WOODEN IT BE NICE

- Challenges and opportunities in modern wooden construction.

CHALMERS

Master's thesis in Master Program(s) Architecture and Urban Design (MPARC) & Architecture and Planning Beyond Sustainability (MPDSD)

Victor Ågren & Hans Ola Sjöberg

Department of Architecture and Civil Engineering
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden

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Supervisor: Jan Larsson
Examiner: Ola Nylander

Department of Architecture and Civil Engineering
Chalmers Unversity of Technology
SE-412 96 Gothenburg
Sweden

PREFACE

Acknowledgments of those who assisted in the work process:

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Of course Family and Friends!

Throughout the thesis the term *Craftsmanship and Craftsman* will not occur. These terms will be refereed to as *Craft* and *Crafts-person.*

RELEVANT STUDENT BACKGROUND

Victor Ågren

Mail: victor.agren@hotmail.com
Phone: 0721806878

Education

Chalmers University of Technology
August 2019 - June 2021
Msc, Architecture and Planning Beyond Sustainability

Chalmers University of Technology
August 2013- June 2018
Bsc, Architecture and Engineering

Relevant Work Experience

Norconsult
August 2018- December 2018
Architectural Internship

Ågren Måleri
August 2006- June 2015
Window restoration/ renovation & Carpentry

Hans Ola Sjöberg

Mail: hans.ola.sjoeberg@hotmail.com
Phone: 0739790894

Education

Chalmers University of Technology
August 2019 - June 2021
Msc, Architecture and Urban Design

University of New South Wales
February 2020 - September 2020
Msc, Architecture, Built Environment

Chalmers University of Technology
August 2015- June 2018
Bsc, Architecture and Engineering

Relevant Work Experience

Herzog & de Meuron
August 2018- June 2019
Architectural Internship

Nord West & Najad
April 2011- May 2013
Boat Builder, Wooden Joinery

ABSTRACT

The Swedish housing stock needs to be enlarged and simultaneously, with *Agenda 2030* in mind, emissions need to be limited. Studies show that replacing steel and concrete with wood can reduce construction emissions.

When researching opportunities in industrial wooden construction it emerges that an extensive housing development with wooden structural systems is a realistic option. With arguments of using wood in a sustainable housing development, this thesis is made with the purpose of investigating and highlighting inherent architectural qualities in relevant wooden structural systems.

The structural systems identified as relevant to utilize because of industrial production methods are *CLT, Light-Frame* and *Post-Beam*. This thesis aims to create an understanding of what challenges and opportunities these researched systems imply from an architectural and structural perspective. Another aim is to provide a basic understanding of the structural function of the systems, which could translate into increased possibilities of developing structural concept designs.

When constructing with wood there is a craft to consider. *CNC-milling* and production of *EWP-products* have the potential to become a vital part of contemporary craft. This thesis researches how and where these techniques can be implemented.

Research has been conducted through research *for-* and *through design*. To gain empiric experiences and come closer to actual design applications, research through design was mainly conducted through model making.

From the results of this thesis, it emerges that there are many ways to create a structurally expressive and genuine architecture based on the unique qualities of wood. This thesis confirms the plausible reality of an extensive housing production in wood and a readjustment towards increased wood construction in the sector. However, questions have been raised concerning the consequences of an increased usage of wood. From recent reports, it becomes clear that with contemporary forestry wood could not be called a sustainable material.

In its strive towards sustainability, the construction sector can not solely settle with mindlessly exchanging construction materials. It needs to, together with related industries, find and readjust to a new sustainable paradigm even if the consequences are inconvenient.

Key words:

Research on wood
Wooden Structural Systems
Industrial Wood
Engineered Wooden Products (EWP)
Cross-laminated timber (CLT)
CNC-milling
Modern Craft

CONTENT

DELIMITATION

This thesis will:

- First and foremost investigate wood as a building material.

- Investigate potential and qualities within different wooden structural systems and *EWP-products*.

- Utilize the academic freedom of not having to consider economic realism.

- Use Wendelstrand as the chosen site to contextualize the research

- Deal with structural concepts, but not structural calculations.

This thesis will not:

- Investigate economical calculations regarding apartment rents or costs.

- Adjust our design or research to fit the development plan of *Wendelstrand* or take a full grip of the development of the whole area.

ABBREVIATIONS

CLT	*Cross Laminated Timber*
CNC	*Computerized Numerical Control*
EWP	*Engineered Wood Product*
GHG	*Green House Gas Emissions*
SDG	*Sustainable Development Goals*
OSB	*Oriented Strand Board*
LVL	*Laminated Veneer Lumber*
WFIB	*Wood Fibre Insulation Board*
CAD	*Computer Aided Design*
RISE	*Research Institutes of Sweden*

DEFINITIONS

CLT	*Cross Laminated Timber consists of wood boards glued together in layers perpendicular to each other. (Gustafsson et al. 2017).*	
EWP	*Composite products of glued wood, produced to have increased capacity and predictability than ordinary timber (Hildebrandt et al. 2017).*	
Structural System	*Structural system, in building construction, the particular method of assembling and constructing structural elements of a building so that they support and transmit applied loads safely to the ground without exceeding the allowable stresses in members*	*https://www.britannica.com/technology/structural-system*
Wooden House	*The definition of a wooden house, is that the main part of the structural system should be made out of wood. The facade can be of another material e.g. brick, plaster and it would still be considered as a wooden house (Gustafsson et al. 2013). This definition will be used in this thesis, a building will be regarded as wooden if the structural system consists of wood.*	
Biodegradation	*Biodegradation is the breakdown of organic matter by microorganisms, such as bacteria and fungi*	
Orthotropic	*In material science and solid mechanics, orthotropic materials have material properties at a particular point, which differ along three mutually-orthogonal axes, where each axis has twofold rotational symmetry*	
Agenda 2030	*A collection of 17 interlinked global goals designed to be a "blueprint to achieve a better and more sustainable future for all"*	
Lamella	*A lamella (plural lamellae) is a small plate or flake and may also be used to refer to collections of fine sheets of material held adjacent to one another.*	
Hygrothermal	*The movement of heat and moisture through buildings.*	

1. INTRODUCTION

POSITIONING

Background & Problem Statement

There is a lack of dwellings in Sweden, in a report from *Boverket* in 2018 it was stated that the Swedish housing stock needed to be enlarged by 641 300 dwellings in a ten-year period *(Boverket, 2020)*. This development is a challenging task, aggravated by the fact that it needs to be done with the minimal amount of emissions and use of resources. The building and construction sector is resource demanding, globally it is one of the main polluters. Alone accounts for almost 40 percent of both the energy usage and emissions *(IEA, 2018)*.

Simultaneously the construction sector is one of the areas where the environmental footprint can be decreased in a relatively cost-effective way. The sector have an opportunity to affect 42 percent of the energy consumption, 35 percent of the GHG emissions, 50 percent of the extracted materials and 30 percent of the water consumption *(Hurmekoski et al. 2018)*. Several comparative studies show that replacing fossil materials like steel and concrete in the structural system with wood based materials is an efficient way to reduce emissions and fossil energy usage *(Dodoo et al. 2014)*.

Evolution in wood construction with increased knowledge and quality of prefabricated *Engineered Wood Products* have made wood a cost competitive and sustainable challenger to concrete and steel systems. It is from an industrial point of view a realistic option to have an extensive housing development with wooden structural systems. *(Gustafsson et al. 2013)*.

The development of wood prefabrication and machine techniques also gives opportunities to process and design prefabricated elements. This could be influential for the architectural expressions and qualities in wooden structures.

Despite efficient assembly, superior technical properties, and ecological advantages the *EWP* products still have small market shares compared to the conventional materials concrete and steel. A principal way to change the strong path dependency of the building sector is knowledge transfer and education at universities which can have spill-over effect to the business sector *(Hildebrandt et al. 2017)*. An affordance of this thesis is that it can add to these spill-over effects.

Purpose and Aim

The purpose of this thesis is to investigate and highlight inherent architectural qualities in the wooden structural systems relevant for an industrial housing production.

It is made with the supposition from Heino Engel that in order to create coherent designs, a conceptual understanding of a buildings structural system is necessary (*Engel, H. 2009*). Similar arguments are made by Karl-Gunnar Olsson who writes that architects have lost the basic knowledge of structure and with that also lost responsibility for forming the conceptual design of the structure. Further he argues that in that act architects also lose a fundamental mean of expression *(Olsson, K-G. 2005)*.

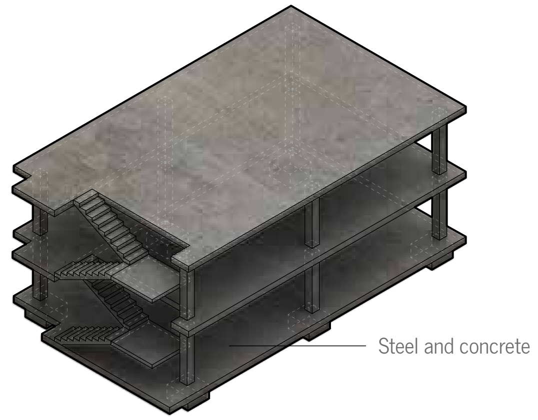
In understanding and developing the structural concept architects can gain control over a fundamental part of the final design. The thesis is made with the purpose to give the reader a basic understanding of how the investigated structural systems function. Further this understanding hopefully could translate into better possibilities of developing a wide range of conceptual structural designs based on the investigated systems.

In researching the wooden structural systems through the perspective of being architect students, the intention is to seize and highlight what is to be considered architectural qualities within the structures. This investigation could add some observations of architectural qualities, that would have been overlooked by investigators with other professional backgrounds.

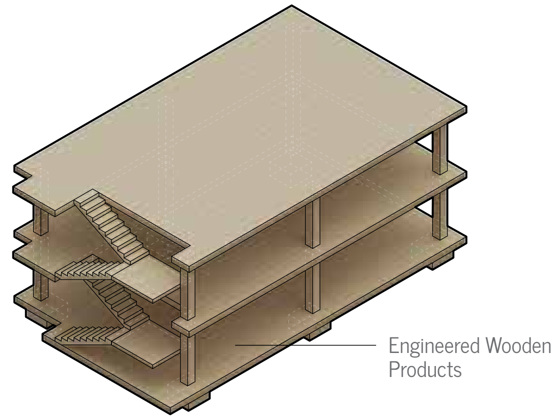
The structural systems have their own individual benefits making it relevant to investigate how they can be integrated in an advantageous way. Starting from the existing systems the thesis project aims to work towards a design proposal that utilizes the individual benefits of the different construction systems.

Wood have a close relation to craft, inevitably when constructing with wood there is a craft to consider. With the entrance of prefabrication and *EWP*-products a vital part of the craft and detailing have moved from the hands of the crafts-person to the drawing board of the designer. A purpose for the thesis is to investigate possibilities in machine made detailing and further to investigate what that means in terms of bringing architectural qualities into housing development.

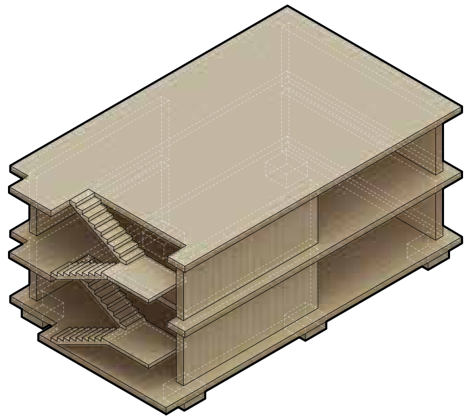
With these investigations there is an intention to promote the repute of wood, not only as a sustainable material but also as a material with great architectural values.



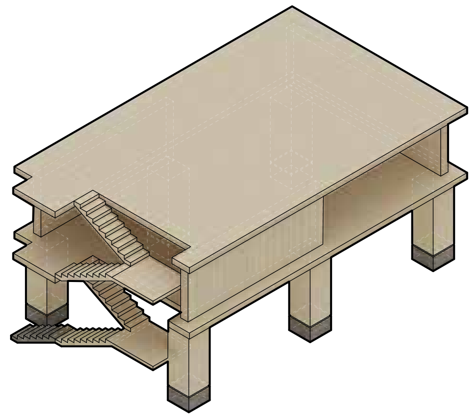
Maison Dom-Ino, Le Corbusier 1915, Re-inforced Concrete



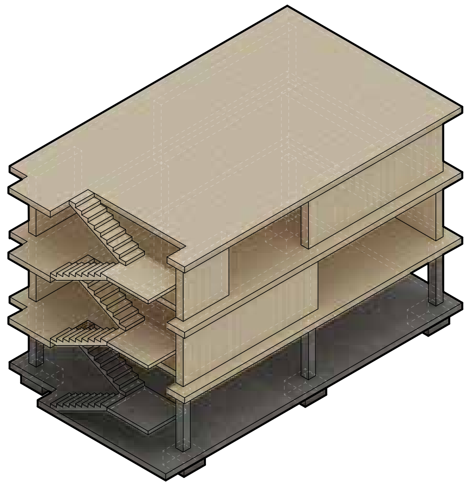
Maison Dom-Ino, Re-Interpreted. Glulam, CLT



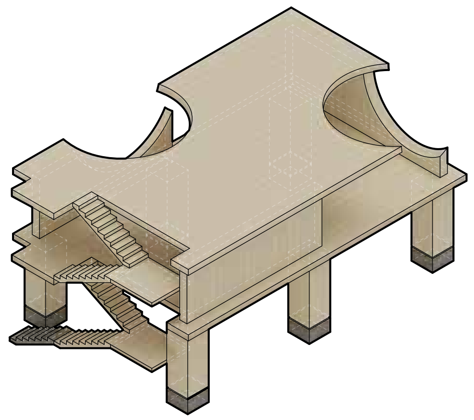
Maison Dom-Ino, Re-Interpreted. CLT



Maison Dom-Ino, Re-Interpreted. CLT Glulam Columns



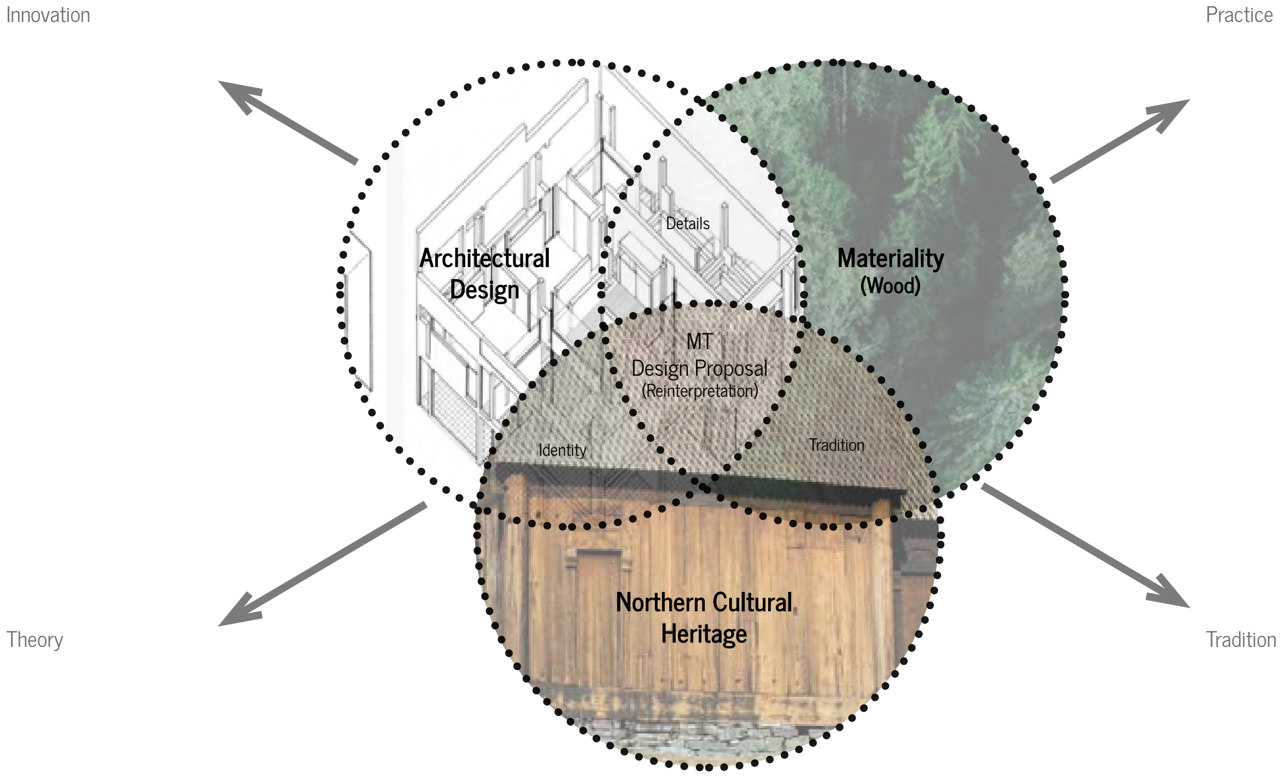
Maison Dom-Ino, Re-Interpreted. Combination, Wood - Concrete



Maison Dom-Ino, Re-Interpreted. Apertures

Research Questions

- What are the architectural consequences, challenges and opportunities using the established timber systems for housing development?
- How and where can wood processing techniques (e.g. CNC-mills, laminated wood) be implemented as modern crafts tools and what architectural qualities can it bring into housing development?



Architectural Scope

Method & Process

The thesis will be divided in four main parts:

Introduction will focus on problem statement and underlying theory relevant for the thesis.

Investigation will focus on research for design.

Exploration will focus on research through design.

In order to inform and develop one another, *Research for- and Through design* will be developed iteratively and in parallel. From the research phases *Design Guidelines* will be developed.

Application focus on developing a design proposal that adheres to the *Design Guidelines* extracted in *Exploration* and *Investigation*

Research For Design:

A background study will be conducted in the *Introduction* phase to understand how structural systems and structure work on a conceptual level. This understanding will in the *Investigation* phase translate to an examination of the wooden structural systems relevant for industrial housing production. Focus will be on the inherent architectural qualities and different structural possibilities/boundaries in each system.

Research will be conducted concerning precedent housing projects made with industrial wood systems. Focus will be how these projects utilize the inherent qualities of wood and the wooden structural system (plan, facade, apertures, structural possibilities, durability/patina, material enhancement etc.)

Research will also be conducted on traditional/vernacular buildings in wood in a northern context. Focus will then be on what makes a wooden structure stand the test of time and how traditional techniques can be reinvented and used in a contemporary context.

Research Through Design:

The thesis will also be based on research through design which means that the *Design Process* is an activity that strives to bridge the gap between theory and design *(Hanington and Martin, 2012).*

Research through design will be developed by an *Exploration* phase, where conceptual designs of wooden construction and modern craft situations will be tested and examined. In order to gain empiric experiences and come closer to actual design applications the *Explorations* will mainly be conducted through the making of models.

A design proposal will derive from formed *Design Guidelines,* the guidelines will be based on findings in the conducted research. Even though the *Design Guidelines* can originate from different time-periods and forms of research, they will still be developed to be applicable on industrial wooden construction in a modern context. The designed project will reflect our analysis and evolve through an iterative design process. It will be developed in certain isolated situations found, in the research, to be of extra interest. This will be done through rigorous testing in first and fore-most drawings and model making (digital/physical).

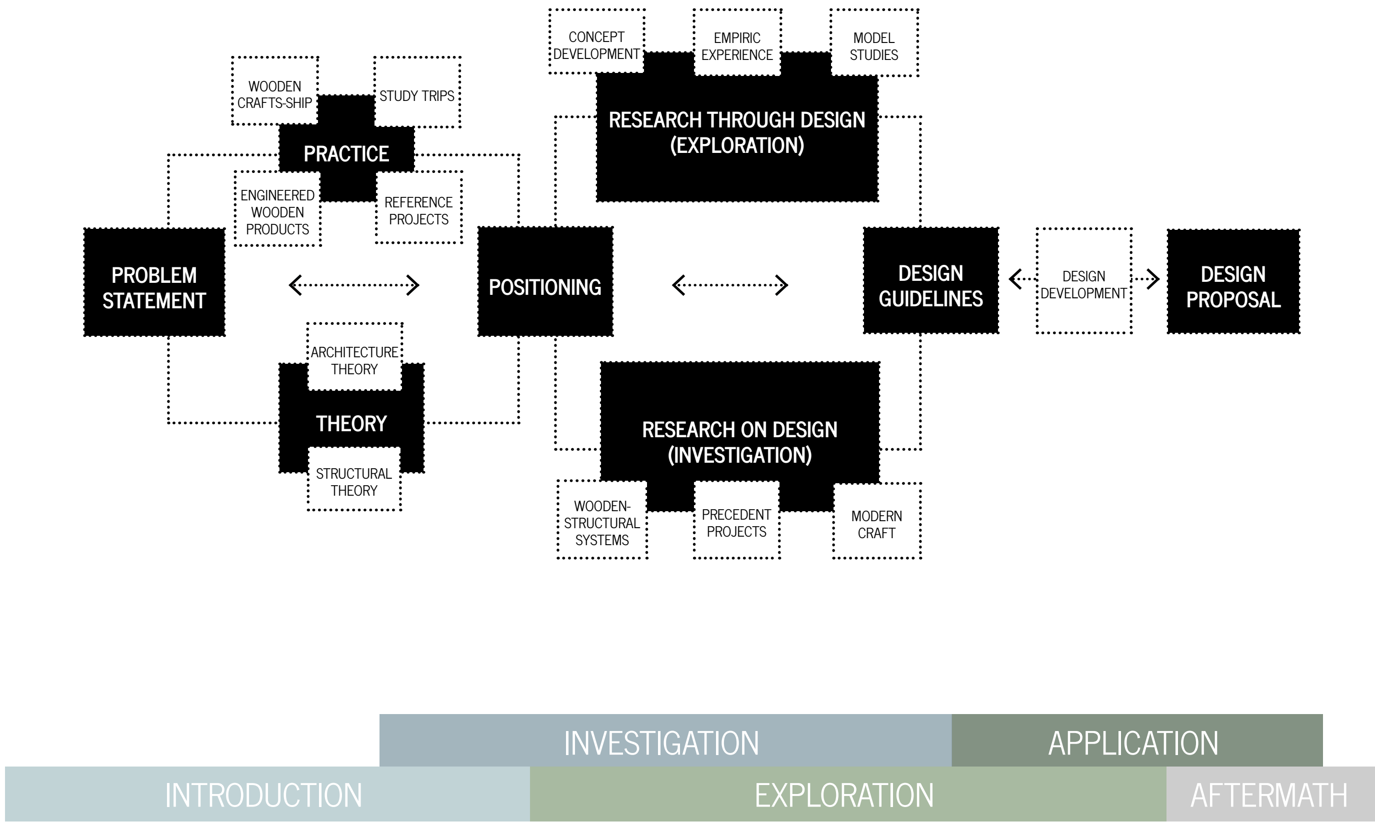


Illustration: Iterative design process

Wood as Building Material

Pros and Cons

Wood has some noticeable benefits compared to concrete and steel. It is light and have a high strength compared to its weight. It can easily be transported to the construction site because of its lightness and easily be processed with simple machines. It also has good insulating qualities and low emissions from production compared to steel and concrete. Disadvantages is the risks of bio-degradation with sensibility to moisture or certain insects, its combustibility and its orthotropic character. These disadvantages can all be predicted and solved with modern techniques *(Al-Emrani et al. 2011).*

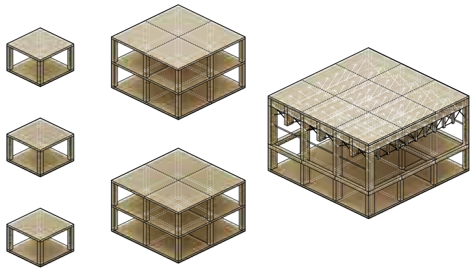


Illustration: Constructions in wood have many benefits

Sustainable Forestry

With the strive for a fossil free economy and limiting the carbon emissions, interest in the forests bio-mass are growing. There are many stakeholders who are dependent on the forest to convert to a sustainable production. The spectrum ranges from the usual stakeholders like construction business, bio-fuel users and pulp-producers to stakeholders with new products like wood based textiles and replacements for plastic. Already today Sweden has a deficit in the forest production and need to import forest mass and the demand will continue to rise. There are many stakeholders who compete for the finite resources of the forest *(Lundmark 2020).*

The forest and its inhabitants are also stakeholders in the competition for more bio-mass out-takes, it needs protected areas for recovery and biodiversity. Recently biodiversity and a healthy forest have been raised as important markers for resilience and protection against an emerging climate crisis and its entailed problems.

With the wrong management forests can become emitters of huge amounts of carbon dioxide. The main problem with today's forestry is the conventional felling methods with clear-felled areas. The clear felled areas are a serious threat not only to biodiversity, it also brings nutrient leakage to close watercourses and during the first 10-12 years the clear-felled area releases a lot of carbon dioxide from degradation of dead roots, stumps and other felling residues. It usually takes 20 years before a growing forest have covered up for that carbon emission *(Bruun 2021).*

There are possibilities to limit the negative impacts of forestry. A sustainable alternative to the clear-felled areas are continuity forestry where the biggest trees are felled and one cut a maximum of 20-25 % of the trees each felling. Continuous vegetation cover protects the area from extermination of biodiversity, leakage of nutrients and carbon emittance from the ground. The smaller trees that binds more carbon dioxide also get increased access of sunlight and nutrients and therefore grows faster *(Bruun 2021).*

If both a conversion to a fossil free economy and biodiversity with sustainable forests should be realizable a more active and sustainable forestry is necessary. With the long change-over times in forestry this needs to be addressed in recency. Even with a sustainable forestry there will always be opposing forces between sustaining biodiversity and utilizing it for reduced climate impact from fossil fuels. Researchers can only provide facts, in the end balancing the negative impacts between forestry and use of fossil resources is a moral question that needs to be decided by the elected politicians *(Lundmark 2020).*

Figure 1. If the wood is cut to clear-felled areas it have a negative impact on biodiversity and carbon emissions and its repute as a sustainable building material is highly questionable (Pierce, 2018)

Climate Impact of Wood

As mentioned in *Sustainable Forestry*, wood can have a severely negative impact on carbon emissions, biodiversity and over-fertilization if the forestry is managed poorly. Still if managed well bio-mass products like wood could be a potent resource in the fight against carbon emissions. Wood is composed of carbon sequestrated from its photosynthesis. If wood is used in long-cycled products, like construction timber instead of short-cycled products, one can talk about carbon storage. A sustainable forestry can speed up the sequestration process in the forest meaning that certain out-takes of bio-mass can stimulate the carbon sequestration. This means that wood from properly managed forests actually can store more carbon than the emittance from its production, making them a carbon storer rather than emitter *(Bruun 2021).*

Even if stored carbon is deducted from calculations wood still has less emissions from production than concrete and steel. In a Life Cycle Analysis comparing the total emissions of a conventional building with concrete structure and a conventional building with *CLT* structure, the *CLT* structure had 20 percent lower total emissions *(Erlandsson et al. 2018).* Another report from *Linköpings University* suggest that the emissions is 40 % lower when comparing a wood building to a similar one in concrete. The report also suggest that if carbon sequestration is included in the calculation the structure even captures more carbon than it emits from production *(Brege et al 2017).* A report from *Linné University* suggest the same (*Dodoo et al. 2014).*

Figure 2. Wood is composed of carbon sequestered from the photosynthesis. If wood is used in long-cycled products the products can be mentioned as carbon storer, (SCA, 2021)

Con-texture of Wood

Wood is structured from many cells connected with its own natural glue called *lignin*. 95 percent of the cells are 0.5-6 mm long fibres. The fibres are pipe formed and glued together in a long chain. The con-texture of many glued pipes makes the material have different strength in different directions. In the direction of the fibres wood is strong both in tension and compression, but across the fibre it is many times weaker since the fibres easily are pulled apart. This makes the material *orthotropic* which means that it has different strength in different directions. This also makes it important to know the fibre direction of a structural element and to at the highest possible extent carry forces in the direction of the fibre *(Al-Emrani et al. 2011).*

From its natural origin and growth wood has certain imperfections it can be knots, twisted fibres, cracks etc. These imperfections gives the material weak spots and affects its structural capacity. In order to limit the influence and spread out the imperfections wood can be cut into smaller *lamellas* and glued together *(Al-Emrani et al. 2011).*

When exposed to moisture wood store the water in the walls and cavities of the cells, this have a big impact on the strength and makes it important keep the moisture levels under control *(Al-Emrani et al. 2011).*

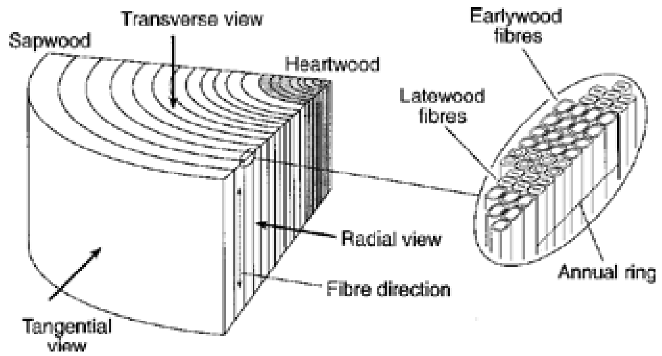


Figure 3. Wood is strong when stressed in the direction of the pipe formed fibres (transverse view), in the direction across the fibre (tangential view) wood is weak since the fibres easily are ripped apart (Hilden, 2004)

Engineered Wood Products

As mentioned the weak spots and imperfections of wood can be limited and evened out by creating composite products of smaller *lamellas* or pieces of wood, glued together. These products are made for a more predictable and strong wood product and the umbrella term for these products are *Engineered Wood Products*. Examples of these products are different kinds of boards with thin layers of wood glued together e.g. *Masonite, OSB, LVL, WFIB, Plywood* etc. The boards can also be used to create different kinds of beams e.g. *Kerto-* or *Masonite* beams. *Glulam* and *CLT* are examples of products where *lamellas* or boards of wood are glued together to create a larger beam, pillar or slab *(Hildebrandt et al. 2017)*.

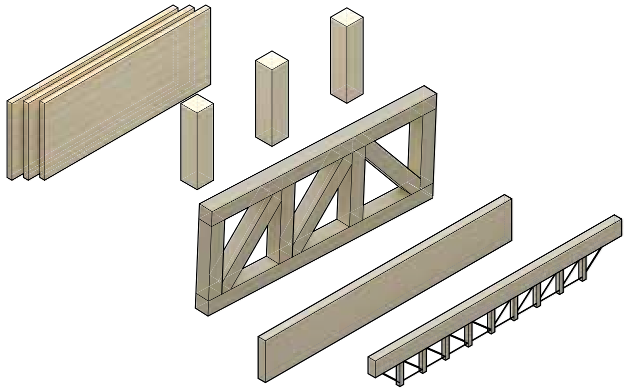


Illustration: The influence of natural imperfections, like knots and twisted fibres, can be limited and evened out through the processing of Engineered Wood Products.

Acoustics

Issues with vibrations and acoustics are more complex in multi-storey wooden structures compared to similar structures made in concrete. This is mainly because of the lighter and more complex configuration of the wood structure. Sufficient insulation of step sound and flank transmission is the acoustical aspects that affects the acoustic comfort most. A lot of research and testing have developed special systems adapted for handling these aspects. With new acoustic calculation methods and systems it is possible to reach good acoustic performance in all wood structures *(Gustafsson et al. 2013)*.

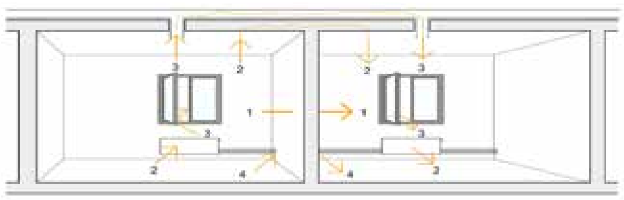


Figure 4. Paths for noise spread to other spaces through flank transmission (Svenskt Trä, 2017)

Energy

Calculating the total emissions of producing and operating a conventional house for 50 years, more than a third of the emissions comes from heating and ventilation. If the house instead is designed as a low-energy house the total emissions from heating and ventilation can be lowered by approximately 45 % (*Dodoo et al. 2014)*.

Decreasing the heating demand in the building stock is a key aspect for limiting total emissions and reaching sustainability goals. Wood can be a suitable material when designing low-energy houses, a benefit is that it has a lower thermal conductivity than concrete and steel. Airtightness is key aspect for limiting the heating demand, because of this it is important to design tight connections and use a plastic membrane that slows or stops moisture and air leakage. A tight construction also have better thermal comfort, air quality and protection against moisture damage *(Gustafsson et al. 2013)*. A positive side effect of building with *CLT* is the increased airtightness, *CLT* structures often perform better than expected in heating efficiency because of its inherent airtightness and from the moisture and heat buffering through thermal/hygrothermal mass (*Kraniotis & Nore 2017)*. In a comparison between similar low-energy houses in *CLT*, *Post-Beam* and *Light Frame* the *CLT* house had a 17-20 percent lower heating demand mainly because of its airtightness (*Dodoo et al. 2014)*.

Figure 5. Airtightness makes the CLT construction perform well as a low energy and passive house (Von Radina, 2014)

Fire

In the end of the 19th century, after many severe city fires, a law prohibiting wood construction taller than 2 floors was constituted in Sweden. This law was kept until 1994, when it was replaced by the European performance based rules that allows taller timber structures *(Landel 2018)*.

Today the combustibility of wood can be handled through the use of certain fire protective paints, flame retardants, encapsulation with materials like plasterboards and with sprinkler systems. Even though its combustibility wood can handle fire loads well, the charring of wood keep its rather fire resistant. The charred parts have a lower thermal conductivity slows the burning process. After 60 minutes of fire the char have reached approximately 40 mm into the wood. This means simplified that if the height of a beam is increased 80 mm it can keep its capacity after 60 minutes of fire. To increase dimensions of wood elements is usually the cheapest way of fire protecting a structure *(Al-Emrani et al. 2011)*.

A sprinkler system with the possibilities to extinguish fire in an early stage is the system that increases the safety for inhabitants mostly. It also opens up possibilities to instead of encapsulate expose wood interiorly in a higher extent. It also makes it possible to have combustible materials in the facade in more than two storeys, have evacuation routes further apart with less demand on its facing material, have less demands on limiting fire spread in ventilation systems and give a reduction in demands of separating load bearing structure *(Gustafsson et al. 2013)*.

Figure 6. The charred parts of wood have low thermal conductivity which slows down the fire process, after 60 minutes of fire the char have penetrated approximately 40 mm into a wooden beam. (Pixnio, n.a.)

Moisture and Weather Protection

Wood has a sensibility to moisture, if not is kept under acceptable levels it can affect structural capacity, lifetime of the structure, indoor environment etc. Because of this it is necessary to ensure that all wood and especially structural elements in wood have sufficient protection from moisture*(Gustafsson et al. 2013)*. Wood exposed of moisture should have the possibility to ventilate and with benefits have a angle steep enough for water to rinse off. Wood structure in connection with damp materials e.g. a concrete foundation should have a moisture barrier (in Swedish "syllpapp") in between the connection. Another tactic can also be to have a non structural sacrifice-board that can be changed when damaged, this can be seen in many old structures.

It is also important to ensure that the amount of moist penetrating the structure during the construction phase is as minimal as possible. For this purpose a short construction time using prefabricated elements is preferable. Still in most cases it is best to have a protective structure over the construction site. Special tents that can be moved up along each constructed floor can both ensure a moisture free construction and speed up the construction time. Lastly it is important to make sure timber products are stored dry both before delivery and on the construction site *(Gustafsson et al. 2013)*.

Figure 7. A weather protection on the building site can ensure a moisture free construction and give a shorter construction time. (Svenskt Trä, 2017)

DESIGN THEORY

Architectural History & Theory

Relevant reasoning and events

Structure

Rem Koolhaas writes in *Delirious New York* that "In the era of the staircase all floors above the second were considered unfit for commercial purposes, and all those above the fifth, uninhabitable. Since the 1870s in Manhattan, the elevator has been the great emancipator of all horizontal surfaces above the ground floor" *(Koolhaas, R. 2014).*

In the end of the 19ths century John Wellborn Root from the well known Chicago architectural firm *Burnham and Root* listed a set of technical specifications enabling buildings at height. These set of rules, he felt, characteristic an American approach which was set apart from the European tradition *(Addis,B. 2007).*

The *Dom-Ino House* is an open floor plan modular structure designed by the Le Corbusier in 1914. It was a prototype which displayed how reinforced concrete could be used to lay the foundation for a mass production of housing. The name is a pun that combines an allusion to domus (Latin for house) and the pieces of the game of dominoes *(Frampton,K. 2020).*

Le Corbusier envisioned an ideal of progress where reinforced concrete and steel allowed for an audacity of buildings reaching 60 storeys. These buildings would be set 230 -275 meters apart creating an abundance of light and fresh air as opposed to " how dust, smells, and noise stifle our towns of to-day" *(Corbusier, L. 2013).*

What followed was an era of the international style where a lot of Corbusiers ideas got a lot of ground. Even though it was designed to create a better society it has, among other, been criticized for lacking human scale *(Jacobs, J. 2016).*

Critical regionalism is a set of ideas formulated by Kenneth Frampton that strives to counter the *placeless-ness* and lack of identity of the International Style. At the same time it rejects the whimsical individualism and ornamentation of Postmodern architecture which had a lot of influence on the prevailing architectural conversation at the time of the writing of the book *Towards a Critical Regionalism (Frampton, K. 1993).*

At the 2014 Venice Bienale architect Valentin Bontjes van Beek and a group of student from the Architectural Association in London built a full-size model of Le Corbusier's seminal *Maison Dom-ino* entirely made out of wood. This shows the potential of *Engineered wooden products* in its aim to replace steel and concrete in modern construction.

Craft

In *learning from Las Vegas* the authors describes the excessive ornate interior of the 1730's *Amalienburg Pavillion* in Nymphenburg as a "Motival bas-relief, Splattered like spinach over the walls and furniture..." *(Venturi, R et al.1967).* This perhaps marks peak of ornate surfaces where the ornament itself almost seem to fall off the wall.

John Ruskin expressed in the late 19th century the decline of morale which followed the industrial revolution. He dreamed of a time before factories and vigorously advocating a return to the handicrafts "where the work produced reflected the shape of the tool and the passage of the workers hand" *(Moffett, M.et al. 2003).*

Ruskins ideas had a tremendous influence on a younger generation of what he called "sensitive men" who put many of his ideals into practice. This helped to formulate the Arts and Crafts movement which flourished from 1850 - 1900 in Britain and later in the United States *(Moffett, M.et al. 2003).* Both *Art Nouveau* and *Art Deco* are movements with the same ideals as *Arts and Crafts* at its core.

Adolf Loos debates at length and argues that ornament has no place in modern times. He describes how "Ornament is wasted labor and hence wasted health. That's how it has always been. Today, however, it is also wasted material, and both together add up to wasted capital." *(Loos, A. 2019).*

However Venturi describes a modern ornament as something different than what perhaps Loos had in mind. He describes How Mies van der Rohe's fire resistant columns is " as complexly ornamental as the applied pilaster on the renaissance pier..." or "how the lush marble veneering of the Barcelona Pavilion with its reputation for rarity connote richness" *(Venturi, R et al.1967).*

Richard Sennet writes about a troubled craftsmen and have fears about the negative impact *Computer Aided Design* might have on architecture where this necessary technology also posses dangers of misuse. He describes that misuses of CAD illustrate that "when the head and the hand are separate, it is the head that suffers" *(Sennett, R. 2008).*

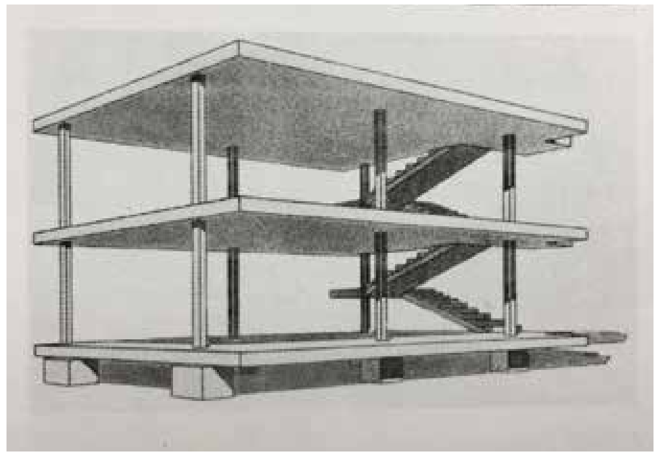


Figure 8. Maison Dom-ino Le Corbusier 1914 (Frampton,K. 2020).

Figure 9. Le Corbusier and Jeanneret, Plan Voisin proposal for Paris 1925. (Frampton,K. 2020).

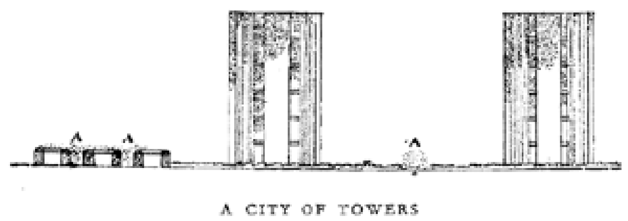


Figure 10. A city of towers (Corbusier, L. 2013)

Figure 11. Le Corbusier's seminal Maison Dom-ino entirely made out of wood (Frearson, A. 2017)

Figure 12. Prudential (Guaranty) Building by Louis Sullivan (Sethuraman, S. 2020)

Figure 13. Victor Hortas Stairway of the Hôtel Tassel. The highly ornate stairwell is an example of the Art Nouveau movement. (Bruselles 2017)

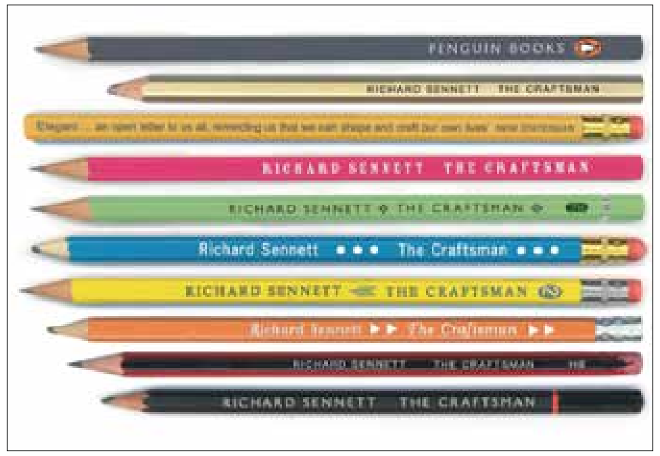


Figure 14. The craftsmen cover - Richard Sennet (Sennett, R. 2008)

Figure 15. Critical Regionalism Cover - Kenneth Frampton

Modern Craft

Computational Craft

What follows are some examples of what we choose to call *Computational Craft*. The ambition is to argue for an expression enabled by computers and executed by machines.

“Material is expensive, Geometry is cheap” ia a quote by Prof. Dr. Christopher Robeller who leads the *Digital Timber Construction group, DTC* at the *Technische Universität Kaiserslautern*. Thanks to Computer aided design we can imagine new ways of craft which can be enabled through modern machinery. *(Robeller, D. P. C. 2021)*

There are two main takeaways from this:

1) Higher complexity does not necessarily mean higher cost.
2) Labour intense processes can be automated.

Villa Hammer

Villa Hammer is a refurbishment and extension of a Swiss villa made by a team from *Herzog & de Meuron* and the architecture-duo *Sauter von Moos*. The ensemble of the new building and the villa stands in a critical dialogue. The new addition emulates the old but also demarcates its own contemporaneity. What was formerly done in heavy stone is now wood and steel. What appears to obey the tenets of a classic centralized order is resting upon a dematerialized plinth. What was once carved out by stone-masons is now brought to fresh expression using digital technologies where CNC milled wood replaces chiselled stone around the columnar windows.

Vidy Theatre

The EPFL laboratory for timber constructions has been managed since 2004 by Professor Yves Weinand, civil engineer and architect. It renews the principles of timber construction through new computation and digital modelling models. Its team of architects, civil engineers, mathematicians and computer scientists is integrated into the civil engineering and architecture sections of the *ENAC faculty (Natural, Architectural and Built Environment)* at EPFL. The Vidy Theatre in Lausanne is fruit of their labour. It is an example of a folded structure of CLT plates where elaborate joints has been enabled through CAD.

Regional Craft

What follows are some examples of what we call *Regional craft*. It aims to show how regional ideas and tradition can be reinvented into practice of today.

One way to counter a sense of *place-less-ness* and lack of identity mentioned by Kenneth Frampton could be to reinterpret traditional and local architecture *(Frampton, K. 1993)*. There are arguments regarding cultural and environmental sustainability in using local materials, techniques and labor *(Salman, M. 2018)* A positive side effect is also the shorter transportation of material. The material could be processed locally and handled using local labour. This way there is a sense of control over the production chain.

Chässerugg

The cable car station of *Chäserugg* can be seen as a reinterpretation of a traditional Swiss cabin. Here we see traditional Swiss alp cabin features like large protecting roof structures and connection to landscape as two defining design elements.

St. Benedict’s Chapel

The St Benedict chapel uses traditional and regional Swiss building materials and carpentry to create a form with a sense of novelty.

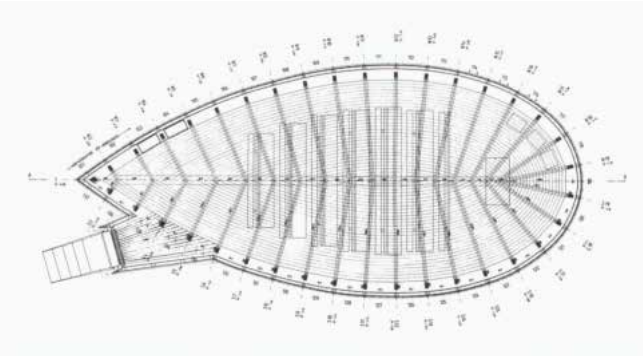


Figure 16. Plan drawing of St. Benedict’s Chapel With its iconic form.

Figure 17. Villa Hammer, Basel, Switzerland by Herzog & de Meuron and Sauter von Moos, 2018 (Domusweb, 2018)

Figure 18. Herzog & de Meuron, Chäserrugg, 2013–2015 (atlasofplaces.com, 2019)

Figure 19. Vidy Theatre, Lausanne, Engineers of wood construction laboratory EPFL Lausanne, Blumer Lehmann AG (Schilliger, 2018)

Figure 20. St. Benedict’s Chapel Peter Zumthor, 1988 (Fischer, 2018)

STRUCTURAL THEORY

Structural & Architectural Practice

Structure is a fundamental part of our physical world and it preserves the form of all material objects. Its importance can easily be neglected but without structure there would exist no objects, shapes or spatiality. This leads us to the obvious conclusion that structure also is the creator of space and shape in the built environment i.e. architecture. Being a constitutional shaper of architecture, structure inevitably affects all forms of architecture even when the structure is hidden away from sight *(Engel, H. 2009)*.

The load bearing capacities of a structure is determined by the material and geometry of its components. In this sense structural engineers just as architects perform their work by settling for a adequate composition of material and geometry. This common denominator implies that in a coherent design the structural capacity and architectural values (function and design) in a high degree are integrated and solved with the same geometry and materials i.e. structure *(Engel, H. 2009)*.

In the book *Structure Systems* Heino Engel argues that calculations have little meaning for understanding the complex behaviour of structural systems or for creating structural inventions. Therefore, with the prerequisite of basic knowledge of structures, development of basic structural concept and design can and should be done by the architect. Further the structure should be seen as a design element and an essential part of genuine architecture *(Engel, H. 2009)*.

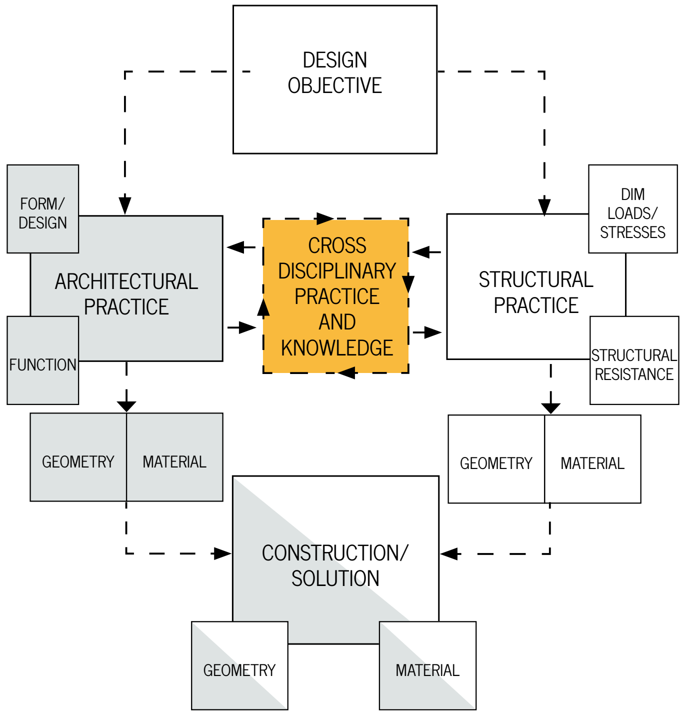


Table With cross disciplinary practice and knowledge many of the architectural and structural matters can be solved within the same geometry and materials i.e. construction

Karl-Gunnar Olsson derives towards the same opinion. In his Academic Thesis *Strukturmekanik och Arkitektur* he explains that traditionally architects and builders had fundamental knowledge and responsibility of the load bearing structure and its resistance. In modern construction with the entrance of rigid calculation methods, the responsibility of the load bearing structure as a whole (not just calculations) have moved into the hands of engineers. This have caused architects to let go of the basic knowledge of structure. In this act architects have simultaneously left the responsibility for not only the structural capacity but also the conceptual design of structure to engineers. Olsson argues that in losing the conceptual design of structure, architects lose a fundamental mean of expression. *(Olsson, K-G. 2005)*.

This reasoning is applicable for the research on wooden structural systems conducted in this thesis as well. Gaining understanding of structure gives opportunities to, as architects, seize architectural qualities within the structure and enhance it. Researching and acknowledging the architectural qualities and possibilities within structural systems expands the available toolbox when creating architecture.

Sverre Fehn was an architect known for integrating architectural and structural design in his projects. When explaining his view of the connection between structure and architecture, he described structure and material as the alphabet he use to write a story i.e. architecture. He rather poetically seizes his thoughts of this relationship in the quotes on the next page.

"I see materials as letters we use to write poetic thoughts....We work with letters, an alphabet, we write a story. The story and its structure are inseparable. The poetic idea needs the support of structure to exist."

Quote from Architecture+Urbanism (Fehn, S. 1999)

"For me, there is no architecture without construction. We work with our alphabet materials such as wood, concrete, bricks, with them we write a story which is inseparable from the structure. And the structure is supported by the poetic idea."

Quote from The Pritzker Architectural Price 1997 Laureate Biography (Hyatt Foundation, 2021)

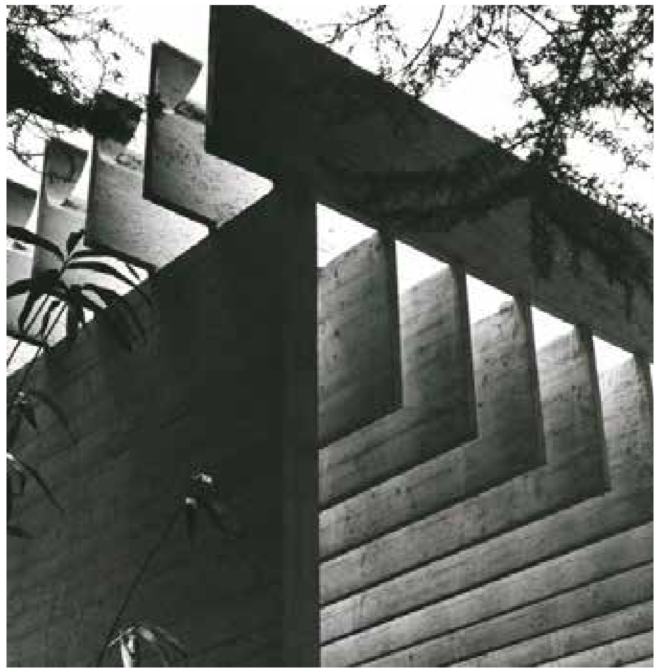


Figure 21. Nordic Pavilion Structure and Architectural qualities are inseparable in the works of Sverre Fehn (oca.no, 2009)

Figure 22. Hedmark Museum Sverre Fehn uses materials and geometry of the structure to tell his architectural story (Peter Guthrie, 2013)

Basic Concept of Structural Systems

A structural system consists of many interconnected elements (also called members) who transfer the loads to the ground. Pillars, beams, rods trusses, slabs are all examples of structural elements. In each element of the structural system the load should not exceed the resistance. The resistance depends on the geometry and material of the element. *(Dahlblom, O., & Olsson, K. G. 2010).*

All structural systems principally preform the three following operations:

1. Load Reception

2. Load Transfer

3. Load discharge

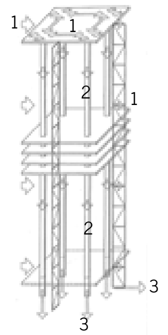


Figure 23. Operations of Structural systems (Engel, H., 2008)

All structures needs to be able to receive stresses and forces from wind, gravity, live loads etc. Nevertheless what really is the essence and defining part of a structural system is how it operates to transfer forces within its members and discharge the forces into the ground. This action needs to be performed without causing any breakage or mayor deformations. This process is called flow of forces and is the basic concept of how a structural system works (*Engel, H. 2009).*

Usually in architectural practice a specific function needs to be fulfilled and for this purpose space is created. That space is in fundamentally created by redirecting the flow of forces from its natural path e.g. vertical forces from a roof are transferred horizontally to a wall and through the wall down to the earth. Thus, having knowledge of the mechanics of redirecting forces is the basis for creating and developing structural systems as a practicing architect (*Engel, H. 2009).*

Structural Systems and its members redistribute loads through different structural behaviors. Structural systems can be divided into 5 different families depending on their mechanics of redistributing forces. Those families are *Form-, Vector-, Section-, Surface-* and *Height Active Structures* (*Engel, H. 2009).*

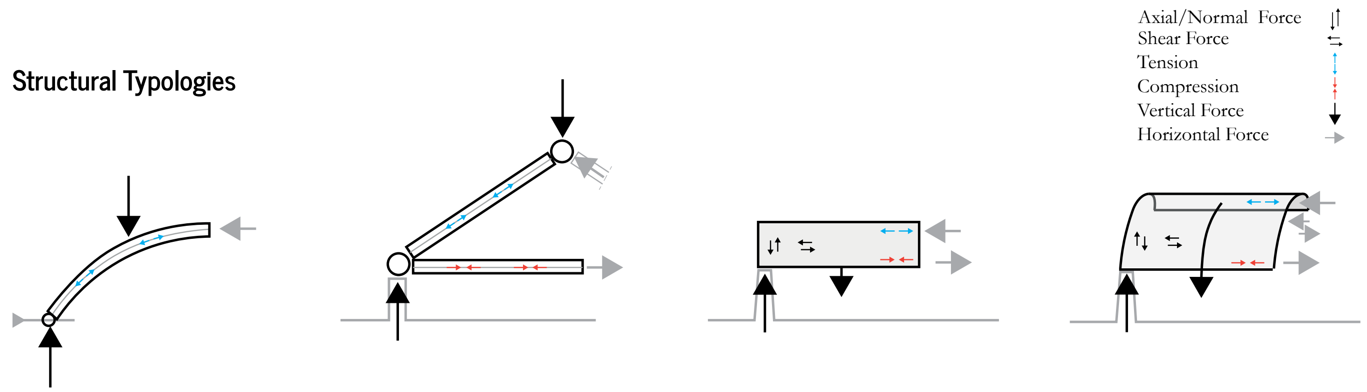
Form Active Structures adjust to forces and redirect them by its form, it carries loads mainly through normal forces in either tension or compression. Typically form active structures have an arching form, e.g. catenary/chain- and thrust line structures (*Engel, H. 2009).*

Vector Active Structures redirect forces through splitting the forces multi-directionally, this is achieved by a composition of many straight tensile and compression members. The members have a cross section so small compared to their length that they can carry loads only in the direction of their length (normal/axial forces). Forces are then redirected only in the strongest (axial) direction of the element bringing a more efficient load bearing, compared to structures carrying forces through bending or shear forces. Common examples of vector active structures are different forms of trusses (*Engel, H. 2009).*

Section Active Structures redirect forces through a system of rigid solid linear elements, who can (unlike vector elements) carry bending and shear (perpendicular to axis) forces. The archetype of a section element is the beam, which carry forces horizontally along its axis and dispatch them into a support. Beam, pillar, slab and frames are all examples of section active elements. Section elements are the most commonly used components in construction sector, this is based on their simple structural behaviour and its faculty to create versatile rectangular spaces (*Engel, H. 2009).*

Surface Active Structures redirect forces through surface resistance and surface design, the members are compression, tension and shear resistant. If the forces are working perpendicular to the surface the element is acting as a slab and if the forces are working parallel it is acting as a plate. The difference between them is that the capacity of the slab is decreasing with increasing surface and the capacity of the plate is growing with increasing surface. Because of this structural behaviour the form of the surface elements/systems can affect its structural capacity. If the members/system are designed to receive stresses parallel rather than perpendicular to the surface the structural capacity increases. *Plate, Folded Plate* and *Shell* systems are examples of Surface active structural systems (*Engel, H. 2009).*

Structural Typologies



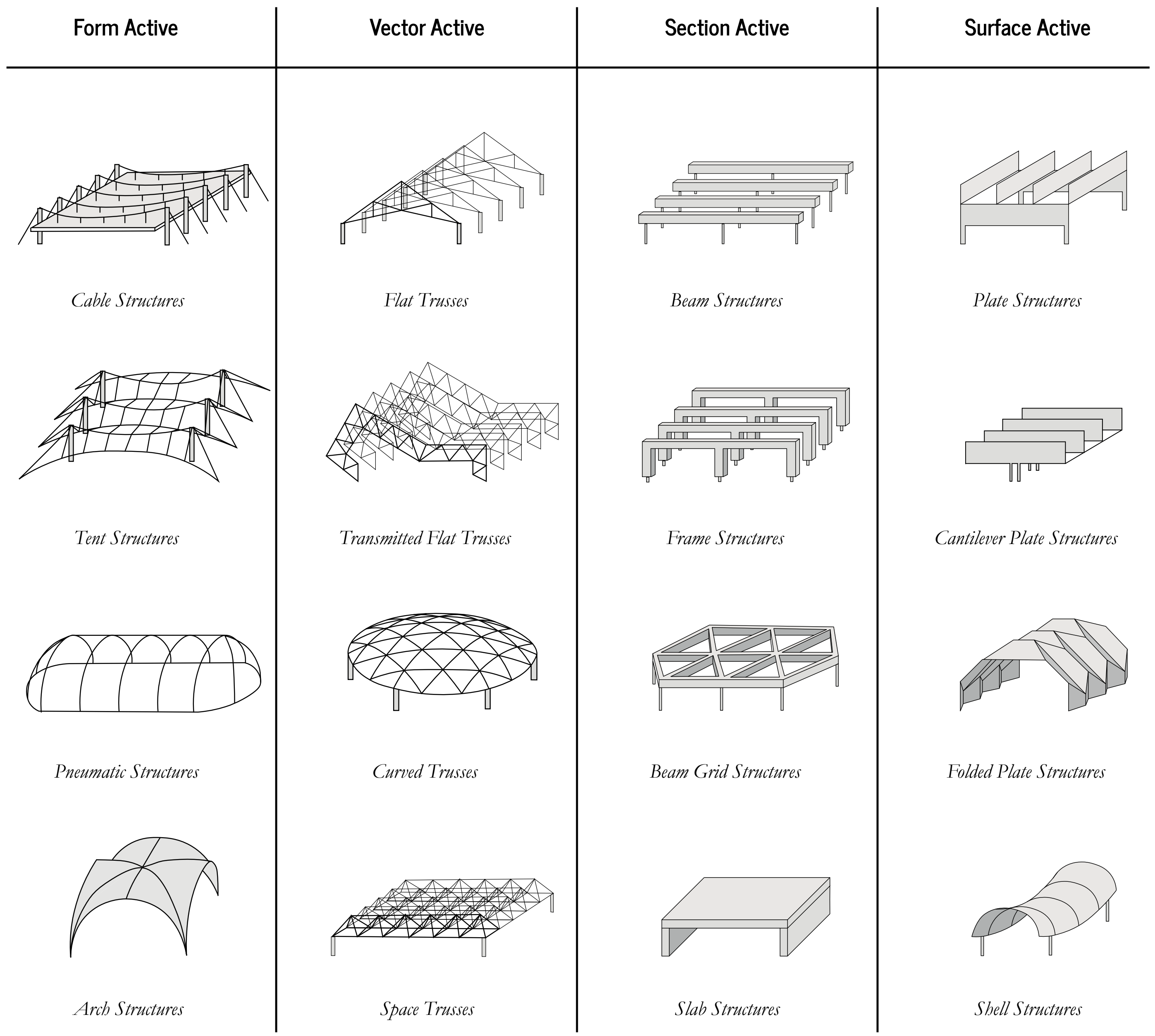


Illustration: The 4 Basic Structural Families divided by their mechanics of load transfer and their different typologies. The examples are collected from Heino Engels book Tragsysteme and redrawn.

Height Active Structures

The *Height Active Structures* differs from the other structural families in the aspect that the structures are not defined by their members mechanic of redirecting forces. Instead they are defined by their structural function which is reception, transfer and grounding of height loads. Height loads are vertical and horizontal loads occurring from added height/storeys, it affects all buildings but in the Height Active Structures they are so influential that the main focus for the structural system is handling these height loads (*Engel, H. 2009).*

Height Active Structures possess no unique structural mechanism for redistributing forces. Instead at element level the system make use of members with structural mechanisms from all the other families, but what defines them at a system level is that they work together as a Height Active Structure (*Engel, H. 2009).*

The horizontal forces from wind increases logarithmic by height and the bending force increases squarely making horizontal forces the structural constraint that usually is most demanding when adding floors on structures *(Johansson, M. 2020).* Lateral stabilization is a central part of all height active structures and at a certain height the stabilization becomes the form-determining factor (*Engel, H. 2009).*

Lateral stabilization can be achieved through bracing, usual forms of bracing are stiff core, shear walls, rigid frames and trussing. Peripheral bracing in the facade have a better effect than central bracing in the core. In cases a combination of different bracing are used. An example of a favourable combination of bracing is between rigid frame, who develop max deformations/stresses at the base and shear wall, who develop max values at the top. Continuous vertical bracing has a better effect than horizontal bracing (*Engel, H. 2009).*

Height Active Structures needs continuity within the load grounding elements, this implies a constraint for the load collection to correspond on each floor. This factor makes the structural system and floor plan interdependent and brings a necessity to develop them in consideration and harmony with one another. Due to the increase of forces when building vertically, the amount of load bearing elements compared to free space on each floor is increased considerably in higher structures (*Engel, H. 2009).*

Height Active Structures can be classified depending on where the load grounding elements are placed. In Bay-Type rises the grounding are placed evenly in a grid, in Casing rises peripherally in the facade and in Core rises centrally. Another type is the Bridge rises where two structures are superimposed, one structural system for load collection and another for load grounding. The indirect load grounding from the superimposed structure can reduce the bulk of load bearing elements and increase the usable floor area (*Engel, H. 2009).*

Because of the desire to decrease the ratio of load bearing elements on each floor all function holding elements like elevator shafts, stair wells, installation shafts, ducts and facade are favourably utilized as structural elements. A well thought out design proposal for a Height Active Structure require holistic knowledge and consideration of; the attributes of vertical structures, the mechanics of structural families, floor plan integration and technical equipment (*Engel, H. 2009).*

Typology of Height Active Structures

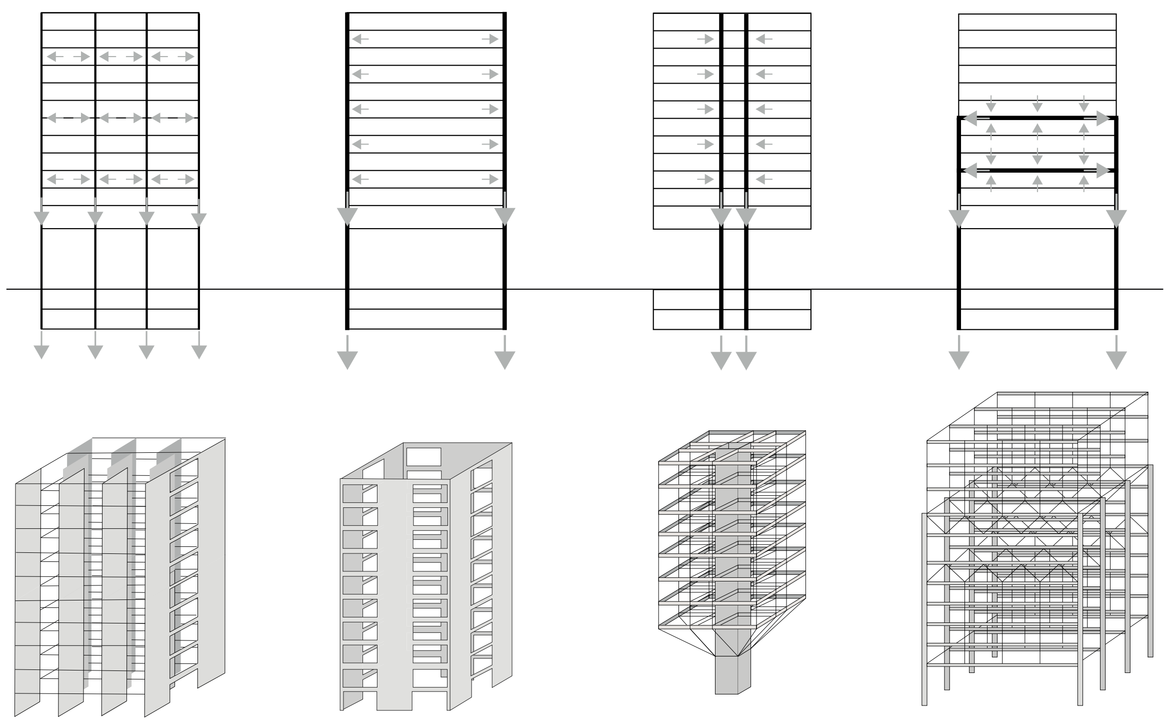


Illustration: The "special" structural family of Height Active Structures and its 4 typologies divided by of their fundamental load grounding. The examples are collected from Heino Engels book Tragsysteme and redrawn.

Wood at Height

As mentioned in the text on *Height Active Structures* when structures begin to add storeys, lateral stabilization becomes a central part of the structural challenge. When it comes to timber structure this is even more true, this is mainly because of the light weight of wood *(Tlustochowicz et al. 2010)*. In wooden structures the lateral stabilization becomes the decisive form-determining factor at lower heights, compared to structures in the heavier and stiffer materials steel and concrete *(Johansson, M. 2020).*

In *Height Active Structures* it was also mentioned that the problems with horizontal stability can be overcome with bracing. Because of the difficulties with wood and lateral stability a combination of these strategies are often necessary. To ensure a sufficient lateral stability, the following wood specific tactics can also come in handy *(Johansson, M. 2020).*

- *Use the facade for bracing/stiffness*, the further out the bracing is placed the more efficient because of the added distance/lever.
- Using facade for stiffness may result in a low degree of perforation, this makes it important to *take advantage of the best daylight and view possibilities*
- *Added weight* means added stability and if the weight is *placed higher up in the building* it has more effect. Examples of how to add weight could be adding concrete to floor slabs, using massive walls, adding a roof gardens etc.
- A *larger footprint* adds stability, a stepping structure or lower anchoring parts can help the lateral stability.
- In cases a *hybrid structure* can be a material saving and more sufficient option. To in places use stiffer materials like steel and concrete can be beneficial
- *Rounded corners* can help to reduce the lateral forces from wind
- Create *stiff joints between elements* to make them continuous over its connections for an efficient load transfer.

The relation between height and environmental impact of a timber building is quite complex. In a RISE report a Life Cycle Analysis comparing the carbon emissions per heated square meter between a 5 storey and two different 20 storey timber structures were made. It shows that the taller buildings have slightly more emissions per square meter than the lower one. The taller buildings have less emissions from foundation, roof and technical equipment like elevators. The taller buildings still had more material use and emissions, this comes from the increased need of structural bulk on each floor and coating of combustible materials. This is just simulations and real actual calculations may change the figures. Development in timber construction could change the current ratio between emissions and height *(Johansson, M. 2020).*

Design Considerations When Reaching For A Tall Timber Building

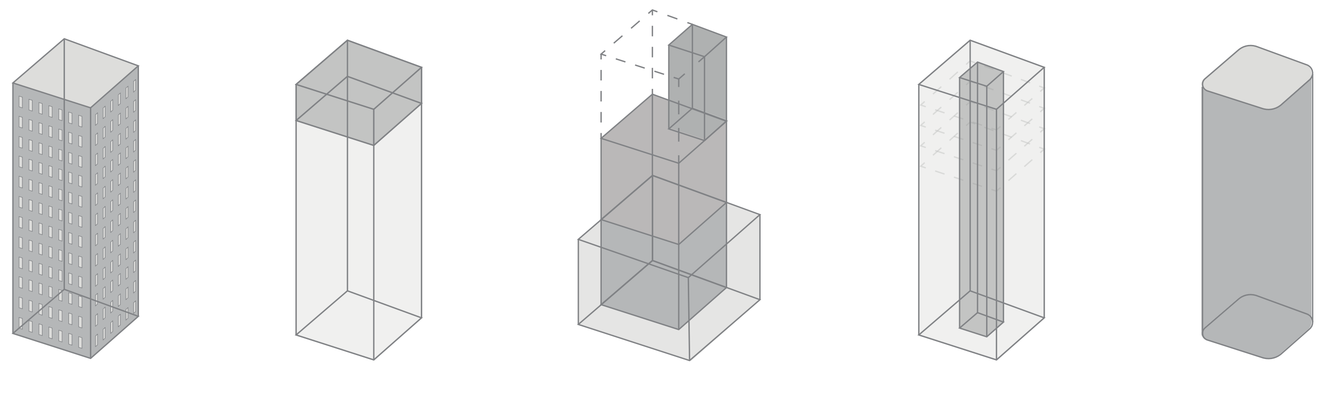


Illustration: Design considerations when designing a Tall Timber Structure. The examples are collected from the RISE report Tall Timber Buildings and

2. INVESTIGATION

INDUSTRIAL WOODEN CONSTRUCTION

Wooden Structural Systems

The definition of a wooden house, is that the main part of the structural system should be made out of wood. The facade can be of another material e.g. brick, plaster and it would still be considered as a wooden house *(Gustafsson et al. 2013).*

Evolution in wood construction the last decades have increased knowledge and brought high performance Engineered Wood Products (EWP:s) with better predictability. The development have made wooden structural systems a realistic challenger to concrete and steel systems in the extensive housing development. Benefits with prefabricated wooden systems is a lower climate impact, competitive price, short construction time, a dry construction and flexibility. The lightness of wood can be both a pro or a con, but in cases it open up possibilities for construction on places where other materials cant be used e.g. on roofs or delicate ground *(Gustafsson et al. 2013).*

Structural systems are principally the same in a wood, concrete or steel construction, but since the characteristics of the materials are different the geometry of the elements/members (thickness, cross section etc) needs to be designed different depending on the material *(Al-Emrani et al. 2011).*

The wooden structural systems most suitable for an extensive development of multi storey apartment houses are massive load bearing walls (in CLT), light frame (load bearing walls of studs and joists) and post-beam structures. These are the established structural systems in housing development regardless of material choice and wood are actually the only material that can be used in all of them. Because of the risk of shear buckling steel can't be used as massive load bearing walls and because of practical and structural reasons concrete can't be used in a light frame structure *(Gustafsson et al. 2013).*

As mentioned earlier structural members of a system redistribute loads through different structural behaviours and can be divided into different families depending on their mechanic of redistributing forces. In wooden light frame and post-beam systems the members are section active carrying axial, shear and bending forces through rigid solid linear elements, e.g. joists, studs , posts, beams and slabs (*Engel, H. 2009).*

In the massive load bearing wall system planar elements of cross laminated timber are used. The cross lamination of the elements makes them redistribute forces in a way that they can function as a surface active elements. CLT elements and structures are commonly used as a conventional section active elements but with its surface active characteristics there is a potential to use them in a more material efficient and ostentatious way (*Aldinger et al. 2019).*

Figure 24. Post-Beam - Housing Project (Moelven, 2012)

Figure 25. CLT - Housing Project (architecture.com, n.d.)

Figure 26. Light Frame - Housing Project. (Smartfönster n.d.)

Modularity & Prefabrication

Byggstandardiseringen, BST, started 1942 and was founded to rationalize construction and standardize building components. With the driving force of BST the Swedish construction sector increased rationalization and construction techniques during the 1940s and 1950s. This development lead to what can be called an industrialized production of dwellings in the 1960s (Nylander 2018). After the record years during the *million homes program* industrialized construction decreased in numbers, but it still has existed more or less frequently, in periods, after the 1960s. Since the beginning of the 2000s industrialized construction have gained importance in the housing sector and prefabrication has been mentioned as a key area for increased production and quality with reduced costs *(Byggnadsforum, Boverket 2008).*

In industrial wooden construction, to streamline and add cost-efficiency, the members of a structural system are often prefabricated and assembled as larger elements. Another advantage of prefabricating wood structures is that dry construction in indoor facilities and short construction time can limit the risk of construction moisture. The members of a structural system can be assembled as linear -, planar - or volume elements *(Gustafsson et al. 2013).*

In the light of an extensive housing development light frame- and CLT systems are produced and assembled as planar- or volume elements. From its composition post-beam systems needs to be assembled as linear elements. Comparing the prefabrication level of the structural systems CLT and light frame systems have the most prefabrication, with a possible completion of 80 percent using volume elements and 20 percent using planar elements. Post and beam with its usage of singular linear elements has the lowest level of prefabrication *(Gustafsson et al. 2013).*

Prefabricated elements are restricted in size, in order for them to be transported to the construction site. For volume elements the maximum size are restricted to an interior measure of 3.7 meters width, 9.6 meters length and an interior ceiling height of 2.5 meters. *(Lindbäcks 2020)* Planar elements in CLT have a restriction of 3 meters width and 16 meters length, but it can differ a bit from producer to producer *(Stenqvist 2019).*

Planar- and linear elements could be part of what is called an open system where components from different producers and systems can be combined, this gives greater possibilities for differentiation. They can be delivered both in an open system and in a closed standardized system depending on the producer and project. Volume elements on the other hand are generally speaking part of what is called a closed system were the producer and subcontractors delivers all components. A system of volume elements is generally more standardized and limited in terms of variation *(Gustafsson et al. 2013).*

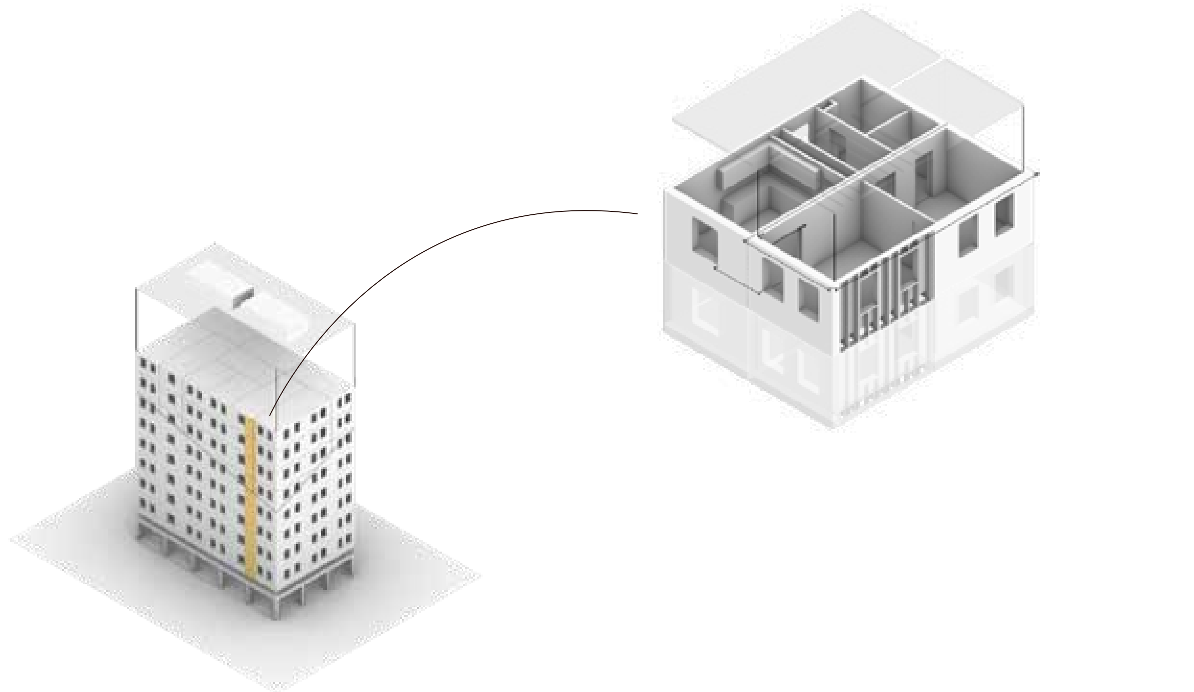


Illustration: Volume Elements have the highest degree of prefabrication with a possible completion of 80 %, it can be delivered with finished installations like electrical wiring, bathrooms, kitchen, plumbing etc. Transportation and production brings restrictions regarding variation, measures, window placement etc. In taller structures it is also necessary with vertical continuity in the facade to handle the lateral stability.

Post-Beam System

Post and beam is a traditional structural system, wooden post and lintel structures existed already in the older Ancient Greek Architecture. The wooden origin can be seen in the stone temples that stands today. An example of that origin is the fluting of the stone columns, which is a retention of the aesthetic of wooden columns. (*Azad et al 2015*).

In the post-war period with its increasing demands for development and industrialized construction, timber lost its position as a primary construction material in the housing industry. Timber was instead passed to more primitive systems like balloon- and platform framing. Even though wooden post-beam structures have been one of the most common construction methods throughout history, concrete and steel has in the last century been the most frequently used materials in post-beam structures. Current demand for flexible construction and environmentally friendly materials challenges the market dominance of steel and concrete and makes systems with Engineered Wood Products emerge as a viable option. *(Tlustochowicz et al. 2010).*

Residential houses around 10-14 floors can conventionally be constructed with glulam timber as pillars and beams (*Gustafsson et al 2012).* In Mjöstornet, an 18-storey and 81 meter tall timber building in Norway, the structural system consists primary of glulam column and beams braced by trusses *(Abrahamsen 2017).*

The components of post-beam structures are prefabricated as individual glulam elements and the structure can be mounted rather swiftly. In residential houses prefabricated floor slabs out of lvl- and glulam beams are usually mounted in-between the beams to save building height. There are both open systems were components are project specific and complete modular building systems on the market *(Gustafsson et al 2012).*
Having neither load bearing walls or facade the post and beam system, through its flexibility, provides a system with high potential for architectural freedom and quality. The system provides flexibility and possibilities in plan(e.g. open spaces), facade and degree of perforation (e.g. placement/size of windows) *(Tlustochowicz et al. 2010).*

As mentioned structures in timber have a tendency of being too light and needs to be stabilized against horizontal forces. Because of the extra lightness of post-beam structures this demand gets even more noticeable. Unlike CLT- and Light Frame constructions who have some built-in stabilization from their walls and just needs additional bracing at a certain height, post-beam structures needs horizontal stabilization regardless of the size or height. *(Tlustochowicz et al. 2010)*

Post-beam structures could be regarded as a less economically viable option for housing developers because of the less degree of prefabrication compared to volume or planar elements in CLT or light frame. Another economical disadvantage is that a post-beam structure can become rather over dimensioned in many cases since the forces that emerges in a residential house are small enough to be handled by bearing walls solely. Principal benefits of the system in housing project can be seen in projects with large windows/perforations, open plans or plans with special spatial configuration. Another benefit of the system is that the load bearing structure takes up a small space of the floor area. The acoustic performance can be another reason since the flank transmission is lower in a structure with pillars compared to one with load bearing walls. *(Gustafsson et al 2012)*

Figure 27. Since all loads are transfered in the Posts/Columns the spaces in between can be left open. (Baunetz, 2017)

Figure 28. A way to allow exposed wood is to make posts and beams overly dimensioned and install a sprinkler system. (Archtonic, n.d.)

Figure 29. The structural system of Mjöstornet, the tallest wood structure in the world, is composed of glulam Posts and Beams, with lateral stability from glulam trusses (ArchDaily, 2018)

CLT-Slab System

CLT or Cross Laminated Timber consists of wood boards glued together in layers perpendicular to each other. In Sweden the boards are in most cases made out of pine or fir *(Gustafsson et al. 2017).*

It is possible to construct houses around 10-14 floors tall with CLT walls as the load bearing structure. In housing projects CLT elements are usually prefabricated to a high degree, it can be prefabricated and assembled as both planar - and volume elements. Perforations and other processing can with advantage be milled on beforehand. The elements can also be completed with windows, insulation, installations etc *(Gustafsson et al 2012).*

The con-texture of wood, with its grain structure, makes it an orthotropic material. The meaning of orthotropic is that it has different characteristics (e.g. strength and expansion) in different directions. Timber is many times stronger in the direction of the grain than perpendicular to the grain, in tension for example it is approximately 30 times stronger in the fiber direction. Gluing every other layer perpendicular to each other evens out these orthotropic differences. It gives a slab that can carry shear and bending loads better in different directions compared to a wood slab where the fibre direction of the lamellas are all the same. Despite the cross lamination CLT slabs should still be considered as a orthotropic material having three main directions with different characteristics. *(Gustafsson et al. 2017)*

The amount of layers in the slab are uneven, usually the number of layers are 3,5 or 7. Depending of the desired characteristics of the end product, one can use different thickness and material in each individual layer. The wood material in the middle of the slab can be of less quality and are usually more of a filling material. The bending forces are most dominant in the outer edges of a cross section therefore it is desired to use a stronger wood quality in the outer layers of the slab. An analogy to this way of thinking can be seen the I-beam where the web is used to build height i.e. lever between the flanges, who carry the bending forces. The ability to use different quality of wood in different layers enables an effective utilization of material. *(Gustafsson et al. 2017)* Material can even be removed from the centre of the cross-section making place for service lines. A study from the MIT-University indicates that 18 percent of the material can be removed without losing any structural performance (*Mayencourt et al. 2018).*

Effective utilization of material, carbon storage in the material, energy effective production and lightweight transportations makes CLT a sustainable material choice. The construction of CLT and CLT structures makes it easy to re-use, recycle or combust to heat/energy. *(Gustafsson 2017)*

CLT is most frequently produced and used as rectilinear elements in plate or slab structures. Still because of its prefabricated production it can be a sustainable, effective and economic choice when designing specially shaped structures like curved ones. The elasticity and strength of wood makes it preserve its structural resistance while being curved, making it a perfect material for curved structures. CLT has a surface active behaviour that together with the possibility for curved shapes makes it possible to create slender and structurally efficient constructions. CLT can be used in Surface Active typologies (see *Structural Typologies chapter)* and in the recent years there are some constructed examples. The research project Urbach Tower from the Stuttgart University in Germany is an example of a surface active structure. *(Aldinger et al 2019)*

CLT components can because of their structural behaviour redistribute loads within the slab and handle concentrated forces in- and out of plane. This opens up possibilities to perforate, cantilever, stack and line/point support wood slabs in new quite ostentatious ways. It gives possibilities for the engineer and architect to think structure in planes and volumes rather than lines *(Brandner et al 2019).*

Figure 30. The chapel from Nicolas Pople Architects is a great example of how CLT-slabs can form a folded plate structure with a large span without beams or pillars. (Dezeen, 2020)

Figure 31. The research project Urbach Tower is an example of how the Surface Active behavior of CLT opens up a range of new structural possibilities with wood. (ICD/ITKE, 2019)

Figure 32. Because of the ability to redistribute forces a CLT-slab can be single supported on top of a pillar without a supporting beam. (Apawood, n.d.)

Light Frame System

Dwellings up to 8 stories can be constructed with a timber light frame construction *(Gustafsson et al. 2012)*. The construction is made out of a frame of studs and joists of constructive timber or glulam in places it is strengthened by trusses, I-beams and LvL-beams. The frame is isolated between the studs and joists and covered. On the inside by a plastic film, a installation layer and a facing material usually a plaster board and on the outside by a membrane against wind and a facade material e.g. bricks, wood, plaster vinyl etc *(Svenskt Trä 2015)*.

The light frame construction is the most frequently used construction in smaller private houses, 90 percent of the detached houses in Sweden are constructed out of wood and a majority of them with a light frame construction *(Gustafsson et al. 2012)*.

In the end of the 19th century, due to fire hazard, a law prohibiting wood constructions taller than 2 floors was constituted. This law was kept until 1994, when it was replaced by the European performance based rules that allows taller timber structures. This prohibiting law made the timber industry focus on small houses. During the 20th century the small house producers evolved their efficiency and developed industrialized construction methods. To shorten time on project site, prolong building season, have better control of moisture levels and to be price competitive many small house constructors started to prefabricate light frame walls-, floor-, roof elements and even volume modules *(Landel 2018)*.

This prefabrication technique developed by the small house builders have been adapted and are now used for constructing larger multi-storey housing buildings. Prefabricated light frame elements for larger housing constructions are produced both as volume- and planar-elements*(Svenskt Trä 2015)*. The elements can come both with or without installations and facade mounted, depending on the project *(Lindbäcks 2020)*.

One of the first developers of multi-story apartment buildings with wood structure in Sweden, was Lindbäcks Bygg. They have used and developed volume models with light frame lumber construction for larger housing developments since the mid 90s *(Boverket 2006)*. Today there are several producers that make multi-storey light frame houses, other large producers are Moelven and Derome. Producers like Eksjöhus who are more directed toward small house development are starting to lean towards producing multi family dwellings.

Limiting the amount of moisture that enter the construction is crucial in all wood construction. One of the benefits with light frame construction is that the elements can be produced in a controlled dry environment. Despite the controlled production to achieve a healthy and durable end result it is important to ensure a assembly process that keep the construction as moisture free as possible. It can be achieved by a quick assembly in right weather conditions or by having a temporary roof to cover sensitive components *(Svenskt Trä 2018)*.

The lightness and prefabrication possibilities of the light frame construction makes it an ideal choice for densification projects. Arguments for this is the quick assembly of the prefabricated elements which makes the construction time and its following obstructions in dense areas as short as possible. The lightness can be a key aspect for possibilities to construct on top of buildings or on delicate ground *(Gustafsson et al. 2012)*.

Compared to a massive slab e.g. a CLT-slab, a wall of studs and joist have less possibilities to redistribute forces and handle concentrated forces. This limits the boundary conditions of the load bearing walls and slabs. The elements need to attach and land on top of each other in a rather conservative way. Possibilities to cantilever walls and slabs are restricted to almost non. *(Lindbäcks 2020)*. .

Figure 33. Light Frame structures are usually prefabricated as Volume Elements and swiftly assembled at site. (Affärer i Norr, 2017)

Photo: Plejadgatan is a good example of how Light Frame Volumes can be completed with a site built facade to fit into the cityscape

Figure 34. Technical Section of a Light Frame structure. (Derome, n.d.)

Processing Opportunities

Supporting wall

The light frame construction is the most frequently used construction in smaller private houses. With CLT construction can be made up to around 10-14 floors. In housing projects CLT elements are usually prefabricated to a high degree, it can be prefabricated and assembled as both planar - and volume elements.

Apertures

When making room for an aperture in a light frame wall the form which follows tend to be of a rectilinear shape due to its structural members. However when replacing the load bearing wall with a CLT element the shape of the apertures are not limited to orthogonal shapes. The CNC-cutter, which is controlled by a CAD software can just as easy make any arbitrary shape or form.

Surface

The light frame is isolated between the studs and joists and covered. On the inside by a plastic film, a installation layer and a facing material usually a plaster board. The CLT element can be left as it is. There is also a possibility to alter the surface appearance in the manufacturing process.

Light frame

A light frame structure is made out of a frame of studs and joists of constructive timber or glulam.

CLT (Substitute)

CLT or Cross Laminated Timber consists of wood boards glued together in layers perpendicular to each other. In Sweden the boards are in most cases made out of pine or fir. It can easily replace the light frame structure and also prefabricated planar concrete elements.

CLT (Milled)

Perforations and other processing can with advantage be milled on beforehand. The elements can also be completed with windows, insulation, installations etc

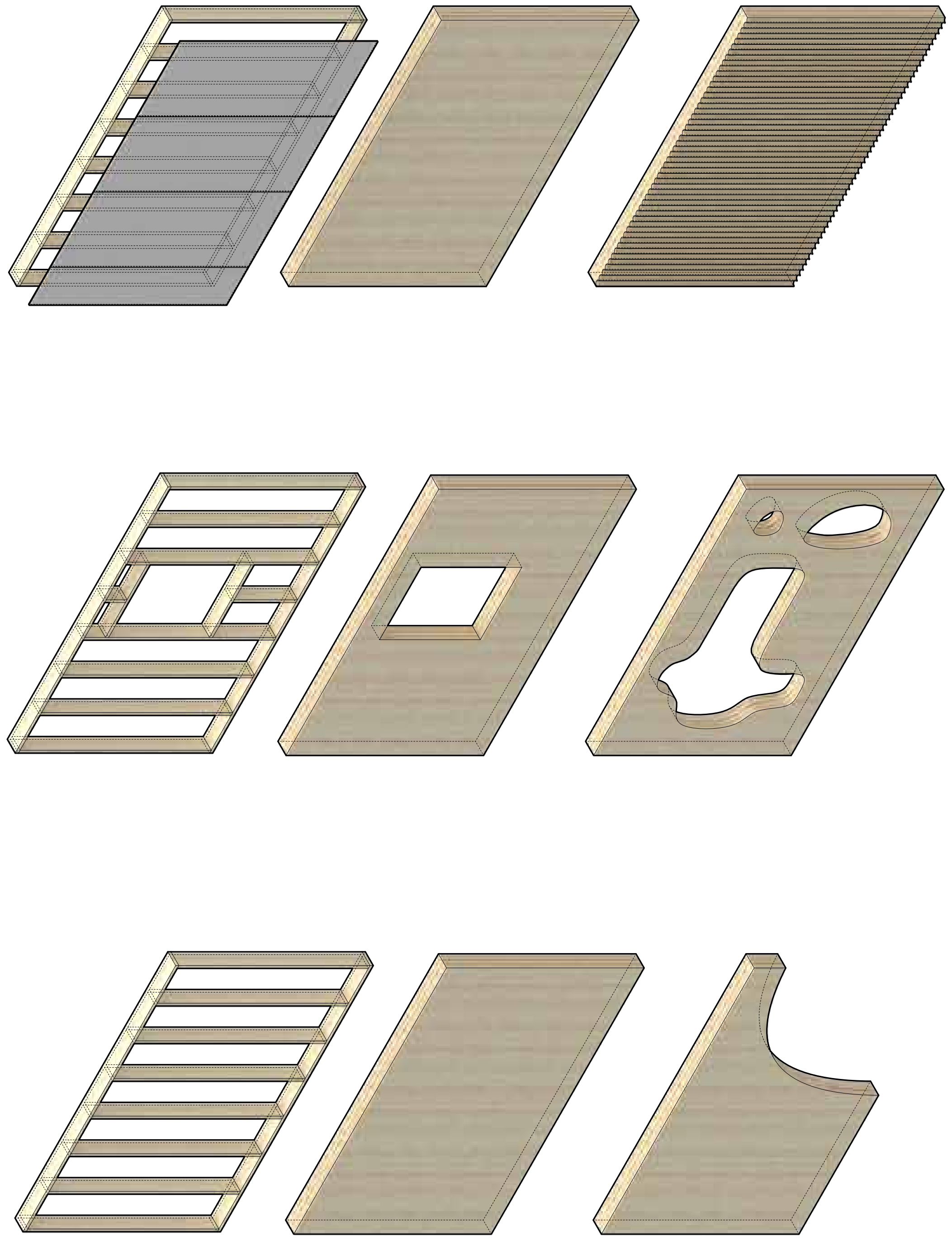


Table Processing opportunities differ between a massive CLT slab and a Light Frame slab of studs and joists.

Comparison of Structural Systems

Number of Floors

Post-beam and CLT systems can reach 10-14 floors and light frame 5-8 floors with their conventional construction systems. There are studies that show possibilities to reach 25-30 floors, but for that further development of lateral stabilization and connections is necessary *(Gustafsson et al 2013)*. The report Tall Timber Building showed a concept design of two CLT houses that were 20-22 floors tall. Calculations showed that the towers managed the restricted oscillations with the help of some additional concrete *(Johansson 2020)*. The tallest timber house today is Mjöstornet and it is built with a post-beam structure and reaches 18 floors.

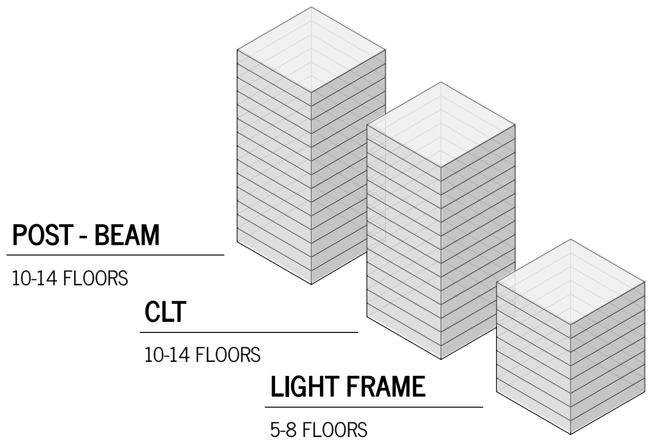


Illustration Comparison number of floors enabled through building systems

Structural Constraints and Possibilities

With a post-beam system the structure is limited to a rather orthogonal grid of load bearing elements. The system offers possibilities for open plans free from structure and long spans with the prerequisite of increased beam heights for longer spans. Something that in the end, if the building height is limited, can infringe on ceiling height and number of floors. For dwellings the structure is often over dimensioned and loads can usually be carried solely by the walls, but if large open spaces or perforations is desired it can be a viable option. *(Gustafsson et al 2013)*.

CLT components can because of their surface active behaviour redistribute loads within the slab, this opens up possibilities to perforate, cantilever, stack and line/point support CLT slabs in a, compared to other wood products, more efficient and ostentatious way. Because of its production methods it can also be used in curved shapes *(Aldinger et al 2019)*.

Since the wall- and floor slabs in light frame structures consists of many linear elements its abilities to redistribute loads are less. This brings less structural freedom as the slabs with its linear elements (studs and joists) needs to attach to each other in order to transmit the loads. Planar or volume elements in light frame can not (like CLT) be curved, cantilevered, single supported or perforated in a challenging way. They need to be stacked in a rather conservative way with vertical continuity*(Lindbäcks Bygg 2020)*.

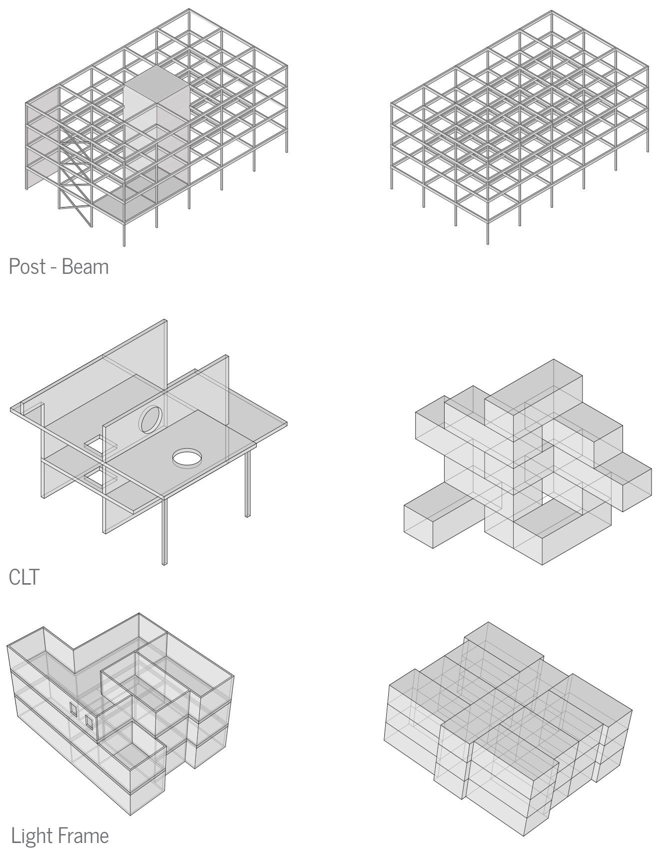


Illustration Structural Constraints and Possibilities

Modularity/Prefabrication

Comparing the prefabrication level of the structural systems CLT or light frame systems have the most level of prefabrication with a possible completion of 80 percent using volume elements and 20 percent using planar elements. Post-beam with its usage of singular linear elements has the least level of prefabrication *(Gustafsson et al. 2013)*.

Planar- and linear elements could be part of what is called an open system where components from different producers and systems can be combined. This gives greater possibilities for differentiation. A system of volume elements is generally more standardized and limited in terms of variation *(Gustafsson et al. 2013)*.

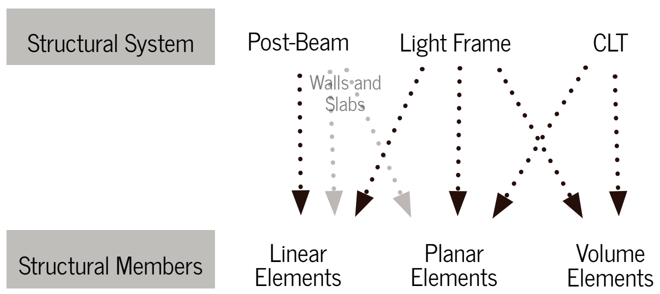


Diagram Connection between Structural system and structural members

Wall Build-Up

Post-beam structures have the most flexibility when it comes to wall build-up, any type of wall can be placed outside the structure . The space between the structural elements can also be left open or glazed *(Gustafsson et al. 2013)*

CLT walls are usually covered by a moisture membrane, insulation and an organic or inorganic facade solution on the outside. On the inside, due to the combustibility of wood, the walls are often clad with a plaster board. With other measures for fire protection, like a sprinkler system, the plaster board can be neglected and the CLT material left visible. Because of the ability to redistribute forces the wall can be perforated quite extensively and freely regarding both shape and position of the perforation. *(Gustafsson et al. 2017)*. The massive CLT walls brings extra airtightness and storage capacity for humidity and thermal energy which makes the indoor climate better and heating need less *(Brandner et al 2016)*.

Light frame structures are insulated and covered by a facade solution on the outside and on the inside by a plastic moisture membrane, a installation layer and a facing board material. The structure can not be visible and a facing material is always necessary on the inside, it can for example be a plaster - or plywood board *(Svenskt Trä 2015)*. The structure does not allow extensive or non-orthogonal perforations and the perforations must always be done with stiffeners over and under the perforation. The position of the perforation can be restricted since the walls often need vertical continuity.

Illustration Wall-build up

Life Cycle Analysis

A consequential-based life cycle analysis comparing the different wooden multi-storey structural systems was made at the Linné University 2014. From the study it emerged that the CLT system have the least and post-beam the most life cycle emissions. The production emissions from the CLT system is 8-14 % lower than a light frame system and 19-25 % lower than a post-beam system. The main reason for the high production emissions from the post-beam system is not because of the wood structure itself, it is from the more extensive use of concrete and steel. For all systems the greatest emissions came from plasterboards and insulation, they consists of 41-59% of the production emissions for the conventional houses, and of 53-64% of the emissions for the low-energy houses. The study also found out that the heating demand for CLT houses is 17-20 % lower compared to the other systems. This is because of the improved airtightness *(Dodoo et al. 2014)*.

Another Life Cycle Analysis from the KTH University was made on three houses with a concrete structure and two with a wooden structure. In that calculation the CLT house also had the least production and Life Cycle emissions, the other wood structure in light frame had the second least emissions *(Erlandsson et al. 2018)*.

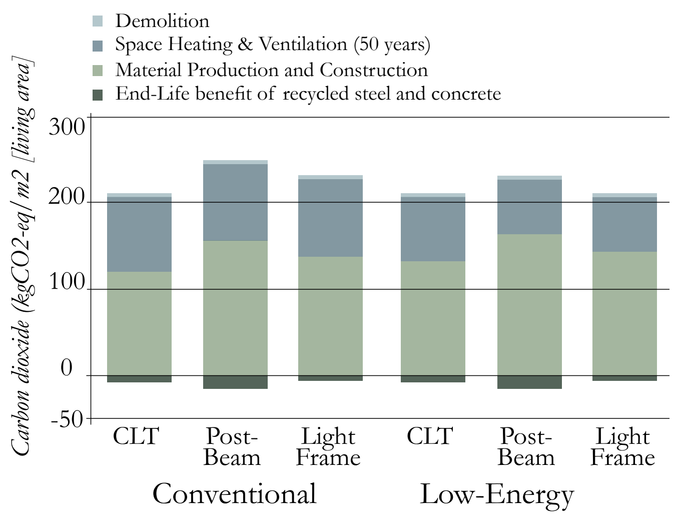


Figure 35. Dodoo (2014). Lifecycle carbon implications of conventional and low-energy multi-storey timber building systems.

PRECEDENTS

Analysis

Evaluation Criteria

Six precedent projects *Plejadgatan, Gibraltargatan, Frostaliden, Kv Fallskärmen, Kajstaden and Nodi-house* where investigated and chosen because of the following main criteria:

- Load bearing wood
- Housing typology (5-15 floors)
- Structural concept
- Swedish context
- Recently built

The reason for this precedent study was to gain insight of the build works of contemporary standards, in a Swedish context. Good examples were sought after and areas of complex situation were pin pointed. This was done so that a comparison between the different projects could be made. This was an attempt to compare the different load bearing structures and how well they tackle different challenges. These areas of interest are:

- Structural System
- Lateral Stabilization
- Apertures
- Details
- Facade
- Exposed wood (Structural honesty)
- Foundation
- Roof structure
- Lobby (Shared space)

Structural system

The three structural systems researched in the study are:

- Post-beam
- CLT (Planar Elements)
- Light frame (Volume Elements)

Post-beam systems have the advantage of allowing a flexible floor plan. A good example this is office space where floor plans must be able to adapt to new tenants needs and desires. *Nodi Office Building* is an example of this. *CLT* systems are better suited if there is certainty that the floor plans will not undergo large changes. Residential buildings like *Frostaliden* and *Kajstaden* are a good example of this.

Volume modules are restricted to a maximum size to fit a truckload and this gives it relatively small dimensions. A module is never slitted between apartments since the distance between the module walls makes it acoustically insulated(Lindbäcks 2020). This is congenial with the idea of *a module* which praises repetition in order to mass produce it. One apartment if larger can be constructed out of more than one module, in general a one room apartment is made of one module, a two room from two etc. In the case of a one room apartment the measure restrictions can be felt a bit. In the visited 21 square meter apartment where kitchen, toilet and hall also needs to be fitted some more square meters would be beneficial for the living standard.

Both of the modular precedent studies are student housing where small apartment and fast construction could be argued for. In *Plejadgatan* and *Gibraltargatan* the stacking of volume elements create an well composed facade with a structured rhythm. Because of the possibility to site-build different forms of façades and roof shapes volume models can be nicely fit into culturally sensible areas like *Plejadgatan*. Interiorly the modules can limit the spatial experience. The monotone repetitive nature of the module with repetition and long corridors can be hard to overcome. An example of this is *Gibraltargatan* who has a dark corridor and stairwell without daylight that gives a rather unpleasant journey from and to the apartments. These spaces are dealt with in a more pleasant way at *Plejadgatan* with a naturally lighted stairwell and large windows letting in light at the ends of the corridor. The many entrances compared to *Gibraltargatans* one entrance with a one way corridor also helps to create a less monotone environment.

A fairly undiscovered area is the possibility of constructing volume elements out of *CLT-Plates*. Such a volume element could draw the advantages of being a *"rigid box"* which potentially could enable cantilevering the modules and more innovative ways of stacking them. Light frame construction only works if the modules are stepped right on top of each other *(Lindbäcks 2020)*.

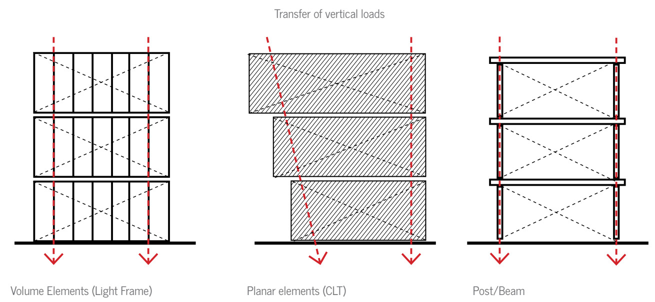


Diagram showing the transfer of vertical loads of the different structures

Lateral Stabilisation

As mentioned before, the lateral stabilization is of extra importance when building with wood because of its lightness *(Johansson, M. 2020)*. These projects deals with that issue in a couple of different ways. The projects that are made from *volume elements* doesn't have a dominant core like the other projects. This is because of the nature of stacking. The relatively low height of *Plejadgatan* makes it likely that the stability is solved with the use of elevator shaft and walls as shear walls. *Gibraltargatan* is a bit higher and the stability is probably solved in the same way but with an additional truss-work that can be seen through a glass facade. The remaining projects have a predominant core with secondary lateral stabilization in the facade. The cores are made out of either concrete or *CLT* elements. One thing to consider when using a stabilizing core of concrete and the remaining structure is in wood is that the materials have different tendencies to expand and shrink (Gustafsson et al. 2013).

Apertures

Volume elements doesn't leave much room for innovative apertures. This is because of how the openings affects the structural properties of the remaining module. The CLT Planar elements has the potential of leaving whole portions out of the wall or even corners as seen in *Frostaliden.* The Post/Beam system has the biggest potential of large apertures as seen in *Nodi.* This has either been neglected or actively discarded in *Kv Fallskärmen.*

POST/BEAM (NODI)	CLT (FROSTALIDEN)	VOL. ELEM. (PLEJADEN)	VOL. ELEM. (GIBRALTAR)

APERTURES

Dissolved facade enabled by a post-beam system.

Windows over corners enabled by CLT construction.

Repetitive features as a consequence of mass produced volume elements.

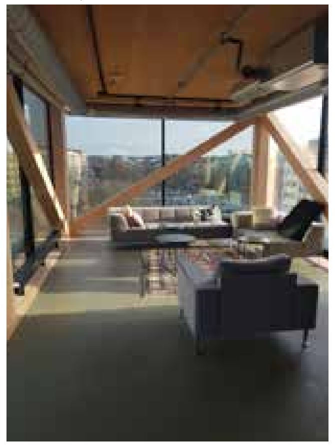
Repetitive windows as a consequence of mass produced volume elements.

EXPOSED WOOD

Detailed photos of exposed Load bearing, Nodi Office building

Detailed photos of exposed Load bearing in CLT.

Figure 36. The modules does not enable any exposed wood (SGS n.a.)



Shared space enabled by post-beam

FACADE

Glazed facade which showcases the wooden structure behind.

Material change at ground level, ceder to corteen.

Material change at ground level, painted wood to rendered screed.

Glazed facade which showcases the wooden lateral stabilization behind.

CORE

Concrete core covered in Wooden panels

Concrete core left raw

Corridors as a result of modules

Stairwell and shared space in CLT and post-beam construction

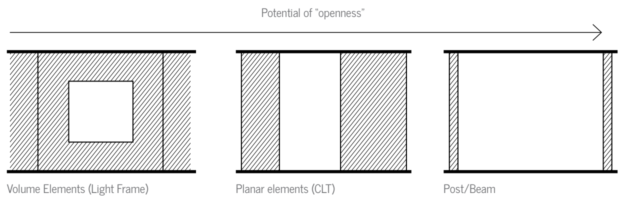


Diagram showing possibilities of apertures within the different building systems

Details

The aim is to better understand the project and how well the wooden construction is handled and showcased in the best way. There is an opportunity to showcase the quality of wooden construction through detailing. Key details has been researched and compared. Details constructed with *CLT* and *Glulam* has the potential of being developed and processed to a high degree. A wood structure needs to be crafted with immaculate precision especially if it is to be displayed, tolerances in wooden construction are *mm* rather than *cm* (which is the case in concrete construction). There are both challenges and opportunities with having such low tolerances when developing details.

Good examples of displayed wood structure is interior load bearing walls in *Frostaliden* and Glulam trusses at *Nodi* and *Gibraltargatan,*

Facade

A sprinkler system is the prerequisite for having combustible materials in the facade in more than two storeys*(Gustafsson et al. 2013)*. This can be seen in *Frostaliden* where Cedar wood is used as cladding material. Cedar wood is a good example of a wood cladding material with great longevity (approx 50 years) and little maintenance. It can be used as facade material in taller buildings where facade renovation is cumbersome (Moelven 2021). At *Nodi, Kajstaden, Gibraltargatan* and *Plejadgatan* the cladding material is a wood board facade, *Kv Fallskärmen* has a plaster facade which shows possibilities of non-organic façades as well.

Exposed wood

There are ongoing studies where it is argued that exposed wood is good to our physical and mental health *(Verma 2016)* The different prerequisites of the systems makes their possibilities for exposing wood uneven. In a Light Frame construction the wooden members need to be hidden behind a protective board, it can be a wooden board but usually of fire reasons a plaster board is used. This can be seen at both *Plejadgatan* and *Gibraltargatan*. Post-beam and CLT constructions have better prospects of exposing wood. *Frostaliden* is a good example where sprinkles as fire protection opens up the possibility to exposing the structural wooden walls.

The load bearing structure has to be protected. Therefore it is not suitable to expose (exterior) the load bearing structure in the facade unless it is thoughtfully and rigorously protected. The core has a potential of being exposed (interior) as well as common spaces where larger spans are required. In apartment buildings this could be implemented in shared facilities.

Foundation

Wooden construction can never be in direct contact with the ground. There is always an inorganic layer separating the wooden structure and the ground it stands on. This is solved with either a slab or plinth in concrete and separating connection material usually in steel. The plinth often have the opportunity to give a distinct architectural articulation. In some of the precedent projects the choice has been to exaggerate this change in structure and letting the facade reflect this, as seen in Frostaliden. Depending on the ground condition of the project different measures have to be taken. Wooden construction is light compared to concrete structures and there are different challenges when making sure the building sits firmly on the ground.

Roof structure

Flat roofs, gabled roofs or other more free-formed structures are all possible when constructing roofs out of wooden construction. A good example of an articulated roof is at *Plejadgatan*.

Lobby (shared space)

Considering the entrance floor and lobby of the projects there is a possibility of showcasing tectonics. The Lobby can be seen as the public space of a building and is an area everybody in the building share. One could therefore argue that this should be an area that is thoughtfully taking care of. It also has the potential of showcasing interesting wooden structure where longer spans might be needed or exposed walls could be left uncovered. Even though not being wood, the common concrete spaces of *Frostaliden* delicately articulates its materiality with its monolithic concrete atmosphere. To create a wooden version of this with the warm sense and tactility of wood is a tempting thought. Wood slabs would also bring a possibility to make a CNC-pattern.

Study Visits

Contemporary

Study visits was carried out to some of the precedent projects during the semester. A focus was put on newly build projects which had one of the three main structural wooden concepts.

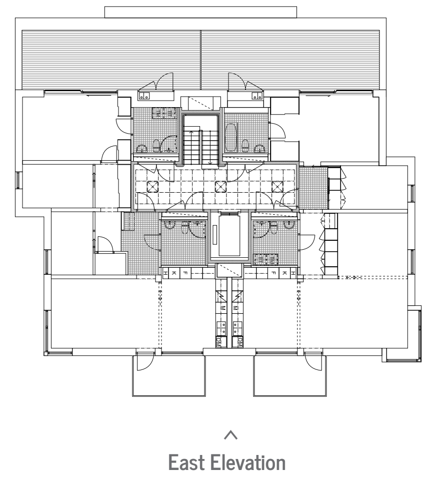
Historical

A study trip was conducted to visit some historical wooden buildings in Sweden. Pelarne Church in Småland is believed to have been built in the midst of the 13th century. At the time iron was a really expensive commodity which led to elaborate wooden constructions which required no nails or screws. The fact that the church still stands today shows both the durability of the carpentry joints as well as the Swedish tradition of constructing in timber. The church's construction consist of a combination of tenon and mortise, notched and peg joints.

COVID-19

During the semester there has been constraints due to the pandemic. Visits to sawing mills, precedent projects and companies have been postponed or hard to plan at all. Perhaps some of the visits can be carried out in the near future.

East Elevation 1:400 Frostaliden Skövde



Plan 1:400 Level 7

Left: Accentuated plinth and soffit.
Right: Patina of facade depending on how exposed the surface is.

Left: Playful ornate facade showing the year of a large renovation
Right: Wooden shingles around window of the church facade.

Left: Original window from the mid 13th century from a time when glass was a rare commodity. Therefore small openings with filleted edges were made to let more natural light in. **Right** Marks from the crafts-persons tool.

Joints and interior apertures in the solid wood made entirely without screws and / or nails.

3. EXPLORATION

MODERN CRAFT

Milled Wood and Glulam

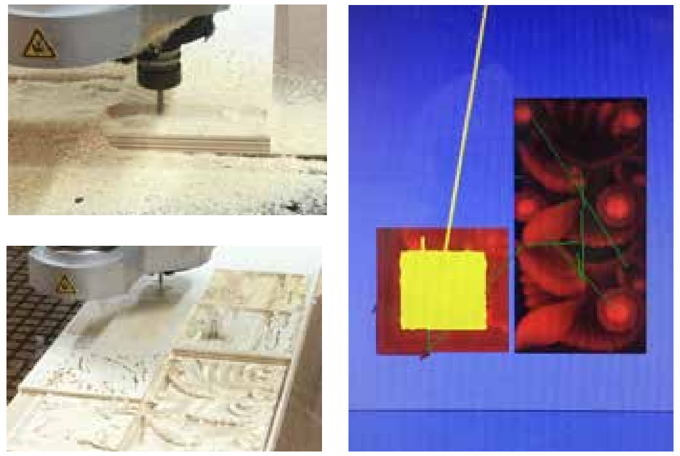
What is Modern Craft?

What is craft? What is handmade? These are questions that occurs when dealing with the phenomenon and affordances of milled wooden products. Humans have been using tools for a long time and it is one of the key aspects that distinguish them from fellow species that roam the earth. Where does crafts stop and where does digital fabrication begin? Is 3D-Modeling a craft? What is the definition of Craft and what does it mean for an object to be hand made? There is a common misconception where it is believed that craft doesn't involve any machines and where digital fabrication doesn't involve any "hands on trade". In both cases the person operating the machine(s) has to have a great deal of knowledge, experience and intuition for how the way the machine works, the given characteristics of the material(s) and in which order things are carried out (process). Could modern tools be used and applied to values of the past? Today high quality products is wanted with the reduction of errors and speed that technology offers, still there also seems to be a demand for handmade objects with the uniqueness which handmade goods come laced with. The mass production which followed the industrial revolution is a capitalist idea, but it is also a socialist idea of providing the essential for all. With the challenges in the 21st century, could the art and craft movement re-enter and merge with the modern production chain?

A definition of what is craft and what is not is hard to make. The tests in this part of the thesis are made with the purpose of examining this matter.

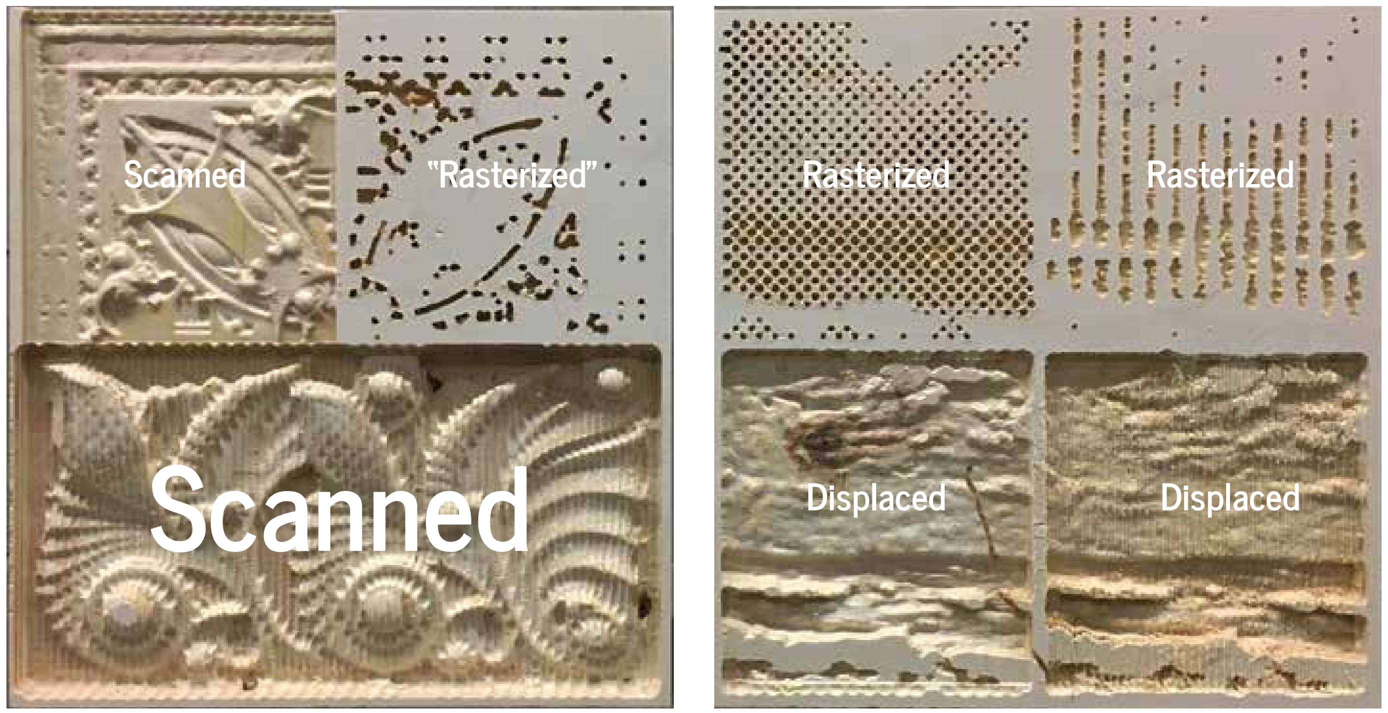
Model study in 1:20 scale, testing how to mill round corners with a striped pattern on a CLT-core

CLT 1:2



Left: 3-Axis milling machine Chalmers Workshop.
Right: Visualisation of toolpath travel

Geometry: Displaced, "Rasterized" & Scanned



Milled 22mm 7 Layered Birch Plywood - 2 pieces - 350x300x22 [mm]

Model Photos: Reused material such as used up skateboards could be reused in a wooden gluing and milling process.


The used skateboards are glued together with a 1-component polyure-thane-glue. The adhesive has a high solidity.


One skateboard is made out of 7-layers of 1 mm veneer (usually birch or maple). Here the ideas of displaying these layers was taken to an extreme.

A 3 axis mill together with computing software was used to re-create a scanned geometry of an already existing ornament.

A Louis Sullivan ornament was used as an example for its rich geometry and evocative nature inspired design.

Close-up of the rich colours of the glued and milled veneers.

A 8 mm drill bit was used in this test. The surface was left fairly rough for its ornamental purposes.

The combination of a undulating geometry, coloured material and the trace of the tool makes up for a rich expression.

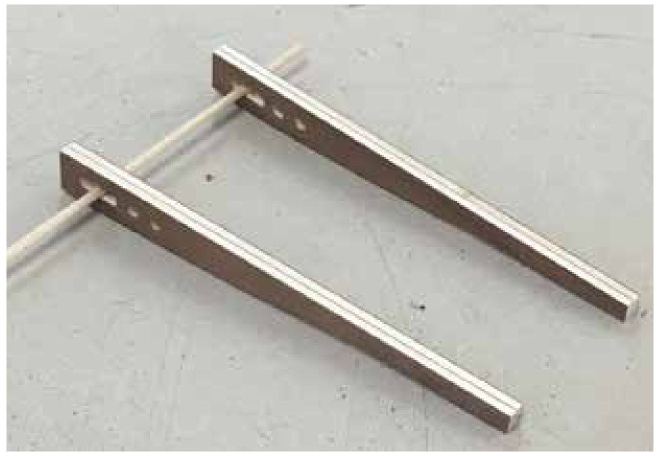
Glulam beam in form press.

Glulam arch

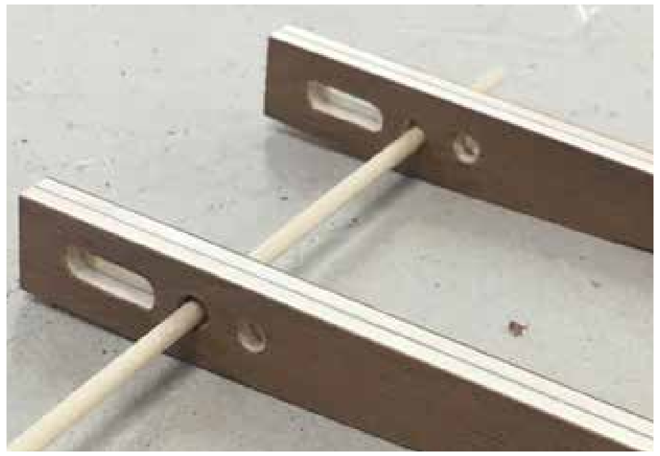
Glulam arch

Glulam arch with shingle panel


Combination of wooden materials to cater technical specifications in Glulam models. Different kinds of wood are usually combined in furniture making.



1:50 models of glulam beams with drilled holes for services

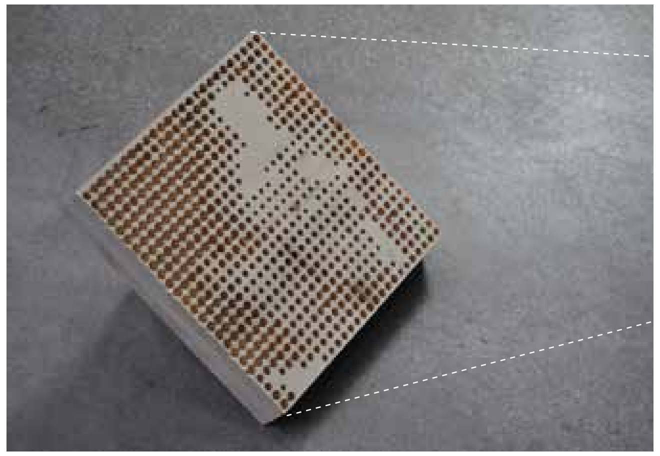


Composite material like glulam beams can utilize less valuable wood in the central parts and use finer materials furthest out, here a walnut veneer.

A collection of different glulam beams

Milled piece CLT 1:2 350x350x65
Milling time: 5 min

Milled piece CLT 1:2 350x350x65
Milling time: 10 min

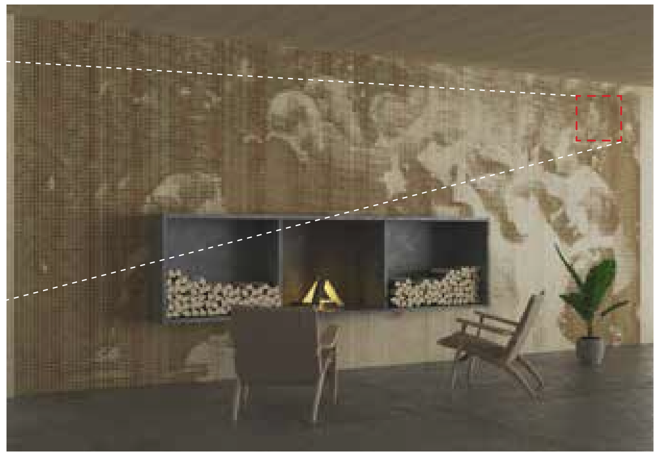


Milled piece CLT 1:2 350x350x65
Milling time: 45 min

Figure 37. Hipp, hipp, hurra! Konstnärsfest på Skagen by Peder Severin Krøyer - 1888 Göteborgs konstmuseum

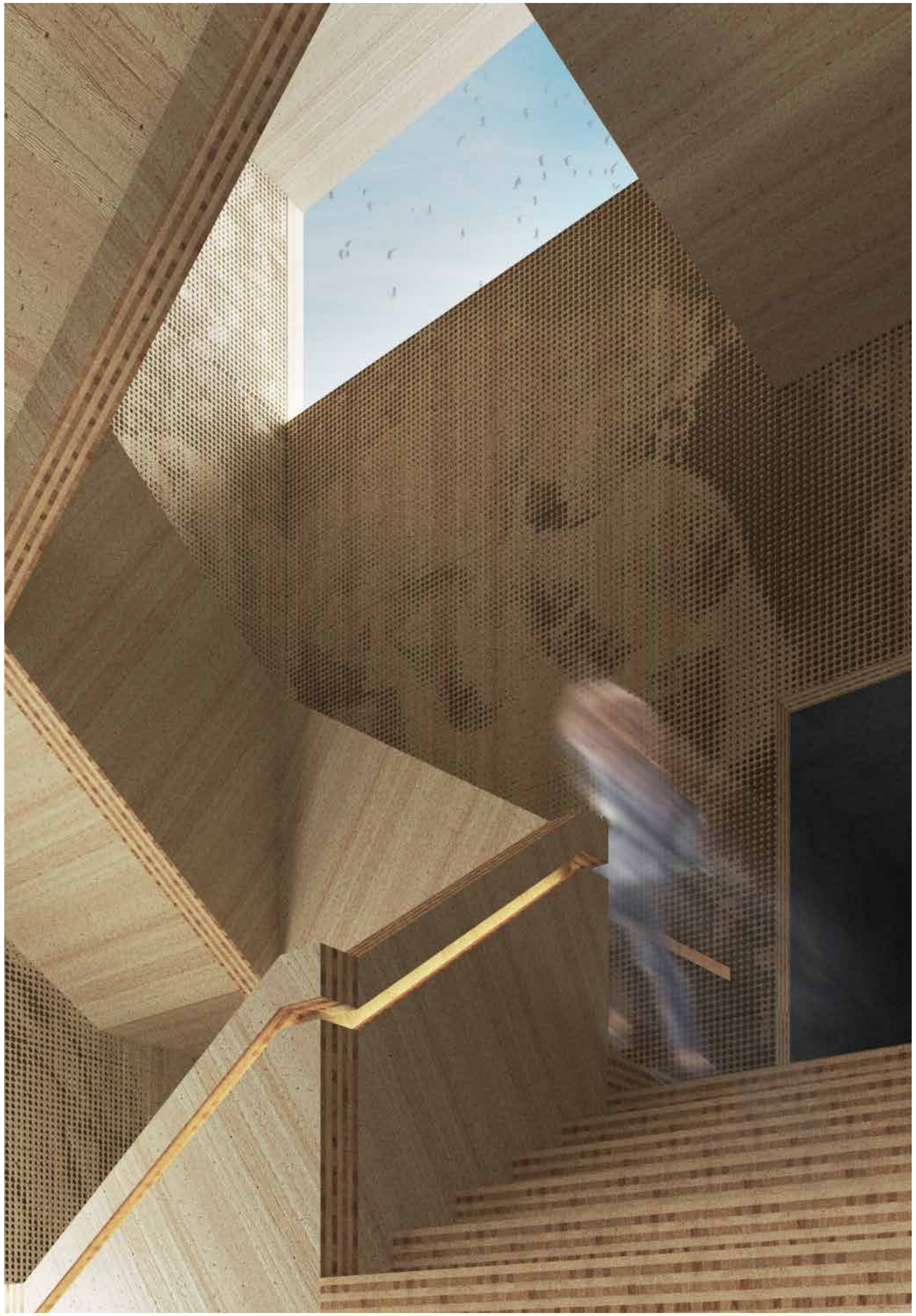
Conceptual visualization: Hotel Lobby
Straight milling pattern

Conceptual visualization: Hotel Lobby
Undulating milling pattern



Conceptual visualization: Hotel Lobby
"Rasterized" Milling Pattern

Rasterized image of painting.



Conceptual visualization: Wooden Staricase
"Rasterized" milling pattern

Architectural Consequences

Model Photos Row 1: Perforations can without any major added costs be ornamented with the help of a CNC-mill.

Model Photos Row 2: Test of using CNC-milled perforations from floor to ceiling or as doors

Model Photos Row 3: Perforations are not restricted to be shaped in an orthogonal way when made with a CNC-mill. The round shape of the milling steel on the CNC-machine actually leaves rounded corners that need to be sawn out for a perpendicular corner.

Model Photos Row 4: Study in how the lighting condition from the same sized aperture changes when bevelled to different extents with a CNC-mill.

CONCEPT STUDIES

Wooden structural concept

Overview

To develop a better understanding of structural composition and aesthetic qualities in the structural systems they were examined in a 1:400 model. The structure models were made to display the essence of the structural systems. The study was made with the purpose of searching for the appearance of the systems when they were condensed to become solely an assembly of its structural elements composed from their structural behaviour.

The models were placed in a landscape model of the chosen site at Wendelstrand.

Volume Elements Light Frame & CLT

Systems with volume modules in both light frame and CLT were reinterpreted. Volume modules placed more conservatively on top of each other could be in either CLT or light frame. The structure with overlapping volume elements are reinterpreted as of a CLT structure and could not be made with light frame since they, as mentioned in *Investigation,* need to "land" on top of each other. The crevasse between elements could probably cause some problems with lateral stability and a system of CLT modules could exaggerate the crevasse more than one from light frame modules.

Post-Beam

Aesthetically the post-beam structures are rather unilateral since they are made from a grid of linear elements. In the models it is distinguishable that the system provide possibilities for a very open and perforated structure. With the prerequisite that horizontal stability is solved, both slabs and walls can be "removed" and spaces in between pillars and beams can be open both horizontally and vertically.

The models could also be interpret as a combination of glulam pillars and CLT-slabs. In such a system beams could be removed and CLT-slabs single supported by the posts.

Planar Elements (CLT)

Since planar light frame elements would need to attach in such a way that the structure wouldn't differ much from one made of volume elements, models were only reinterpret as CLT-slabs.

The models explore structures composed of continuous vertical and horizontal CLT-slabs, structure could be expressed as dissolved in-between the slabs. Perforations would rather originate from the space in-between the slabs than from perforations in the slab itself. Also structural possibilities of cantilever the slabs were explored in places.

Model photo Volume Elements reinterpret in light frame and CLT. The structures with overlapping volume elements are reinterpret as they were made of a CLT structure and could not be made with Light Frame because of its structural behaviour.

Model photo Aesthetically the post-beam structures are rather unilateral since they are made from a grid of linear elements, the system provide possibilities for a very open and perforated structure. Models could also be interpret as a combination system of CLT-slabs single supported on glulam pillars.

Model photo The models explore structures composed of continuous vertical and horizontal CLT-slabs, structure could be expressed as dissolved in-between the slabs. Perforations would rather originate from the space in-between the slabs than from perforations in the slab itself

Plan Consequences
of Structural Systems & Core Placement

Central Core
Conceptual plan tests with the structural systems situated around one central core where staircase, elevator and wet surfaces are gathered. A central core that household these facilities in the darker core can use the light parts as qualitative rooms.

Split Cores/ Dual Cores
Conceptual plan tests with the structural systems situated around one central core with staircase and elevator and two more separated cores. The separated cores household wet facilities for two apartments. Around the core a semi-open space is created.

4 Cores (Exposed Cores)
Conceptual plan tests with the structural systems situated around one central core and four separated cores. Each apartment has a separate core that household wet facilities for the apartment. An open plan is situated around the exposed core which can be circulated.

Post/ Beam
Post-neam systems are easily adapted and can be fit into the structure with different numbers of cores. If the core is placed to create a certain quality e.g open spaces, it can also preserve these benefits because of its flexibility. Issues with creating nicely spaced rooms can arise if the core and the grid of the system isn't synchronizing well.

CLT (Planar Elements)
CLT-systems are easily adapted and can be fit into the structure with different numbers of cores. If the core is placed to create a certain quality e.g open spaces, it can preserve these benefits by using a load bearing facade. Issues could be that the facade can become quite monolithic and if a more perforated facade is wanted it can be hard to keep the open spaces around the cores.

Light Frame (Volume Elements)
It can be difficult to fit Volume Elements around the cores and more cores makes it even harder. If the core is placed to create a certain quality e.g open spaces, it can not preserve these benefits. This because it needs to surround the cores with rectangular elements having all load bearing walls. When the cores are increased in number, the number of Volume Elements increase meaning it can be hard to shape qualitative rooms.

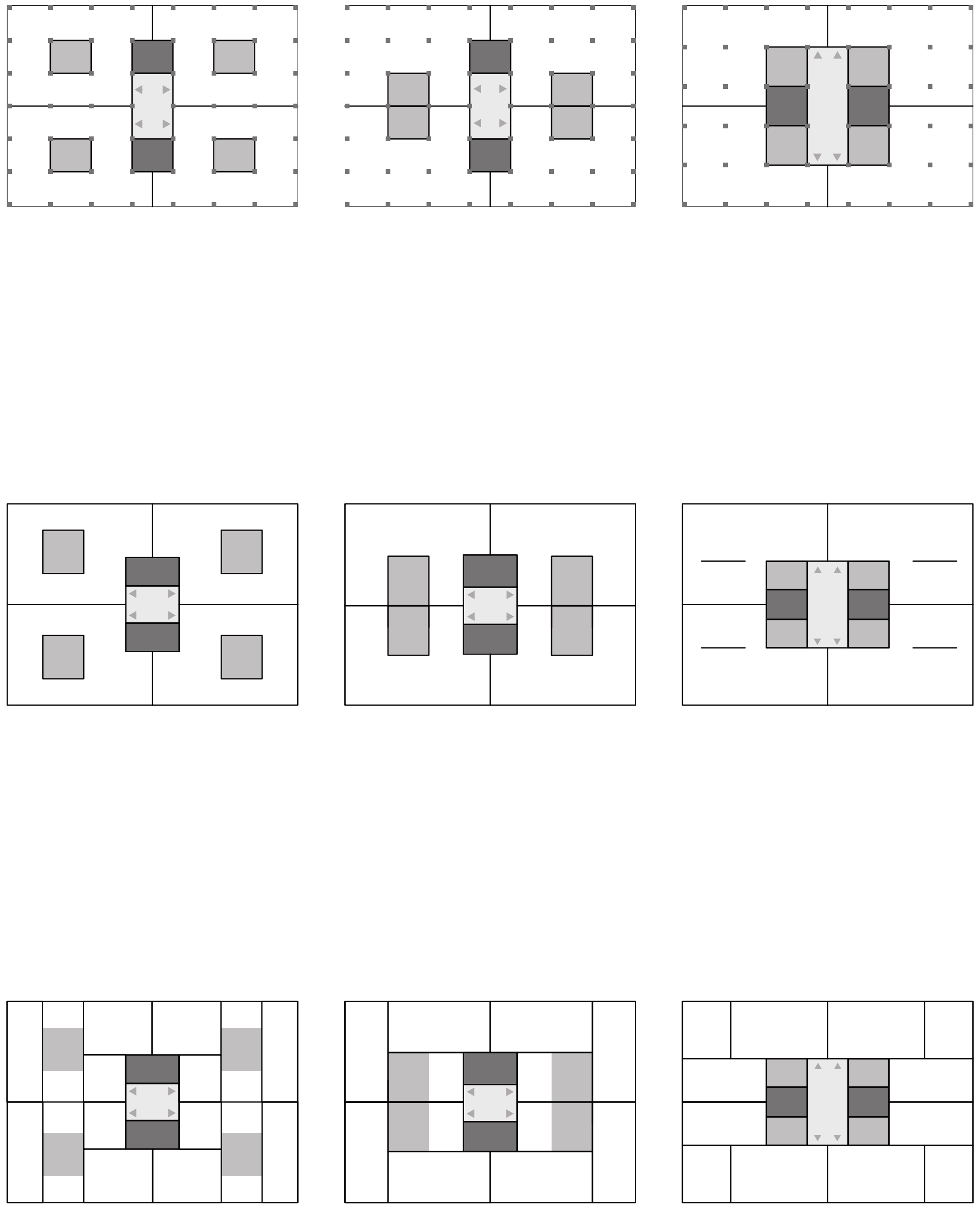


Table Plans showing the implications of structural systems versus placements of structural cores

Key Moves

Structural Concept

From the former studies in structure models and plan a structural concept was formed around a combination the findings. The structure became a superimposed version of load bearing walls/cores in CLT and a Post-Beam system.

The center of the building is composed by a more closed structure of CLT walls. Outside the closed entance and bedroom area all apartments have an individual core with wet surfaces included. Around the core an open plan with apertures from floor to ceiling is possible through pillars. Sliding walls between the core and posts/CLT-wall makes it possible to have a flexible plan with changing rooms. The sliding walls can be hidden inside the core and the CLT-wall between the apartments.

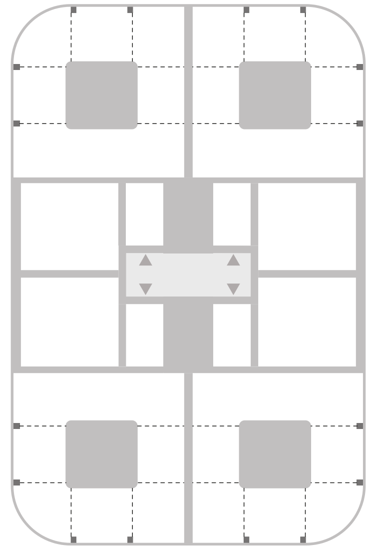


Illustration Plan of superimposed structure of CLT walls/cores and Post-Beam. Light living spaces are created around a separate core with the help of pillars. Sliding walls between Posts/CLT-wall and core creates possibilities for a

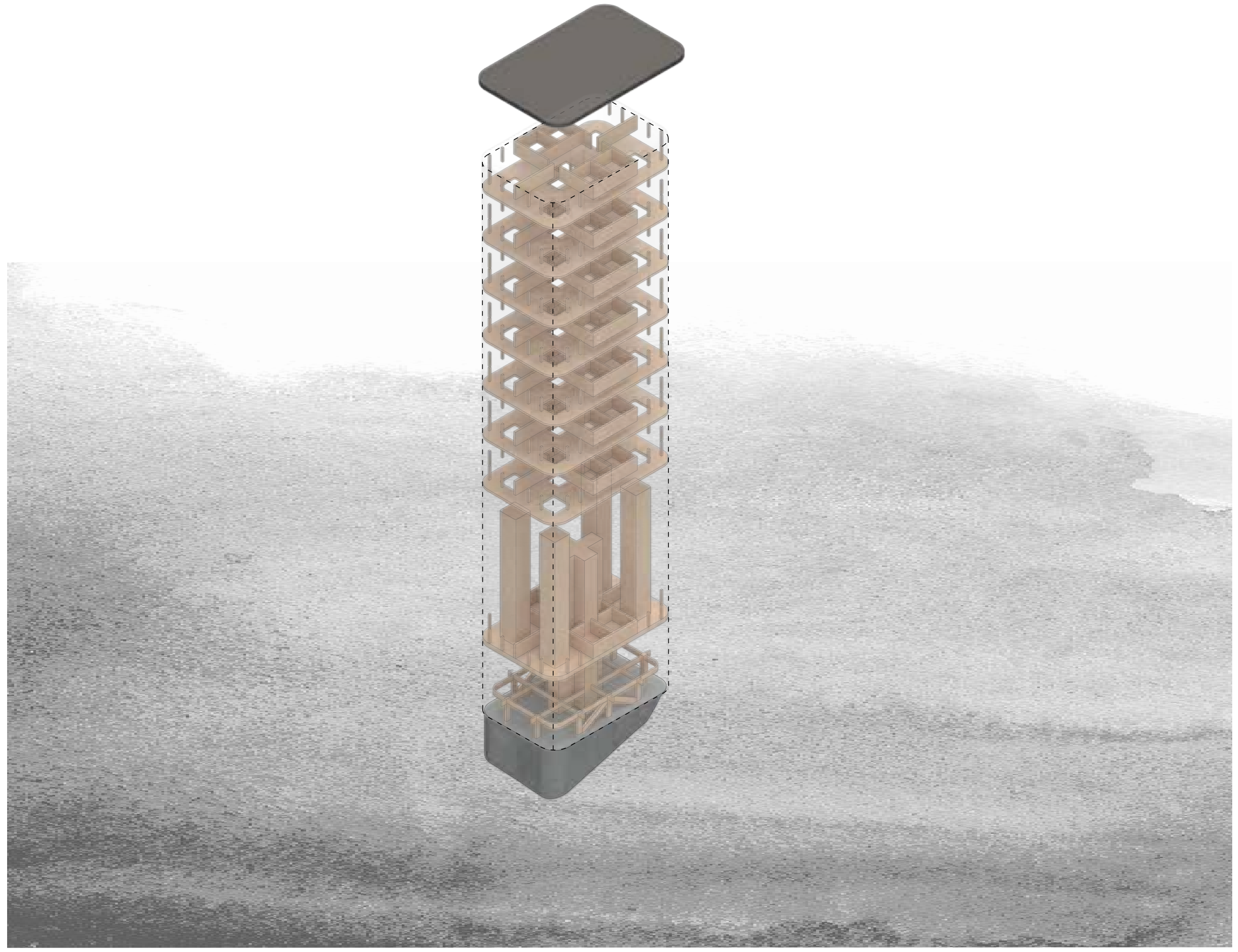


Illustration The wooden structure is placed on a concrete plinth to level the slope of the site, the central core runs through the whole structure to create a stable structure. On top of the concrete plinth a truss-work and the core keeps the entrance floor open and creates a public space. Each floor slab is upheld by the four separate cores. CLT-walls and Posts. The cores (inluding CLT-walls) together with the floor slabs makes the structure rigid against lateral forces.

Structural Concept Development

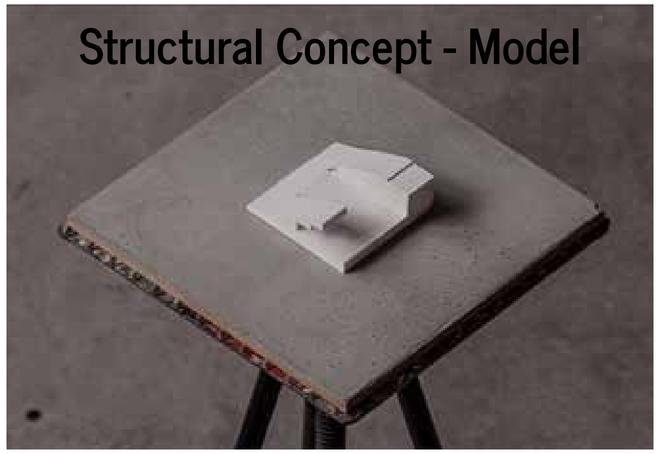
Post-Beam

Planar Elements CLT

Volume Elements Light Frame/CLT

Superimposed Structure

Structural Concept - Model

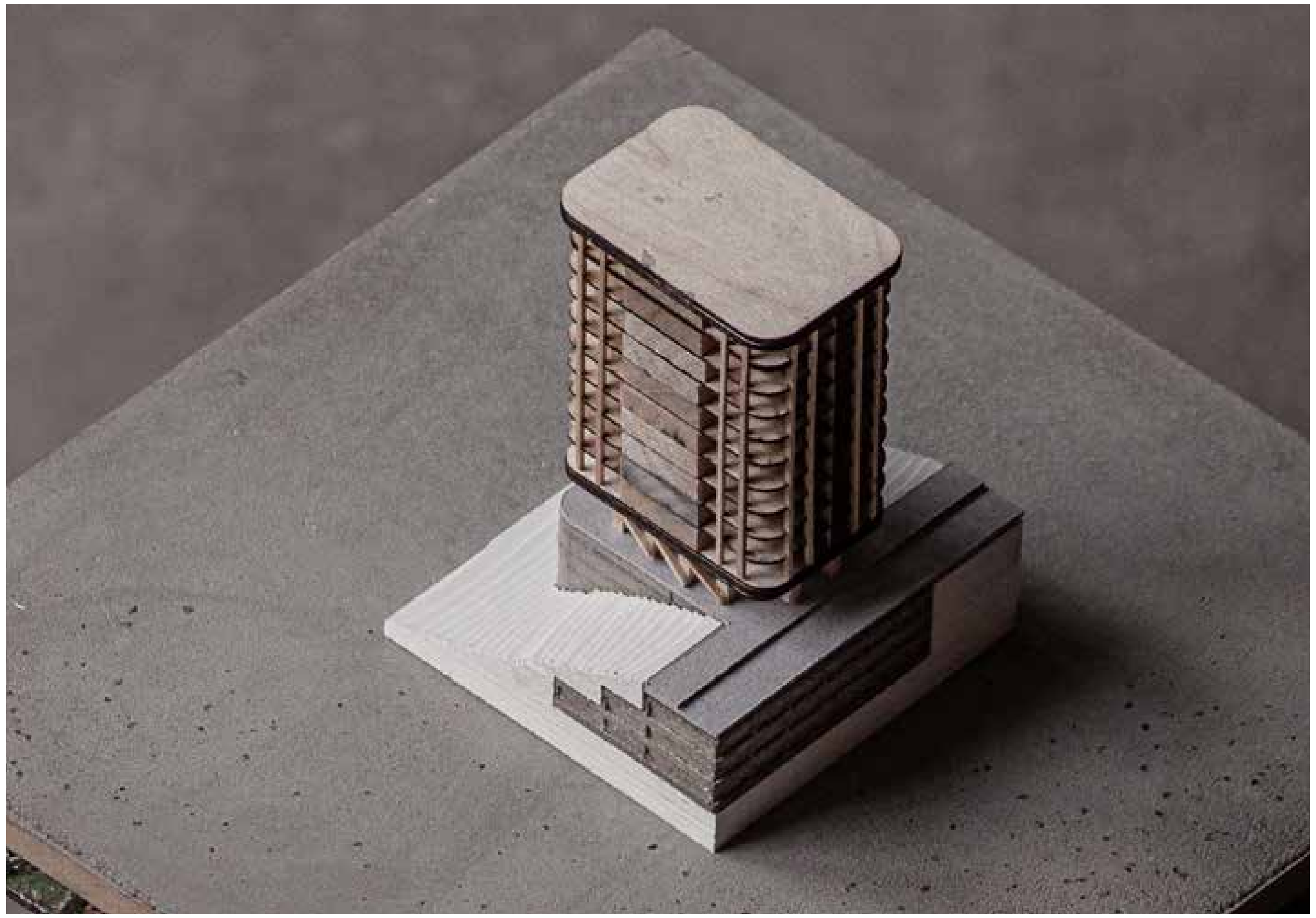


Model photos The building is situated in a slope on the ground of an old quarry.

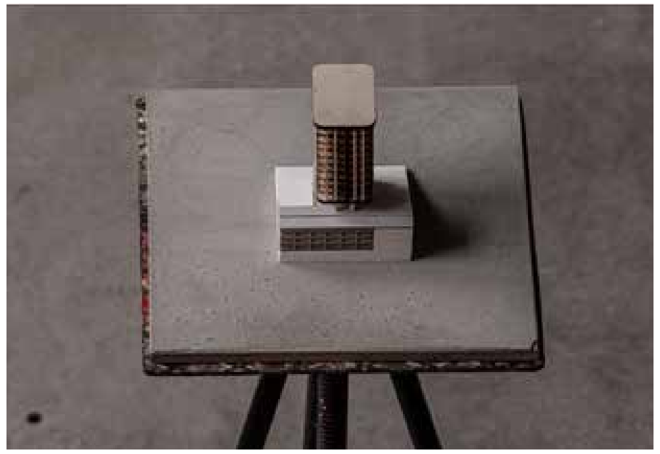
A parking garage is planned in immediate contact with the building. The garage will also cater the parking needs of the surrounding dwellings.

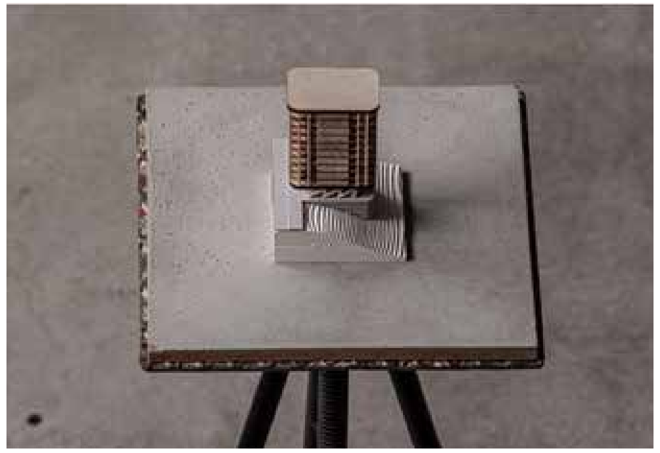
An accentuated plinth in direct contact with the garage is created to level the height difference and solving the connection to the ground.

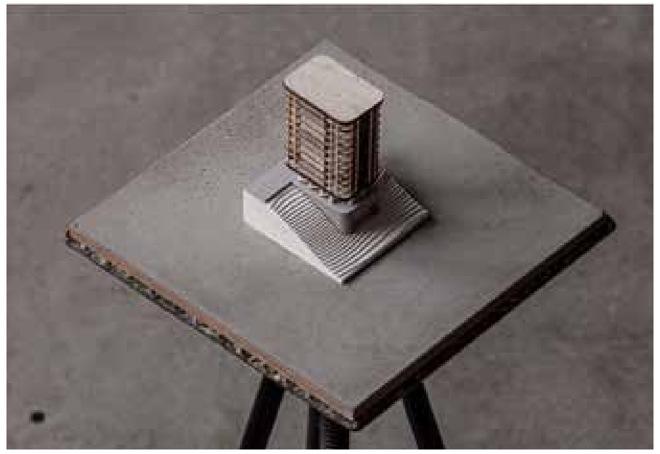
A walking platform is created which is reached from the street level.

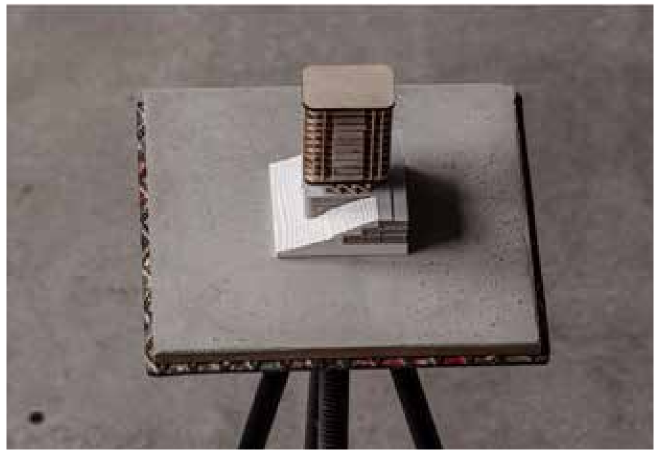


Immediate Situation Model 1:400 The wooden volume is lifted above ground. Massive Glue-laminated beams and columns lifts the structure and creates a public viewing platform overlooking lake Landvetter.









Model photos above: Structural Concept model Isometric views.

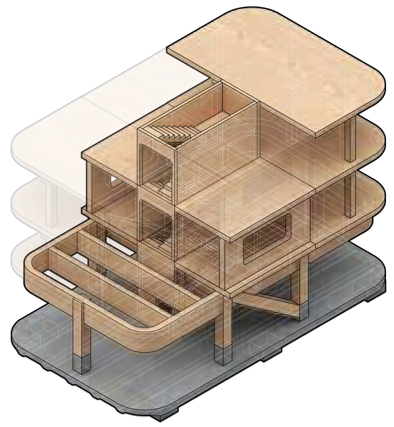
4. APPLICATION

DESIGN PROPOSAL

Design Guidelines

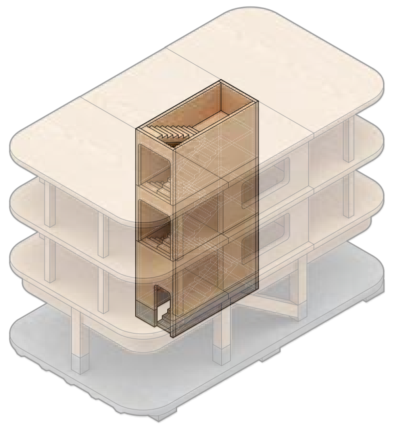
Modern Wood

01. Load Bearing Wood



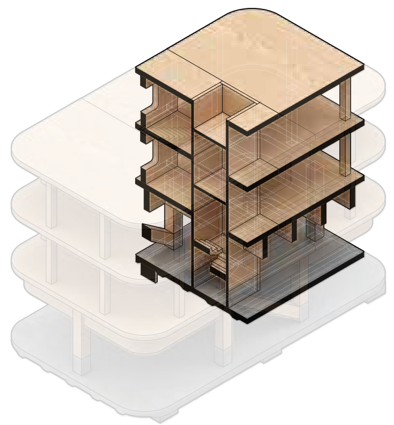
When possible Engineered Wooden Products should be the load bearing material.

02. Continuous Cores and Risers



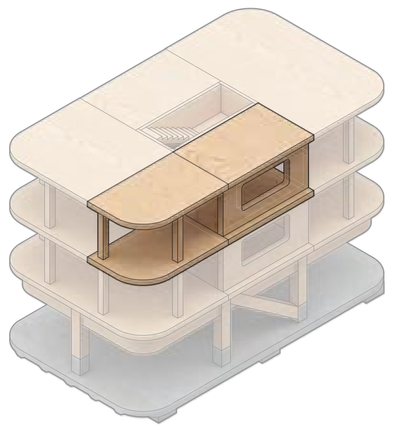
Cores and risers made from CLT should run through the building, giving it lateral stabilization.

03. Structural Honesty/Concept



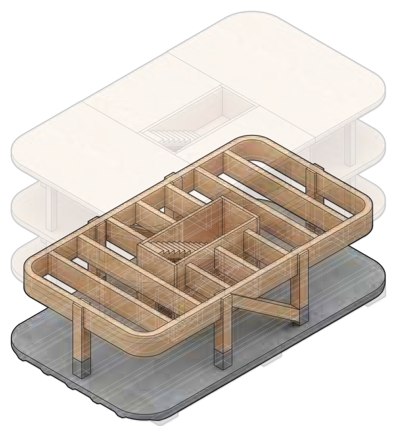
The design should adhere to and follow the logics of the structural concept. Construction is form. The clarity of structural order solve problems and give character to the interior. Where possible, material should be left exposed.

04. Apertures



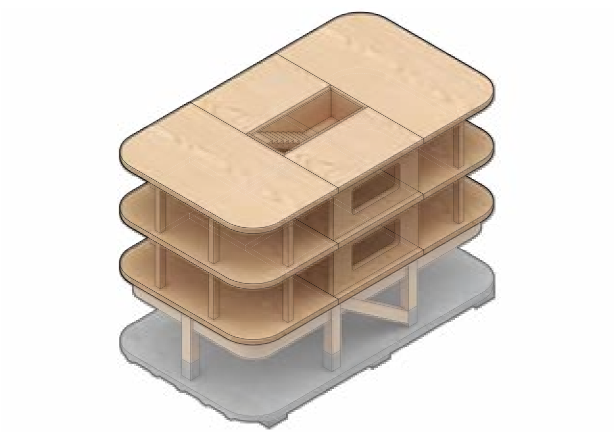
Apertures are created as an opening in a surface or between two or more structural members

05. De-materialized Plinth



The de-materialized plinth creates a public platform and protected entrance situation

06. Rounded Corners



Rounded corners help diminish vertical wind loads.

Traditional Wood

07. Dry Feet

01. Dry Feet Wooden architecture traditionally changes material when reaching the ground.

08. Protected structure

Exposed load bearing structure is rigorously protected.

09. Variation

Tactile changes in shape and form within the same material is used to create a variety in expression. (Pelarne Church, Vimmerby, Småland)

10. Compactness and Outdoor Neutrality

Traditional wooden houses are characterized by a clear structural order against a neutral volume. (Granhult church, Småland)

11. Foundation Adjustable to Nature

Figure 38. Stone foundations is typically used to cater differences in height which is needed when placing houses in slanted landscapes. (Båthus vid Björnö slott, 2020).

12. Accentuated Soffit

Traditional wooden architecture emphasizes and embellish cantilevering structures. ("Landshövdingehus" in Landala, Gothenburg)

Design Project

Wendelstrand

Wendelstrand is a housing development situated on the shores of *Landvettersjön*. The ambition is a residential area built in wood. Next Step is the developer and they have provided information concerning the established development. It concerns 750 homes, preschools, and nursing homes as well as the landmark *Lakehouse* with a restaurant, coworking office and gym. The area is adjacent to a nature reserve. Schools, services and public transport are in the immediate area and with public transport to *Gothenburg* only 15 minutes away.

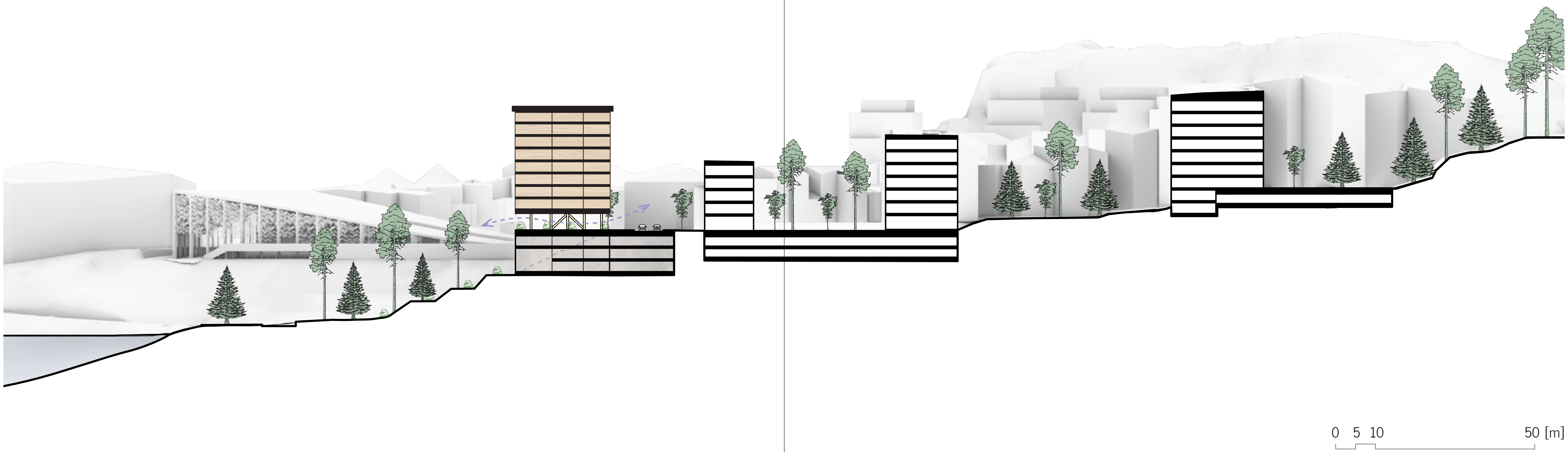
The aim was to apply the research onto a specific situation and *Wendelstrand* seemed like a suiting site. The design proposal adheres to the *Design Guidelines* extracted in *Exploration* and *Investigation*. Even though the *Design Guidelines* can originate from different time-periods and forms of research, they will still be developed to be applicable on industrial wooden construction in a modern context.

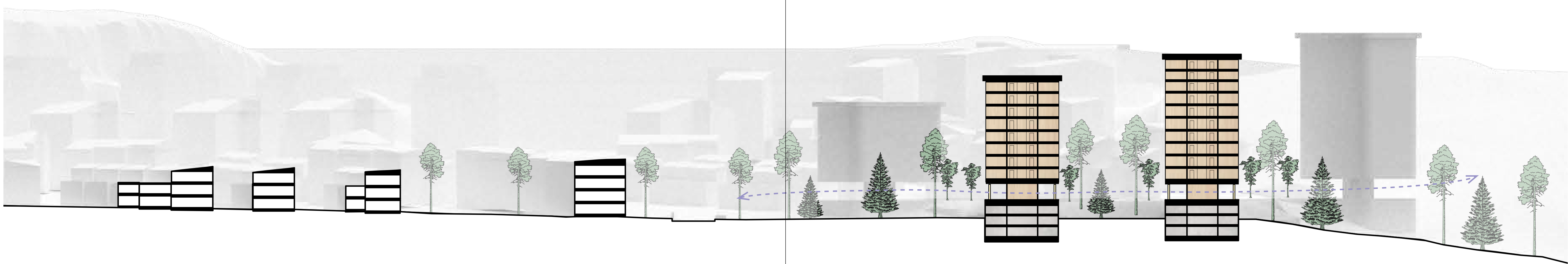
The research have been applied to four buildings in the south-east part of the site. They where chosen first and foremost for their potential in size, height and scale. Our design guidelines and design could just as easily be applied to the building on the northern part of the site or any other approximately within the same scope.

The site turned out to be rather difficult first and foremost due to the height difference and planned garage attached to the chosen buildings. This became a driving argument for designing an accentuated plinth which also could serve the entire community of *Wendelstrand* as a viewing platform overlooking Lake Landvetter.

Location Plan

Site Plan 1:1500 Wendelstrand

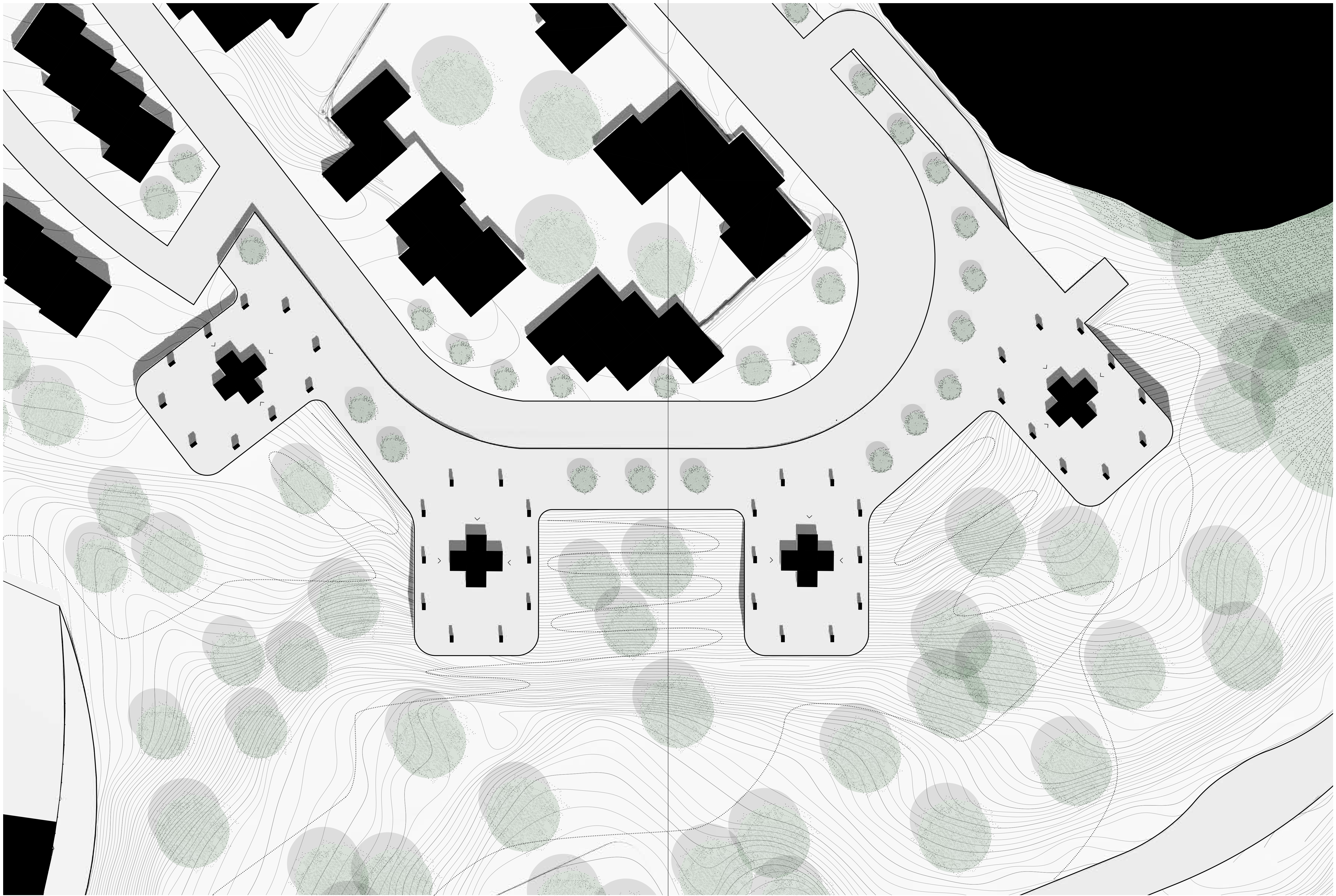




Section Site

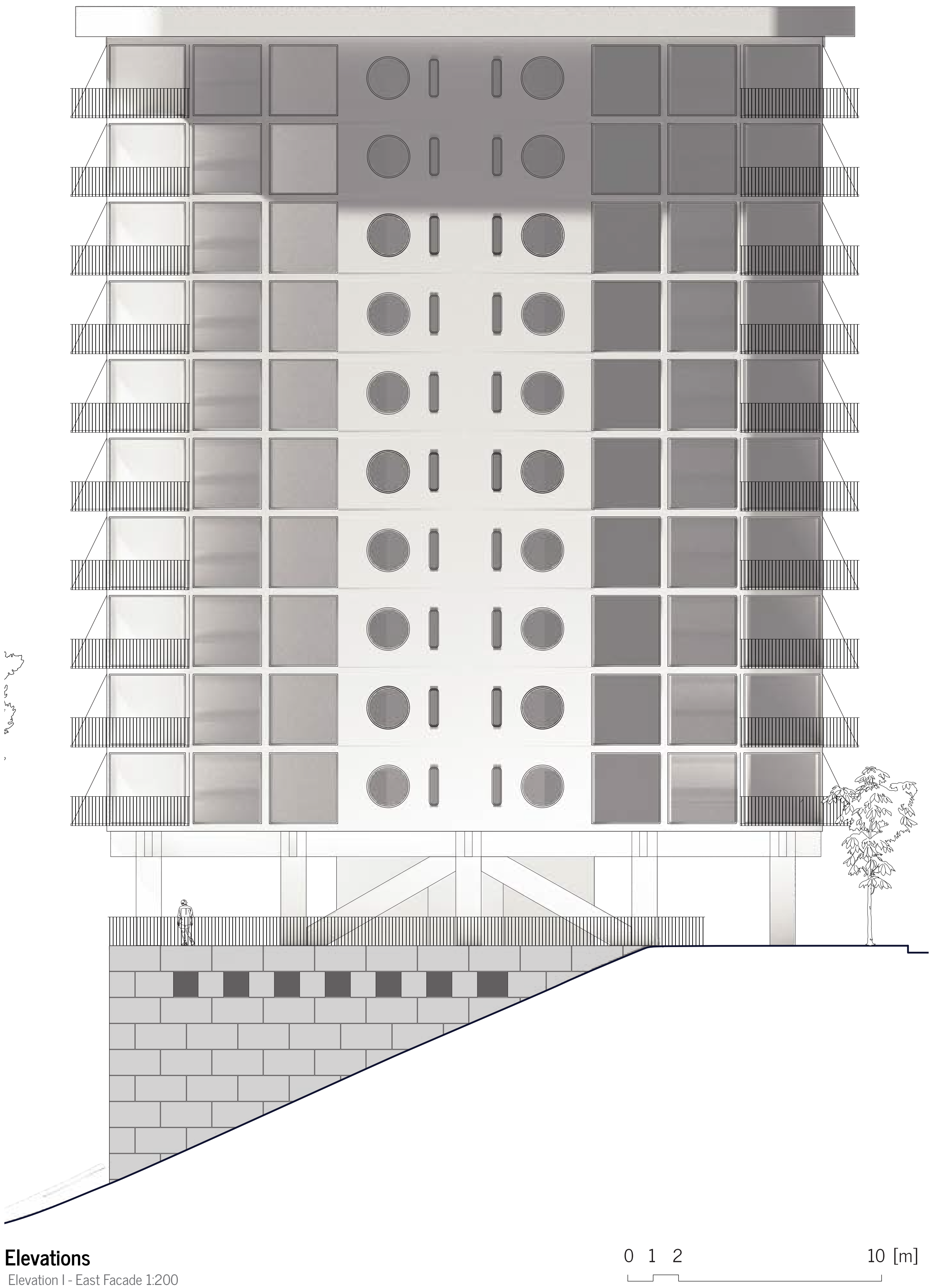
Site Section B-B 1:1000 West - East

Site Plan
Plan 1:500 Sun/shadow condition 12:00 - 21 June



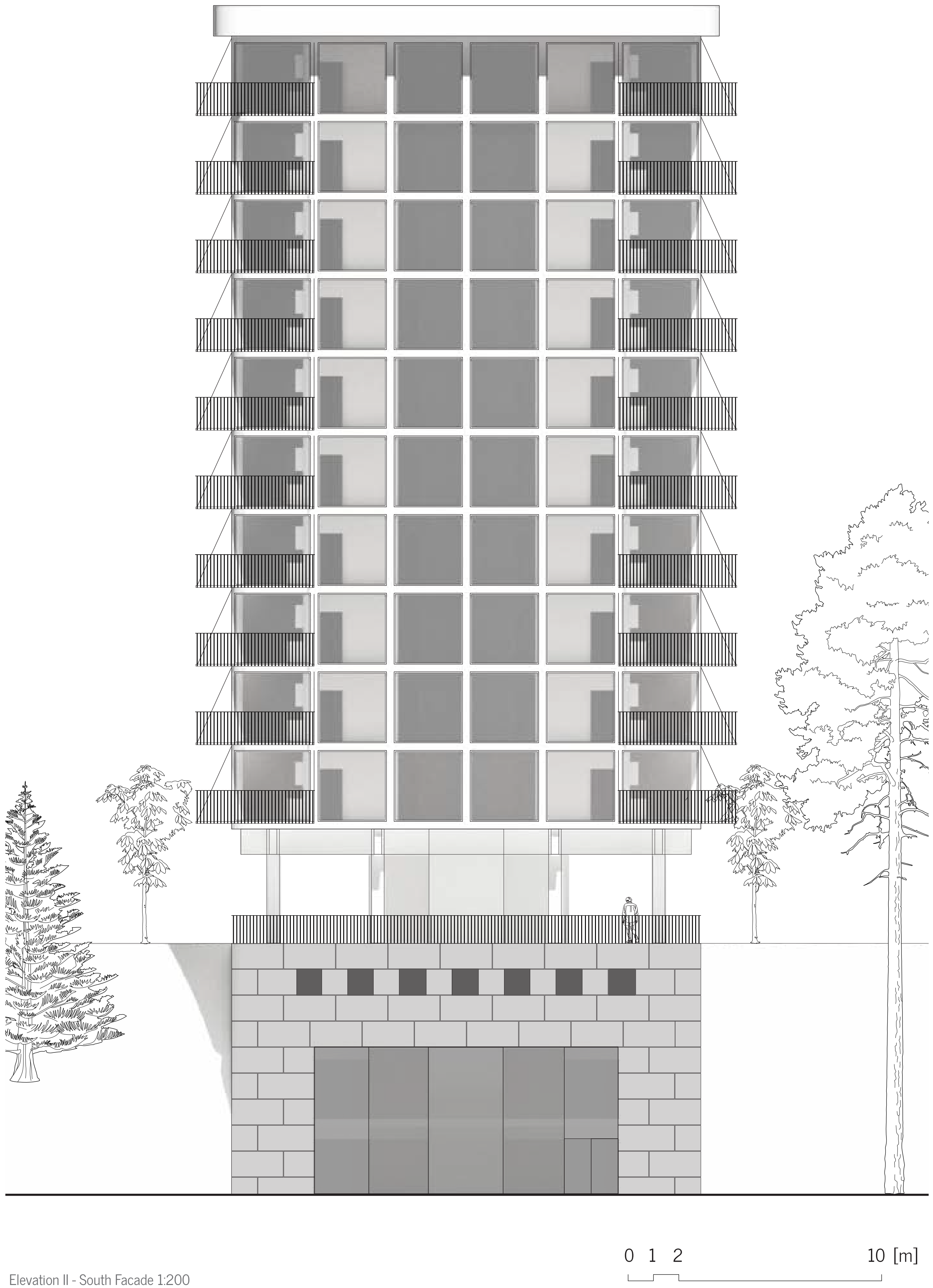
Site Plan Ground Level

Plan 1:500 Public space on entrance level



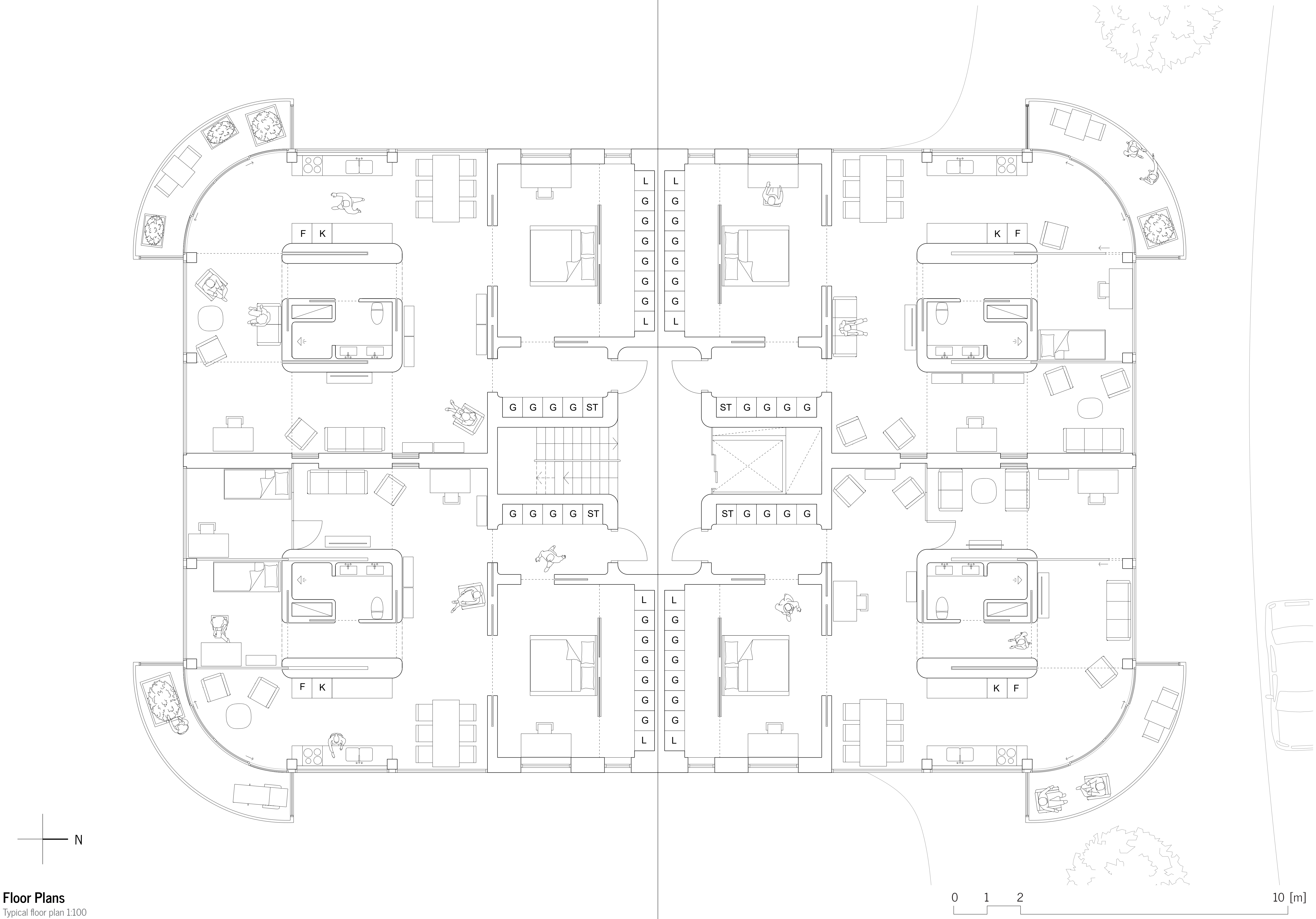
Elevations

Elevation I - East Facade 1:200



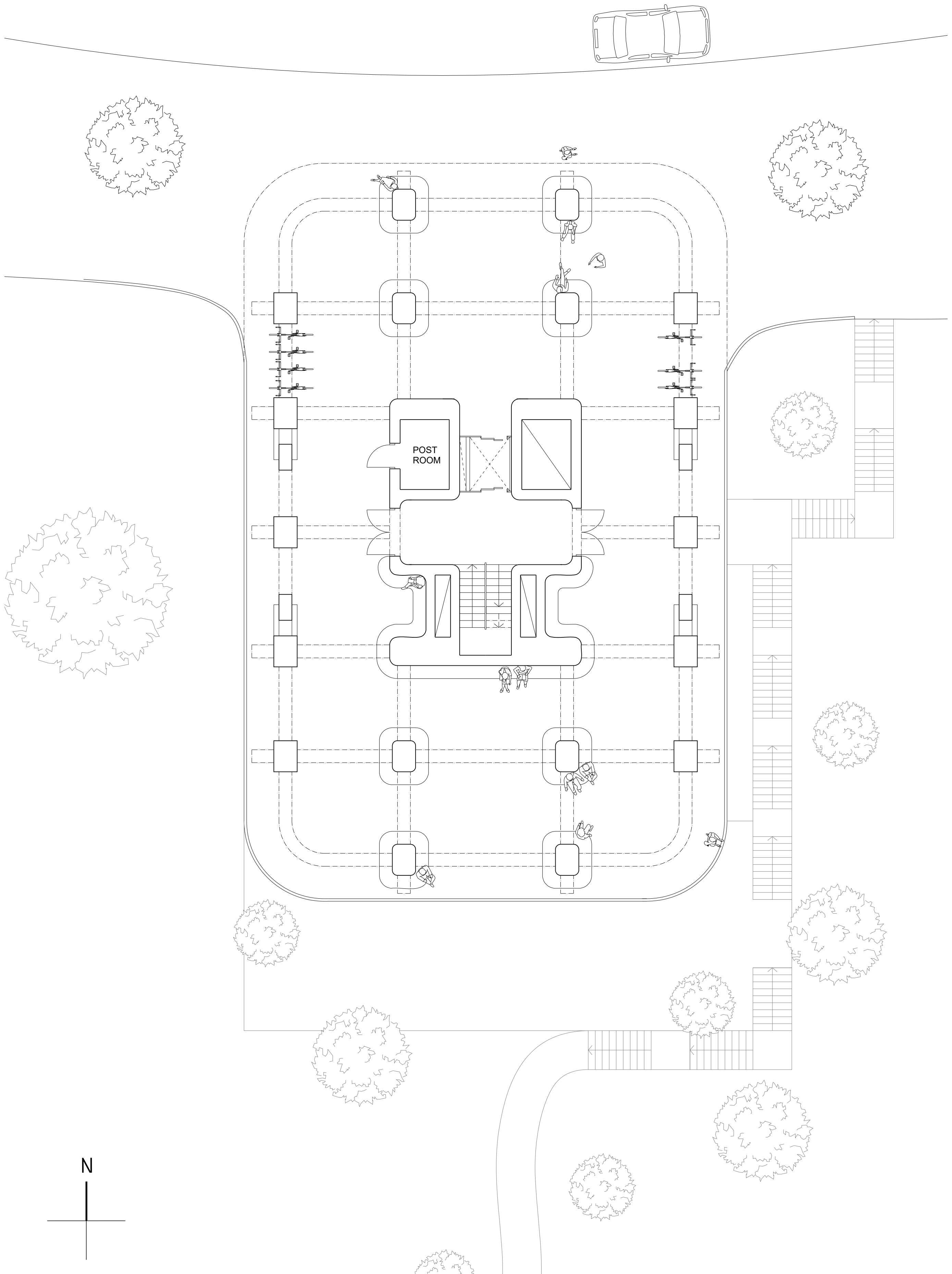
Elevation II - South Facade 1:200

Section
Building Section 1:200



Floor Plans

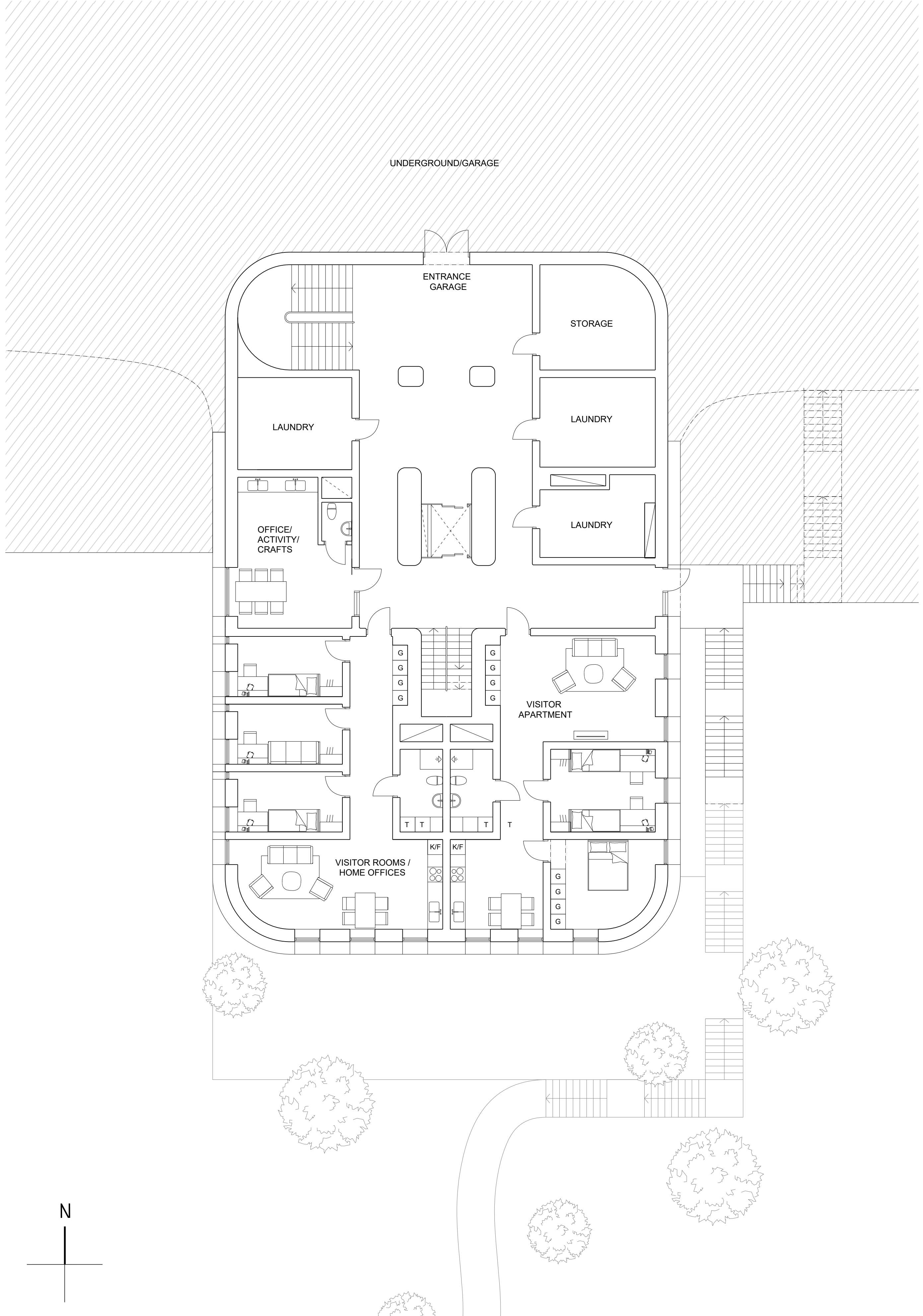
Typical floor plan 1:100



Plan

Entrance floor plan with viewing platform 1:200

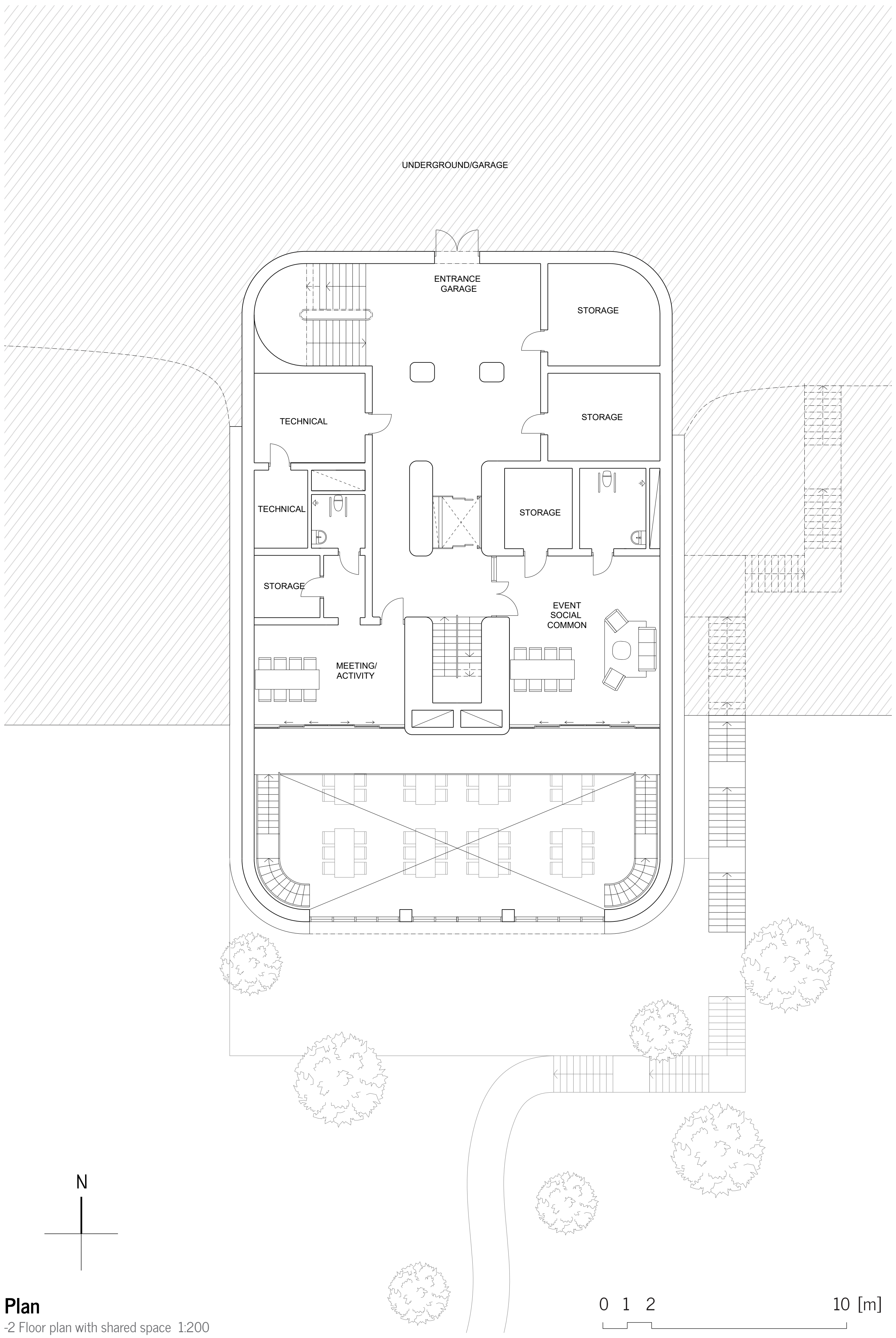
0 1 2 10 [m]



Plan

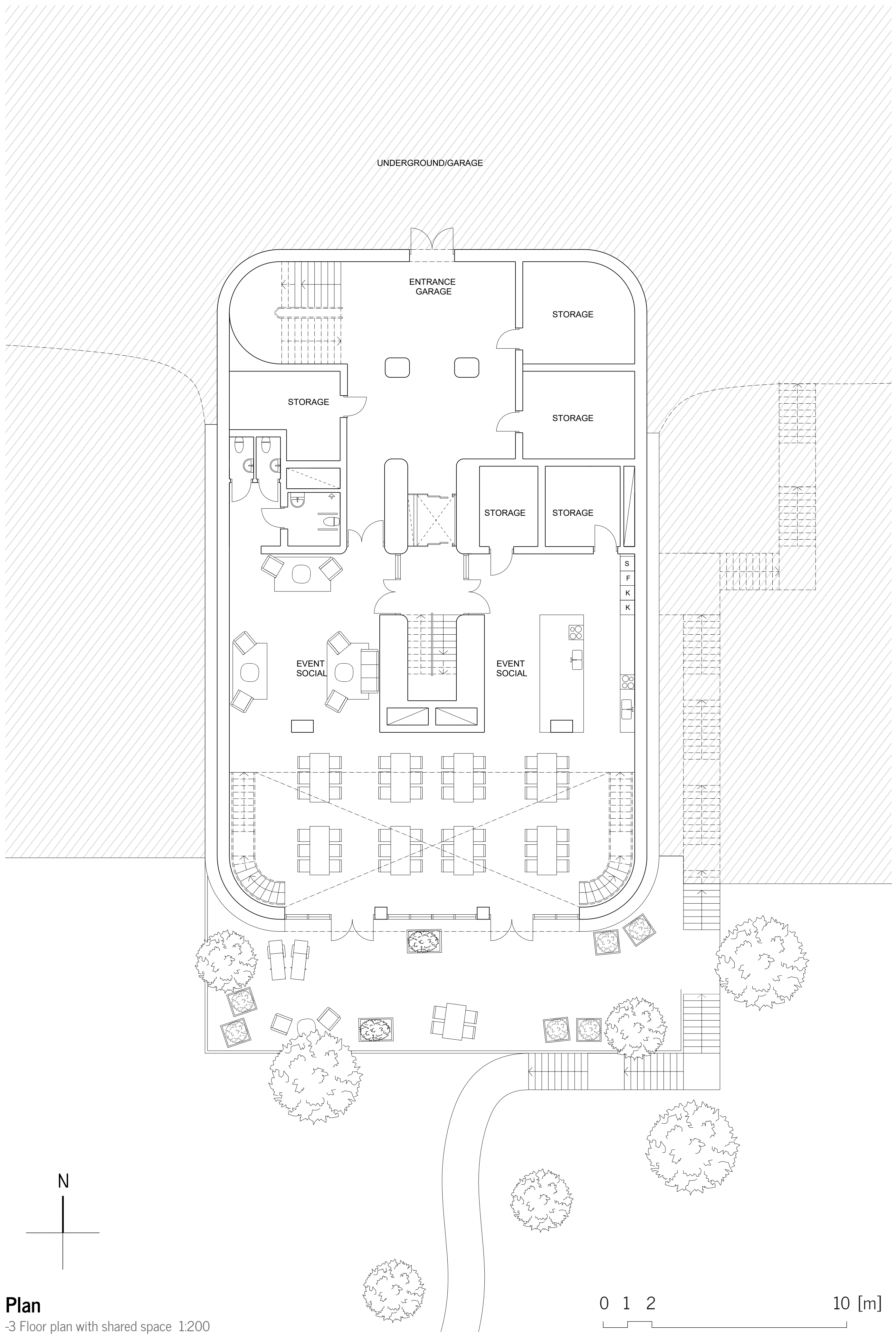
-1 Floor plan with Shared space 1:200

0 1 2 10 [m]



Plan

-2 Floor plan with shared space 1:200



Plan

-3 Floor plan with shared space 1:200

Technical Section
Section 1:50

0 0.5 1 5 [m]

Corresponding Elevation
Elevation 1:50

0 0.5 1 5 [m]

Model Study Apartment

A 1:20 Model was made of one apartment. (A floor slab is composed of four apartments and a central staircase) t was made to showcase wooden structure and spatiality in the apartments. Sliding walls can make the apartments change from an open 2 room to a 3 and 4 room apartment

Flexible Plan Study

The apartments have an open plan around the core which holds facilities like wet surfaces, shafts and plumbing. The plan is flexible with the possibilities to create more rooms through sliding walls in the wall and core. The Apartment can change between a 2, 3 and 4 room apartment.

3 room version with a smaller room

3 room version with a bigger room

4 room version with a bigger and a smaller room

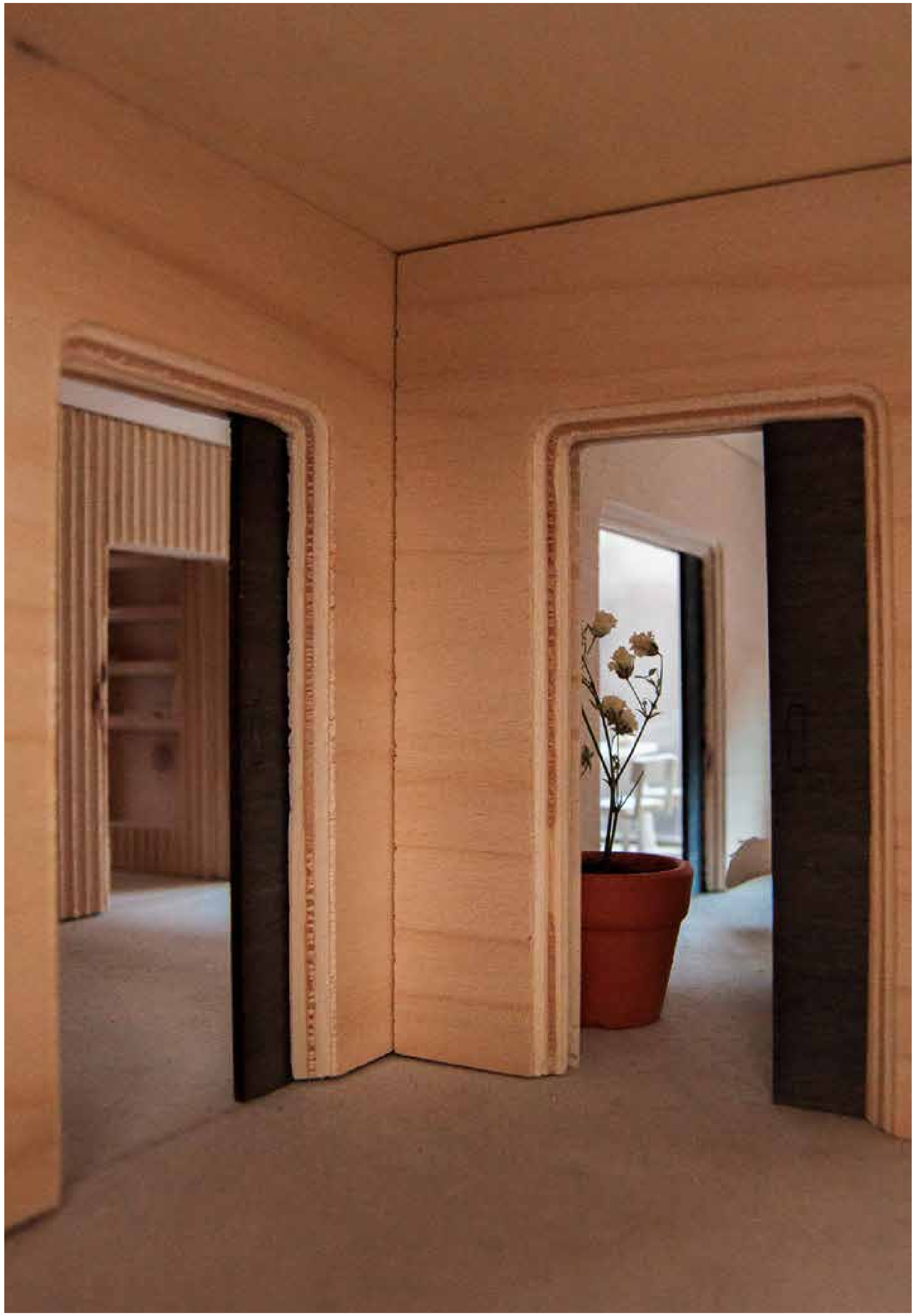
4 room version with two smaller rooms

Perspectives from Model

Interior view of the rounded slab and window, the rounded corner limits the wind loads

Interior view of the passage between core and bedroom

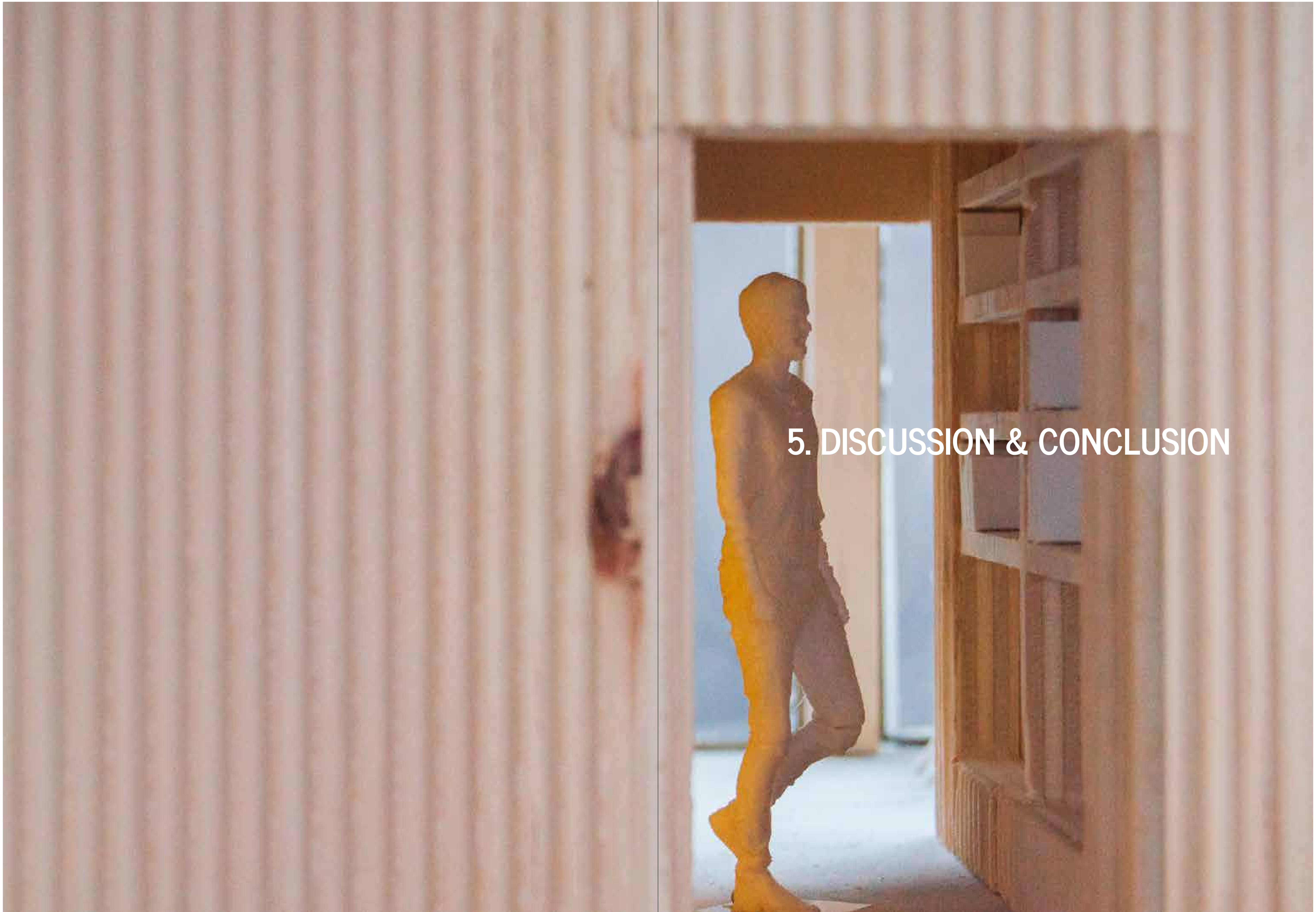
The sliding walls of the floor plan can be kept open or closed with more rooms as a consequence. To the left is an example of how the sliding wall shapes an extra room and to the right an example where the floor plan is kept open.



View from the hall, sliding doors are placed between the two CLT-slabs that forms the load bearing interior walls

View from the hall of a milled round aperture in the bedroom.

Different apertures tested in the bedroom



5. DISCUSSION & CONCLUSION

CHALLENGES & OPPORTUNITIES

When reading reports, taking part of discussions in the constructor sector and looking at built examples it becomes clear that a significant segment of the sector are readjusting to constructing with wood instead of concrete and steel. There is also no doubt that from a technical, knowledge and economic perspective, the business, after an adjustment period could handle an extensive housing development using mostly wooden structural systems.

Despite the positive future prospects of replacing steel and concrete with wood in constructions the sense is, from a sustainability perspective, still rather ambivalent. Recent reports from *Naturvårdsföreningen* and *Svenska Lantbruks Univeritetet* underline that with the contemporary way of handling forestry with clear-felled areas, causing emissions and harm on biodiversity and water courses, wood could hardly be called a sustainable material. From the report from *Naturvårdsföreningen* it is stated that there are ways to run a more gentle and sustainable forestry and still have significant out-takes of bio-mass. A correct forestry could positively stimulate the sequestration in the forests as well.

Concerned parts of the building sectors have raised their voices for a more sustainable sector and many settled for wood to be the simple, but as we seen, not fully true answer. If sustainability truly is desired the sector, just as all society, need to stop look for simple answers and understand that a fundamental conversion from the customs of today to a brand new praxis is necessary. Since both the production chains in and affects of construction is of great complexity it is hard to know how to act sustainable. Results of *Life Cycle Analyses* can give indications of sustainable measures but it is important to be aware that it can exclude important impacts on vital systems outside the analysis.

As seen in comparative reports wood still causes less emissions from production than concrete and steel. Even when including the hard to measure negative side effects on the viability of the forests, wood plausibly is a more sustainable material than its alternative. Still it is important to stress that it is not enough to just change fossil building materials to wood. To ensure a sustainable development the construction sector and related business sectors, like forestry, needs to take real actions and adjust to new paradigms no matter if the consequences are inconvenient or uneconomic.

Knowledge of how biomass out-takes affects the forests could raise arguments of treating extracted wood with respect by exposing it interiorly and highlighting its qualities through processing and crafting. Findings from researchers about health benefits and better indoor climate from exposed wood adds reasons for not hiding wood behind layers of plasterboard. Especially when studies show that plasterboards together with insulation is the material that causes the most emissions in a conventional housing projects.

From the thesis it is obvious that with the new EWP-products and processing techniques there are a vast number of ways to create structurally expressive and genuine architecture based in the uniqueness of wood. With wood products like CLT and Glulam that can cantilever, be single supported, curve, bend and span there are endless structural possibilities and ways of expressing unique structures clearly identified as wooden.

When approaching wood at a closer distance, it opens up for unique architectural solutions. The soft character of wood makes it possible to process it with for example the techniques explored in this thesis. Structural capacity together with the possibilities for crafting and processing the material are unique for wood.

For a long time wood was the main construction material available in a northern context. Now we may look towards a renaissance to our origin with locally produced goods and labour. We think that wood has an increasingly important role to play over the upcoming years and with modern processing techniques there is also a possibility that crafted detailing will be seen at a higher extent. We see that a wooden architecture could reach a higher potential and position itself as a building material with its own architectural qualities and expressions and not just be a replacement for steel and concrete.

Wood is a modest material with natural flaws and rich character. Despite the natural imperfections wood is a suitable material for architecture where observers comes closer to and interacts with the materials. The genuine graining and warm tactility makes wood a delightful material to come close to. This sympathetic nature makes it an ideal choice for housing projects where dwellers should feel like they want to come close to the founding structure of their home rather than become distanced from it.

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List of Figures

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Hans Ola Sjöberg and Victor Ågren

CHALMERS

Department of Architecture and Civil Engineering
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden