heartwood can have less than 50% of moisture content.

There are two different types of moisture in the wood. The first type is freely available water in the hollow cell cavities and the second type is water that is bonded to the cell walls (Rowell 2012). As follows from the definitions of water types in the wood, the freely available water in the hollow cell cavities evaporates first, and only after that water that is bonded to the cell walls start to evaporate.

The wood's capability to absorb and release the moisture is connected to the moisture movement phenomenon. Moisture movement can be explained as a swelling and shrinking process. Swelling and shrinking movement of the wood is not coordinated through all directions of the fibres. The movement is least when it is parallel with the fibres and most when it is tangential with the fibres. Total cumulative movement in all directions is called volumetric shrinkage or swelling. The movement typology s presented in Figure 1.

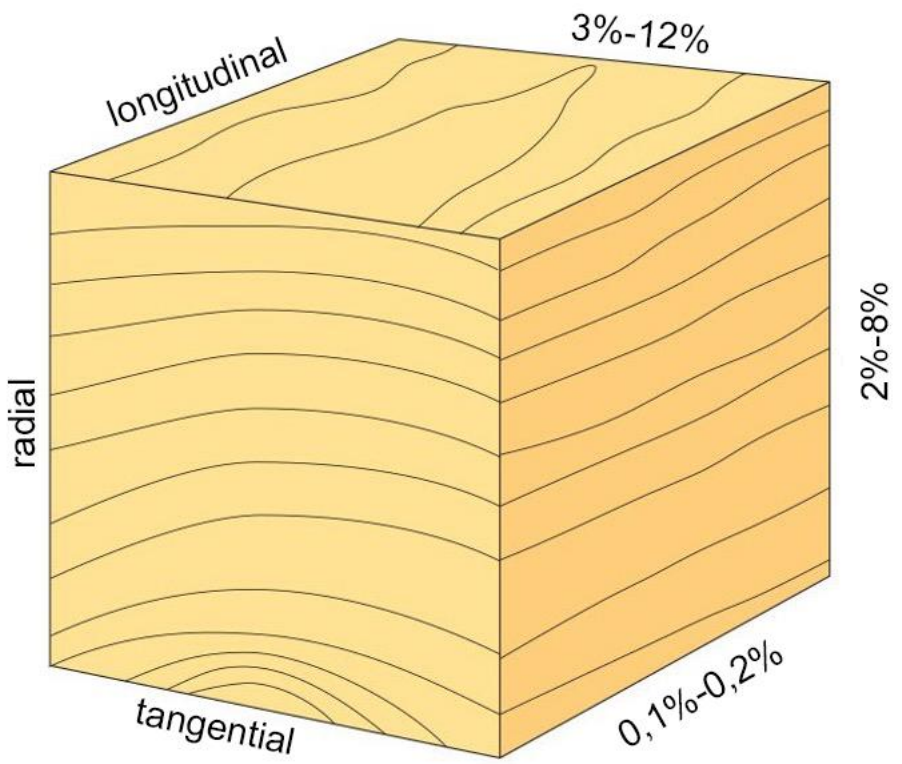



Figure 1. Swelling or shrinkage movement of wood

From Figure 1 it is possible to see, that longitudinal movement of wood is the smallest, about 0,1% to 0,2%, and, therefore, it is almost insignificant to the volumetric shrinkage or swelling. Radial dimension shrinkage has more significant impact on volumetric shrinkage or swelling than longitudinal dimension movement and varies from 2% in the stable wood types to the 8% in the least stable species. Tangential shrinkage or swelling can vary from 3% to almost 12%. The changes in these three dimensions affect the overall volumetric change typically between 9% and 15%.

The effect of wood shrinkage or swelling of one wood element doesn't necessarily creates a problem, but the cumulative effect of moisture movement in the system of wood elements have a significant impact on building structure and stability capabilities, and therefore should be considered properly. This aspect is especially important for the tall wood buildings and therefore extra-attention should be paid to the material specifications. This reasoning explains the preference of the kiln drying of almost all materials for the tall wood buildings.

The kiln drying process has received its name from the main element in the drying system, the kiln, or oven. Wood is stacked on racks to allow the heated air access to all the members in the load. Kiln's charges are also sorted by species or dimensions to optimize the drying process and to ensure the correct moisture level in all members of the load. During this process, the temperature is properly controlled to ensure that drying doesn't occur too quickly, which can affect defects to the wood member (Green and Taggart 2017). The moisture content can be reduced by kiln drying to the suitable level, which varies depending on the wood species. The most typical target moisture content is however around 12%. In the result of kiln drying process the volume of wood member decreases through shrinkage and simultaneously the strength of the wood member increases significantly and allows the wood materials use in the tall wood buildings.

#### 2.3.1.2 Strength

The strength of the wood, its weather resistance and dimensional stability are dependent on the wood species. This relation is affected by the strength characteristic dependence on the wood's density. Density can be calculated as a relation of wood mass to the volume of wood at a given moisture content, usually 15% or 12% (Rowell 2012). In own turn, the strength of the wood measures its capability to withstand the given load without any damages. This characteristic is therefore one of the most important for the wood material suitability assessment to the tall wood building.

The strength of the wood depends also on the direction of the applied load and its type. In structures five main load types can be defined: compression, tension, bending, shear, and tension (Green and Taggart 2017). Wood's main strength characteristics are highest for applied tension and compression forces in the longitudinal direction and weakest when the force is applied in the tangential direction.

High variability of the natural wood characteristics in its solid sawn form, where grain can vary from tighter to more open and some natural defects as splits, checks and knots can be present, means that predictability of wood performance can be difficult in the industrial manufacturing level. These factors affect the need for engineered wood products, where all the variables of end-product can be controlled through the different manufacturing steps. Engineered wood-products, which are created by layering or bonding of wood, are strongly connected with adhesives, bonding agents and additives.

#### 2.3.1.3 Adhesives, bonding agents, additives

The bonding agents, different adhesives and additives have played an important role in the wood-based materials development. All of these substances are used either to connect together different wood subparts or to increase the wood performance in the fire or moisture test. Also load-bearing performance can be significantly increased with the help of these substances. From the wood adhesives the most commonly used is glue. The adhesion capabilities of glue are depended on the wood-adhesive bonding chain (Ülker 2016). However, the growing need for "greener" environmental-friendlier adhesives has initiated different several research, which aim to eliminate the formaldehyde emissions from particleboard adhesive (Ülker 2016).

Bonding agents are used mostly to assist the sheet, chips or fibres press together to form the wood-based materials. Adhesives can be divided into three main categories: organic, semisynthetic and synthetic adhesives. However, as it was mentioned above the synthetic adhesives are the most commonly used at the moment. Different organic adhesives are mostly at the experimental stage of its development (Ülker 2016). Therefore, their role in the wood-based materials industry is quite minor (Kaufmann et al. 2018).

### 2.3.2 Wood materials

Solid sawn wood materials will be presented only briefly, because of its minor role in construction of tall wood buildings. As it was described above, the low predictability of solid sawn wood performance affects its constructional incompatibility to the technically high-demanding projects. Also, wood species affect the wood performance. In Finland the most common wood species are pine, spruce and birch (WoodProducts 2021).

Wood materials however are much more than solid sawn wood and can be divided into two main categories, which are solid wood – bar-shaped materials and mixed products. The solid wood – bar-shaped materials include both the bonding agents-free materials and laminated beams. The typology of solid wood products is presented more specifically in Table 2 and visualized in Table 3.

Table 2. Typology of solid wood products (Kaufmann et al. 2018)

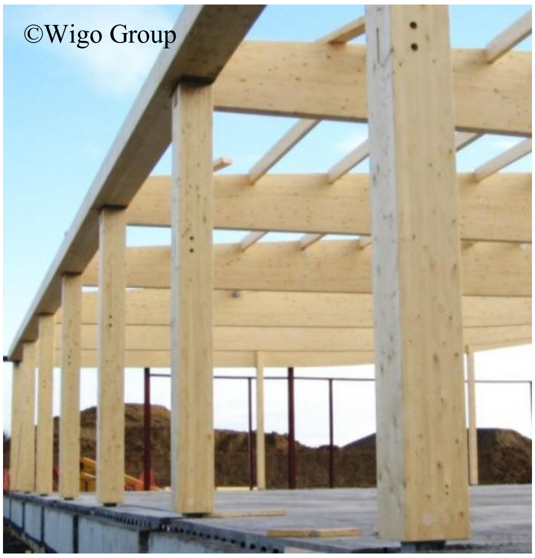
| Material | Components | Name | Wood species | Main applications | Secondary applications |
|---|---|---|---|---|---|
| Solid wood – bar-shaped materials | Solid wood | Solid softwood timber | Spruce, fir, pine, larch, Douglas fir | Load-bearing structures, formwork, cladding, walls, roofs, framing | Civil engineering, timber structural engineering |
| | | Solid hardwood timber | Beech, oak, maple, alder, birch, cedar, ash, eucalyptus | Interiors with the excellent visual qualities | Timber structural engineering |
| | Finger-jointed solid wood | Construction timber | Spruce, fir, pine, larch, Douglas fir | Load-bearing cross sections for ceilings, walls, roofs and framing sections | Stacked element |
| | Laminated beams | Double/triple laminated beams | Spruce, fir, pine, larch, Douglas fir, poplar | Visible wall, ceiling and roof structures with large cross sections | |
| | | Glued laminated timber | Spruce, fir, pine, larch, Douglas fir, western hemlock, cedar | Universal, all bar-shaped structural components, ceiling elements, long-span structural components subject to heavy loads | Straight and curved beams with very stable forms and high visual quality |
| Mixed product | Composite beams | Lightweight timber beams/ supports | Flanges are made mostly from construction timber, glued laminated timber, or laminated veneer lumber; webs are made mostly OSB or hard wood fiberboard | Wall supports, ceiling and roof beams, framing with high thermal insulation requirements | Supports for concrete formwork |

Table 3. Visualization of solid wood products

Solid softwood timber

Double/triple laminated beams

Solid hardwood timber



Glued laminated timber

Construction timber

©MetsäWood


Lightweight timber beams/ supports

### 2.3.3 Wood-based materials

Wood-based materials, or engineered wood products (EWP), are created by the bonding together wood strands, veneers, or small sections of solid lumber or other forms of wood fiber (Green and Taggert 2017). This kind of structure allows to produce larger entity, which is much stronger and stiffer than sum of the original parts and its specifications can be predicted with much better accuracy. EWP became possible because of the developed industrial processes for the wood modifications. Another reason for EWP development has been increasing use of the residues and lower grade trees for the producing of more versatile and consistent products, which are significantly larger than single tree entity (Markström et al. 2018). This also enables much larger percentage of the tree to be used than, for example, would be possible to use for the production of solid sawn lumber.

The smaller ingredients for the larger wood member entity are usually kiln-dried, what makes the EWP more dimensionally stable than solid wood products could be, because of their natural variability. EWP are products with high typology variability, but the most common types of EWP are plywood and glulam. Typology of EWP also includes a range of pilot materials, which are only at the beginning of their development path.

The materials, which are presented next in this part, are both materials, which are currently used in the constructions of tall wood buildings, and materials, which haven't passed yet all the safety and technology requirements tests but have a great development prospective. All these materials are produced in the strictly controlled manufacturing environments with the help of different bonding and pressing techniques. According to Green and Taggart (2017) these kinds of conditions help to produce EWP in a wide range of thicknesses and in widths up to 2.5 or 3.0 meters. The length of these kind of products is limited only by constraints of logistic possibilities. Also, some of these materials allow to create seamless jointing. In the following parts will be presented specifications and main characteristics of Massiv Holz Mauer (MHM), Laminated Veneer Lumber (LVL), Cross-Laminated Timber (CLT), Glued Laminated Timber, Wave Layered Timber (WLT), Dovetail Layered Timber. In Figure 2 is presented the typology of EWP.

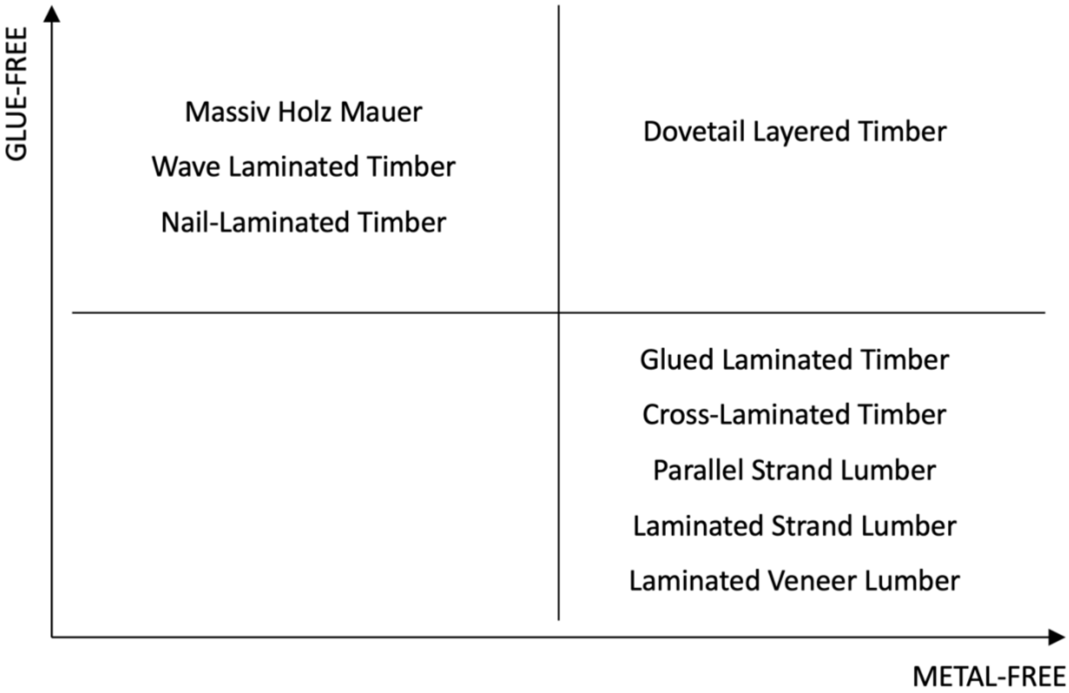



Figure 2. Typology of EWP.

#### 2.3.3.1 Massiv Holz Mauer


The MHM (Massiv Holz Mauer) was developed in 1978 when MHM Entwicklungs GmbH was established in Bavaria by Hans Hundegger. MHM is an element wood-based material which consists of cross-stacked board layers that are fastened together with aluminum nails. The strategical dimensions of this kind of EWP are a maximum width of 3 to 4 meters, and length at most 6 meters, with thickness between 11,35 and 34 centimeters. The wood specie which is usually used for the MHM is softwood. The main application of MHM elements is load-bearing or non-load-bearing wall structures. MHM element is neither suitable for a slab structures nor for bar structures.

Use of the aluminum groove pins in the production of the MHM elements allows to create extremely stable and strong wall elements through the resilience features of the aluminum groove pins. This kind of construction allows reduction in the use of any adhesive agents to the minimum. The absence of the adhesive agents in the element creates the permeable construction which is connected with the intrinsic properties of wood. These kinds of specifications allow the structure of MHM elements without the vapour barriers.

Also, insulation of the MHM elements does not require any additional measures. In the first phase of manufacturing of the MHM elements, the strength-graded dried boards are grooved longitudinally and milled with a lateral half-point, which ensures better lateral fit of the boards. This kind of grooving of the boards creates air pockets inside the MHM structure, which improves the thermal insulation of the board. The maximum depth for the grooves is about 3mm.

In the second phase of the production process, the elements are manufactured fully automatically. First, the boards are pressed together lengthwise and transversely, after which the board layers are nailed together with grooved aluminum nails layer by layer. The nailing process is conducted as well fully automatically. In the finishing phase elements are processed into ready-to install elements by CNC machining.

The fire resistance characteristics are difficult to specify with high accuracy because of the air pockets and slits in the MHM board, which make it difficult to conduct wood charring test. At the same time the manufacturer (Massivholzmauer 2021) claims that MHM can be classified as F90 B material as a result of official measurements. In Finland it is however recommended to cover the MHM elements with non-combustible materials (Puuinfo 2021).

Sound insulation characteristics of solid wood panels are usually quite poor. Therefore, for the use in the residential buildings, additional sound insulation can be beneficial. Also, sound insulation is improved by layered dense structures by adding mass and sound-absorbing insulation layers to the structure.

The MHM surface can stay uncovered for the interior use. The drying process for the elements makes the wood dimensionally stable and resistant to parasites, which in turn means that this kind of timber construction doesn’t require chemical wood protection. Wood surfaces in the interior can also act as an indoor moisture compensator. However, the use of wood in the indoor spaces should be coordinated with fire regulations for the wood buildings. In exterior situations the use of wood protective chemicals is also reduced to the minimum.

### 2.3.3.2 Laminated Veneer Lumber


The LVL (Laminated Veneer Lumber) material is created by combining or bonding of thin wood veneers in the way, that the grain of all veneers is parallel to the longitudinal direction (Green and Taggart 2017). One of the most common construction materials has been first created for the aircraft industry in 1941. The great demand of LVL products has initiated significant amount of research, which enhanced the development of LVL (Hiziroglu 2016). The construction of LVL has enabled the production of LVL in lengths, which are far beyond conventional lumber lengths. One of its main benefits is high performance predictability and diverse application range. The main applications of LVL are beams, joists, trusses, frames and components of roof, floor and wall elements (MetsäWood 2021). For the use as beams, joists and trusses the LVL panels are usually cut, but for use as roof, floor or walls LVL can be left in panel forms. Also, diverse industrial applications are possible, for example, door and window manufacturing. LVL panels are also able to resist lateral forces through the diaphragm action. This kind of action can be achieved by detailing the joints between panels to transfer these kinds of loads (Green and Taggart 2017).

The process of manufacturing of LVL products starts with drying and grading of the veneers. Later production stages include bonding with waterproof glues additives. Mostly LVL is free from warping and splitting, unlike plywood, which is layered in the horizontal direction. This is affected by dispersing throughout the material or eliminating of the knots, slope of grain and splits. However, there is still a risk of wrapping in the case of improper warehouse storing (Hiziroglu 2016). LVL can be also produced by the partial cross-laminating of the panels, when approximately fifth part of the veneers are oriented perpendicularly to the other veneers in the billet. This kind of hybrid system allows to increase the crushing strength resistance of the LVL.

Main dimensional specifications of LVL panels are dependent on both production and transportation possibilities. The maximum width of veneer is 2,5 meters and the thickness varies in the range between 27 and 75 mm. Production technologies allow to produce LVL panels, which are 25 meters long. Also, transportation possibilities limit the length of the panels to 25 meters. The standard height of the panels depends on the manufacturer. Other important specifications of the LVL panels are the span range, which is typically between 5 and 12 meters.

#### 2.3.3.3 Laminated Strand Lumber


The LSL (Laminated Strand Lumber) material is created by layering of dried and graded wood veneers, strands or flakes with help of moisture-resistant adhesives into larger entities (Kurt et al. 2012). The strands for the LSL material are made mostly from the fast-growing aspen or tulip polar wood species. The direction of the strands in the LSL material is the same to the LVL case. Strands are organized parallel to the longitudinal direction of the panel. This kind of structure gives the LSL panels one-directional spanning capability. For LSL is also typical these kinds of specifications as high strength, high stiffness and dimensional stability.

The LSL is primarily used in the structural framing in the residential, commercial and industrial constructions (Canadian Wood Council 2021). This material implementation in the tall wood buildings include same kind of range as for other purposes. It can be used in the wall, floor and roof structures. LSL is also suitable for the use in vertical structures, when the floor height is significant, what creates also larger wind loads to the vertical members on the building.

Main LSL specifications are quite typival for all engineered wood products and focus on the high performance predictability in strength and stiffness properties, and dimensional stability that decrease significantly twist and shrinkage. Customization of LSL panels through the cutting, notching or drilling should be implemented according to the manufacturer's recommendation. These kinds of requirements from the manufacturer's catalogues and technical reports are one of the primary design guides for the architects. Despite the great moisture resistance capabilities of LSL, as any other engineered wood products created with the help of chemical additives, the LSL should be protected from the weather during site storage and after the installation. Moisture protection needs to be ensured also during the transportation from the manufacturer's site to the jobsite. Dimension range of the LSL panels is highly depended on the individual manufacturer's specifications, but maximum width of the panels is typically about 2.4 meters.

### 2.3.3.4 Parallel Strand Lumber


PSL (Parallel Strand Lumber) is created by bonding of the veneers into long strands, which are layered parallel to each other. The bonding of the veneers is conducted under the pressure with adhesives. This type of EWP has been invented, developed, commercialized and patented by MacMillan Bloedel in the early 1980s in Canada. The company has marketed its product by the Parallam name. Parallam is the only commercially manufactured and marketed parallel strand lumber product (Weyerhaeuser 2021).

PSL can be manufactured from any wood species, but the most typical are Douglas fir, southern pine, western hemlock and yellow poplar. Like other engineered wood products, PSL properties are significantly improved through manufacturing processes which have removed the growth imperfections from the wood strands. The manufacturing method has affected the specifications of this material, which is characterized by high load-carrying capacity. This material is able to support heavy loads over long spans. The main applications of the PSL in tall wood buildings can be posts and beams. Generally, it is applications which demand high bending strength and load bearing capacity.

Manufacturing features allow producing of PSL billets, which maximum cross section is 300mm x 460mm, with standard cross-section of 300mm x 300mm and it can be cut to the suitable length on site, which simplify significantly PSL installation. The maximum length of PSL is typically up to 18m. PSL is usually treated with preservatives during its fabrication, which preserve it from the moisture damages and PSL therefore can be used in the high humidity conditions. Another important feature of PSL is its aesthetic appeal. It is a visually attractive material, which can be used in applications, where material appearance is important.

### 2.3.3.5 Cross-Laminated Timber


CLT (Cross-Laminated Timber) is a cornerstone of tall wood building development. CLT was first introduced as an innovative material in 1990s in Austria and Germany (Karacabeyli et al. 2013). This material is created by layering and bonding together of multiple layers of boards, typically three, five, seven or nine layers, which are placed at right angle to one another. Layers are usually bonded together with the help of bonding agents, mostly with glue. Boards, which are used in the structure of the CLT, is kiln-dried dimension lumber. Boards can also be finger-jointed and glued in the longitudinal direction. The structure, which is constructed by altering layers of lumber create an excellent rigidity in both directions, what expand the range of CLT applications. Also, double layering in the same direction is possible, with the following double layers which are oriented to the perpendicular angle to previous ones.

CLT panels have been rapidly developed during last 15 years (de Kuilen et al. 2011). CLT layers bonding have been developed to be possible in multiple ways. The most common way is to use chemical bonding agents, but also variety of other methods is possible. Layers could be bonded together by the mechanical fasteners. The example of this kind of fasteners can be for example nails, which connect layers in opposing angles. This method allows to achieve the required structural performance. Another method refers to the use of the wooden dowels, which re inserted to the pre-drilled holes in the CLT panels (Green and Taggart 2017). Wooden dowels should be dried to the lower moisture level than panel itself, which allows them to expand to achieve suitable moisture content and therefore create ultra-tight fit to the panel, which is capable to resist load affected to the panel.

CLT is versatile material with high dimensional stability features, which is extremely suitable for the se in the multi-storey buildings. It is supported by good dimensional stability and two-way spanning capability. Main dimensional characteristics of the CLT is that the maximum length of the panels can be up to 16 meters and is extendable with mechanical joints and glued connections. Maximal width can be up to 3 meters and different standard dimensions are 0.6 meters, 1.2 meters, 2.4 meters and 3 meters. Thicknesses of the panels varies from different manufacturers, but maximum thickness can be up to 500 mm (de Kuilen et al. 2011).

As it was mentioned before, panels are usually created by boards, which are layered at the certain angle to each other. However, in some cases, when the special load-carrying capability is required, the boards can be layered in the same direction, usually affecting the double layers at the faces of the panels. The main application of the CLT panels are walls, floor and roof elements. In the wall elements panels are usually oriented with the grain located vertically to the applied loads. In the same way, the grain of the outer layers of the CLT are usually oriented parallel to the longer span (Green and Taggart 2017).

CLT is one of the most researched materials for the tall wood buildings at the moment. Its structural performance is quite close to the traditional concrete elements (de Kuilen et al. 2011). However, its sustainable and lightweight features create it an optimal variant for the tall wood buildings. This material can be used both in an architectural grade, with the outer layer's appearance, or in the structural grade, with the outer layer covered with a surface finish.

### 2.3.3.6 Glued Laminated Timber


Glued laminated Timber (Glulam) is one of the oldest engineered wood products. It was already used in Europe in the early 1840s. However, its rapid development started after glued laminated timber has been patented in Switzerland in 1901 (APA 2021). Glued laminated timber is produced by gluing together individual pieces of dimension lumber either in a straight or curved form in the way, that grain of all pieces is located parallel to the longitudinal axis of the wood member (Moody and Hernandez 1997). The manufacturing process remains almost the same now as at the time of invention, but its strength capabilities have been continuously developed. The lumber, which is used today for the production of the glued laminated timber, is divided to the three main high-strength grade called “lamstock”. The highest grade is L1 and accordingly L3 is the lowest (Roos et al. 2009).

The wood species used for the production of the glulam depend on the geographical location of the manufacturing site. In the North America the most typical species are Douglas fir, SPF, larch or Southern yellow pine. For the manufacturing sites in Northern Europe and Russia, the most usual is to use red pine and white spruce.

The glulam is typical material for the structural members, because its manufacturing process allow to create much larger entities, than the trees from which the components lumber is sawn (Moody and Hernandez 1997). Lamstock, which is used in the glulam, is typically supplied in nominal thickness of the 25 or 34 mm, and standard widths, which are 80 or 170 mm. Length is normally about 3 meters, but pieces can be finger-jointed or glued to achieve longer pieces (Green and Taggart 2017). The preparation of the lamstock to the production of glulam, include the kiln-drying of the lamstock to the 10-14% moisture content and the end-gluing together of individual lamstock pieces to achieve the required length. After this, multiple laminations can be glued together under pressure to achieve the desired shape and length of the glulam. For example, central section of the glulam can be deeper to response to the increased stress that normally occurs in these regions. The variable cross-sections are also possible for the arches to response to the same stress reasons (Moody and Hernandez 1997). Another possibility to increase glulam element response to the compressive and tensile forces in the upper and lower laminations is to specify them to have a higher strength class. Glulam can be glued to the entities of any length and, therefore, this material allows for open floor plans, which are unconstrained by columns. It creates the wide range of architectural applications especially in the public projects. Glulam is also visually attractive material, which can be left exposed. Glulam is also used for the vertical loads and glulam columns can extend over multiple floors. When manufactured with waterproof glues, glulam can be used for exterior use.

### 2.3.3.7 Nail-Laminated Timber


NLT (Nail-Laminated Timber) was invented in the 1970s in Germany. NLT is created by nailing together solid sawn framing members, which are arranged side by side on edge to create the solid element. Nowadays also screws and spikes are used as well (Gong 2019). This kind of structure offers considerable benefits as unique aesthetic, flexibility of form, fast construction and a light carbon footprint. Its manufacturing is relatively easy as it doesn't require capital investments for specialized manufacturing (Green and Taggart 2017). NLT can be manufactured by experienced carpenters in a conventional wood shop. However, in this case it is difficult to speak about the volumes of elements, which are required for the public constructions.

NLT can be produced by a wide range of species, for example, as Douglas fir and SPF. The main dimensional specification of the NLT refers mostly to the length of the prefabricated panels, which is usually about 3 to 8 meters. The other limitations to the NLT panels size are related to the transportation restrictions.

The difficulty in the specifications of the NLT is that specification of the whole element is based on the grade of the solid sawn material, which was used in the production. Therefore, there is no clear specification for the fabricated panels themselves. Also, the absence of continuous glue layers in the structure of the NLT panels affects its fire resistance capabilities, and therefore additional sealing should be used on the site to prevent the passage of the smoke or other fumes, through the structure (Green and Taggart 2017). The sound insulation capabilities of the NLT panels are quite similar to the other massive wood elements, and have room for the improvement. Therefore, additional layers are usually used to increase the performance of NLT panels. Also, NLT is quite sensitive to water-related damage, and, therefore, it requires proper care procedures.

Main applications of the NLT are floor constructions, especially for the industrial and commercial buildings (Gong 2019). Nowadays the application of NLT panels has widened its ranges and it is a popular material for the floors, ceiling, wood walls, stairs and elevator shafts. Its popularity can be explained mainly by the possibility to stay exposed as a natural wood finish (Naturally:wood 2021a).

#### 2.3.3.8 Wave Layered Timber


In the last two parts of this material representation will be presented innovative materials, which are under development at the moment. WLT (Wave Layered Timber) has been invented in Finland by Aalto Haitek, which have been established in 2017. It is a glue-free material, which is created by layering of the lamellas with wave-shaped profiles (Siren 2021). This technique relies on the natural moisture induced shrinking and swelling of wood, which supports the structure with tightly compressed members. The assembling of the WLT demands however the metal fasteners, which compress the parts of the elements.

The WLT elements are produced usually from the Scots pine. At the moment there is undergoing detailed research to define the specific physical properties of this wood specie in the structure of the WLT panels (Siren 2021). This research enables the WLT launch to the market during 2021. However, the WLT technique is suitable for most timber species.

The benefits of the WLT include the support of multiple methods of installation from a piece-by-piece approach to the installation of larger pre-constructed elements. Other benefits consider WLT's aesthetical features. Also, it is eco-friendly material, which enables creation of thin, curved or straight structures without chemical additives. Its manufacturing is relatively low-cost and requires only simple tooling, which enables production of WLT by small and mid-size producers (Siren 2021).

This product is under development at the moment and has been tested only in some pilot projects. One of the pilot projects has been a kindergarten pavilion-style building in Toholampi (Siren 2021). Therefore, WLT is a promising wood-based material, but its implementation to the high-demanding constructions, as tall wood buildings, demand significant development, verification and certification procedures.

### 2.3.3.9 Dovetail Layered Timber


Dovetail Layered Timber product is an innovative massive wood-based product, which is developed and researched by group of researchers, which include professor of architecture history Olli-Paavo Koponen, associate professor Markku Karjalainen and post-doctoral researcher Emre Ilgin from Tampere university (Koponen et al. 2021). The main idea of this product is use of traditional dovetail joint to create the solid element. Its main benefits refer to its glue-free and metal-free structure, which distinguish it from all other engineered wood products.

The development process of Dovetail Layered Timber includes at the moment the patenting procedures and different load bearing, fire-resistance, sound insulation and moisture-resistance capability tests. The possible partner for the Dovetail Layered Timber manufacturing is Aalto Haitek, which invented WLT elements. The possible date of market launching is difficult to estimate at the moment.

## 2.4 Current structural solutions

The architectural language of any buildings is connected to the structural systems of their construction. Structural systems affect all the aspects of the building, both interior and exterior. Therefore, it is significant for the purpose of this thesis to cover current possible structural solutions to get an understanding of modern tall wood buildings. The main characteristics of structural systems is strength, rigidity and dimensional stability.

Structural systems are intended to resist loads. Loads can be divided into vertical and lateral loads. The vertical loads are created by the self-weight of the structures, snow load on the roof and forces applied by the occupants and their belongings. The lateral loads refer mostly to the wind loads. Both of these loads should be considered for the building of any height. However, the role of the lateral loads increases significantly when a tall building is the case.

This kind of external forces affect the structural systems of building by creating the compression, tension, bending, torsion or shear forces inside the structures. The main idea in structural stability is to transmit and resolve all the forces through the horizontal and vertical structure members to the ground (Green and Taggart 2017). However, in the case of wood buildings one more transformation force should be considered, the shrinkage of wood. This movement capability of wood should be designed in detail for the vertical structural elements. Through the shrinkage, structural elements can change their elevation and alignment to each other. Also, the integrity of the building envelope could be damaged due to the shrinkage process (Green and Taggart 2017).

The ideal situation for the vertical load transmission to the ground level would be the shift through the continuous or superimposed structural elements, for example, posts or panels. If the design requires significant shifts in the vertical load paths, then it is required to use, for example, transfer trusses or transfer beams (Aicher et al. 2013). For the vertical load transfer to the ground the tall wood building can be designed with the platform or balloon structure. The main principles of the platform and balloon structures are presented in Figure 3.

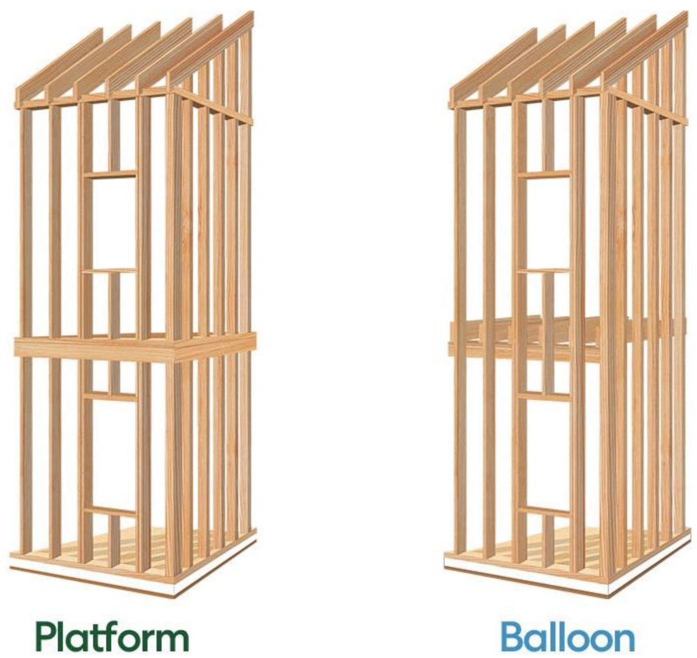



Figure 3. The type of vertical load transfer in the structural systems (ThinkWood 2021).

In the case of platform structure, the vertical load elements are one storey high and, therefore, the floor participates in the vertical load transfer to the ground. If the vertical elements are CLT panels, the supportive elements should be added to the structure to avoid the damaging of the floor platforms, because loads are directed perpendicular to grain. This challenge can be solved by the holes in the platform structure, which are filled with wood dowels, steel pipes or concrete (Green and Taggart 2017). The main idea in this solution is to transfer the vertical load from the upper vertical element straight to the lower one, without affecting damaging load to the horizontal structures. The same kind of solution could be applied to the post-and-beam structure. The examples of this kind of jointing between the wall elements and floor platform is presented in Figure 4.

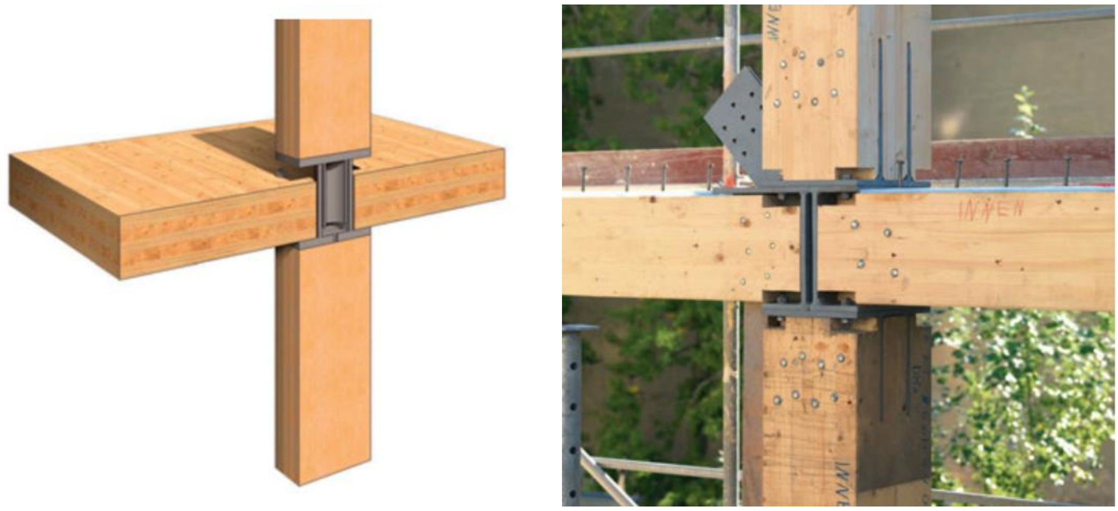


Figure 4 a, b. The floor-wall joints in the platform structure (Kaufmann et al. 2018).

To resist the lateral loads in the structures affected, for example, by wind the three methods could be used, which are rigid (moment) frames; braced frames; or shear walls on the perimeter of the building. Shear walls can be located both systematically around the building and concentratedly in groups, for example elevator or stair shafts. These methods could be used separately or all three together. The lateral structures should be located to the two main directions according to compass, east-west and north-south. The shear walls and brace frames should be connected by the vertical structural as floor, roof or both. This kind of anchoring assist the load transfer to the ground level and increase the stability of the structures (Green and Taggart 2017).

As it was mentioned above, the loads should be transferred to the ground level. In the ideal case it would happen through the consistent from floor-to-floor lateral systems. In other words, through the cross bracing or shear walls, which are located in the same vertical plane. Also, stair and elevator shafts transfer the loads to the ground level. Both of these systems could be constructed from concrete or wood. Although the use of concrete stair and elevator shifts is quite common nowadays, there is no constructional reasons to avoid wood for this use. However, sometimes wood limitation for this kind of use is justified by budget, efficiency, structural engineer preferences or local fire safety requirements (Green and Taggart 2017). If the combination of concrete stair and elevator shifts and wood structures is used, then the movement between the wood and concrete elements should be considered. This kind of cases would be discussed later in the part 2.4.3 Hybrid Systems.

One of the important features connected to the wood structures is ductility. Ductility can be defined as solid material's capability to deform under stress without losing its load-bearing capability (Malo et al. 2011). In the case of tall wood buildings, the structural elements are mostly rigid, what brings the connections to the point. Two kind of behavior are typical for the connections in the tall wood buildings: "elastically" and "plasticly". The elastic behavior refers to the "absorbing moderate wind or seismic forces without permanent deformation" (Green and Taggart 2017). Plastic behavior refers to the transmission of extreme forces, such as major windstorms or earthquake. Plastic behavior allows the minor damages in the construction but prevent the disastrous collapsing of the buildings.

Next in this chapter will be explained three main current structural solutions. First will be an explanation of massive timber panel systems, which will include an explanation of modular element structures. Next to be covered post-and-beam systems. And lastly the variety of hybrid systems will be looked at.

### 2.4.1 Massive Timber Panel Systems

The massive timber panels systems are constructions, where both vertical and horizontal loads are carried by solid wall panels, which are arranged in two main directions (Green and Taggart 2017). The solid wood wall panels are usually made from CLT panels. However, also the dowel laminated timber panels are used in this type of structures. This kind of structural system affect the flexibility of building adaptability to the new needs. The solid wall panels are usually configured identically on each floor to shift the loads to the ground level effectively and therefore is quite rigid to the changes. Because of this, the massive timber panel systems are usually used for the residential buildings, with fixed needs of the occupants. The dowel laminated timber, cross-laminated timber and laminated veneer lumber panels are used both for the vertical and horizontal structures. These panels can be used in different combinations, which are presented in Figure 5. However, any of these massive timber panels can be combined both with hybrid and frame elements.

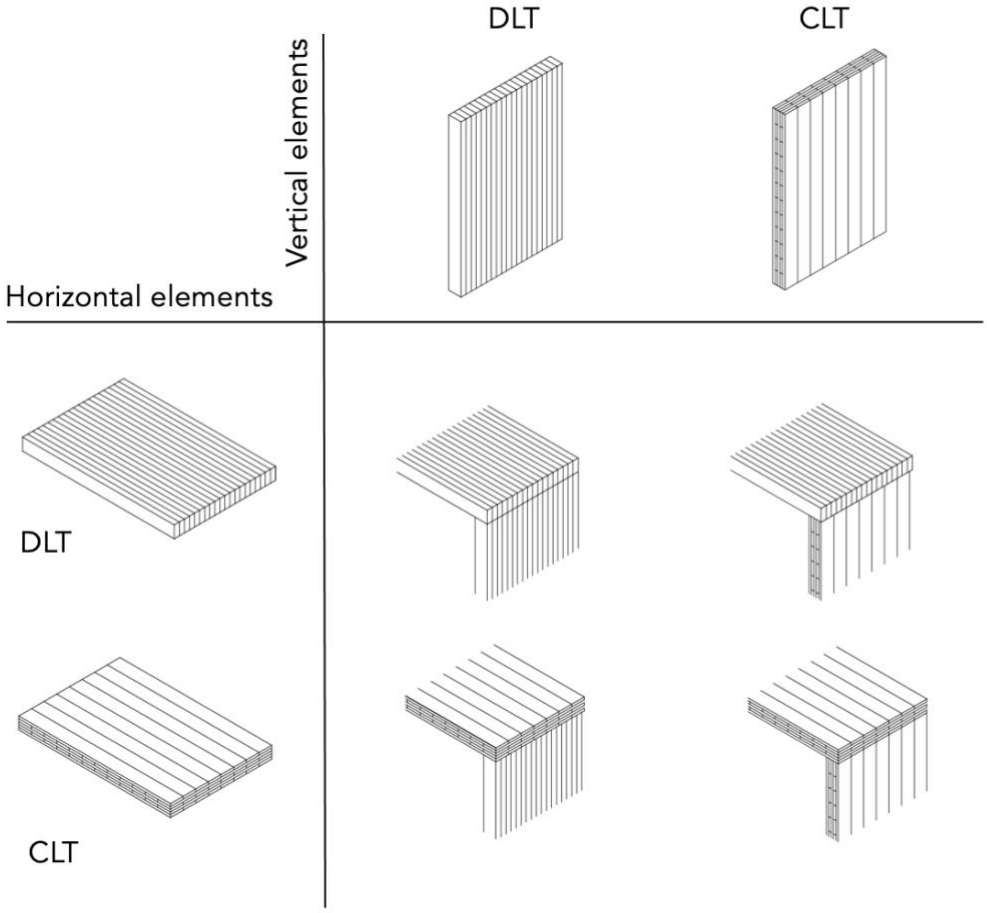



Figure 5. Combination of massive timber panel systems.

**Dowel laminated lumber panels**

In the case of dowel laminated timber walls, the nail-laminated timber, which was presented in this thesis, is the most traditional, but the most difficult for subsequent working, because of the steel nails in the structure. Another variant of the dowel laminated panels is laminated panels, which are joined by the solid wood dowels. This kind of systems can be modified on site in the same way, as solid wood panels. The dowels can be inserted vertically or diagonally. The diagonal jointing of the laminated timber can make the panel's form more stable. Also gluing of boards for the panels have become more common and is conducted in the same way the glued laminated timber is processed.

According to the Krötsch and Hub (2018) the boards in the dowel laminated timbers can be processed in different ways to suit the best its end use. These processing methods include plane, rough sawn, sharping and chamfering. Also, different profiles can be manufactured to allow, for example, cable ducting or acoustic features.

As for the structural features then it is important to know, that dowel laminated timber panels can transfer very heavy vertical loads (Krötsch and Hub 2018). However, the cross-sectional axis is much weaker and should be improved through additional structures, which are for example wooden composite boards attached to the one side of the panel to resist the wall-directed horizontal loads or top/bottom plate to absorb loads applied transverse to the direction of the wall (Krötsch and Hub 2018). Openings in the dowel laminated timber panels should be created with the help of additional structures, for example, lintel beams or parapet transoms. Small openings can be made without trimmer joists.

Figure 6. Dowel laminated timber wall panel (©Andrew Latreille Photography).

The dowel laminated timber ceiling features are quite similar to the dowel laminated timber wall features. The main difference of dowel laminated timber ceiling from other timber ceilings is its structural height, which is the lowest from all structures. It however always requires the linear support. The rigidity of the dowel laminated timber ceiling is not enough to be used alone for the horizontal structures and therefore are used in the combination with the suitable wood-based material panels. In the same way, as for wall panels, the small openings are created by drilling of the panels, but larger opening should be created with the help of trimmer joists.

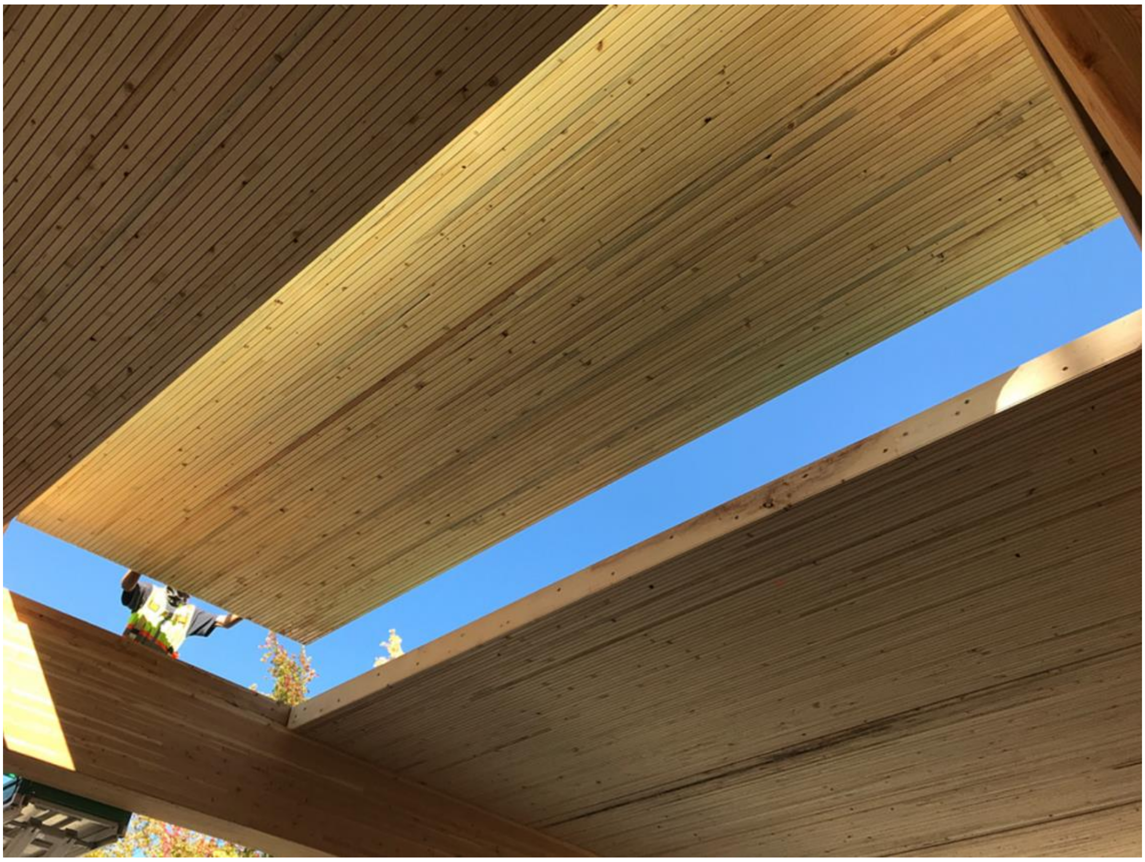


Figure 7. Dowel laminated timber ceiling panel in Lakeview office building (©StructureCraft).

**Cross-laminated timber panels**

Cross-laminated timber is the most common material of multistorey wood buildings in Finland (Paavola 2019). The main reason for this is its high prefabrication capability and high stiffness of the CLT. High prefabrication suitability is affected by the CLT panels' capability for fast jointing and assembling. CLT wall panels can carry heavy vertical loads if the boards are vertically located in the panel. Also, horizontal loads are well absorbed by CLT panels, because of their homogenous cross section. These features explain the CLT elements suitability and favor for the multistorey constructions. Opening to the elements are usually made during panel manufacturing. There are two main variants for the opening creation: opening cut out of the homogenous sheet and opening as a gap between elements (Krötsch and Hub 2018). The cut out the homogenous sheet usually creates considerable amount of waste, and therefore should be carefully designed. One of the main advantages of the CLT is a possibility to create free-shaped openings.

Figure 8. CLT wall panels (©Novatop).

In the same way as with the DLT elements, the CLT panels doesn't have significant difference between the ceiling and wall elements. There are multiple ways to connect the ceiling elements, and the choice should be based on the ceiling slab's rigidity, airtightness and fire safety requirements (Krötsch and Hub 2018). Four main joint methods, which are butt joint, element overlapping, top joint and tongue-and-groove joint, are presented in Figure 9.

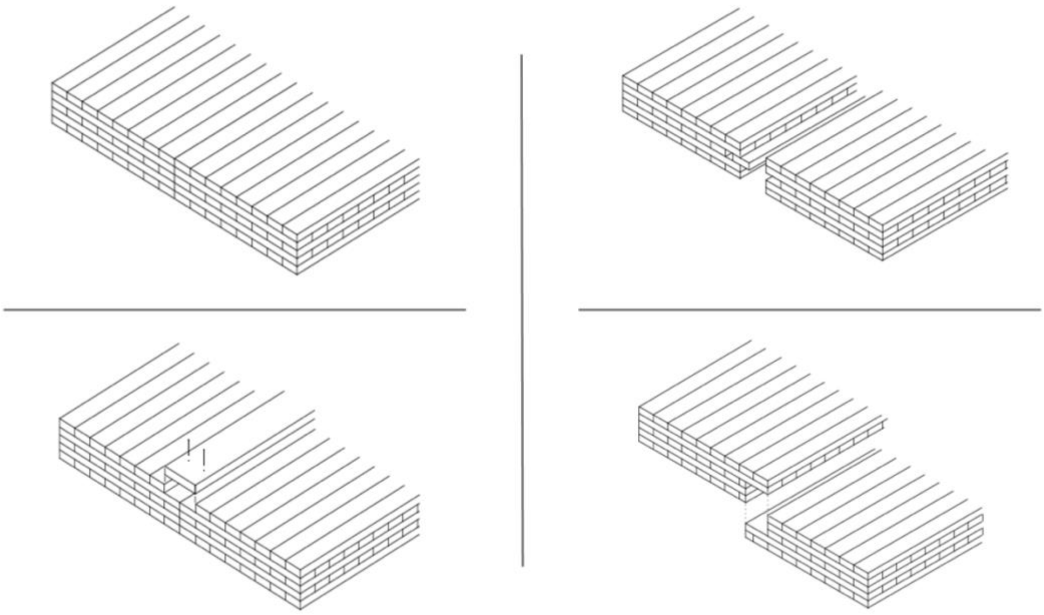


Figure 9. CLT ceiling joint possibilities (Krötsch and Hub 2018).

The thickness and therefore number of layers together with support situation affect the spans possibilities of the CLT ceiling panels (Krötsch and Hub 2018). The main load-bearing direction of the CLT ceiling panel is parallel to the direction of the panel's top layer. To ease the load-bearing capabilities of the CLT ceilings, the supports could be moved from the ends of the panel toward its centre. The CLT elements unlike DLT forms the rigid plates and in the case of proper jointing of the panels have a capability to brace the building.

Figure 10. CLT ceiling panel assembling (©Wigo.info).

**Modular systems**

The CLT elements can be prefabricated and assembled to the three-dimensional entities during the manufacturing. This kind of systems are created from the massive timber elements, usually CLT. The massive timber elements service both as load-bearing structures and solid envelope of the modules. The modules are usually created in the way, which allows the absence of the load-bearing structures inside the modules. However, the technical capabilities of the modular systems are manufacturer-depended and therefore should be investigated on case-by-case base.

Figure 11. Modular element from massive timber elements (©Skanska).

The modular systems provide the designers with high variety of design possibilities. The modular systems are usually used with additional elements, which are assembled on site. This kind of elements are, for example, corridors and roof. Also, a wide range of balconies are available using this kind of structural system. Some of the cantilevered modules require columns. The variability of the modular systems according to the modular elements manufacturer, StoraEnso, is presented in Figure 12.

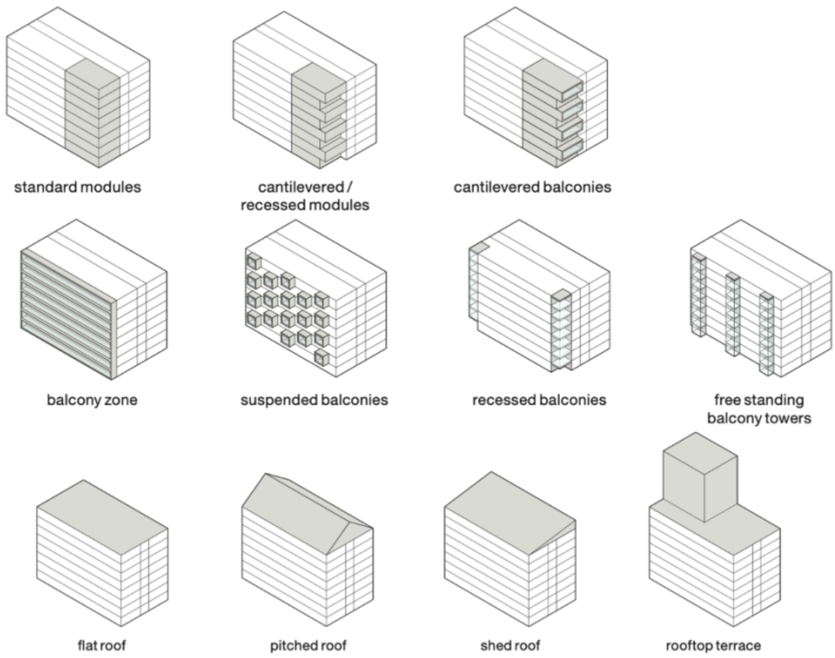



Figure 12. Modular elements variability (©StoraEnso).

### 2.4.2 Post-and-Beam Systems

Post-and-beam systems, alias frame systems, are created by interconnected columns and beams which carry the vertical loads in the building. Post-and-beam systems are especially suitable for commercial, institutional and assembly occupancies, because it allows great possibilities for the interior flexibility (Green and Taggart 2017). This kind of system allows the creation of different architectural appearance of the building, than in the massive timber panels systems. The columns allow for creating a large area of glazing on the facades and therefore the architectural language of the building is changed. Buildings thus have a clearer possibility to indicate they are public, not residential buildings. In some cases, post-and beam structures require the additional cross bracing or shear walls to create the dimensionally stable structures (Green and Taggart 2017).

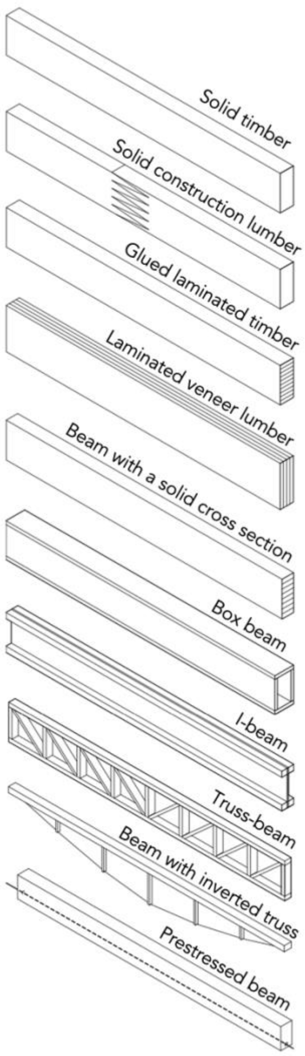



Figure 13. Beam typology (Kaufmann et al. 2018).

Columns have quite similar behavior as wood-based materials wood panels. Both columns and beams can be produced from solid timber or solid construction timber. However, this kind of material choice affects and limits the cross-section of the structural elements, which has a great impact on load-bearing capabilities of the structural elements. To overcome the limitation of the wood materials, it is quite typical to utilize the high-performance wood-based materials, for example GLT or LVL. The diversity of the beam typology has been widened by multilayer sheeting. The beam combination with the multilayer sheeting creates box beams, or girders, or able to create wide range of different geometries. Different kinds of beam typology and geometry is presented in Figure 13.

There is wide range of possible joints between the vertical and horizontal members of the system. Some of them are based on the hybrid solutions with utilizing of the steel connections. Other ones are based on the principles of traditional timber construction. Post-and-beam joints enable the shift of the heavy loads from upper to the lower supports without putting pressure on crosspieces.

### 2.4.3 Hybrid Systems

In some cases, the use of purely wooden structure systems isn’t an optimal solution. Therefore, in addition to satisfy the requirements of the structure program it is important to design the efficient and economically optimal structure. These hybrid systems can be a option for the optimal wood structures design. This kind of solutions are common and can be made to answer architectural, structural, environmental or economic reasons (Balasbenah et al. 2018). Also, local construction practices or regulations can affect the choice of the optimal structural system. Hybrid systems include the use of wood in the combination with other materials to achieve the high load-bearing capabilities and the optimal use of wood-based materials.

The combining of wood with steel, concrete or glass allow to create the systems where the structural efficiency is enhanced. In the hybrid systems, designers can create taller and larger wood structures with longer spans. The mixing of the materials in the structural systems creates the possibility to utilize the strengths of each of them. In this way, designers can achieve both the structural and building performance. The hybrid structures also create the expressive structures. Therefore, this kind of structure systems can serve practical and aesthetic functions. According to Zhou et al. (2014) hybrid systems also improve the structures seismic performance. In Figure 14 is presented the world's tallest hybrid timber tower under construction.

Figure 14. The world's tallest hybrid timber tower under construction, Australia (©SHoP)

When the use of massive timber panel systems is typical for the residential buildings, and post-and beam structures for the commercial, institutional and assembly occupancies, hybrid systems actually are suitable for all kind of purposes. Hybrid systems can be used to create residential towers, industrial warehouses or sports stadiums (NaturallyWood 2021b).

In the next chapters is presented the wide range of modern hybrid timber systems. First is presented pre-stressed self-centering systems. Next the hybrid systems with steel elements are presented: steel moment frame with CLT infill panels and mass-timber balloon-frame with steel links. And, lastly, the hybrid systems with concrete elements will be covered: the timber-concrete jointed-frame concept and timber-concrete composite floors.

### 2.4.3.1 The self-centering timber systems

The self-centering timber timbers development have been motivated by the recent concept of seismic resilient structures and societies. The use of this kind of systems is especially required for multistorey buildings, which are located in earthquake-prone regions (Cui et al. 2020). The self-centering timber systems are able to overcome the low joint rotational stiffness, which is typical for the post-and-beam timber structures. The best features of this kind of structural systems are wood elements capability to promote the initial lateral stiffness and the lateral load-resisting capacity combined together with the steel energy dissipation mechanism, which relies on the yielding of steel members and nails fasteners in the wood elements (Cui et al. 2020). The visualization of the self-centering timber system is represented in Figure 15.

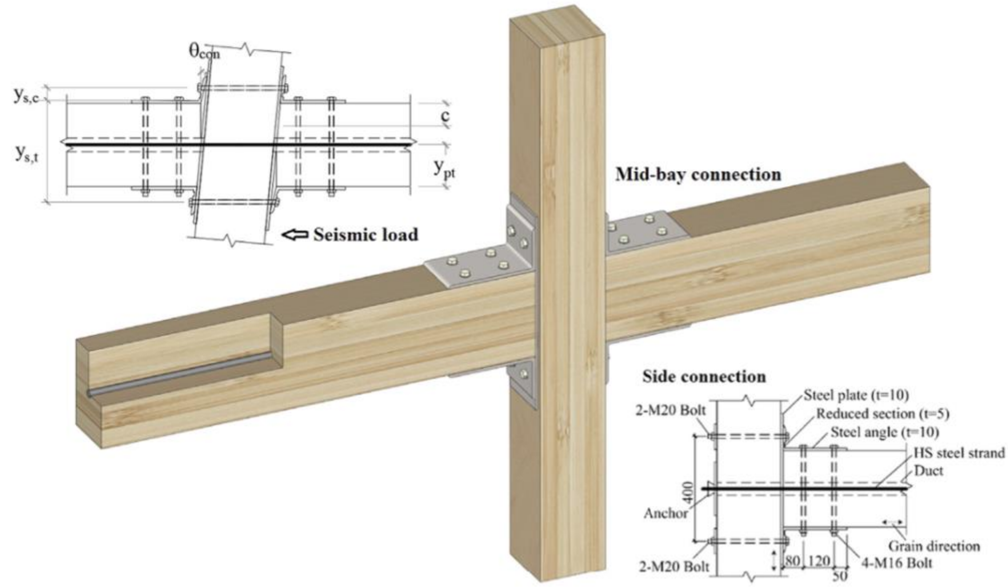



Figure 15. Post-tensioned joint of the self-centering timber system (Shu et al. 2019).

Despite the clear benefits if the self-centering timber system, their development and number of researched related to this topic are relatively low. Because of this, the number of possible implementations is limited compared to the other timber structures. The most common version includes three main structural components: post-tensioned moments-resisting steel frame, wood beam-to-wall system and friction dampers that are assembled to the beam-to-wall connections to dissipate the energy (Garlock and Li 2008). Another version refers to the use of the prefabricated infill light-frame wood shear walls as a wood element (Cui et al. 2020).

### 2.4.3.2 Steel moment frames with CLT infill panels

The second version of the self-centering timber systems is steel moment frames with CLT infill panels. In this case have been combined beneficial properties of steel frames together with CLT shear walls. The main benefits of CLT shear panels are connected to the possibility to provide high tensile strength parallel to the grain and high compressive strength perpendicular to the grain of timber (Vogiatzis et al. 2019).

The overall idea of the hybrid systems is to utilize the maximum benefits of each materials. The use of CLT elements allow to significantly reduce the weight of the floor and wall systems (Dickof 2013). The composite action of this kind of structure system is achieved with the help of discrete connectors, steel frames and infill walls. The connectors are needed to fix the wall elements to the steel frame and therefore ensure effective energy dissipation in the case of seismic activity of any kind (Ganey et al. 2017). Systems however is constructed in the way, which allow the connectors to deform and therefore dissipate the energy in the system. This characteristic is achieved by the gap between the wood elements and steel frames (Tesfamariam et al. 2014). The connections between the elements are typically L-shaped steel brackets. The steel brackets are bolted to the steel frames and nailed to the CLT infill walls (Tesfamariam et al. 2014). The principle of the steel moment frames with CLT infill panels is presented in Figure 16.

Figure 16. The principle of the steel moment frames with CLT infill panels (Bezabeh and Tesfamariam 2016).

#### 2.4.3.3 Mass-timber frame with steel links

The use of steel links is quite a common practice for hybrid timber structures. The steel connections can be both exposed and hidden. The preferred version of the steel links in mass-timber frame is pre-engineered connectors, which are factory installed and are simple for the design, because of their standardization. There are plenty of steel links for mass-timber frame systems. One example is the concealed beam hanger with which is possible to achieve high fire-rating regulations and have a rotational capability to control the structure performance during seismic and wind events (Structurlam 2019).

It is also possible to use mass-timber frame with custom steel connections if there are not suitable options from the pre-engineered connectors. The customized steel connections are needed when the common shapes and geometries are not appropriate. The advantages of this kind of connections is the possibility to create innovative architectural shapes. The disadvantages of custom connectors include their less predictable behavior than tested, pre-engineered connectors (Structurlam 2019).

Steel links in the structure allow it to overcome the CLT floor panels weakness to vertical loads and transfer the vertical load from the upper levels to the ground level. While steel connectors are mostly used for structural solutions, they also have the capability to create fascinating architectural forms by exposing the wood structures and their engineering solutions to the environment. Examples of the steel links or connectors use in the wood structures is presented in Figure 17.

Figure 17. The interior of the Design Building in Amherst (©Leers Weinzapfel Associates).

### 2.4.3.4 The timber-concrete jointed-frame concept

As discussed previously, for massive wood structures despite all their benefits have plenty of disadvantages: low structural weight, floor vibrations, long-term differential shortening and fire performance. The low structural weight is a disadvantage in the case of the lateral loads and consequential structure uplift (Baker et al. 2014). The search for the solution for these challenges has created the timber-concrete jointed-frame concept. This structure system includes primarily the use of wood in the shear walls, floor panels and columns (Baker et al. 2014). In the timber-concrete jointed-frame cast-in-place concrete with steel reinforcing is used for the joints of the massive wood structural elements. The timber-concrete jointed-frame structure creates an efficient solution for a variety of tall wood buildings. This kind of structure can create diversity and compete with more classical solution for tall wood buildings: reinforced concrete and structural steel systems (Baker et al. 2014). At the same time the timber-concrete jointed-frame concept is able to reduce the carbon emissions by 60 to 75% (Baker et al. 2014). The example of the typical floor diagram for the timber-concrete jointed frame system is presented in Figure 18.

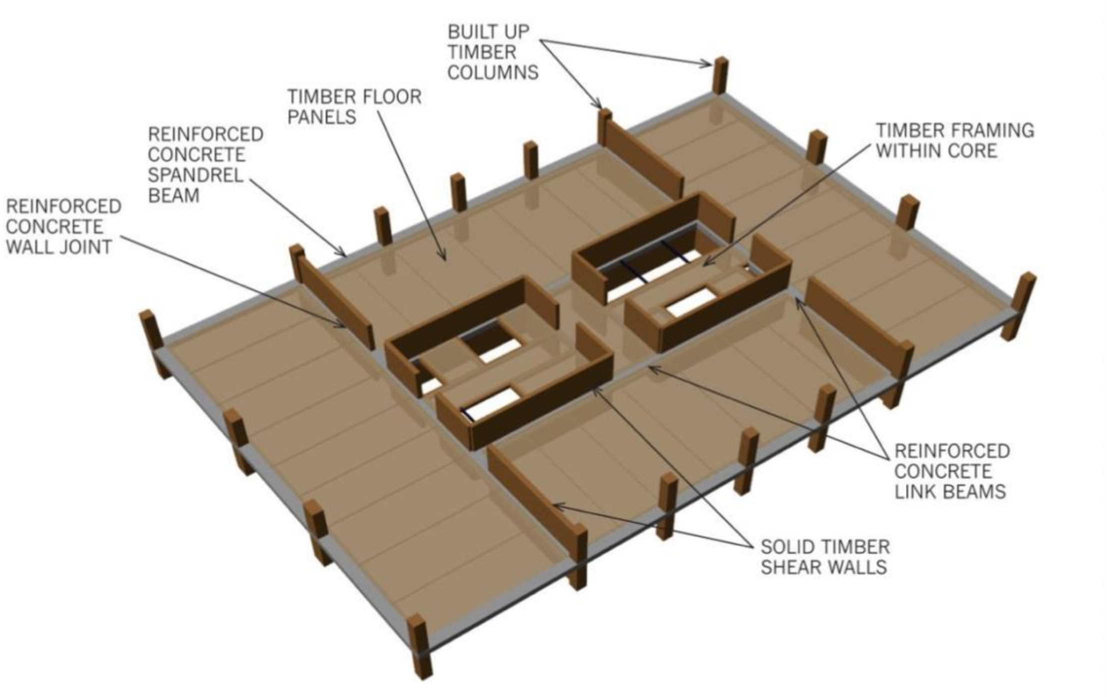



Figure 18. Typical floor diagram of the timber-concrete jointed-frame system by Baker et al. (2014).

Beside the advantages of this kind of structure, there is disadvantages of wood members which effect the overall performance of the system. Despite the very little movement parallel to grain the wood members the possibility of creep should be considered during the design phase to avoid the shortening of the structure in the long term (Baker et al. 2014). The shortening of the vertical elements is enforced by the weight of the concrete joints. However, the detailed knowledge on this effect requires additional research (Baker et al. 2014).

#### 2.4.3.5 Timber-concrete composite floors

Timber-concrete composite floors combine the advantages of pure wood slabs and pure concrete slabs. This is one of the most common hybrid-timber structures in Finland. The combination of the wood and concrete for the composite floors brings significant improvements to the purely wood or concrete slabs. These improvements relate to the increased stiffness, load carrying capacity, significantly improved sound insulation, decreased vibrations, decreased overall load of the structures, and decreased carbon emissions (Dias et al. 2018). This kind of hybridization enables the integration of electrical and mechanical systems into the composite panels (StructureCraft 2021). One another significant benefit of timber-concrete composite floors is reduced amount of the concrete in the structures which speeds up the building phase and, therefore, reduces costs, which helps to keep the structure economically efficient.

In the Woodworks webinar by Skidmore, Owings & Merrill (2017) has been presented the design methodology for the timber-concrete composite floors, which includes 5 main steps. First step refers to the calculation of the sectional properties of CLT according to the manufacturer. In the next step the designer should select the fastener type and determine slip stiffness according to the manufacturer. Third step relates to the calculation of the effective composite stiffness. Forth step refers to the calculation of the apparent stiffness or model rolling shear stiffness losses. And last step refers to the calculation of the serviceability and ultimate limit states and evaluation. Despite the fact that this kind of analysis isn't typically a part of the architect's responsibilities, this work should be done with the structural engineer in the beginning of the design process to understand the architectural possibility of the chosen structure system. In Figure 19 is presented the visualization of the timber-concrete composite floor.

Figure 19. Visualization of the timber-concrete composite floor (©StructureCraft).

## 2.5 Architectural language

In this master's thesis the concept of architectural language will be used to discover and leverage the "signifier" and "story-teller" role of the tall wood buildings, which is affected by structural solutions and structural possibilities. The interpretation of the architectural language concept would be based on the notes for the Thinking about Architecture: An introduction to Architectural Theory by Collin Davies (2011). However, also the author's notes for the understanding of the architectural language concept, affected by the entire environment and other's architects talks about this topic would be part of this chapter. Interesting additions to the concept presented in the book have been presented by Daniel Libeskind at TEDxDublin in 2012 (TEDx Talks 2012) and Ludwig Mies van der Rohe (Bauhaus Movement 2016).

I believe that this concept can be a key to understand and to create architecture. In the beginning of my work, I have mentioned that despite the fact that architecture in its physical appearance has very static nature, the forces behind the architectural development represent anything but a static character. Architectural development is shaped by highly dynamically mutable forces, which enhance the architectural diversity in all its shapes. And during all these developments the architecture actually "speaks" to its environment. It addresses the time it is present in, it addresses the thought of its designers and its address the society's logics it is inspired by. However, the notice of time, can be argued. According to the Ludwig Mies van der Rohe (Bauhaus Movement 2016) "architecture belongs to the epoch, not even to the time". The art monumented in the architecture will express the spirit of the sense of the whole epoch not only the transient time it was created in.

The static nature of physical building differs it from any other language art present in the world, for example music, which is unfolding over time (Davies 2011). The architecture is extended in three dimensions and able to be perceived at one time at least for one of its aspects (Davies 2011). Architecture can be experienced spatially, texturally and functionally. The textural language of the buildings is especially important for tall wood buildings. The wood has provided the tall buildings with material diversity, which feels different and behaves spatially different.

The building can tell the visitor about its purpose. The function of the building in the most cases can be easily read from building appearance. Humans can easily distinguish a residential block from a railway station or school. Therefore, architecture can fulfill the function of written or spoken words (Davies 2011). Maybe a better word to explain the idea of architecture as a language would be the term of “signifier”, when building assigns to itself a certain message to the environment.

While “reading” the architecture the observer should remember that the language is two-way process, which involve both the readers and writers. And not always the reader gets the same message as writer has put in its creation. Therefore, both the readers and the writers contribute to the meaning of the “message” or “sign” (Davies 2011).

Linguists may argue, that language is not only what we write or speak, language is a sign system. To understand the organizing principles of this system it is important to understand the constituents, which affect it. This kind of constitutes can be for example *parole* and *langue.* These concepts have been originally formed by Swiss linguist Ferdinand de Saussure (Davies 2011). Their originally definitions explain the parole as “individual utterances, spoken or written, like sentences”. The langue concept refers to the “whole body of the language” (Davies 2011). However, the parole/langue mechanism doesn’t just contain or organize meeting, it creates meaning. Therefore, meaning is not a stable thing, it changes according to the context. The meaning of the word is also dependent on its difference from all the other words. The diversity of words therefore creates the context for the defining of the parole and langue. To the meaning of the word can be applied the deductive method, which means that new word can be defined by all the things it does not mean. Therefore, the word is not a positive or negative thing.

To apply this theory to the architecture the few important notes should be made. First, the relationship between the signifier and signified in the architecture can be referred to the relationship between word and the thing which is signed by the word. Second, the signs can be divided into three main categories, which are icon, index and symbol. Icon refers to the signifier recall relation to the thing it signifies. Index points to the thing which it signifies, like a “road sign pointing to a destination” (Davies 2011). Symbol refers to the relationship, which create an “arbitrary link, sanctioned only by tradition and not relying on any kind of resemblance” (Davies 2011).

In this master’s thesis the architectural language would be utilized to analyze the signifiers and meaning in the case of tall wood buildings. The parole and langue concepts will be used in its adapted meanings. The point concept will be used to explain the details, like words, of the building entities to understand the constitutes behind the langue of the building. Langue refers, therefore, to the expression of the building entity and its context.

# 3

# 3. RESEARCH DESIGN AND METHODOLOGY

In this chapter will be presented the research methodology application to the architectural research and reasons behind the choices of the certain methods and tools. Firstly, the research approach and theories behind it will be discussed. After this the data collection method will be represented. Separately, the third part will discuss the data analysis methods. Lastly, the evaluation of research design will be represented.

## 3.1 Research approach

In this thesis would be applied the qualitative case study approach is applied. The qualitative research approach has been chosen as it refers to the collecting and analysing of non-numerical data (Merriam and Tisdell 2015). The non-numerical data is used in this research to understand the concepts, opinions and experiences about the tall wood buildings.

The qualitative research can be divided into two main categories, which are basic and applied research (Merriam and Tisdell 2015). The main motivation of the basic research is connected to the intellectual interest in a phenomenon and therefore its goal is to extend the existing knowledge. The applied research can be applied to improve the quality of practice of a particular discipline (Merriam and Tisdell 2015). The purpose of the applied research is slightly different to the basic research. Through the applied research the researcher strives to create the guide for other researchers or, as in this case, designers, which can be applied in the practice. In this thesis the applied qualitative study has been chosen to answer the research questions of this thesis.

There are many different forms of the applied qualitative study. One of the applied qualitative research forms is evaluation research, which is utilized for the goals of this thesis. According to Merriam and Tisdell (2015) the main idea of the evaluation research is to collect data or evidence according to the goals of the program, process, or technique. The collected data is used then as a basis for the decision making.

To achieve the purposes of the qualitative study the case study approach has been applied. The idea of the case study approach adapting to the architectural research have been presented in the “Architectural research methods” book by Groat and Wang (2013). The case study definition presented by Yin (2009) have been modified by Groat and Wang

(2013) to suit the best the goals and conditions of the architecture research and has taken a shape of the following definition: "A case study is an empirical inquiry that investigates a phenomenon or setting". This thesis will adapt also the case study structure proposed by Eisenhardt (1989). The structure of this thesis is presented in Table 4.

Table 4. The structure of the master's thesis

| **Step** | **Activity** |
|---|---|
| Getting Started | Focusing of the effort through the construction of the possible a priori constructs and definition of the research questions |
| Selecting Cases | The cases are chosen theoretically, not randomly |
| Crafting Instruments and Protocols | In this thesis is utilized multiple data collection methods |
| Entering the Field | The flexible data collection methods are overlapped with data analysis. |
| Analyzing Data | Within-cases analysis of data |
| Shaping Hypotheses | Iterative tabulation of evidence for the constructs |
| Reaching Closure | Theoretical saturation when possible |

To address the objectives of this master's thesis the multiple-case study has been adopted. As the idea of this thesis is to discover the architectural language variables in tall wood buildings concept then the natural choice was to use the multiple cases (Yin 2009). The multiple-case study allows the researcher to create more compelling evidence and therefore is considered as a more robust study approach (Herriott & Firestone 1983). The multiple-case study offers the analytical benefits to the researcher. The analytical benefits of multiple-case study can be achieved with the help of comparison and replication of the case findings (Yin 2009).

To achieve the theoretical and empirical saturation of this master's thesis six cases have been chosen. To discover the architectural language of tall wood buildings extensively the cases have been chosen from different locations and therefore building logics. Three of the cases are located in Finland: Lighthouse in Joensuu designed by architecture studio

Arcadia, Puukuokka in Jyväskylä designed by architecture studio Oopeaa and WoodCity in Helsinki designed by architecture studio Anttinen Oiva Arkkitehdit. Other three cases are Mjøstårnet located in Brumunddal, Norway and designed by architecture studio Voll Arkitekter, and, lastly, HoHo Tower located in Vienna, Austria and designed by architecture studio Rüdiger Lainer + Partner Architekten.

## 3.2 Data collection

The empirical part of this research is divided to the two main studies, which are Conceptual Studies and Empirical Understanding of Architectural language of Tall Wood Buildings. The Conceptual Studies of this thesis is conducted by architectural evaluation, archival studies and interviews. The second study, Empirical Understanding of Architectural language of Tall Wood Buildings, is conducted mainly with the help of interviews. Therefore, this thesis includes multiple data sources. According to Yin (2009) the multiple data sources help the researcher to discover and therefore address wider range of historical, attitudinal and behavioural issues. Yin (2009) mentions that finding and arguments of the case study which are based on the multiple data sources is “much more convincing and accurate”.

As it was mentioned above the first study of this master’s thesis consists of architectural evaluation, archival studies and interviews. The architectural evaluation of the cases and archival studies of the case materials are strongly interdependent and conducted simultaneously. To discover the architectural language of the case buildings the design period drawings have been utilized and the architectural evaluation have been conducted with the help of these papers. Also, photography research has been conducted to estimate the feasibility of the design solutions and final implementation solutions. Mainly the internet archives of the architectural magazines and architecture studios websites have been utilized. However, also some drawings have been obtained directly from the building’s designer.

Both of the studies have utilized the interviews. The interviews for this master’s thesis have been designed as a semi-structured interview to expand the possibilities to define the new knowledge. All the questions for the interview are open-ended questions and designed according to the theoretical review. The structure of the interview was updated after the third interview, because the experience of the first interviews highlighted the need for more general and open questions, which are not necessarily connected to the particular case building. The structure of the interview is presented in Appendix A.

All the interviews were carried out in the period between the May and April 2021. A total of nine interviews were conducted in this period. The duration of the interviews was at least 30 minutes and at maximum around one hour. Most of the interviews were conducted through video/audio conferencing, but some of the respondents answered to the interview questions in written form.

In order to avoid the biases of having interviews with persons from the same background, the interviews have been conducted both with the architects of the case buildings and with the experts of the wood building and wood manufacturing field. All the oral interviews have been audio-recorded with the permission of the interviewees. This approach has allowed the researcher to elaborate on the answers and therefore follow the ideas of semi-structured approach.

The interviewees are presented in this thesis through the acronyms. The list of the conducted interview together with the position and area of expertise of the interviewee and duration of the interview is presented in Table 5.

Table 5. List of interviews

| **Position** | **Field of expertise** | **Acronym** | **Length (min)** |
|---|---|---|---|
| Architect | Case building designer | A1 | 42 |
| Expert | Wood Building | B1 | 44 |
| Expert | Wood Building | B2 | 35 |
| Architect | Case building designer | A2 | written answers |
| Architect | Case building designer | A3 | 28 |
| Architect | Case building designer | A4 | 60 |
| Expert | Wood-based materials | C1 | 48 |
| Architect | Case building designer | A5 | written answers |
| Expert | Wood-based materials | C2 | written answers |

## 3.3 Data analysis

The data analysis in this master's thesis was inspired by the Gioia methodology (Gioia et al. 2012). The qualitative character of the collected data has affected the choice of the Gioia methodology despite the fact that this methodology is not that apparent for the architectural research. The main idea of this approach is to adopt the point of view, observed during the empirical study, and avoid the forced categorisation of the observed data to the existing theories. This is the main consequence of the traditional approach, which concentrates too much on the construction of the elaboration to the existing theories. This kind of search for the evaluation can blind the researcher to the possible new knowledge (Gioia et al. 2012).

The Gioia methodology proposes to analyse the obtained data simultaneously with the interviewing (Gioia et al. 2012). Already in the interviewing phase can be defined the 1st order concepts. The idea of the 1st order concept is to define all the possible data categories obtained from the interviews and observation of the drawings of the case buildings. In this step the number of categories is enormous, which can create sort of "lost" feeling for the researcher (Gioia et al. 2012). However, it is the only way to find the echoes of the new theories.

After the 1st order concepts have been defined the researcher have started the search for similarities and differences among the 1st order concepts. After this kind of trimming the number of the left concepts become to be more manageable. In this step the additional interview questions are possible to emerge (Gioia et al. 2012). After the 1st order concepts have been processed the 2nd order themes are formed.

During the 2nd order analysis, the researcher is already able to identify the emerging theoretical concepts. These concepts can help the researcher to describe and explain the phenomena, which is observed in this research (Gioia et al. 2012). During this step the manageable set of the themes and concepts can be categorised to the so called "aggregated dimensions".

With the help of the Gioia methodology in this thesis have been created the data structure, which is orchestrating the structure of the data representation in the empirical part of this work. After the data structured is formed the researcher have possibility to shift between emergent data, themes, concepts, dimensions and the relevant literature to both define the new concepts and define the precedents of the findings in the existing knowledge (Gioia et al. 2012). The aggregated dimensions and second order themes are presented in Table 6. The overall data structure is presented in Appendix B.

Table 6. The aggregated dimensions and second order themes of data structure.

| ***Aggregated Dimensions*** | ***$2^{nd}$ Order Themes*** |
|---|---|
| The main limitation is imagination. And budget. | Collaboration is vital for the project success<br>Tight budget creates boundary conditions for design |
| Responsible design is vital for the tall wood building development. | Thoroughness in design and creative application.<br>Tall wood building identity. |
| The purpose is everything for the tall wood building. | Tall wood buildings are great for the symbol purpose.<br>Tall wood buildings are not that suitable for residential purpose. |

# 4

# 4. FINDINGS

In this part is presented the findings of the empirical research. The empirical research of this master's thesis is a combination of the two main studies, which are Conceptual Studies and Empirical Understanding of Architectural language of Tall Wood Buildings. The decision to divide the case research and the findings emerged from the interviews was made after the interview structure was modified to more generic questions. At this point it become clear that more value could be achieved if the findings from the interviews could be presented separately despite the fact that data from both empirical researches had been analyzed simultaneously and interdependently.

## 4.1 *Study I* Conceptual Studies

The Conceptual Studies section includes the discovery and elaboration of the six case studies of tall wood building in Finland, Austria and Norway. For the Conceptual Studies have been chosen Lighthouse in Joensuu designed by architecture studio Arcadia, Puukuokka in Jyväskylä designed by architecture studio Oopeaa and WoodCity in Helsinki designed by architecture studio Anttinen Oiva Arkkitehdit, Mjøstårnet located in Brumunddal, Norway and designed by architecture studio Voll Arkitekter, and, lastky, HoHo Tower located in Vienna, Austria and designed by architecture studio Rüdiger Lainer + Partner Architekten. The basic indormation about the case buildings is presented in Table 7.

Table 7. Basic information about the case buildings.

| | Mjøstårnet | HoHo Tower | Lighthouse | Puukuokka | Wood City |
|---|---|---|---|---|---|
| Height (m) | 85.4 | 84 | 50 | 29 | |
| Number of storeys | 18 | 24 | 14 | 8 | 8 |
| Completed | 2019 | 2019 | 2019 | 2015 | 2020 |
| Area ($m^2$) | 15500 | 25000 | 6000 | 5250 | 20000 |
| Purpose | Public, office, hotel, residential | Residential, offices, hotel, serviced apartments, wellness | Student-housing | Residential | Office, hotel |
| Location | Brumunddal | Vienna | Joensuu | Jyväskylä | Helsinki |
| Structure system | GLT, CLT | Hybrid (GLT/CLT-concrete) | LVL/CLT large panels | CLT modular unit | LVL/CLT |
| Architect | Voll Arkitekter | Rüdiger Lainer + Partner Architekten | Arcadia Oy | OOPEAA | Anttinen Oiva Arkkitehdit |
| Builder/Client | AB Invest | Güner Kerbler, Caroline Palfy | Joensuun Elli Student-housing | Lakea Oy | SRV Rakennus Oy |
| Contractor | Hent | Handler Bau GmbH | Eero Reijonen | Stora Enso JV-Rakenne | SRV Rakennus Oy |
| Structure engineer | Moelven Limtre, Sweco | Woschitz Group | A-Insinöörit | Sweco | Sweco |
| Structure manufacturer | Moelven, MetsäWood | Hasslacher Norica Timber, Meyr Melnhof | Stora Enso | Stora Enso | Stora Enso |
| Fire safety consultant | | Kunz – die innovativen Brandschutzplaner | Markku Kauriala Oy | KK-Palokonsultti Oy | |

For the case studies multiple data sources have been exploited, such as the building's drawing archives, previous interviews with the stakeholders of the projects and knowledge obtained directly from the designers through the interviews. For the structuring of the case buildings' elaboration the aggregated dimensions defined by the Gioia methodology have been utilized. In the next parts the case buildings will be discussed on the base of the three main dimensions:

1. The main limitation is imagination. And budget
2. Responsible design is vital for the tall wood building development
3. The purpose is everything for the tall wood building.

The conceptual studies part will go through these three main categories and present the case features according to the aggregated dimensions.

### 4.1.1 The main limitation is imagination. And budget.

All the data sources in this thesis have presented the great potential of the wood structures for tall wood buildings. According to the respondents and the literature, the main things, which should be considered when designing tall wood buildings are fire regulations, structural solution and the budget. The fire regulations can be turned to the good of the tall wood building architecture appearance if project designers are able to create a deep and confident collaboration. All kinds of limitations or boundaries in the tall wood constructions can be turned for the benefit of the project. However, the only limitation, which is difficult to overcome in any type of project, is budget. In this part the case buildings will be studied in the terms of architectural language achieved and created through the applied fire regulation and structural solution methods.

### *Case I* Mjøstårnet

Figure 20. Mjøstårnet (©Ricardo Foto).

The choice of Mjøstårnet for this thesis was natural. It is impossible to ignore the world's tallest wood building in this kind of research. Mjøstårnet is recognized as a world tallest "all-timber" building according to the Council on Tall Buildings and Urban Habitat (CTBUH). The "all-timber" refinement is an important, because in the world exist tall timber buildings, which are higher than Mjøstårnet, but their primary structure includes non-timber elements. The "all-timber" structure definition however allows to use the non-timber connections between the elements (Foster et al. 2016).

The glass amount in the facades have been reduced to serve the building's purpose effectively. Facades became now a composition of the wood panels and glass openings. The architect's rationalization for the wooden facades have been connected with the tall wood building identity. However, the researcher's personal opinion differs with the case building architect's, but this point will be discussed more furtherly in the part 4.1.2 Responsible design is vital for the tall wood building development. Despite this comment, researcher cannot help but agree that wooden facades fit to the environment perfectly and enforce the *langue* of the Mjøstårnet.

According to Elgsaas (2021) his first sketches for the tower included the timber exoskeleton wrapped with glass shell. However, the constructional solution for this kind of architectural solution would have been too complicated. In a wood building, as well as in any other structure solution, the design should first of all remain sustainable as reasonable. This affected the designers' decision to search for a more buildable solution, which would stay within time and budget (Elgsaas 2021).

The new, developed solution included the combination of playful wood facades and post-and-beam timber structure strengthen by diagonal beams. This structural solution has created the expressive architectural language of the Mjøstårnet. The massive diagonal beams have become strong *parole* elements in the building, which comprise the "reliability" message to the environment and building users. This *parole* was present both for design and stability needs. The stability function refers to the large glulam trusses ability to carry and transfer both the horizontal and vertical loads tot the ground level. The overall load-bearing structure of the building have been implemented by the glulam and laminated veneer lumber elements with the hollows filled by Rocwool. Some of them have also the concrete screed on the top of the elements (Elgsaas 2021). The secondary load-bearing structure for three elevators and two staircases consists of CLT walls, which however does not contribute to the building's horizontal stability (Elgsaas 2021). The structure system of the Mjøstårnet is presented in Figure 21.

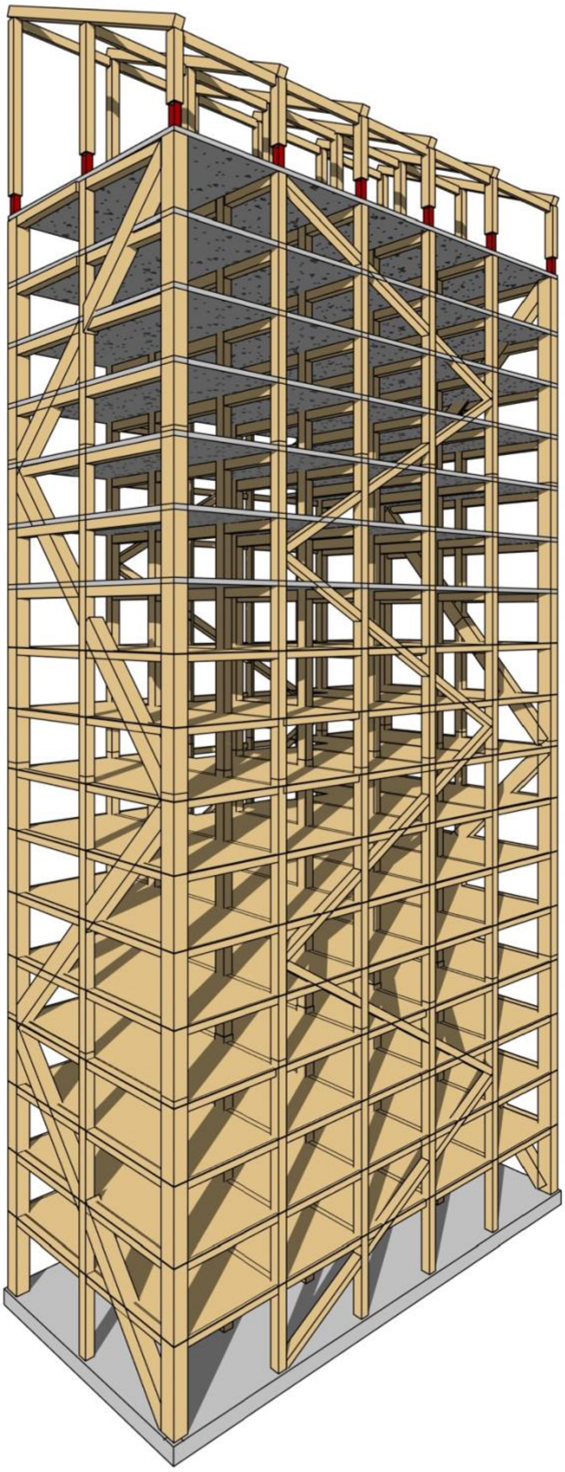


Figure 21. Structure of Mjøstårnet (©Moelven).

To ensure the stability of the building, it was anchored to the bedrock located 50 meters below the ground level (Elgsaas 2021). The optimized solution for the floor structures has been developed in the collaboration with all the project parties. Floor structures from the second storey to the eleventh are implemented by hollow-box floor elements. This solution reduced the structure's weight and optimized the use of wood in the structures compared to the CLT floor panels. These systems are faster to assemble, and they are effective for the acoustic and fire regulation requirements. The hollow-box floor elements are multifunctional and can be used for the building service engineering installation. The maximum floor span which can be achieved by this system is up to 10m, but in Mjøstårnet it is 7,5m. Therefore, the larger architectural flexibility can be achieved by this system (Elgsaas 2021). The example of hollow-box floor system by Lignatur manufacturer (2021) is presented in Figure 22.

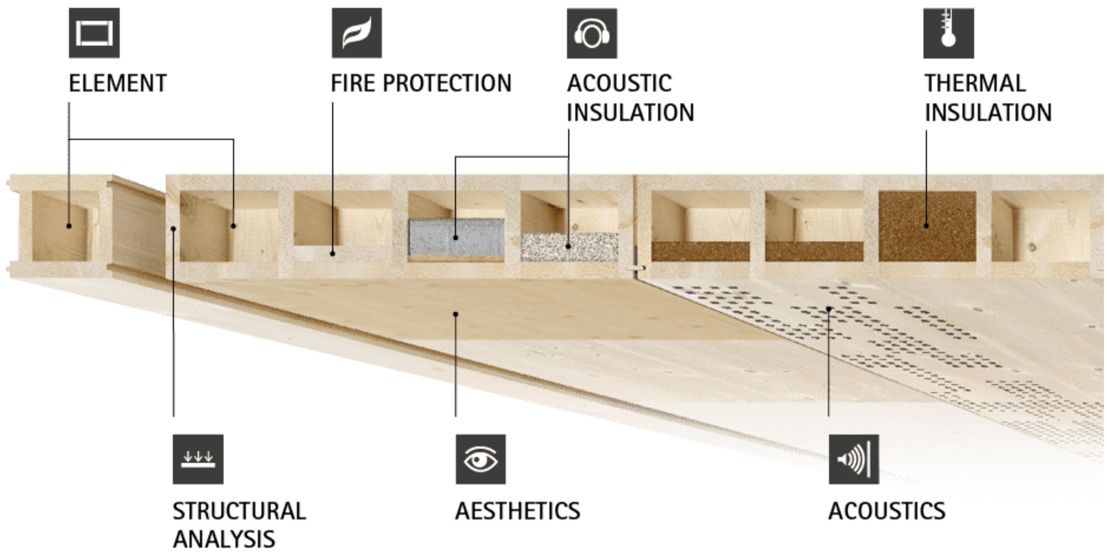



Figure 22. Hollow-box floor system capabilities (Lignatur 2021).

Floor structure from the 12$^{th}$- to the 18$^{th}$-storey is implemented by 300mm thick concrete elements, which were partly prefabricated and partly cast in-site (Elgsaas 2021). This kind of solution made the structures heavier to the top of the building. The heavier structures on the top are needed to meet the wind-induced acceleration criteria for the residential buildings. Concrete floors made it possible to achieve the maximum horizontal deflection of 14 centimeters, which is very little for the 85.4 m high building (Elgsaas 2021). Despite that fact, the wind-induced acceleration on the 17$^{th}$-storey is on the limit of what is allowed for residential buildings.

The floor structures enhance the stiffness of the timber skeleton (Elgsaas 2021). The glulam beams are used to transfer the main vertical loads to the ground level. Interestingly glulam beams were used both to support the hollow-box floor elements and concrete structures. The typical section of the glulam beam in Mjøstårnet is about 625x720mm, the diagonal trusses have a cross section of 625x990mm, and the largest corner columns have cross section of 625x1490mm. As was mentioned before, the structural wood elements have been joined by steel connections.

The close cooperation of all parties has allowed the fast and simplified construction site phase. All the elements have been prefabricated, coded and shipped to the site to be assembled. The structure of Mjøstårnet has been completed within 1 year (Elgsaas 2021). Assembly was implemented without a trial stage, which significantly accelerated the construction of the building, despite the fact that this kind of solution represented a considerable risk (Elgsaas 2021). To reduce the risk of water damage, the ends of the CLT panels and end grain of glulam columns and diagonal trusses have been temporarily protected from weather (Elgsaas 2021).

All the structure elements in Mjøstårnet are fire tested to withstand required minutes of fire, which is 120 minutes for main load-bearing systems and 90 minutes for secondary load-bearing systems. To ensure the 120 minutes of fire for the main load-bearing systems, their cross-sections have been oversized by 80mm in each dimension (Elgsaas 2021). The structures are also designed in such a way, so they can withstand the timber deck falling to the floor below. This kind of structure is able to withstand a complete fire, which is allowed to develop freely. However, two separate sprinkler systems are installed to the building, and floors are constructed as separate fire cells.

To prevent the fire spread through the facades, which is one of the main fire regulation requirements in the case of wood facades, the wood façade panels are divided by Firestops (Elgsaas 2021). The Firestop is created by the steel plates and dowels between the storeys of the building, which are embedded into the timber for approximately 85 mm (Elgsaas 2021). This solution dictated by the fire regulations became one of the Mjøstårnet *parole,* which describes the building and creates its identity. This solution paradoxically enhanced the height impression of the Mjøstårnet and in the same time balanced the verticality of the tower with this horizontal sectioning. The element of the façade system is presented in Figure 23.

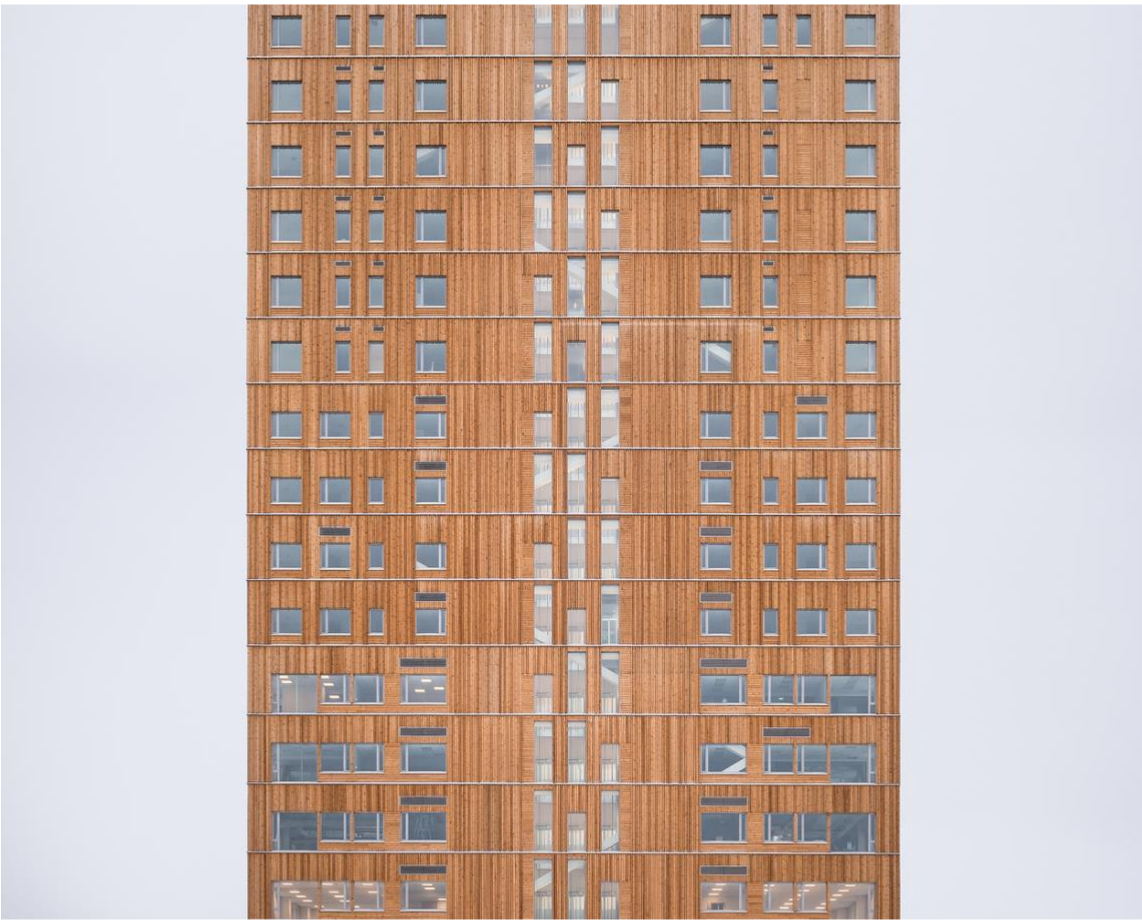


Figure 23. Element of the Mjøstårnet facade (©Woodify).

***Case II* HoHo Wien**

Figure 24. HoHo Wien (©RLP Rüdiger Lainer + Partner).

HoHo Wien can be defined as a composite building according to Foster et al. (2016). Foster et al. (2016) proposed the extension of then existing guidance on the classifying of the tall wood building, which has been now adapted by the CTBUH (2021): “A composite building utilizes a combination of steel, concrete and/or timber acting compositely in the main structural elements, thus including an otherwise steel or timber building with a concrete core”. The core of the HoHo Wien with elevator shifts, staircases and escape routes are made of reinforced concrete for reasons of statics and bracing, but the structure of usable areas is made from wood and wood-composite elements (Grausam 2021). The internal columns are made from the glulam, wall panels are made from CLT, floors are composite of cross-laminated timber and edge panels are made of precast concrete (WoodSolutions AUS 2020). The structures of the usable areas are docked onto the concrete core, which provide the designers with architectural flexibility of plans. The CLT walls do not participate in the vertical load bearing and therefore can be removed if needed. This method achieves high sustainability and economic efficiency of the project (Grausam 2021). High sustainability and economic efficiency indicators of HoHo Wien indicated the project to be feasible (Grausman 2021). The structure principle of HoHo Wien is presented in Figure 25 and overall structural solution in Figure 26.

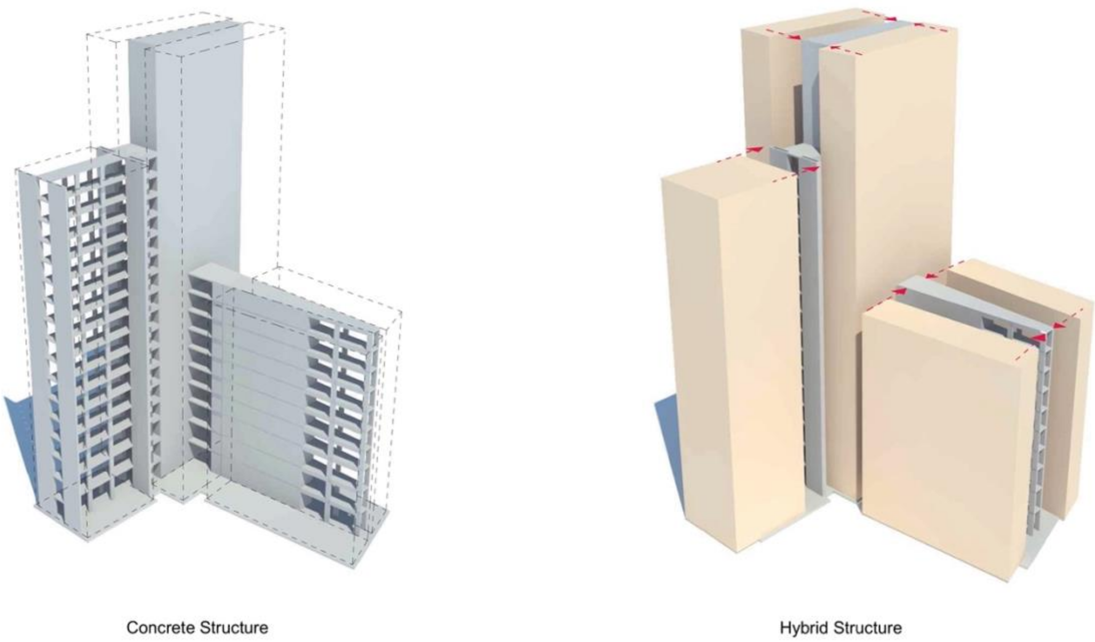



Figure 25. Structure principle of HoHo Wien (© RLP Rüdiger Lainer + Partner).

The decision to use a hybrid structure for HoHo Wien was influenced by the possibility to exploit the material-specific advantages and optimize the overall system (Grausman

2021). The timber use in the structure of the building allowed savings of about 2,800 tonnes of carbon-dioxide emissions compared to a reinforced concrete structure (Grausman 2021). This volume of emissions is equal to the twenty million car kilometres, which is a considerable saving.


Figure 26. Visualization of the structure solution (© RLP Rüdiger Lainer + Partner).

The structural and architectural solution in this case has created strong linear elements in the external expression of the building. Some of those linear elements are underlined by the glass ribbons in the facades, others are created by the difference of the façade materials or deepening on the surface. These linear elements are strong *parole,* symbols in the building, which creates its identity. HoHo Wien is created by strong linear elements, both in the massing and facades. Their combination manifests the aspiration to create the “tree”, the symbol, which also inspired the design of the facades. The verticality of HoHo Wien can be seen from the facades presented in Figure 27.

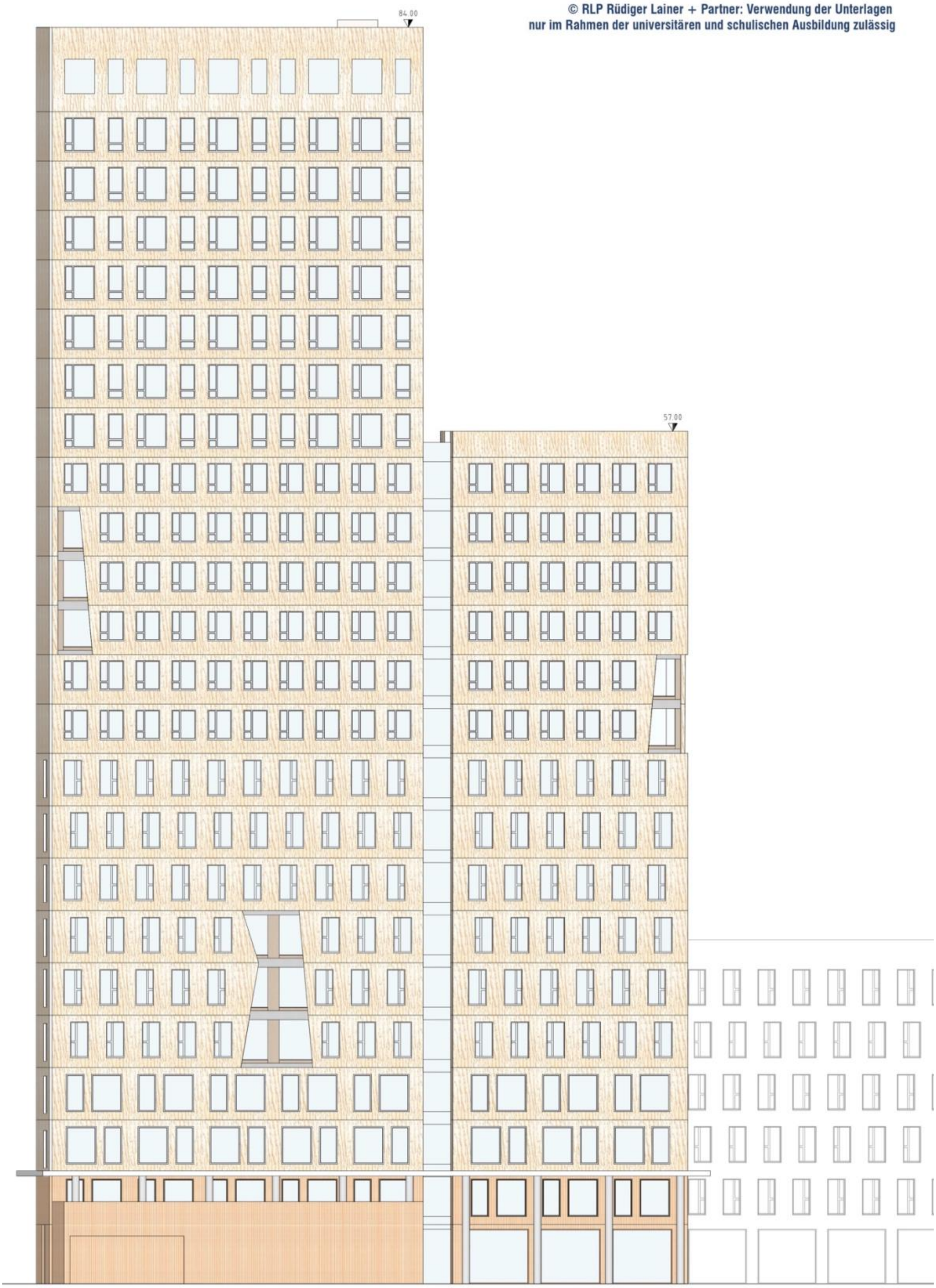



Figure 27. Facade of HoHo Wien (© RLP Rüdiger Lainer + Partner).

As well as in the case of Mjøstårnet, the building has been constructed with the use of the prefabricated structural elements. This ensured the performance characteristics of the elements with high accuracy. All the structural systems of HoHo Wien have been tested first in the pilot project, HoHo "Next", which was built immediately before HoHo Wien. HoHo "Next" is a six-storey building, which allowed the designers of the project to "test the structural systems, get further efficiencies and understand the installation methodology" (WoodSolutions AUS 2020).

### *Case III* Lighthouse

Figure 28. Lighthouse Joensuu (© Arcadia).

Lighthouse Joensuu is the tallest composite timber building in Finland. The design phase has been conducted in the deep collaboration with contractor and material manufacturer. An important remark would be that structural solution has a significant impact on the architectural design of the project. Architects had to be flexible in their own design, to create the structurally challenging building. However, the fluent collaboration between all parties of the project had a great impact on the project's success.

The structural solution for this project was chosen according to economic efficiency and includes the use of LVL and CLT panels. The first floor of the building is constructed from concrete. Vertical load-bearing structures from the second storey to the fourteenth are implemented by LVL wall panels which thickness varies from 126mm to 162mm. Floor structures on the same storeys are implemented by CLT panels which thickness varies from 180mm to 220mm. Interesting that in this case the structures were designed to be lighter and thicker to the top of the building. This method allowed to optimize the wood use in the structures and also serviced the structural performance of the building.

The structure of the building is stiffened with steel bars, which extend to the foundation and bedrock. The bars are installed inside the LVL panels and normally they are one-storey high. Bars are tightened with bar extensions and stiffened every three floors. The overall number of the bars is 94, but only 34 of them are full-length and extend to the top of the building. The structural engineer of the project highlighted that utilizing steel bars in a tendon bar method has been an innovative approach (Rantamäki 2021). This kind of structure system can be restrictive for possible future changes, but serves the building's current purpose perfectly. The tendon bar extensions are presented in Figure 29.

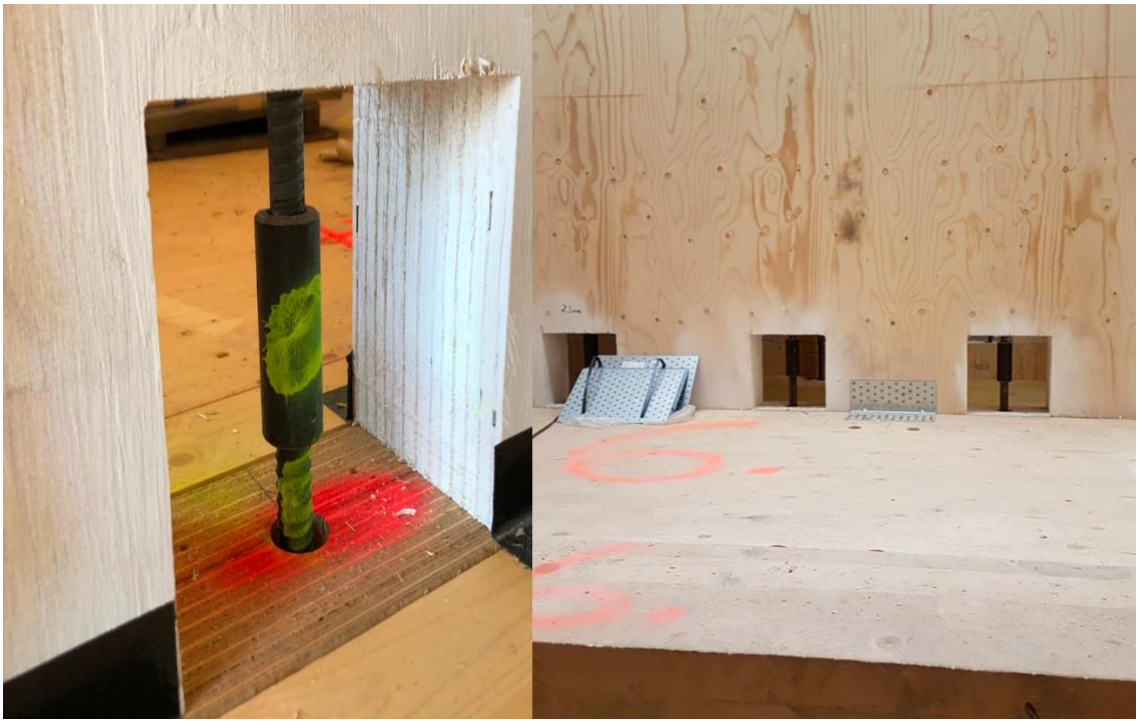


Figure 29. Tendon bar extensions (©Arcadia).

The elements for the Lighthouse's structures were prefabricated in Varkaus according to the given dimensions. After this, the panels were transported to Loviisa, where the panels were processed to the installation-ready state. The data model was explicitly utilized to process the panels with precise sizing. For the elements' assembly and storage on the site a 400 $m^2$ tent was constructed to protect the elements from the moisture damages (Rantamäki 2021). The use of the prefabricated timber elements for the building allowed the construction of a whole storey within two weeks (Rantamäki 2021). The equipping of the elements in the tent is presented in Figure 30.


Figure 30. Equipping of the elements in-site (©Arcadia).

As it was mentioned in the part 2.2.1 Fire regulations, tall wood buildings should be designed according to the P0 fire class, which mean that all fire requirements should be considered on case-by case basis. For this project functional fire measurement were conducted, and new solutions were developed for load bearing capacity and fire safety (Rantamäki 2021). To meet the required fire safety level building designers ended up using automated sprinkler systems, mechanical smoke extraction, two staircases and protective covering for the load bearing structures. The fire measurements allowed for leaving 20% of wood surfaces visible but, according to the architect of the project, the aesthetic features of used structure elements' surface weren't visually attractive (Sallinen 2021). The fire tests were also performed to ensure that structure will not collapse in the case of sprinkling malfunction. The structure elements of the building are measured to the R90 fire class.

The choice of the façade material was influenced by various issues, but the main ones however have been serviceability and fire regulations. The facades are implemented by stone slabs in different shades of white and grey. The verticality of the façade panels can be defined as one of the *parole* of the Lighthouse Joensuu. The verticality of the panels highlights the verticality of the tall wood building and strengthen the expression of the building for the observers. However, along with the facades remain one more element, which can be described as a *parole* of the building: the light artwork. The designer team of Lighthouse included the light artist Kari Kola, who have created the permanent light artwork on the walls of the building. This light artwork affects also the identity of the building and intensify the name of the project.

### ***Case IV*** **Puukuokka**

Figure 31. Puukuokka, Jyväskylä (©OOPEAA).

Puukuokka is a great example of wood architecture in Finland. It was the first eight-storey "all-timber" building in Finland completed in 2015. The project initiation was strongly affected by the City of Jyväskylä's policy and Stora Enso's interest in the developing of CLT products. Another reason, which has made this project possible, is the fire regulation update which was published in 2011. New fire regulations allowed the construction of wood buildings up to eight storeys. This project was the first of its kind, a pilot project, which has initiated the multistorey wood building in Finland.

This project succeeded mainly because all the parties of the project have been interested to build from wood. According to Anssi Lassila (2021) the teamwork is important in all kinds of projects, but especially in wood building projects. In this project there was a lot of collaboration with the structure manufacturer. Puukuokka uses modular prefabricated CLT modules, an approach that reduced the site construction phase to only six months. It also ensured the quality of the structures and reduced the exposure to weather. It is important to understand, that at the time of Puukuokka's construction, Stora Enso had only started the manufacturing of the modular CLT elements. These conditions required a lot of collaboration between the element manufacturer, architects and structure engineers.

Modular structure elements set the conditions for the architectural design by technical possibilities of the manufacturing. Mainly it considered dimensions and weight of the modules. The modules, which were used for Puukuokka have been 4.5 m wide, 12 m long and 3.2 m high (Lassila 2021). Nowadays, the elements could be larger, but weight is still the main limitation for the modules' size. However, the architect has been able to create "an architecturally intact and interesting ensemble, where the facades and the balconies are inseparable parts of the structure frame" (Lassila 2021). The architect's attitude to the boundary conditions of the modules was the reason for the intact architectural entity. Lassila (2021) has mentioned that: "Boundary conditions do not ruin anything; you just have to know how to apply them".

The main load bearing material in the structure is CLT panels made of spruce. The vertical loads are carried by CLT wall panels, which are connected vertically by corner steels and threaded rods. The roof CLT panels perform as stiffening diaphragm, which transmit the forces to the vertical CLT elements. The CLT modules are stacked on top of each other and because of this the floor construction is a combination of 80 mm thick roof panel and 140 mm thick floor panel. There is an 80 mm thick air gap between the elements. The designers of Puukuokka have optimized the use of wood in the project, and thickness of the vertical CLT elements varies from 100 mm on the top of the building to 120 mm in the first four storeys. The structure diagram by OOPEAA is presented in Figure 32.

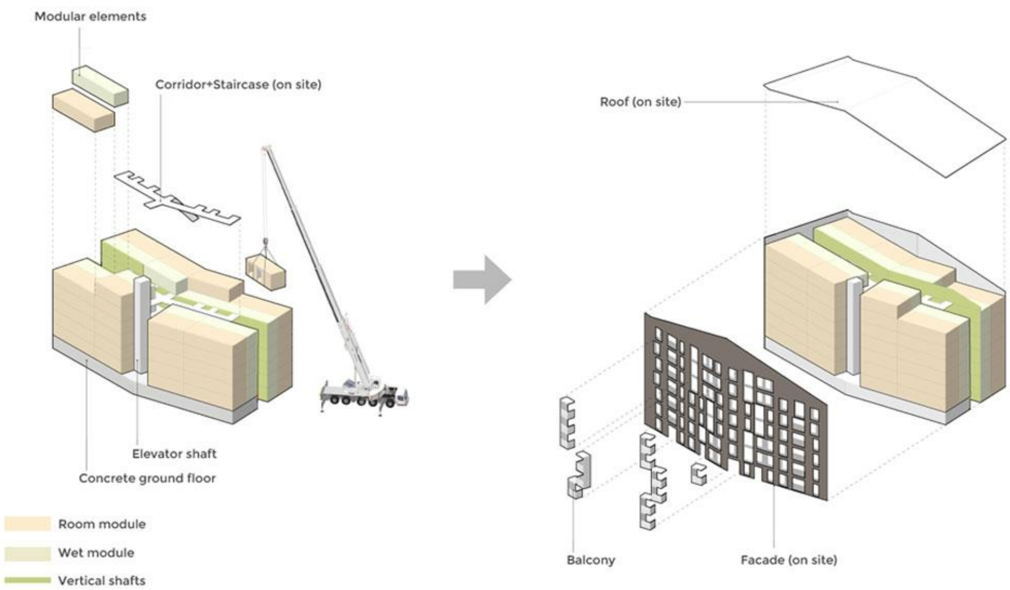



Figure 32. Structure Diagram of Puukuokka (©OOPEAA).

The architectural language of Puukuokka is affected strongly by its modularity. Modules create masses concentrated around the corridors and staircases. This is quite near to the HoHo Wien expression, but in different scale and created by different tools. The massing principle can be defined as one *parole* of the building, which can be experienced mainly from the inside of the building. The strong verticality of the masses is balanced by the balcony elements and sloped roof expression. Both balcony elements and sloped roofs expression can be defined as other *parole* of Puukuokka, which create strong identity for this wood ensemble.

**_Case V_ Wood City**

Figure 33. Wood City, Jätkäsaari (©Tuomas Uusheimo).

All previous Finnish case buildings presented in this thesis have been residential buildings, which dictated their architectural language. Their facades and structure have been clear about what they represent. This case however is something different to the previous ones. The Wood City is the first office/hotel ensemble on this kind of scale in Finland. The project was initiated by an architectural competition which was won by architecture studio Anttinen Oiva Arkkitehdit. The architecture competition allowed the architects to have "free hands" with the design and create unique ensemble, which was based mainly on the architect's assumptions on the structural capabilities of the building. To clarify, the Wood City name refer to the wood buildings block, which includes two residential buildings and hotel/office ensemble. In this thesis name Wood City will refer only to the hotel/office building.

The main challenges in the design of the Wood City were its architectural and structural uniqueness. Different structure systems were considered for this project until the LVL post-and-beam structure was selected as the best option. The building's structure includes stiffening concrete shafts and flexible screw joints. The use of the concrete shafts as a stiffening structure element makes Wood City a composite wood building by the definition of Foster et al. (2016).

In the beginning of the design process, there were no standardized design values for LVL elements and structural designers had to make a lot of assumptions (Sweco 2021). This kind of conditions demand deep and confidential collaboration between the parties of the project. The architect highlighted that especially the collaboration between fire safety consultant and structural engineer was important for the success of the project (Oiva 2021). However, in this case there was one more important party, which affected the design of the interior spaces in the building. The office building is designed to be the Head Office of Supercell, Finnish mobile game development company. In this case, the user had the possibility to affect the interior spaces and, therefore, significantly affect the whole design process. The detail of the interior space can be seen in Figure 34.

Figure 34. The lounge of Wood City office building (©Tuomas Uusheimo).

The use of the LVL post-and-beam structure enables the architectural flexibility of the interiors, which can be modified in the future according to the changed needs. This kind of structural solution affect also the architectural flexibility of the facades. The wall elements are implemented by CLT panels, which, however, do not contribute to the building's horizontal stability. This kind of structure enables large glass openings on the facades, which create a unique architectural language of Wood City. Facades seem to be hung as a fabric from the load bearing structure. This effect is intensified by wavy façade lines on the first floor and ceilings, which are visible through the glass interior. This building has very clear architectural language, which manifest about its purpose and material of the structure. Façade's vertical glass ribbons, wavy lines of the façade elements and free-form large glass surfaces are expressive *parole* elements of the building.

### 4.1.2 Responsible design is vital for the tall wood building development.

All the interviewees have agreed with the opinion that bad wood building, and especially bad *tall* wood building, detracts notably from the reputation and culture of the wood architecture. One of the main benefits of the tall wood building is their sustainability. Wood constructions are manifested to be one of the tools of climate change prevention, because of the reduced carbon dioxide emissions of wood structures compared to the steel or concrete structures. However, the benefits of the bound carbon dioxide in the wood structures decrease significantly if a wood building is demolished in short time after it is completed because of a fatal design or structural mistake. Therefore, the tall wood buildings should be designed responsibly. Responsibility should be considered both in the use of the "living" wood material and in the overall quality of the design. This part will consider two second order themes related to the "Responsible design is vital for the tall wood building development" aggregated dimension, which are thoroughness in design and creative application and tall wood building identity.

#### *Case I* Mjøstårnet

Mjøstårnet is all about wood. This material is basically everywhere. Despite the fact, that it could seem very natural solution for the tall "all-timber" building it is not that easy to implement because of the fire regulations. Fire regulations would normally recommend covering the structural elements in the building with the non-combustible material to make the wood structures fire performance comparable to the concrete. However, the Mjøstårnet's designers were able to achieve sufficient structure's fire performance by increasing of structure elements' cross-section dimensions. It was important for the designers to keep the wood surfaces visible in the building to keep the connection to the beautiful nature environment of Brumunddal. Also, several research studies have pointed out the positive effect of wood surfaces on the well-being of the inhabitants (Nyrud and Bringslimark 2009; Alapieti et al. 2020).

Figure 35. External view on the Mjøstårnet (©Ricardo Foto).

The visible structure elements in the interiors also play a vital role in the interior design of the building (Elgsaas 2021). The massive internal columns participate actively in the design of the interior spaces. The large diagonal glulam trusses participate in the design of the building both internally and externally. The glulam trusses are visible from the outside through the windows in the building, which structures the facades and affirms the wood structure of the building to the entire environment. The visibility of these elements has a significant role in the creation of the identity for Mjøstårnet. These are some of the most apparent *parole* elements in the building, which create together the *langue* or identity of the tall wood building. The element of the Mjøstårnet facade and the role of the glulam trusses in it is possible to see in Figure 35.

The possibility of seeing and feeling the building's wood structure was also important for the apartment buyers. Most of them "asked to know where the columns and beams were visible because that's the apartment they wanted to buy" (Elgsaas 2021). Besides the well-being enhancing functions of the wood surfaces in the interior, the visible massive wood structures also bring a sense of "safety" to the tall wood building. The element of the restaurant's interior is presented in Figure 36.

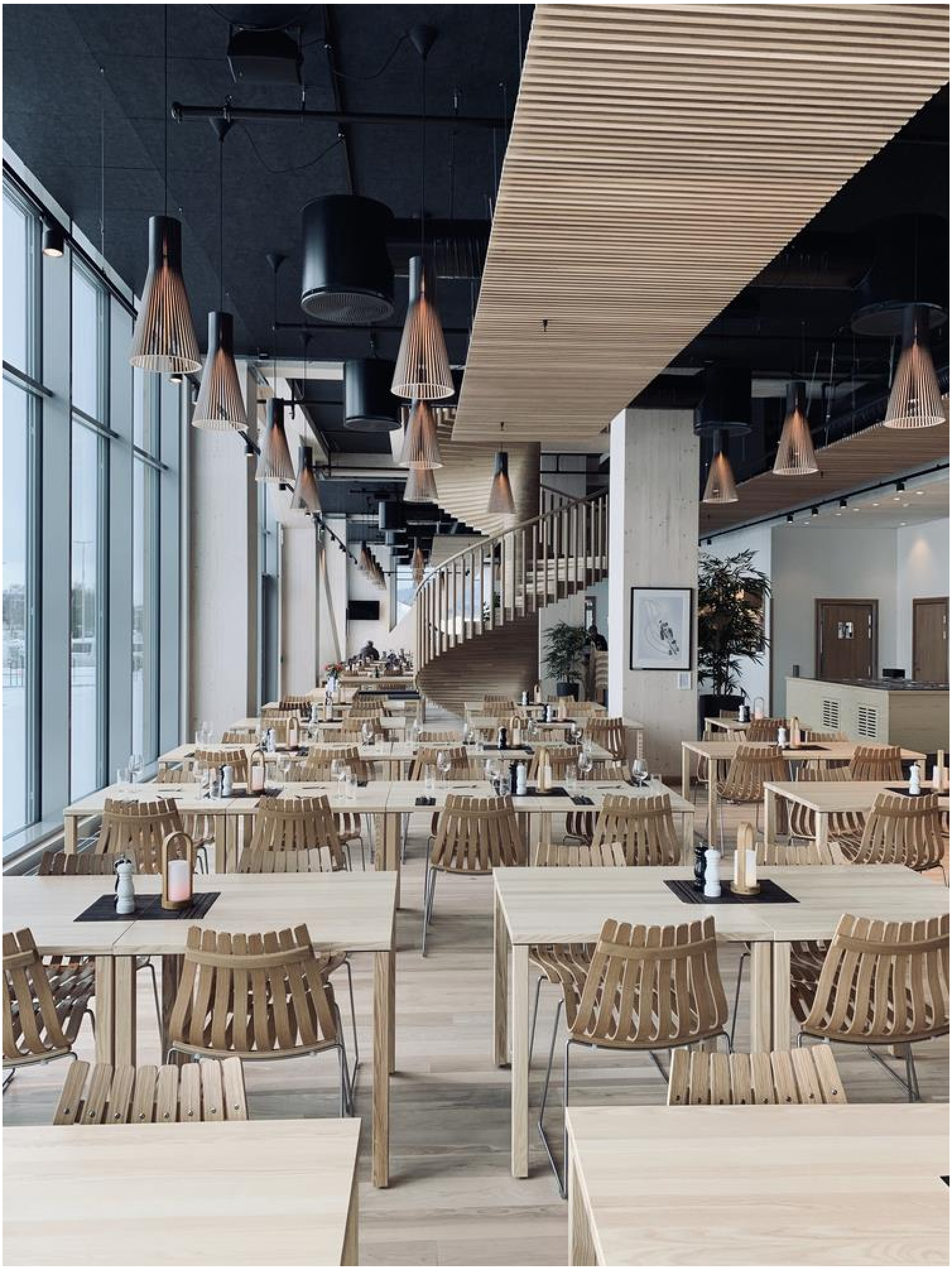


Figure 36. Interior of Mjøstårnet (© Øystein Elgsaas).

Wood is also the main material of the facades, as was mentioned in part 4.1.1. The wooden facades for the tall wood building are very difficult to implement in Finland. The main reason is fire safety regulation. Another, however, considers the serviceability of the food facades in the case of tall wood buildings. The serviceability and long-term sustainability of the wood surfaces are highly dependent on the choice of the wood species. Designers of Mjøstårnet decided to use a “thermo wood product, made from Swedish pine that has been modified through a heat and steam process, making it non-toxic, dimensionally stable, resistant to decay and resin-free” (Elgsaas 2021). The facades’ Firestop elements have been implemented from the Acidproof steel to prevent rust drippings to the wood cladding. Facade design also try to control the simultaneous aging of the panels due to the weather impact.

### *Case II* HoHo Wien

The thoroughness design in the HoHo Wien starts from the flexibility of interior spaces for the possible changes in the future. This is mainly affected by the office nature of the building, which could have different rentals in its lifecycle. The room design can be easily adapted to the changing needs of the rentals also after the constructions have been completed. This kind of changes are possible because of the glulam beam structures in the building. CLT walls do not participate in the load bearing of the vertical forces and therefore can be removed. The offices are therefore created in modular format. In addition, the structure reduction to a few simple elements makes it cost-effective. Thorough design of the interior spaces makes the building sustainable in a long-term perspective. The element of the interior spaces is presented in Figure 37.

Figure 37. Interior of HoHo Wien (©SIGA).

As a hybrid building, HoHo Wien is designed to utilize the benefits of used materials to create an effective and optimized system. This considers not only the structure systems of HoHo Wien but also the material of the facades. The façade consists of two natural materials, which have been chosen according to their functionality and construction. These façade elements are larch formwork and eternit façade panels (Grausman 2021). The larch formwork is used for the ground floor and first floor of the HoHo Wien, and it is also the façade material for the whole HoHo Next building. The eternit facade panels cover the HoHo Wien building from the second floor to the roof level. These panels have a very low susceptibility to damage and, therefore, very long-life span. This kind of capabilities are especially important for the tall wood building, where the repair of the damaged facades is resource-and cost-intensive. Panels are also characterized as fire-resistant, sound-absorbing and durable. Based on these reasons, I believe that this kind of façade material choice is the *parole* of HoHo Wien, which symbolizes sustainable building methods. Even in the case of partly non-wood facades, HoHo Wien retains its identity as a wood structure building. The external view on HoHo Wien is presented in Figure 38.

Figure 38. HoHo Next and HoHo Wien (©SIGA).

### *Case III* Lighthouse

Lighthouse Joensuu is the first wood building of its height in Finland. Deep collaboration between the architects and structural engineers allowed to keep the budget of the project under control, which was important for the builder. This has affected the architectural and structural solutions. However, the most it has affected the use of wood in the interiors and exteriors of the building. The wood in the interiors is covered because of two main reasons: strict fire regulation for the demanding tall building project and the aesthetical features of used structure elements, which manufacturing was just developing in Finland at the moment of the Lighthouse construction. The façade material was chosen according to the serviceability of the material, which is a significant characteristic of the façade material for the tall building. Facades have been created by maintenance-free fiber cement board, which is also fire-resistant, sound-absorbing, and durable. According to the architect of the project, if he would have the possibility to design this building again, he would try to keep more wood surfaces visible in the interior of the building, which has been made possible in the last update of the fire regulations (Sallinen 2021). However, he would still design the facades from non-wood material because of the long-term sustainability. The facade of Lighthouse is presented in Figure 39.

Figure 39. Lighthouse Joensuu (©Arcadia).

Lighthouse is a pilot project of tall wood building in Finland, and therefore experience gained from this project is valuable for the tall wood building development. The construction phase and post-construction performance of the structures are explicitly researched by the local polytechnic students. For this purpose, a notable amount of sensors is installed to the structures of the building.

### *Case IV* Puukuokka

The architect of Puukuokka has great experience in wood architecture, which is possible to see in the building's design. According to Anssi Lassila (2021), there are design and structural solution which work better with wood, not with concrete for example. It is important to detect this potential and utilize it in the design. For example, "the parking hall can be located under the house, and it can be a cold space, this is not a problem" (Lassila 2021). This approach has been used in Puukuokka project.

Both interior and exterior are made with respect to the used material. There were certain requests from the client toward the design of the building, and one of them was related to the staircase design. The client wanted that staircases would stand out from the concrete structure building's staircases. Architects have been able to keep the wood surfaces partly visible in the staircases and keep the staircases full of light and space. The result was very public and intimate at the same time, a certain combination between the private house and apartment building (Lassila 2021). The staircases and main entrance to the building can be considered as *parole* elements of Puukuokka. The staircase of Puukuokka is presented in Figure 40.


Figure 40. Staircase of Puukuokka (©OOPEAA).

The wood is also used for the facades of the building. It is important to understand that Puukuokka's height is around 29 m, which makes the serviceability of the facades less resource-and cost-intensive. The facades use larch formwork, which have been pre-painted, which reduced the construction phase time. The fireproof larch formwork has been used for the ground floor.

### *Case V* Wood City

Wood City's location affects both the architectural and structural solutions. The structural, construction method, and material solution should consider the proximity of the sea, which affect strong wind and humidity. These facts have a significant effect on the aging of the façade materials. Wood City's facades are made by the combination of the dark glass surfaces and CLT panels visible surfaces. At the moment of completion, the wood surfaces have natural light brown shade, which, however, will age to the grey shades with time. When this happens, the façade will remind more and more the sea surface by its colorworld, and water glimmers by glass surface reflection. This vision is observer reflection on the architectural language of the building, which can differ from the original meaning which architect has created for its creation. However, as it was mentioned in part 2.5 Architectural language, both the readers and the writers contribute to the meaning of the "message" or "sign" (Davies 2011). This idea can be seen from the visualization of Wood City presented in Figure 41.

Figure 41. Wood City visualization (©Anttinen Oiva Arkkitehdit).

The location of Wood City also affects its identity. Wood City is located near to the port area of Helsinki, and therefore the impression of Wood City is among the first impressions of city visitors, which arrive through the port area. Wood City can be defined as a landmark of Helsinki, which participates in the identity creation for the whole city. Its landmark identity is affected both by the tall wood building structure and location relevancy.

### 4.1.3 The purpose is everything for the tall wood building.

Multistorey wood buildings and, especially, tall wood buildings are expensive projects at the moment. Therefore, the decision to undertake this kind of project should be well-justified. The justification of this decision can be connected to the purpose of the tall wood building. Will it be the residential building, office building, or mixed-use building? The purpose of a tall wood building plays an important role in the architectural language of the building and, first of all, in the justification of the project to the society. In this part will be presented the purposes of the case tall wood buildings in this thesis.

### *Case I* Mjøstårnet

Mjøstårnet is a mixed-used tower, which consists of 18 stories. In the building are mixed private and public spaces, which make it multifunctional. It means that this building is providing a variety of choices for its users. If someone wants to experience living in the wood tower, they can buy an apartment. But if someone wants only to visit the world's tallest wood building with an amazing view, he is able to do it by visiting a roof terrace or by staying at the hotel. The program of the building is presented in Figure 42.

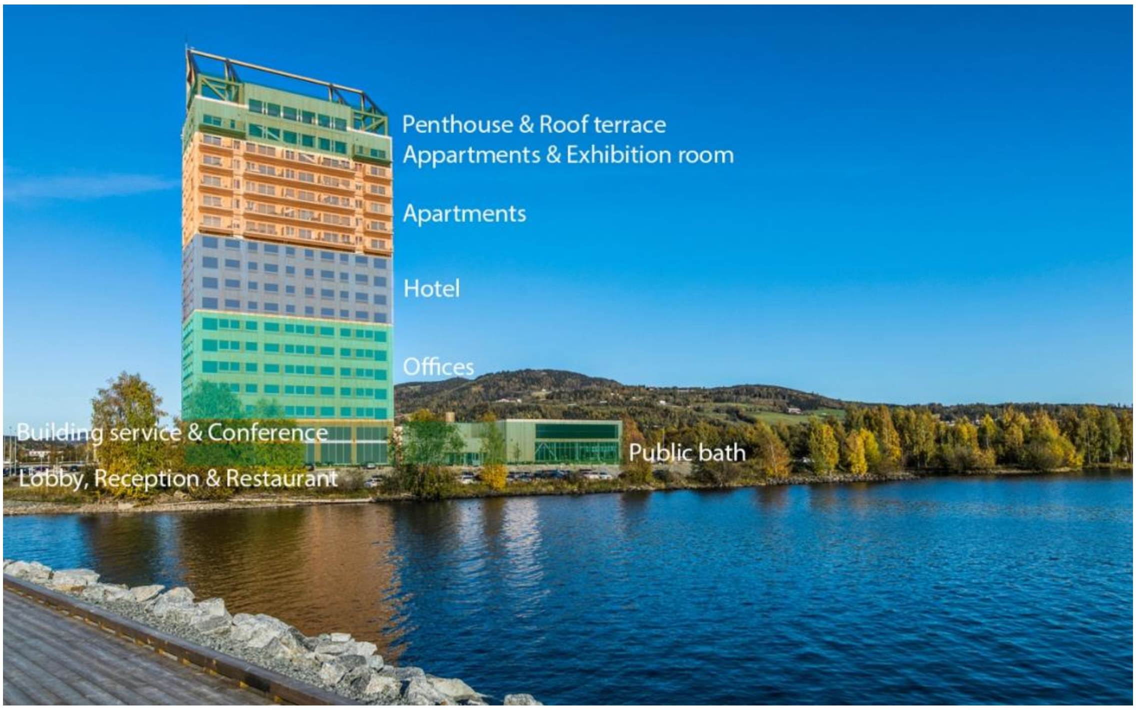



Figure 42. Program of Mjøstårnet (© Ricardo Foto, modified).

Brumunddal is a small city with only 10000 residents, therefore, there is no need for an 18-storey residential tower. But the city of Brumunddal needed a new landmark, which will attract visitors to the city. Mjøstårnet copes perfectly with this role and attracts visitors all around the world. It has become a symbol of tall wood buildings in the world.

### *Case II* HoHo Wien

HoHo Wien has been designed by the affection of mixed-use development in Vienna. The main idea was to create the city inside the city. And designers succeed with this task. Ho-Ho Wien is a mixed-use tower, which includes commercial space for use as restaurants, health, beauty, and wellness centers, offices, a hotel, and apartments.

Therefore, HoHo Wien supports the urban development of the city in a sustainable way. Figure 43 presents the program of HoHo Wien.

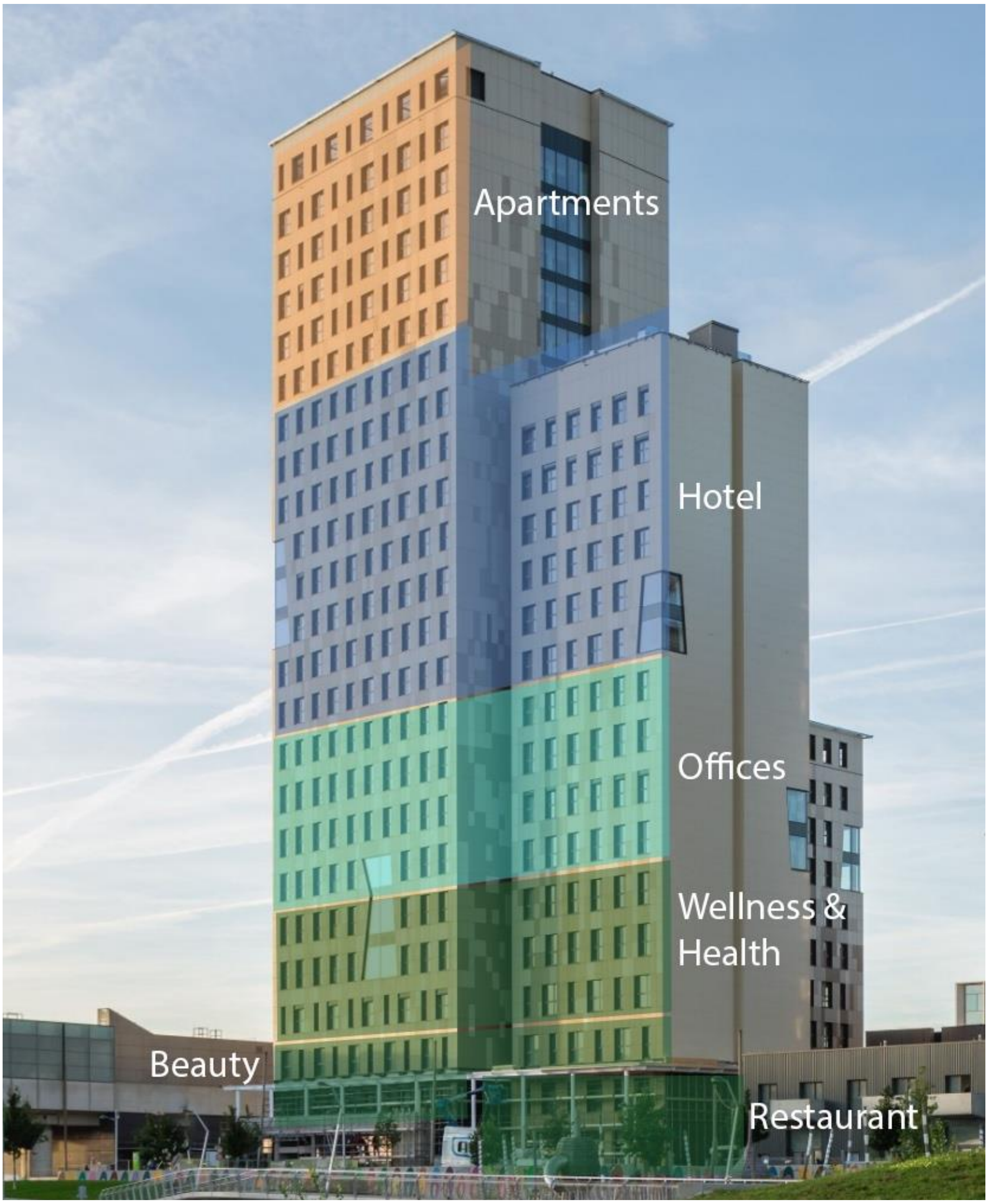



Figure 43. Program of HoHo Wien (© Cetus Baudevelopment, modified).

### *Case III* Lighthouse

Lighthouse project has been initiated by a sudden need for student housing in Joensuu. In 2018 university campus in Joensuu received students from the Savonlinna campus of the University of Eastern Finland, which has been closed. The shift of the student to Joensuu demanded 720 new student apartments. Local student-housing provider, Joensuun Elli, in collaboration with the city of Joensuu, has made a decision on the implementation of the tall wood building to meet the need for the student apartments. The wood as a structure material has been chosen because of the city's effort to profile itself as a pioneer in timber construction and forestry. (Tulonen 2020) Therefore, Lighthouse's purpose is student-housing. The program of the building is presented in Figure 44.


Figure 44. Program of Lighthouse (© Arcadia, modified).

### *Case IV* Puukuokka

Puukuokka project has been initiated by Lakea, and it was realized in collaboration with the city of Jyväskylä (Oopeaa 2021). Mainly the city's strong policy toward creating ecologically and socially sustainable multi-family housing has affected the design solutions. Puukuokka consists of three buildings, which purpose is residential apartments. The program of Puukuokka is presented in Figure 45.


Figure 45. Program of Puukuokka (© Mikko Auerniitty, modified).

### *Case V* Wood City

Wood City's office and hotel building is part of a wood building block in the center of Helsinki. The office building is designed to be the Head Office of Supercell, a Finnish mobile game development company. The Wood City hotel building is rented at the beginning of 2020 to Meininger Hotels chain (Rakennuslehti 2020). The program of Wood City is presented in Figure 46.


Figure 46. Program of Wood City (©SRV, modified).

## 4.2 Study II Architectural language of tall wood buildings

This chapter presents the findings that emerged from the interviews conducted in this research. The findings are grouped under three main categories, which, as described in chapter 3.3 Data analysis, arose from the first-order coding of the interview data. The structure of Study II will remain the same as in Study I to make the integration of findings from the case research and interviews as smooth and clear as possible. Based on these reasons, the findings that emerged from the interviews will be discussed on the basis of the three main dimensions:

1. The main limitation is imagination. And budget
2. Responsible design is vital for the tall wood building development
3. The purpose is everything for the tall wood building.

In this part, the data obtained from the interviews will be presented as pure as possible to don't override the researcher's interpretation to the valuable data obtained from the interviewees. As Gioia et al. (2012) mentioned, the researcher "does not consider it own right to be a bull in a china shop". The researcher's own interpretation of the obtained data will be represented in the Conclusions part of this thesis.

### 4.2.1 The main limitation is imagination. And budget

All the interviewees have agreed in the opinion that for the design of tall wood building the main limitation is imagination. Even the most difficult design solutions can be implemented if the designers of the project are able to create deep and confidential collaboration. Because tall wood buildings are definitely difficult design solutions. Interviewee A4 explains:

*"We have a feel for where to go, usually on the upper limits. [...] Then we start to think with the structural engineer [...] and then the professionalism and solution-seeking of the structural engineer and a certain kind of innovation-thinking is a key. Oddly, but solutions can be found when you have a good structural engineer. You will be able to find the answers even to the difficult questions. The significance of the structural engineer is irreplaceable. It's easy to say it won't work. Yes, solutions can always be found."*

Interviewee B2 has a very similar opinion on the dignity of the collaboration, and he has elaborated on this topic from his experience:

*"My experience is that one often can even tell you that something is impossible. Anything is possible as long as work is done for it. Then, of course, is always possible the kind of incompetence in the team. [...] There is always a little inconvenience, but a solution can always be found. An inspiring starting point can affect other designers to also be fully committed to the design. [...] First, there is only one solution [...] the project make progress, and there are already five solutions."*

However, for this kind of collaboration, the architect should have at least a basic understanding of the materials and structures, which are used in the project, and the capability to apply the knowledge and regulations creatively. Interviewee B2 explains the architect's tasks as follows:

*"Of course, the basic task of an architect is architectural design. Traditionally, structures are managed by the structural engineer, HVAC technology by other designers. But I always liked the fact that the architect is quite often the chief designer, and in this case, he should*

*manage at least at some level other design areas. Yes, the management of the ensemble is the architect's most important skill."*

He elaborated further on the skills, which architect should have for the tall wood building design:

*"[...] applicability of regulations and creativity are really important in my opinion, [...] eight-storey wood building is not the easiest design task. [...] The most important feature is the management of the ensemble and creativity, knowledge, and creativity. However, knowledge does nothing if it cannot be applied creatively."*

The importance of the collaboration has been highlighted by interviewee A4, who has also agreed with the interviewee B2 on the need for the architect's skills to manage the ensemble of the design and applicate the knowledge creatively:

*"Good partners are needed: a fire safety designer and a structural engineer. It helps that the designers of the office have a basic understanding of fire regulations in wood construction and their application possibilities [...] a basic understanding of different structural systems and their possibilities. The project will not be designed alone; therefore, cooperation with other designers is important."*

Interviewee A1 highlighted that especially for wood building design, an architect should remain next skills:

*"[...] understanding and idea about what we are doing and how we are doing it. The architect must have knowledge of the material and its possibilities. It comes through practice. All kinds of skills are needed, and they need to be developed all the time to be able to make more interesting and better solutions and develop architect's own skills at the same time."*

It is important to understand that tall wood building is an exception even in global practice. Because of this reason, new knowledge and new solutions are needed for the design. Therefore, it is normal that architect possibly doesn't have knowledge about wood structures and their capabilities. Interviewee B2 gave an excellent advice for this kind of cases, which is also suitable for the young architect which design their first project in any kind of area:

*"[…] it is so worthwhile in the first projects with tall wood buildings […] of course you should get that information, read the regulations and so on. And then I've noticed that people are willing to help. The construction supervision is there to help, and you can ask them if you don't know something […] you can ask the structural engineer if you don't know. There is no need to pretend to know everything."*

B2 has also noticed that equality is important for collaboration in design projects. If there are hierarchy issues in the team, collaboration can be very difficult.

One of the main features of the tall wood building is using of prefabricated materials. This has a significant effect on the collaboration process. Interviewee A3 remembered from his tall wood building project the next details:

*"The structure designer and material manufacturer have been involved from the very beginning because they set the boundary conditions, which is the maximum size of the element and so on. The design process has been concentrated to the beginning of the project; more details are planned already at the draft stage. The architect must have an idea of the structural systems, which will be used for building implementation."*

According to B1, the stiffening of the tall wood building is a major issue, which affects the architectural language of the building. He also claims that wood building is full of boundary conditions more than opportunities. Therefore, the creative application of these kind of boundary conditions is a key to a successful project.

All the interviewees agreed that overcoming the challenges, which arose in a tall wood building project is possible. However, there one major boundary condition in any kind of project: the budget. Interviewee A4 mentioned that:

*"If the budget is underestimated, it will be more difficult, but things will always work out."*

According to these opinions, the creative application and good design team are able to overcome all kinds of challenges in the project. Collaboration also should be started at the beginning of the design process to define the used structure system for the building and give therefore the designing "grid" to the architect. The wood building is full of boundary conditions, but good design can be achieved only through their creative application.

### 4.2.2 Responsible design is vital for the tall wood building development

In the interviews have emerged two second order themes related to the "Responsible design is vital for the tall wood building development": "thoroughness in design and creative application" and "tall wood building identity". All the interviews have pointed out that the design of tall wood buildings should start from the material's features. Interviewee B1 said that:

*"The tree is a living dead, affected by all environmental factors."*

This kind of material features has a significant effect on the design process and the end result. The material can become, and should become, the part of the design method. Through this kind of way of thinking, the architect is able to create a sustainable and architecturally intact ensemble. This idea was supported by interviewee A1:

> *"My design method is that the material is part of that architecture, it produces certain solutions that are possible, and the material manifests itself in the end result."*

The material manifestation in the end result is especially important for the wood building. Interviewee B2 elaborated on his experience in the next way:

*"It is often disappointing to go inside a wooden building, and not even the single wood surface can be seen there. Fire regulations restrict the use of wood inside, which is, of course, okay, but a good designer will be able to find a solution to that as well."*

All the interviews revealed the importance of the wood surfaces in the interior of the building. The importance has been discussed in terms of tall wood building identity, but also in terms of humans' well-being. Interviewee A2 explained his point of view:

*"The visible grain in the tree gives a positive connection to nature. Several studies show a lower level of stress in rooms with visible wood interiors. […] Physically, there are also effects that give positive results with wood interior. The low heat conductivity of wood gives greater tolerance to air temperatures. In addition, the ability of wood has to*

*absorb and emit moisture has a positive contribution to the energy balance in the house. […] It is also discussed whether the wood's ability to buffer moisture also affects other components in the air that can be transported with moisture, such as smoother CO2 levels or less particulate matter."*

In the case of tall wood buildings, the visible wood surface would most likely be the surface of the EWP. There is a lot of factors that affect the aesthetical features of the visible wood surface. Therefore, if the architect designs the building in a way, which allows leaving the wood structures visible, he should ensure that the wood surface is of sufficient quality. This point came up from several interviews. For example, interviewee A4 explained it as follows:

*"If the wood surface remains visible, then it is important to ensure the quality of the visible wood surface. In the worst case, it can stay quite poor looking. You need to be aware of that. The architect has to visit the manufacturing site to see the finished wood elements before it leaves to the construction site."*

Interviewees highlighted that use of the EWP structures is beneficial for the overall quality of the building. Elements are mostly prefabricated, and only minimum machining is done on-site. This kind of structure also significantly reduces the length of the site phase (A2; A3; A4; C1; A5).

An interesting observation was that almost all interviewees agreed that the identity of the tall wood building is created mainly from inside of the building. The special role in identity creation belongs to the structures of the tall wood building. Interviewee A4 explains:

*"[…] I like tectonics in architecture […] when the wood structure is pretty modular, I think it's nice that its modularity is reflected in the building design. […] that not only the pillars are visible in the building but also the beams, and together they form a certain kind of rhythm to the interior. It is goal-oriented in wood construction. Structural purity should be highlighted. […] disturbs the mess of mixed structures in modern construction; structures are not visible and are made in very*

*strange tunings. […] a holistic approach to architecture, in the sense that the structures are also a bright part of the ensemble […].”*

Almost all the interviewees agreed that the use of wood in the facades is not mandatory for tall wood building identity creation. Interviewee B1 explains:

*“[…] the structure is the most important […] instead of making greenwood facades, which have to be maintained every five years, or even completely renewed every fifteen years. It feels like it is turning against itself and its purpose.”*

Interviewee A4 continues:

*“[…] it is such a misconception that the facades of a wooden building must be made of wood […]. Yes, wood can also be used on facades, where it is appropriate if you want to emphasize on the facades that the building is wooden […]”*

Some of the interviewees highlighted that industrial wood buildings should learn from the traditional wood buildings. In Finland, there are traditions and culture of wood building, which should be utilized to create higher quality wood constructions. According to interviewee B4, for example, the aging of wood should be considered in the beginning of the design process and as an architectural tool:

*“[…] design should take into account the variation in the color of the wood. […] wood can be maintained to gray evenly […] water, rain, wind affect […]. Also, wood surfaces in the indoors change.”*

Even though tall wood buildings have a reputation of sustainable architecture forerunners, the reputation of tall wood buildings can be ruined by bad wood buildings. Interviewee B2 explains:

*“I feel a little bit concerned while looking at some wood buildings […] whether this is good generally, or whether the project turns against wooden constructions […]. The architect should design responsibly, that wood building will still look good in 50 years.”*

Therefore, sustainable design is significant for tall wood building development. Thoroughness in the design is able to create architecturally interesting buildings that last for a few generations at least and more. Also, responsible and optimized use of wood materials is able to enhance the development of tall wood buildings.

### 4.2.3 The purpose is everything for the tall wood building.

The construction of tall wood buildings is connected with demanding structural solutions, which affects the high cost of the overall project. Therefore, the tall wood building construction should be justified. Different opinions arose in the interviews about the suitable and justified purpose of tall wood buildings. Opinions are also divided according to the location of the interviewees. Quite common opinion has been that in sparsely populated land, there is no need for tall wood buildings that is intended solely for residential use. For example, interviewee A1 comments:

> *"[...] this may not be what you should strive for. [...] Comfortability and light [...] can be lost if we are designing very tall buildings. There are no great benefits from a tall wood residential building in sparsely populated land."*

Interviewee A3 agreed that at this moment, there is no need for tall residential buildings in Finland, but he highlighted that mid-rise wood buildings should become more common:

> *"At this moment, it is not intended to make more tall wood buildings in Finland. Wood construction should become more common. Almost all of the tall wood buildings in Finland are student housing [...]. The private constructor does not dare to initiate this kind of project. Wood material should get cheaper. If it is wanted to make wood buildings more common, then it should become more common in a lower construction first."*

However, interviewees highlighted that tall wood building has a great marketing potential for the city development. Both the building and architecture studio, which designed it, got really big attention all around the world. Tall wood buildings are still an exception even in the global architectural practice. Based on these reasons, it can be concluded that tall wood building is not that suitable for residential purpose, but great for landmark and symbol meanings. This kind of purpose should be considered at the beginning of the design process. Interviewee A4 elaborated on this kind of purpose for tall wood building and specified:

> *"[…] if such landmarks are made so they must be high quality. High quality standards should be developed to justify tall wood building […]."*

Interviewee B1 also noted that tall wood building should be designed to fit the urban environment to which it is designed:

> *"There are still many challenges and development possibilities […]. The starting points of the structural system for tall wood architecture are challenging […] As we bring a children's drawing to the art exhibition just because it's nice, then it can be here […] If wooden structures do not bend to it if it produces only awkward buildings, and if we forgive because it is tall wood building, then we are wrong with it."*

# 5

# 5. CONCLUSIONS

This chapter discusses the main conclusions of this research. First will be provided answers for the research questions. The answer to the research questions will be based on the theory presented in chapter 2. Theoretical Background together with findings of empirical research, presented in chapter 4. Findings. After this will be presented emerged topics for further research. The three research questions of this thesis are:

**RQ1: Are tall wood buildings able to express an unambiguous architectural language?**

**RQ2: What kind of message/significance does the design of tall wood buildings have or should it have?**

**RQ3: What are the main limitations for tall wood buildings?**

The main goal of the first research question was to define the main features of the tall wood building's architectural language, estimate the architectural intact of tall wood building, and therefore, define the tall wood building's capability to express its architectural language unambiguously. The second research question refers to the definition of the message or signs that are characteristic for tall wood buildings. The answer to this research question required the evaluation of the interior and exterior attributes of tall wood buildings. The goal of the third research question was to define the main limitation for the tall wood buildings and, therefore, to understand the factors, which affect the tall wood building development.

The creation of unambiguous architectural language depends on the architect's capabilities to manage an "organic" wood material. Research revealed that an architect's previous experience in wood architecture is seen as a benefit, but however is not mandatory to create an architecturally intact and interesting ensemble. The absence of the previous experience in wood architecture can create a possibility to reveal innovative approaches for the design of tall wood buildings. In the case of tall wood buildings, the creative application of wood structure and wood material boundary conditions is seen as a necessary ability. The knowledge of the material and structures, as well as this creative knowledge application, can be elaborated in collaboration with structural engineers and fire safety consultants.

Structure systems significantly affect the architectural language of tall wood buildings. The height of the structures creates special requirements for the thickness of the structural elements and sets the boundaries for possible architectural solutions. Therefore, the design process should contain deep collaboration with other members of the design team in the early stages of the project. However, to keep the architectural entity management, an architect should create the first architectural drafts based on the "feeling" of the structures and then, in collaboration with the structural engineer, outline the feasible solution, which will become the basis grid for the architectural scope.

The use of wood material imposes certain restrictions on the design specter. Øystein Elgsaas (2021) presented people's concerns about wood material for tall buildings: "*Wood burns people say. -But so, does steel, we answer*". The case buildings, which were discovered in this thesis, correspond exactly to buildings with a concrete frame by their fire performance. This kind of wood frame and wood surface capabilities have been achieved by the particular fire-safety design. Fire regulations are as important for tall wood building's architectural language as structural solutions. However, tall wood buildings are exception even to the global architectural practice. This affects the absence of pre-specified fire regulations for wood buildings, which are higher than 28 meters. Case-specific functional fire measurement should be used for tall wood buildings, which is identified by fire class P0. All the fire safety solutions should be developed in this kind of project on a case-by-case basis. According to these reasons, the role of the fire safety consultant increases significantly. Deep collaboration between fire safety consultant, structural engineer, and architect is required in the project to take full advantage of the used material and its capabilities. Through this kind of deep and equal collaboration between the designers, the innovative architectural ensemble can be developed. The building created by the thorough design contributes to the creation of the unambiguous architectural language.

All these factors together refer to the evolving nature of the tall wood building culture. It is important to understand that tall wood building doesn't have stereotypical expression yet. Therefore, we cannot have a certain "vocabulary" and discover the tall wood building creation according to the *signs* explained in the *vocabulary*. Both architects, and of course all design team together with him, and observer acts as *linguist*s, which generate the architectural language of the new generation. Despite the evolving nature of tall wood building's architectural language, its unique in its appearance. This fact argues in support of tall wood building ability to create unambiguous architectural language.

As it was described above, the architectural language of tall wood buildings has evolving nature, which refers to the evolving nature of message and signs, which tall wood building should or can keep. This research defined two main categories of messages and signs, which occur from interviewees and research of case building: messages/signs which occur in the interior spaces and messages/signs which occur in the exterior of tall wood buildings. These two categories are united by a common goal to manifest the wooden nature of the building.

In this research have emerged that specifically interior signs are important for tall wood building identity. These kinds of signs and messages can be created through the visible wood surfaces or through the tectonics of wood structures. The interpretation and tools for the creation of messages and signs in tall wood buildings are architect-specific, and therefore, the large variety of messages is possible for this evolving architecture phenomenon. Visible wood surfaces have been seen as one of the most powerful tools for message creation in interior spaces. This kind of favor is based on the wood's positive effect on human's well-being, which has been stated in different researches. Possible interpretations of messages created by visible wood surfaces can be "warm", "cozy", "natural", and many more. However, one message stands out from others: "safety". Visible massive wood structures can signal their safety to the users of the building. The same message relates also to the tectonics of wood structures. The pure structure beauty of wood structures should be highlighted in tall wood buildings. The characteristic modularity of wood structures is a beautiful sign of tall wood buildings, which should emerge both in the interior and exterior spaces.

Exterior signs and messages of tall wood buildings can be created through facades of the building or through the characteristic wood structures, which emerge from the exteriors. An important note, however would be, that architects have not seen it necessary to implement facades from wood. In some cases, it could be justified to use wood for the facades to intensify the effect of wood building. However, wood's high need for maintenance is one of the main reasons for the architect's choice in favor of other more durable solutions. Based on this, structures can become one of the strongest messages or signs of tall wood buildings. Massive wood structures in the interiors can be visible through the glass surfaces on the facades and therefore also organize the exterior expression of the building. Some structures can extend over the building's main dimensions, and, in this way, structures can override the appearance of tall wood buildings. This method, however, is not favored because of the unveiling of wood structures to possible weather damages.

During research has emerged interesting opinion that different wood protection methods can be utilized as an architectural method. Protection methods can be related to sun protection of the wood surfaces both inside and outside of the building. Also, wood surface aging capability should be considered in the design of tall wood buildings. Different shade variations can be applied to create interesting architectural ensembles and to create messages and signs of tall wood buildings. Therefore, the modern industrial wood buildings should absorb the long-term practices and experience of traditional wood buildings. Especially in cases when wood architecture has been part of national history for a very long period. Based on this fact, Scandinavian countries are the best bases for the sustainable development of wood architecture.

Another message or sign type of tall wood building relates to the different material optimization methods. Material optimization is considered as a sustainability enhancing method for tall wood buildings. Material optimization can be achieved through the use of hybrid structure systems, which utilize the benefit of each material used in the structure. In some cases, the pursuit of using wood for all the structures in the building is not reasonable, and therefore other materials should be accepted to the structural systems. The use of materials can also be optimized through the varying structural thickness of the elements. For example, thinner structural elements can be used on the top of tall wood buildings.

Three main limitations for tall wood buildings have been discovered in this research. These limitations are structural systems, fire regulations, and budget. Structural systems for tall wood buildings are quite rigid now and therefore significantly affect the architectural solutions. One of the main requirements to the structural systems is connected to the stiffening of the structures. This turned out to be one of the most challenging requirements for the structures of tall wood buildings. However, in collaboration with a good structural engineer, it is possible to overcome this challenge. Fire regulations is another significant limitation of tall wood building. The use of case-specific functional fire measurement demands from the wood structures fire performance, which is comparable with fire performance of concrete structures, which is obviously quite challenging. All the structural solutions should be developed case-specifically to meet the requirements of fire regulations. If the architect would like to leave some wood surfaces visible, then the design team should be able to address the sufficient performance of wood structures in the case of fire. The main requirements relating to the structural performance in the case of the full absence of firefighting measures. Therefore, structures should be able to withstand both fire and cooling phases without significant damages, which can lead to the collapse of tall wood buildings. Designers should envisage safe exits for building users and safe work conditions for rescue service. This kind of requirement demands a significant amount of studies on the fire performance of modern wood-based products, which are used for the structures in the building. The last limitation is the most significant of the three presented ones. As it was addressed, the structural system and fire regulation limitations could be overcome if enough work is done for it. However, the budget is something that defines how much work could be done for tall wood building systems development. Therefore, it is the challenge, which limits tall wood building in the clearest way.

Based on this knowledge, the researcher has come to the opinion that tall wood building is justified for landmark or symbol purposes with mixed-use and sufficient budgeting of the project, at least in Scandinavian countries. For the residential purposes in Scandinavian countries, which are sparsely populated, the use of mid-rise wood buildings (up to 28 meters) could be more justified. This would allow creating architecturally intact and affordable housing with a sustainable purpose. Therefore, in Scandinavian countries, the wood building should be generalized first for mid-rise buildings. The tall wood buildings should be developed more for mixed-use and landmark purpose.

In this research have emerged plenty of topics, which have a great potential for tall wood building development. One of the topics relates to the further development of glue-free wood-based materials and their possible utilization for tall wood buildings. This kind of product already exists, for example, WLT and DLT, but their utilization for industrial wood building requires further development and research. Another topic relates to the fire performance of wood structures in multistorey wood buildings. Plenty of studies is already ongoing for this topic, but mostly abroad. Further development of digitalization tools for the design of tall wood buildings could significantly enhance the development of tall wood buildings. Digital tools can be combined with high-performance artificial intelligence to support the work of the whole design team. Tall wood buildings emerge plenty of research prospects for the development of sustainable architecture with respect to its environment.

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# LIST OF FIGURES

# LIST OF INTERVIEWS

Lassila, Anssi, Architect, Director, Founder, OOPEAA

Hirvilammi, Teemu, Architect, University Instructor, Tampere University

Heikkinen, Pekka, Architect, Professor of Practice, Aalto University

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Hartmann, Hannah, Massiv-Holz-Mauer Entwicklungs GmbH

Ojala, Aleksi, Fire Safety Specialist, L2 Paloturvallisuus Oy, A Jensen Hughes Company

# APPENDICES

**Appendix A1:** Interview structure

**Appendix A2:** Updated interview structure

**Appendix B:** Data structure

## Appendix A1: Interview structure

**Interview structure:**

*The initial purpose of the interviews is to define the main challenges and design methods in the case of high-rise wood building. The goal is to define the current design and technology possibilities for the high-rise wood constructions and especially the limitations which restrain certain design-solutions for the architectural appearance. The objective is also to understand the relationships between the professionals from different fields, which are involved in the design process of high-rise building and the information transactions between the actors.*

*The following themes have arisen from the literature:*

- *Hybrid construction solutions are the most common for the high-rise wood buildings.*
- *Wood constructions demand more space than concrete or steel constructions*
- *Government regulations put strict frames for the possible design solutions.*
- *The collaboration between parties in the project is vital for the project success*

1. **Start**
    1. Recorder on
    2. Permission to record, classification of information
    3. Introducing the interviewers
    4. Introducing the research topic
    5. Interviewee's background and position in the project
    6. Short introduction to the studio
2. **Architect's interview template**

    a. **Background of the designer**

    i. Have you been familiar with wood buildings before "X" project?

    ii. Do you have previous experience with wood buildings?

    iii. Which kind of capabilities do you have/need in your office to design high-rise buildings?

b. **Background of the project**
    i. Who initiated this project?
    ii. Which kind of background data did you get for this project?

c. **Design**

    i. What was the start point for your design?
        a. Structural possibilities
        b. Architectural appearance
    ii. Which kind of challenges have you met in the design process?
    iii. Was it easy to overcome those challenges?
    iv. Which kind of message/sign does your design keep?
    v. Whatr is the main point to consider when designing from wood?
    vi. What is the main benefits of the wood buildings?
    vii. Was there design solutions, which wasn’t possible to implement?

d. **Collaboration with other designers**

    i. On which stage of the process you collaborated with structural engineers? Material manufacturers?
    ii. Who was your partners/ advisors in this project?
    iii. stora enso, reijonen. a-insnöörit
    iv. How easy was the iteration process in the project?
    v. tuttu etukäteen

e. **Post-processes related to the project**

    vi. Are you satisfied with your project?
    vii. Joensuun, wood Joensuu,
    viii. Were there some issues, which required your attention after the project was completed?
    ix. amk Karelia, tunnistimia, rakemmuksen sisällä
    x. asiakaskyselyt
    xi. ääneneristävyys?

f. **Future issues**

xii. What would you like to know, when you start your next project?
xiii. What have you learned from this project?
xiv. yhteistyö valmsiajien kanssa, markkinavetoista
xv. Which kind of future do you see for the high-rise wood buildings development?

**3. Manufacturer's template**

**a. Wood-based material development**

i. How developed/tested the wood-based materials are at the moment?
ii. Which kind of materials are suitable to high-rise wood building?
iii. Which kind of development perspectives do you see for wood-based materials?
iv. What are the manufacturing conditions for wood-based materials?
v. What is the manufacturing capacity for the wood-based materials?

**b. Design process**

i. Which kind of experience do you have in the high-rise wood building?
ii. How common are this kind of projects?
iii. At which stage do you need the manufacturing pictures from the architect/engineer?
iv. Are the changes during the manufacturing possible?
v. Which kind of challenges (e.g. time) does changes affect to the manufacturing process?

**c. Material features**

i. What is the maximum size for the CLT (other wood-based materials)?

ii. What is the maximum transportation size for the wood-based materials?
iii. What is the maximum area for the openings in wood-based materials?
iv. What is your opinion on the most important features of the wood-based materials, which need to be taken into account in the design process?

**d. Collaboration with designers**

i. How easy/difficult was the collaboration with designers in the design process?
ii. Could you answer all the questions which designers had for you to continue the project?
iii. Did there arise any issue for development of the wood-based materials in the collaboration process?

**e. Future issues**

i. How do you see the future of the high-rise wood building?
ii. What would you like architects would know, when they design high-rise wood buildings?

## Appendix A2: Updated interview structure

1.Which kind of capabilities is needed/required in the architectural offices to design high-rise buildings?

2.What should be the start point for the tall wood building design?

a. Structural possibilities
b. Architectural appearance,

3. Which kind of challenges are possible to arise in the design process?

4. How easy it is to overcome those challenges?

5. What is the main point to consider when designing from wood?

6. Which kind of message/sign does the wood design should or can keep?

7. What are the main benefits of the wood buildings?

8. What are the limitations which affect design solutions to make them impossible to implement?

9. On which stage of the process should the designer collaborate with structural engineers? Material manufacturers?

10. Which kind of development perspectives do you see for wood-based materials?

11. How developed/tested the wood-based materials are at the moment?

12. Which kind of future do you see for the high-rise wood buildings development?

## Appendix B: Data structure

| 1st Order Concepts | 2nd Order Themes | Aggregated Dimensions |
|---|---|---|
| Confidential relationships with other designers. | Collaboration is vital for the project success | The main limitation is imagination. And budget. |
| Deep collaboration for the effective design. | | |
| Design solution affected by the regulations | | |
| Tall wood building is an exception even in the global practice. | | |
| The design is concentrated on the first stages of the process, because of the prefabricated structures. | | |
| The end result is synthesis. | | |
| The application of boundary conditions is a powerful tool in tall wood building. | | |
| The economical rigidity of wood structure for the tall wood buildings. | Tight budget creates boundary conditions for design | |
| Wood for the structures should be generalized and therefor be more affordable. | | |
| The number of boundaries in the wood buildings is larger than number of possibilities. | | |
| Challenges overcoming is easy. Difficult only if money has ended. | | |
| Site phase of wood building is fast. | | |
| Wood is special living “dead” material. | | Responsible design is vital for the tall wood |

| | | |
|---|---|---|
| Architecture is starting from the wood features. | Thoroughness in design and creative application. | building development. |
| Wood for interiors not facades. | | |
| Quality requirements for visible wood surfaces should be increased. | | |
| Structures are high-quality because they are prefabricated. | | |
| Industrial wood building should learn from traditional building | | |
| Stiffening of structures is important for wood construction | | |
| Wood surfaces inside the building have positive effect on humans' well-being. | | |
| To leave the wood structures visible, the wood surface quality should be ensured. | | |
| Jointing in the structure of the wood buildings can be developed. | | |
| Quality regulations should be developed for the tall wood buildings. | | |
| Material optimization is important. | | |
| The wood intensity for the interiors | Tall wood building identity. | |
| Structure elements for the design purpose | | |
| Protecting as an architecture tool. | | |
| Interior wood application for well-being and wood building identity. | | |
| Tall wood buildings doesn't have stereotypical expression yet. | | |
| The identity of the building is created from inside the building | | |

| | | |
|---|---|---|
| Large wood structures bring architectural beaty to the building. | | |
| Wood building structures should be visible. | | |
| Wood structures are usually quite modular, this modularity should be visible. | | |
| The purity of the structures should be exposed. | | |
| The structures should be visible also from the outside. | | |
| The signifier role of the tall wood buildings. | Tall wood building are great for the symbol purpose. | The purpose is everything for the tall wood building. |
| Great marketing potential of the tall wood building. | | |
| Identity tool for the city. | | |
| Not that suitable for residential construction, but great for landmark and symbol meanings. | Tall wood building not that suitable for the residential purpose. | |
| Sound insulation is good for voice-noise but bad for vibration-affected noises. | | |