



TALL MASS-TIMBER BUILDING

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requirements for the degree of

Master of Architecture

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Keywords:
Mass-Timber, Cross Laminated Timber, Tall Wooden Structures, Co-living

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Abstract

How can we as design professionals contribute to increase the use of less carbon-intensive materials to build our growing cities?

Cities are experiencing a resurgence in population growth and therefore the building industry ought to attend this demand with sustainable solutions. One way of responding to the growing urban population and increase demand for housing as well as to make efficient use of our limited resources is to increase the density in our cities. Since steel and concrete have high material strengths, we currently use either steel, concrete or composites of them to build skyscrapers. Unfortunately, both of these materials have a large carbon footprint. The design community has the challenge to achieve net-zero emissions buildings by the year 2030, and the efforts now should be focused on using less carbon intensive materials, such as timber.

While cultures around the world have built with wood for centuries, recent technological innovations, such as Cross Laminated Timber (CLT), is allowing for new applications of wood as the main structural material and the potential to use it for large-scale projects. However, as expected with a new building material some constraints have still to be overcome.

For my thesis, I desired to explore this issue through the design of a tall building using mass timber as its main structural material. Engineered timber is here, the future is bright!

TALL MASS-TIMBER BUILDING

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Abstract General Audience Abstract

Urban population is growing faster than ever before and at the same time, we have started to suffer the scarcity of resources. One way of responding to the growing urban population as well as to make efficient use of our limited resources is to increase the density in our cities.

We currently use either steel, concrete or composites of them to build skyscrapers. Unfortunately, both of these materials have a large carbon footprint. While cultures around the world have built with wood for centuries, recent advances in wood-based building materials and construction techniques have made it possible to use wood even in large-scale projects. However, as expected with a new building material some constraints have still to be overcome.

For my thesis, I desired to explore these issues through the design of a tall building using timber as its main structural material.

Dedication

This thesis work is dedicated to the three women I love most: Elsy, Jenny and Felicia. You made and make me who I am. You are always by my side and I feel extremely lucky to be your son, husband, and father.

Mom, from you I learned that I should always give my best.
Beloved wife, my dream to become an architect wouldn't be possible without your unconditional and constant support.
Beautiful daughter, thanks for keeping me awake during the long nights!

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Introduction

My relationship with timber started long time ago. I lived in a house made out of wood and rammed earth, in San Agustin-Colombia, for the first seven years of my life. I can remember the smell coming from the wooden floor, and still feel how cozy it was to lay my head on it. For some reason, I liked it better than the soft rug. Later we moved to Bogota, a big city, where brick and concrete were not only the predominant building materials but somehow a synonym of a more developed and stable home.

Later on, before I started to study architecture, and during my first visit to my wife's home country, Sweden, I was very impressed by the quality and beauty of the traditional wooden country houses. The thing I most liked was the very simple layout, with a robust appearance. Years after, and with my eyes focused on buildings, I also realized how beautiful the contemporary wooden houses in Scandinavia could be. Researching some of those projects, I started to find information about 'engineered' wood. First about Glue-Laminated and Nail-Laminated Timber and finally I heard of Cross Laminated Timber (CLT), as a very promising material for construction. My interested in CLT grow and in 2016, after I listened to the TED talk by Michael Green about CLT where he spoke about the impact of traditional building materials on global warming and explained the advantages of designing tall buildings with timber, I decided that I wanted to use CLT for the design of my thesis project.



Fig. 1. The wooden floor at my parent's home in San Agustin, Colombia.

We all know that cities are experiencing a resurgence in population growth and therefore the building industry ought to attend this demand with sustainable solutions. One way of responding to the growing urban population and increase demand of housing as well as to make efficient use of our limited resources is to increase the density in our cities. Since steel and concrete have high material strengths, we currently use either steel, concrete or composites of them to build skyscrapers. Unfortunately, both of these materials have large carbon footprint. The design community has the challenge to achieve net-zero emissions buildings by the year 2030, and the efforts now should be focus in using less carbon intensive materials, such as timber.

While cultures around the world have built with wood for centuries, recent technological innovations, such as Cross Laminated Timber (CLT), is allowing for new applications of wood as a building material and the potential to use it for large-scale projects. However, as expected with a new building material some constraints have still to be overcome.

In order to contribute to the increase use of less carbon intensive materials, through my thesis I desired to explore these issue by designing a tall mass-timber building using CLT as the main structural material.

Through this journey I first learned about the material properties, its advantages and limitations through literature review and through attending a timber AIA seminar and a digital fabrication conference (ACADIA 2016) as well as some webinars for design with engineered timber. Thereafter, I studied some tall buildings that use timber as its main structural material, most of them are just concept ideas.

Later on, after I found a site where it made sense to build a tall timber building, and after analyzing the Stockholm's needs of housing, I was interested in the concept of co-living and co-working spaces as an expression of a growing 'shared economy'. I then initiated the design of a flexible layout that could integrate structure and architecture.

This speculative work intends to be a source of future ideas for modular timber structures using CLT and flexible co-living units.

What is CLT?

CLT stands for Cross Laminated Timber which is a solid wood construction product consisting of at least three bonded single-layer panels arranged at right angles to each other. It currently can measure up to 2.95×16 m. CLT solid wood panels are made up of several layers and are available in different panel thicknesses depending on structural requirements. CLT is made of spruce or pine wood derived from sustainable forests. The North American CLT is typically made of three-, five-, seven-, and nine-layer panels

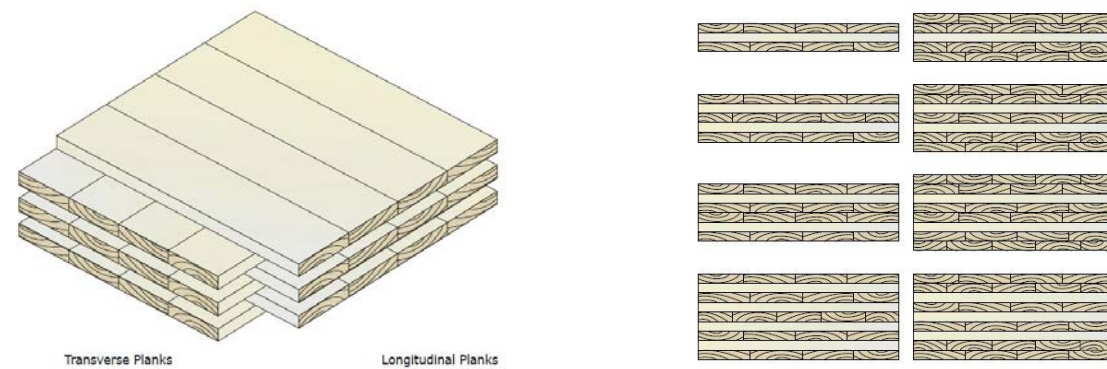


Fig. 2 and 3. CLT panel configuration and Examples of CLT cross-sections.



Fig. 4. Nordic pine forest during winter time.

of 2x6 lumber finger-jointed lamstock. In the US, CLT is manufactured using 2x6 lumber from trees harvested in sustainable managed forests, mostly from Mountain Pine Beetle kill trees. Most of the CLT comes from sustainable forests and has PEFC certification. PEFC stands for “Program for the Endorsement of Forest Certification Schemes” and is the label for wood and paper products derived from environmentally, economically and socially sustainable forestry operations along the entire processing chain. For the consumers, the PEFC label gives confirmation that the purchase of a labeled product guarantees and supports environmentally sound forestry management. It guarantees that the product has been subject to monitoring in accordance with rigorous criteria from the forest to the end product.



Fig. 5. Sample of CLT 5 Ply.

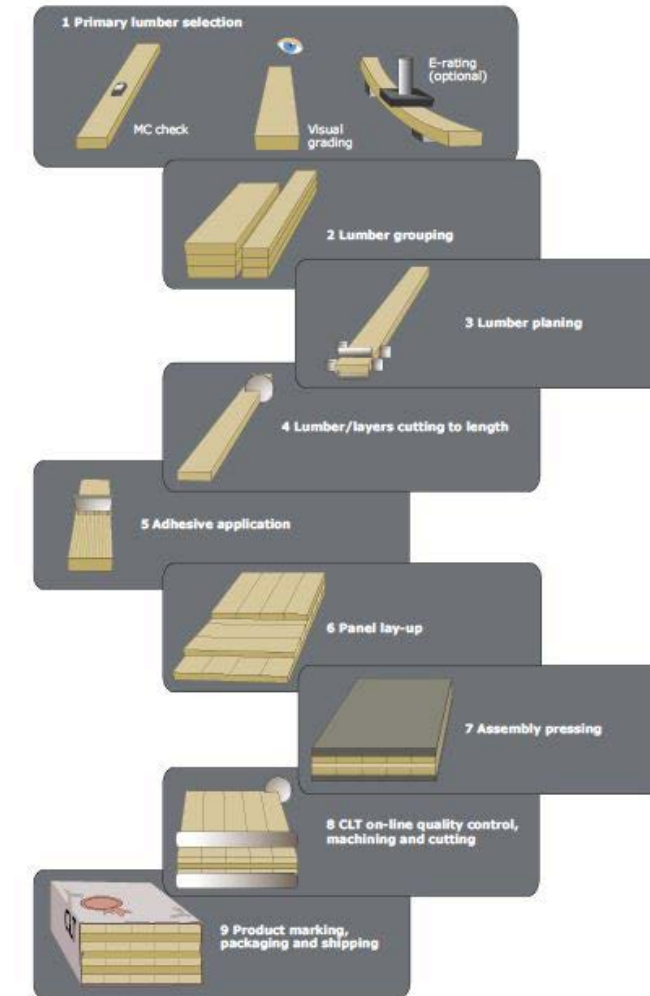


Fig. 6. The manufacturing process of CLT products.

Why to build with CLT?

Since steel and concrete have high material strengths, we currently use either steel, concrete or composites of them to build skyscrapers. Unfortunately, both of these materials have large carbon footprint. One of the primary ingredients in concrete is cement, and to make cement limestone need to be ground up. In addition to the energy required to maintain that heat, approximately 1 ton of carbon dioxide is emitted per ton of cement produced, according to the UN^[1]. And because concrete is the second-most consumed substance, after water, on the planet, cement production accounts for as much as 8 percent of human-produced carbon dioxide emissions.

Wood, one of the oldest building materials on earth, has always been valued for its beauty, abundance and practicality. Recent technological innovations, such as Cross Laminated Timber (CLT), is allowing for new applications of wood as a building material and the potential to use it for large-scale projects. New mass timber structural panels like CLT are not only fire resistant, but allow for buildings that are cost effective to erect and energy efficient to build and maintain. In addition to being renewable and sustainable, the harvest, transport, and manufacturing of wood yield far less pollution and requires less energy compared to other common building materials. Therefore, if we want to contribute to mitigate climate change, wood is the answer. In fact, wood is the only building material that can both reduce and remove carbon from the atmosphere.



Fig. 7. A 5,000-seat stadium, for the British football club Forest Green Rovers a design commissioned to Zaha Hadid Architects, to be built mainly of engineered wood.

Advantages

Engineered Timber has many benefits to offer as a building material. The following is a short list of its main advantages:

A renewable material that sequesters carbon

Wood is the only building material that can be harvested. Timber is also a single-source material. Steel and concrete require significant fossil fuels to extract needed raw material and numerous processes to manufacture. For instance, steel requires the following raw ingredients: Iron ore, coal, carbon, manganese, chrome, nickel, and tungsten. In the case of concrete, we need: sand, limestone, gypsum, water, silicon, phosphorus, sulphur, among others. Furthermore, since engineered wood is made out of small sections, we can use very small trees that are normally discarded. Most importantly, because plants take carbon dioxide during the photosynthesis process, they not only use CO_2 but also store it. "Carbon sequestration is the process involved in Carbon capture and the long-term storage of atmospheric carbon dioxide"^[2]. If we don't use the wood, the trees decay and emit carbon back into the atmosphere. Going further into the life cycle analysis of a building, some experts even talk about the possibilities to recycle and in some cases reuse the timber based products.

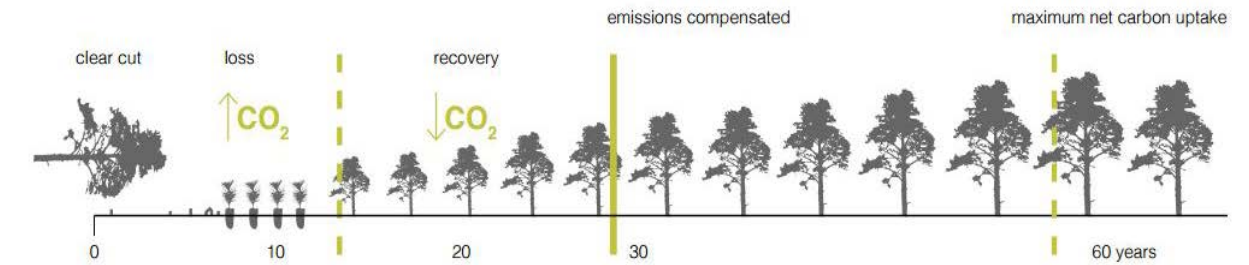


Fig. 8. Diagram: Net yield of GHG emissions between the ecosystem and the atmosphere in a clear felled area.

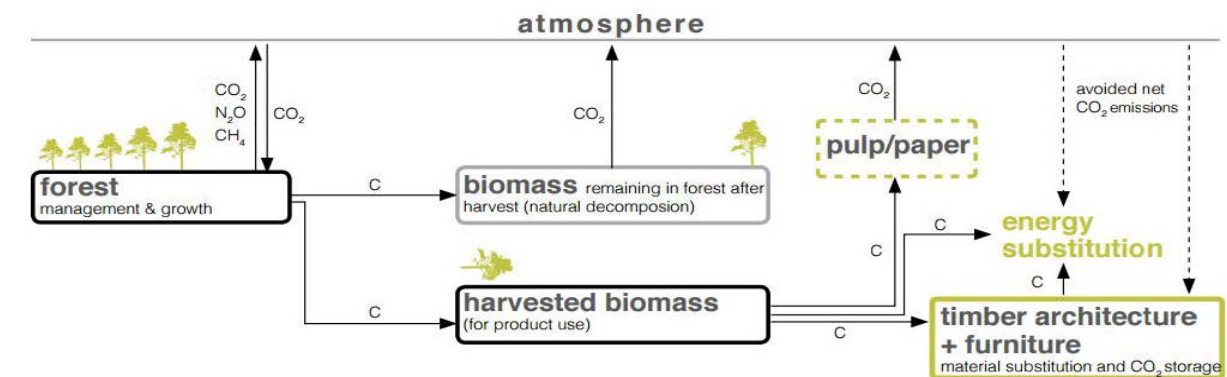


Fig. 9. Scheme of GHG flows and carbon stocks for forest products substituting non-forest products.

Its mechanical properties

The special arrangement of the components of the engineered wood products makes them stronger than raw wood. Every product has its own strengths and works better under specific loading conditions. Nevertheless, comparing material strength to weight ratio, we find that timber has 20 times more strength per unit mass than concrete:

Concrete	5.22	KN.m/Kg
Oak	115 - 113	KN.m/Kg

The research made by SOM, considered a load of 1,200 kips (5,337.86 KN) as the typical axial compression in a column of a tall building. Under this load condition, the required section for a timber column is 2' X 2' and a W14X99 (1' 2") for a steel column. Comparing these two columns, made of timber and steel for a tall building, we find that they have very similar axial stiffness.

	Axial stiffness	Movement
Steel	7000 k/in	0.17"
Timber	6700 k/in	0.18"

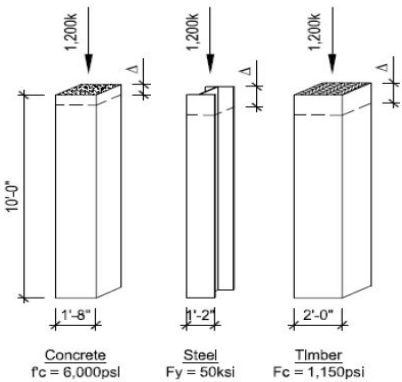


Fig. 10. Material Axial Stiffness Comparison (SOM).

In addition, the fact that mass timber weighs less than other materials also has a number of potential benefits, including smaller foundation requirements and lower forces for seismic resistance. Researchers have conducted extensive seismic testing on CLT and found panels to perform exceptionally well with no residual deformation, particularly in multi-story applications. In Japan, for example, a seven-story CLT building was tested on the world's largest shake table. It survived 14 consecutive seismic events with almost no damage^[3]. CLT also offers good ductile behavior and energy dissipation.

Thermal performance and energy efficiency

Wood's cellular structure contains air pockets that limit its heat conductivity. The precise manufacturing of CLT using CNC machines, panel joints also fit tighter, so limits air leakage, which results in better energy efficiency for the structure. As a result, interior temperatures of a finished CLT structure can be maintained with just one-third the normally required heating or cooling energy.

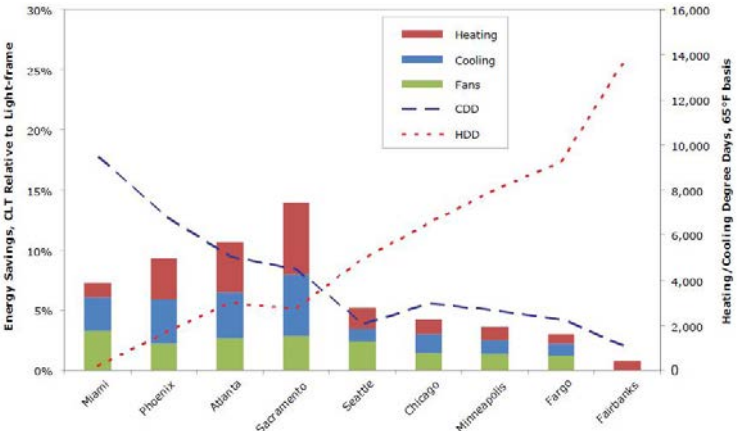


Fig. 11. Energy savings from CLT thermal mass for a four-story multi-unit residential building (left axis), with heating and cooling degree days (right axis).

Architectural control from the design to the built process

Reduced on-site labor alleviates shortages and cost. Because panels are prefabricated, erection time is greatly reduced, which improves efficiency and results in lower capital costs and faster occupancy. Wall, floor and roof elements can be pre-cut, including openings for doors, windows, stairs, service channels and ducts. Insulation and finishes can also be applied prior to installation, reducing demand for skilled workers on site.

Clean construction site contributes to improved safety. CLT panels are manufactured for specific end use applications, which results in little to no site waste. Plus, manufacturers can reuse fabrication scraps for stairs and other architectural elements, or as biofuel.

Factory prefabrication reduces construction tolerances. It is relatively easy to increase the thickness of a CLT panel to allow for longer spans requiring fewer interior support elements. Manufacturers use CNC machines to cut panels and openings to exact specifications, often to meet very tight tolerances (within millimeters). Plus, when field modifications are needed, they can be made with simple tools.

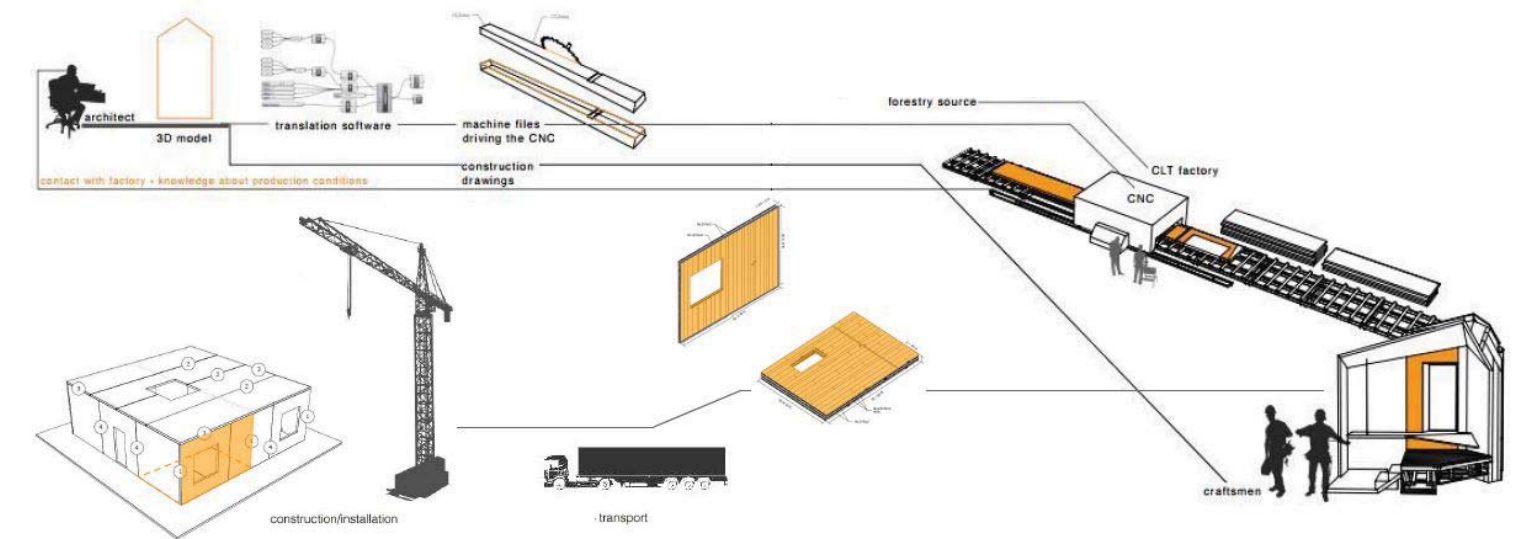


Fig. 12. Working flow, from the designer to the final product.



Fig. 13. Biophilia is humankind's innate biological connection with nature.

Biophilia effect

“Biophilia is humankind’s innate biological connection with nature”^[4]. Timber has a unique human-nature connection that has always been intuitive, but is now being documented in research. There is evidence that biophilic design can have a positive impact, from reducing stress and anxiety, to improving the quality and availability of respite from work and in increasing levels of self-reported well being^[5].

A Canadian study showed that when wood is used in the interior of buildings, it was perceived by a majority of people as more “warm,” “inviting,” “homey,” and “relaxing” than all other tested materials^[6]. Also another study has shown that wood panels were associated with decreased depression or dejection, while steel increased both^[7].

Challenges

The rapid acceptance and increase of use of CLT by the more progressive building industry still have to deal with some immediate challenges. Among them we have:

Lack of coordination and education

In order to overcome the challenge of introducing a new construction material, the efforts ought to be better coordinated. The industry, the academy, and the practitioner designers have already started to test and develop new material assemblies and more efficient building typologies. However, in order to generated enough information to permit the acceptance and safe use of CLT in high rise buildings, and to avoid overlapping efforts, there is a need for a platform to better share information and coordinate efforts.

Also, there is currently a lack of higher education on modern timber engineering in the U.S. A large number of engineering schools in America, do not even have timber design curriculum. Furthermore, those schools having any component of timber structural design need to update their courses to include the design of structural engineering wood. The current education on new trends of timber construction has been heavily relied on outreach seminars and short courses at the professional level.

Building Codes

One of the first step needed to introduce a new product for engineering design is the development of its standards. While it is encouraging to see new building systems and materials such as CLT starting to be embraced in the 2015 International Building Code (IBC), proposals are already underway to expand options for wood design in the future building codes. Currently, the ICC (international Code Council) is accepting public comments on code change proposals to be incorporated into the 2018 IBC, and building code officials are already reviewing recommendations from the American Wood Council

(AWC). Notably, two proposals submitted by AWC would allow up to nine stories of mass-timber construction up to 30 meters tall^[8]. Currently, the building code only permits up to five stories for residential structures and six stories of heavy-timber for certain types of commercial structures. In order to change the building codes, CLT will need pass safety tests including fire resistant assemblies and seismic performance.

Light structure / Overturning

Due to the lightness of the material (relative to concrete), there exist needs for performance-based vibration design guidelines for mass-timber floors, as the design sometime is controlled by stiffness rather than strength. Wind-induced vibration in tall wood buildings is another design consideration that needs evaluation from both occupant comfort and structural performance perspectives. Coupling vibration research with acoustics research could also be beneficial.

Building performance

Wood is traditionally viewed to be less resistant to environmental deterioration compared to other building materials. There is a lack of data on how large-scale timber buildings will perform over time. Also, building moisture research is needed to demonstrate the hygrothermal performance of CLT and tall wood buildings during transport, construction, and operation cycles. However, data collection may take a relatively long period of time.

Connections

There is always a need for innovation in connections and the subsequent testing and research to validate their performance and development of design guidelines. However, this part of research can likely be conducted by the industry via a proprietary product model, as it has been done for some existing special connections for mass timber framing.

Myths about timber engineered products

There are some myths that goes against timber engineered products. Some of them are fire resistance, acoustic performance and aging. Thanks to recent research and physical testing engineers have found that many of those 'weakness' might be a mere speculation.

Timber does not ignite until it reaches 480 °F. When it catches fire, timber develops a protective char layer. Large timber beams have better fire resistance than unprotected steel beams of similar size because the interior of timber remains much cooler. In average, building fires reach temperatures of 1300 °F to 1800 °F and while timber stays strong, steel weakens as its temperature exceeds 450 °F, and at 1400 °F steel retains only 10% of its strength^[9].



Fig. 14. A wooden beam supporting two collapsed steel beams after a fire.

Tall Wood construction today

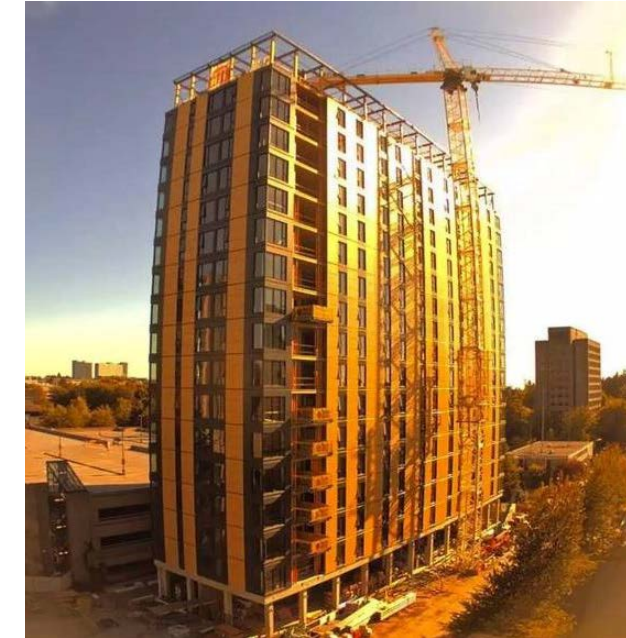
For many years, timber played a major role in the rapid growth of cities in the United States. Wood was one of the most easily accessible building materials for hundreds of years in North America. However, after devastating fires in the 1800s, specifically in Boston and Chicago, the building regulations limited the use of timber in construction. Because of these restrictions and also in part because the development of new technologies allowed new construction materials, the result was the concrete and steel cities we see today.

Timber became a secondary option and continued to be used to build the framework for low height buildings, mainly two story houses. However, from the time I started my research, nine months ago, I have been able to witness an incredibly fast development in the construction technology using engineered wood as a main building material. Following, I'll bring some of the most relevant examples, from my perspective.

Today the tallest timber building is the 'Brocks Commons' located at the University of British Columbia in Vancouver. The building was designed by Acton Ostry Architects and allocates 33 four-bedroom units and 272 studios for students. The building has 18 floors and stands 54 meters tall. The construction was completed ahead of schedule; after work started in November 2015, it took less than a year to complete. The project was completed with Architekten Hermann Kaufmann of Austria as tall wood advisors, Fast + Epp as structural engineers, GHL Consultants Ltd. as science and building code consultants, and Structurlam as the provider of the mass timber

package. Brock Commons is a 'hybrid design' that combines mass wood and concrete, with costs that are comparable to all concrete and steel structures.

The construction is comprised of a one story concrete podium, two concrete cores, and 17 stories, where the floor slabs are CLT panels. The concrete cores provide the lateral stability, while the columns that are made of Glue-Laminated Timber carry vertical loads. The Glue-Laminated Timber columns are fitted with steel connectors that provide a direct load transfer between the columns and a grid of CLT panels. (Figures 23 and 24.) The building also meets the new seismic design requirements of the 2015 National Building Code of Canada.



*Fig. 15. 'Brocks Commons' Vancouver, Canada.
18 Story Building*

At the time of its completion (Sept 2016) the largest timber building in North America was the 'T3 Minneapolis' (T3 stands for timber, technology and transit), by Michael Green Architects. The project is located in downtown Minneapolis at the North Loop. The office building has a structure built entirely from wooden slabs, columns and beams. According to the firm the wood structural system made it possible to erect the tower faster than a steel- or concrete-framed building of similar size. Workers constructed 180,000 square feet (16,720 square meters) of timber framing in under 10 weeks.



Fig. 16. 'T3 Minneapolis'. 7 Story Building.

Thanks to a design competition organized by the U.S. Department of Agriculture, aiming to promote the building timber industry, two firms received funding last year and their buildings will break down construction lately this year. 'The Framework', designed by Lever Architecture, will rise to 12 stories after it breaks ground in Portland, Oregon.



Fig. 17. 'The Framework'. Portland, Oregon. 12 Story Building.

The other one, a wood tower design by SHoP Architects, '475 West 18th' will be constructed in New York. Both firms have done extensive research and are developing new building techniques, which they hope will become a precedent that may encourage the building codes and regulatory authorities to accept timber as a main building material in the US.



Fig. 18. 475 West 18th. NYC, US. 12 Story Building

On the other side of the Atlantic, the use of Engineering Wood started earlier. The 'Murray Grove' building, located in London, was the first urban housing project completed in 2009 to be constructed entirely from prefabricated solid timber, from the load bearing walls and floor slabs to the stair and lift cores. The building was completed within 49 weeks and consists of 29 fully insulated and soundproof apartments. The nine-story tower is built from a tight honeycomb of structural wall panels, with a timber core that provides stability together with the outer structural wall. The outer wall has inset balconies with structural balustrades that provide additional strength.



Fig. 19. 'Murray Grove'. London, UK. 9 Story Building

The tallest building today in Europe is the 'Treet', a 14 story-housing tower located in Bergen, Norway. Designed by architects Artec and engineered by Sweco Norway, the structure comprised of a mix of CLT and Glue-Laminated Timber, built on concrete ground floor. The structural system combines, a exterior load-bearing walls and Glue-Laminated Timber columns with a three stories cross bracing, and prefabricated modular flats, using only Norwegian wood. The modules were stacked four stories high, with two platforms (above on the 4th and 9th floors) being anchored to the Glulam frame. Another four story of modules are then stacked on top of each platform, thereby enabling the developers to build 49 meters height. To prevent it from swaying in strong winds, the Glulam frame has been reinforced with diagonal Glulam braces whilst concrete floor slabs

have been installed on the top of the 5th and 10th floors, and on the roof. The concrete floor slabs are not a part of the structural system that carries the lateral loads, but have been installed to add weight in order to reduce movement within the building.



*Fig. 20. 'Treet' Bergen, Norway.
14 Story Building*

There are also several timber tower projects that are expected to be completed before 2020. A few cases are discussed here:

In Vienna, Austria the 'HoHo' will be the world's first 24-story building made of wood structure. About 75 percent of the building will be made of wood, starting from the ground floor.

*Fig. 21. 'HoHo' Vienna, Austria.
24 Story Building*



Architect Sou Fujimoto has won a competition for a housing complex in Bordeaux, France. His winning proposal includes a series of 14-story timber towers with a total height of 50 meters. Titled 'canopia', the mixed-use scheme includes residential units, offices, and retail outlets.

*Fig. 22. Euratlantique. Bordeaux, France.
14 Story Building*



The 'HAUT' (stands for 'haute couture': tailor-made architecture), is a 21 story residential building, designed by Team V architecture, which is expected to start its construction during the second half of this year in Amsterdam, the Netherlands.



Fig. 23. 'HAUT' Amsterdam, Netherlands
22 Story Building

Sweden leads the way with more timber buildings scheduled to be built over the next few years. It has been actively pursuing research on timber construction and has made adaptations to its building code in response to new advances in timber technology. Today Sweden is faced with the challenge of overcoming its shortage of housing in the midst of high rates of immigration. With its long history of sustainable practices it is continuing this approach by addressing this problem through the design and construction of timber buildings. While there are dozens of 6 story housing projects that are being built right now, I would like to mention the two tallest timber buildings that are contemplated to be completed within the next 5 years.

The first one is an 18 story mixed use development, including among others, a hotel and a cultural center, which is planned for construction in the northern city of Skellefteå. The architectural design was done by White arkitekter and is still in early stages of design, but is expected to be the state of the art in timber technology, not only for its location but also because its owners wanted to celebrate the traditional and fast growing timber industry that characterizes this region.

Fig. 24. Skellefteå Hotel. Skellefteå, Sweden.
18 Story Building



The second project is a housing tower located in Stockholm. The project is a 34 story building designed by the Danish firm, C.F. Møller, as the winning entry in a competition organized by Swedish building society HSB Stockholm, scheduled to open in 2023 to coincide with the organization's 100th birthday.

The government of Sweden is currently funding comprehensive research that involves several stakeholders, from the academia, to industry, through consultants and designers. A common effort aiming at the same goal is to expand the knowledge and help the industry and lawmakers to take informed decisions that might finally help update the current building codes.



Fig. 25. Wooden Skyscraper. Stockholm, Sweden.
34 Story Building

I would also like to mention the development of wood construction in Australia. The International House in Sydney is a seven-story commercial building designed by Tzannes which is currently under construction. This timber structure is composed mainly of Glulam and CLT, and will be the first modern engineered timber building in Australia.



Fig. 26. International House. Sydney, Australia. 7 Story Building

Also, there is a not-for-profit company, Forest and Wood Products Australia Limited (FWPA), that provides integrated research and development services on wood construction and is actively involved in the technical design of some timber buildings built in Europe. This includes the 'Puukuokka', a housing project with three towers up to 8 stories high that was completed in 2015.



Fig. 27. PUUKUOKKA. Jyväskylä, Finland. 9 Story building



Fig. 28. Oakwood Timber Tower. London, UK.
80 Story Building

There is a concept design for a 'real' timber skyscraper in London. The 'Oakwood' timber tower is an 80-story building (nearly 300m), designed by PLP architecture and engineered by Smith and Wallwork, and with additional support from researchers from Cambridge University's department of Architecture. The conceptual proposals currently being developed would create over 1,000 new residential units in a 93,000 square meter mixed-use tower and mid-rise terraces in central London, integrated within the Barbican.

The Site

Norra Djurgårdsstaden, The Stockholm Royal Sea Port is the largest urban development in Sweden.

Located north of the old town, surrounded in the east by the Baltic Sea and south by the Royal National City Park, the former oil storage, and industrial area is now being renovated to become the largest urban development in Europe by 2030.

The project expects to provide more than 12,000 housing units and 35,000 working places, with the required environmental standards, to be a state of the art green eco-district.



Fig. 29. Aerial view of Stockholm, from east. The Royal Sea Port in the foreground.

Stockholm, Sweden

Looking for a site where it made sense to build a tall building using engineering wood, I considered two main factors. First, a place where timber is commonly available material and secondly, a place with high population growth.

Within the group of countries, members of the Programme for the Endorsement of Forest Certification (PEFC), the first five in terms of wood production are Russia, Brazil, Canada, Sweden and the United States^[10]. From the list, Canada and Sweden are the countries with a more advanced technology for timber products. In its particular case, Sweden is covered to 70% of forest and is one of the main producers of construction timber products not only in Europe, but in the world.

Timber has been the main building material for the ancient Scandinavian cultures, not only for the construction of ships but also their homes. Many centuries of accumulate experience have helped them to masterize the use of wood as building material.

In addition, its capital Stockholm is one of the fastest growing cities in Europe. In order to address the shortage of housing, due to the increase of almost 55% of the population in only 15 years (from 923,516 inhabitants in 2015 to 1'425,000 inhabitants projected for 2030), Stockholm's authorities have targeted to build 140,000 new housing units by 2030^[11].



Fig. 30. Traditional scandinavian timber construction.

Norra Djurgårdsstaden

The Stockholm Royal Sea Port is the largest urban development in Sweden. Thanks to a decision taken in 2010, by the Stockholm's City Council, this development is going to be a sustainable urban district and an international model for sustainable urban planning.

Just ten minutes away from central Stockholm by bicycle, the area is a former industrial site around decommissioned gas and oil storage cisterns. Toward the south lies the Royal National City Park and to the east, the Baltic Sea. Towards the west and the north, the area blends with a more residentially consolidated part of the city.

The Stockholm Royal Sea Port is divided in four areas: Hjorthagen, Värtahamnen, Frihamnen and Loudden. The construction has already started in the northern area and will continue towards the south, with Loudden being the last because it needs a longer process of soil remediation.

The area will be transformed into an urban eco-district that interacts with port operations and the existing residential areas to include at least 12,000 housing units and provision for 35,000 new working places.

Norra Djurgårdsstaden | Stockholm Royal Sea Port



Fig. 31. Stockholm Royal Sea Port, location plan.

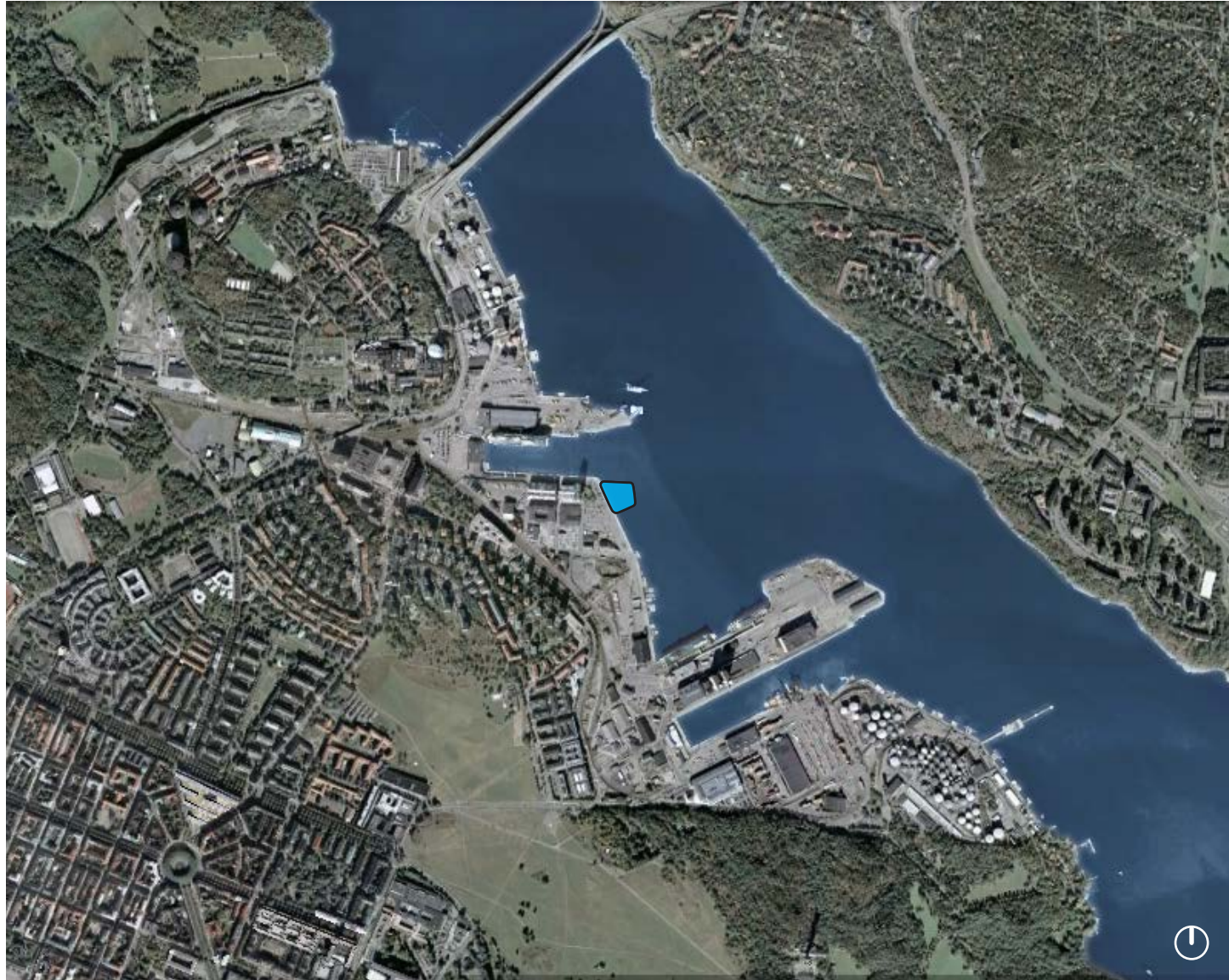


Fig. 32. Norra Djurgårdsstaden, satellite imagery.

0 0.25 0.5 1 Km

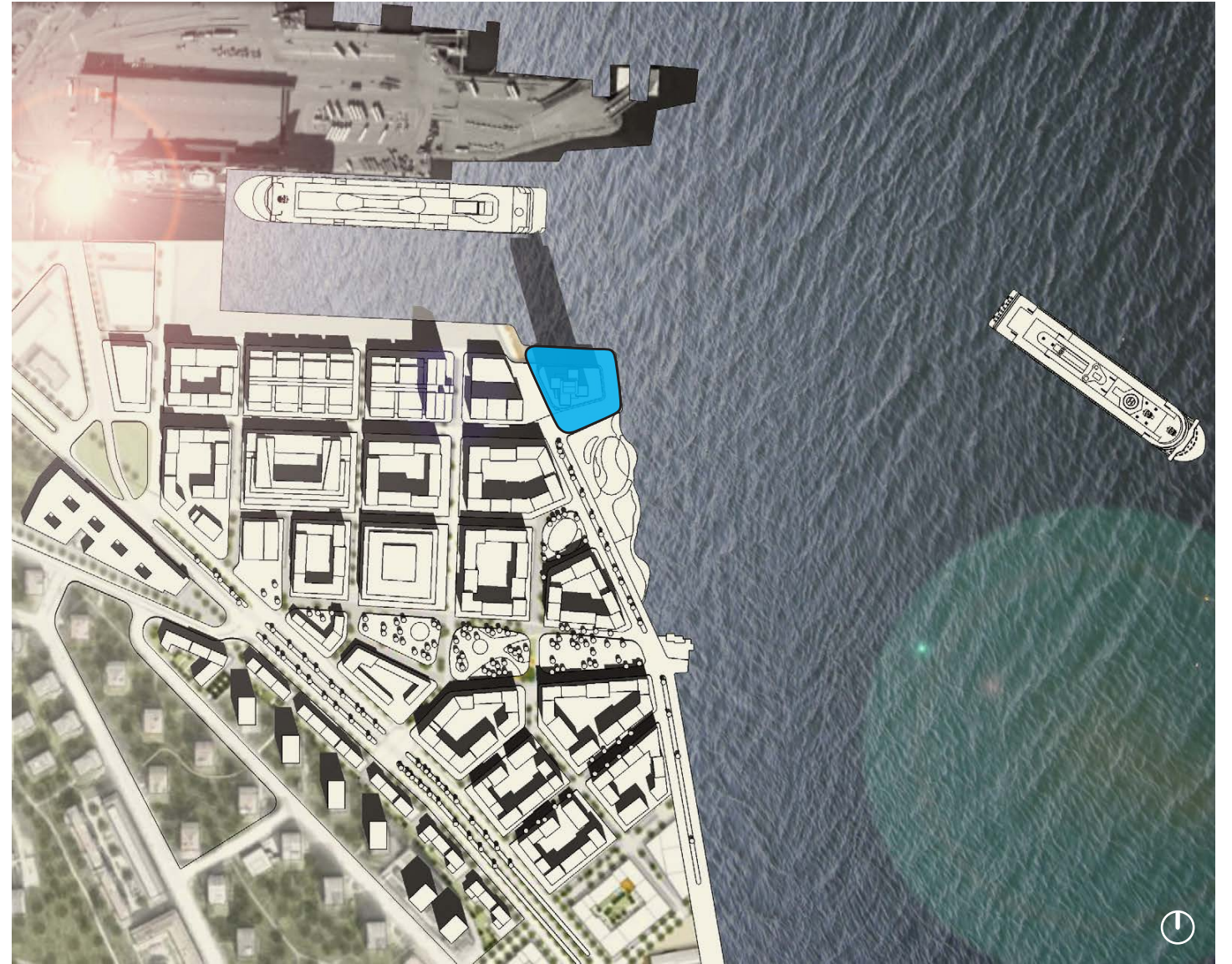


Fig. 33. Master plan for Värtahamnen and the site location.

0 50 100 200 300 m

The Program

Nowadays, thanks to the digital platforms the peer-to-peer exchange of goods and services is helping to optimize the use of resources and is becoming more popular, especially among young people. The most known platforms of this model, sometimes called 'shared economy', are Airbnb and Uber. The concept is very successful among 'millenials' and the idea to share is stronger than the idea to own, mainly because now young people is more aware of the scarcity of resources, the global warming and the negative impact of the economic crises in a society based only on the consumption of goods.

The real estate have not been an exception and the concept of shared working spaces have spread around the world. Not only the efficiency of sharing expenses but most importantly the interaction between people is something that new generations praise for helping with the cross-pollination of ideas and innovation. In North America, a venture called 'Wework' is leading this business model. Young startups, feel attracted by the generous communal spaces, the connectivity as well as the flexible monthly membership.



Fig. 34. Wework Chinatown neighborhood, Washington, DC



Fig. 35. 'Kombo' A co-living concept by Utopia Arkitekter



Fig. 36. Wework Williamsburg, New York, NY

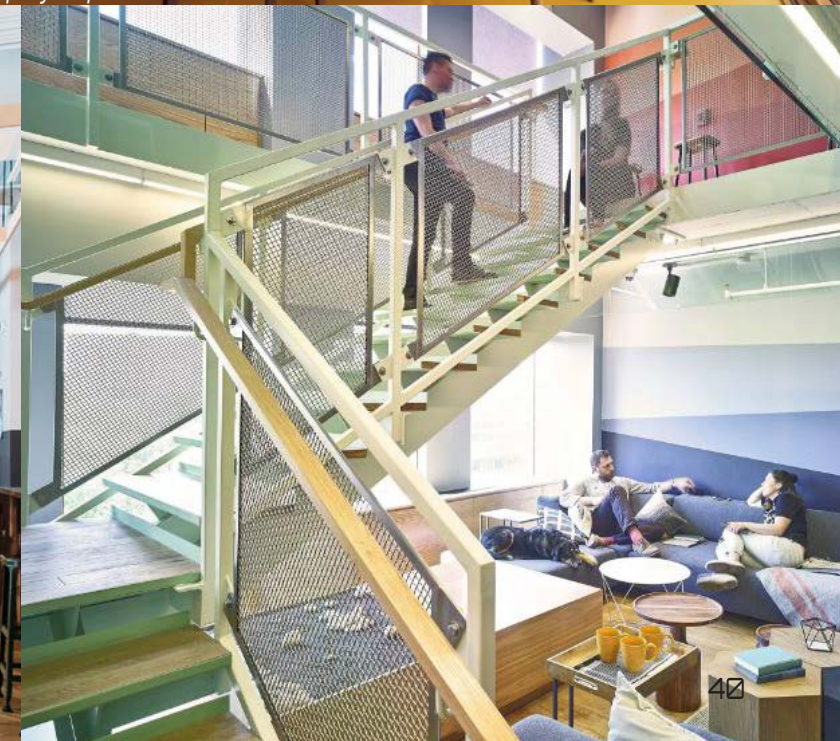


Fig. 37. WeLive, Crystal City, Arlington, VA

In Sweden, the real estate market is regulated and controlled by the government and even though the authorities have an organized vision of the housing needs, Stockholm has a shortage of housing units. The Population is growing and at the same time construction of new housing has been decreasing over two decades, even if this trend now is slowly changing.

A very well known example of the negative implications of how the housing market works, was the case with Spotify. Last year, along with other tech companies like Klarna, Skype, Mojang and King, they published an open letter. In the letter, the founders of Spotify, warned that they would have no choice but to leave Sweden. They said that a lack of affordable rental property in Sweden makes it very difficult to attract new talent from overseas. "The rental system in Sweden is broken because of the lack of available rental apartments, and because too few apartments are being built. Politicians and the government must make sure that more rental housing is built," they said^[12].

Not only the influx of refugees but also the mobility within the expanding European Community, due to the economic crisis on southern countries, has been the reason for the rapid population growth in Stockholm. People in the waiting list is increasing, and the average time to get an apartment to rent is between 8 to 10 years. The majority in waiting list is 25 to 35 years old and the households average size ranges between, 1 to 2 people. In addition, construction in Stockholm is expensive, among other reasons because the cost of labor is higher than any other country in Europe.

Aligning to the Stockholm's City Council vision for this eco-district, I believe it makes sense for the program of this building to propose both: co-living and co-working spaces. In addition, the ground floor will be reserved for commercial activities, mainly restaurants and cafes.

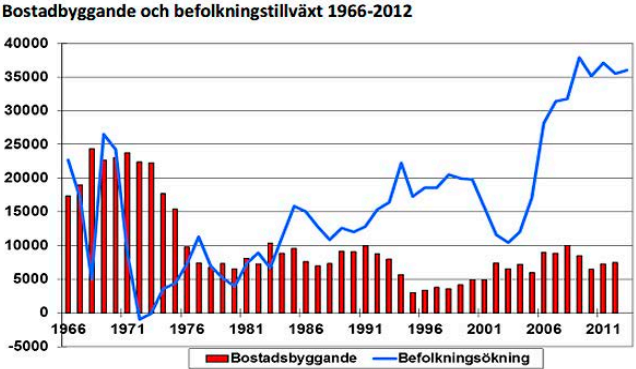


Fig. 38. Building construction and population growth 1996-2012

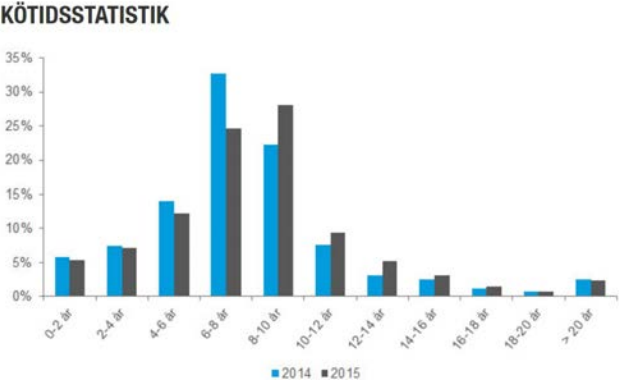


Fig. 40. Time on the waiting list to rent an apartment

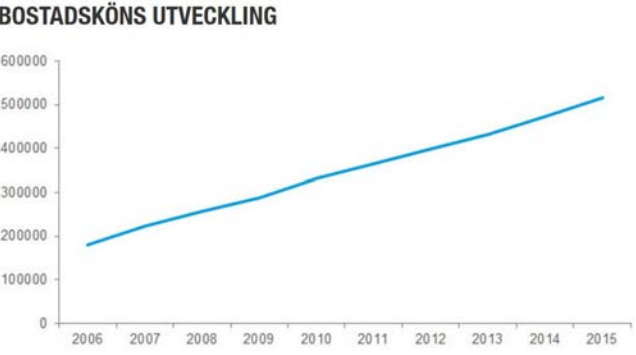


Fig. 39. Evolution of the waiting list

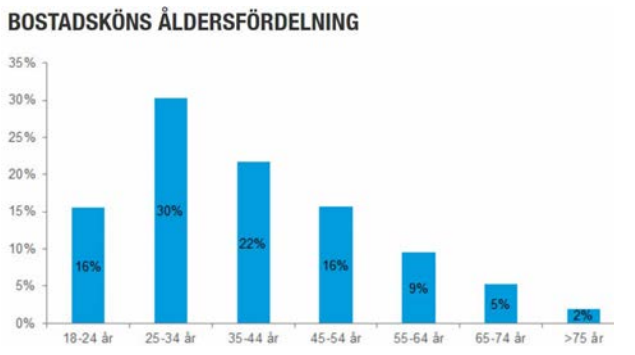


Fig. 41. Age of people on the waiting list

Considering the household profile that we can extract from the statistics, and giving the conditions of the real estate market in Sweden, it make sense to focus the design efforts to propose flexible housing solutions mainly, for single people between 25 and 35 years old. The aim is to provide a layout for co-living units that could be adjusted to the future demands of the market, providing not also shared units but also apartments for single persons, and young couples.

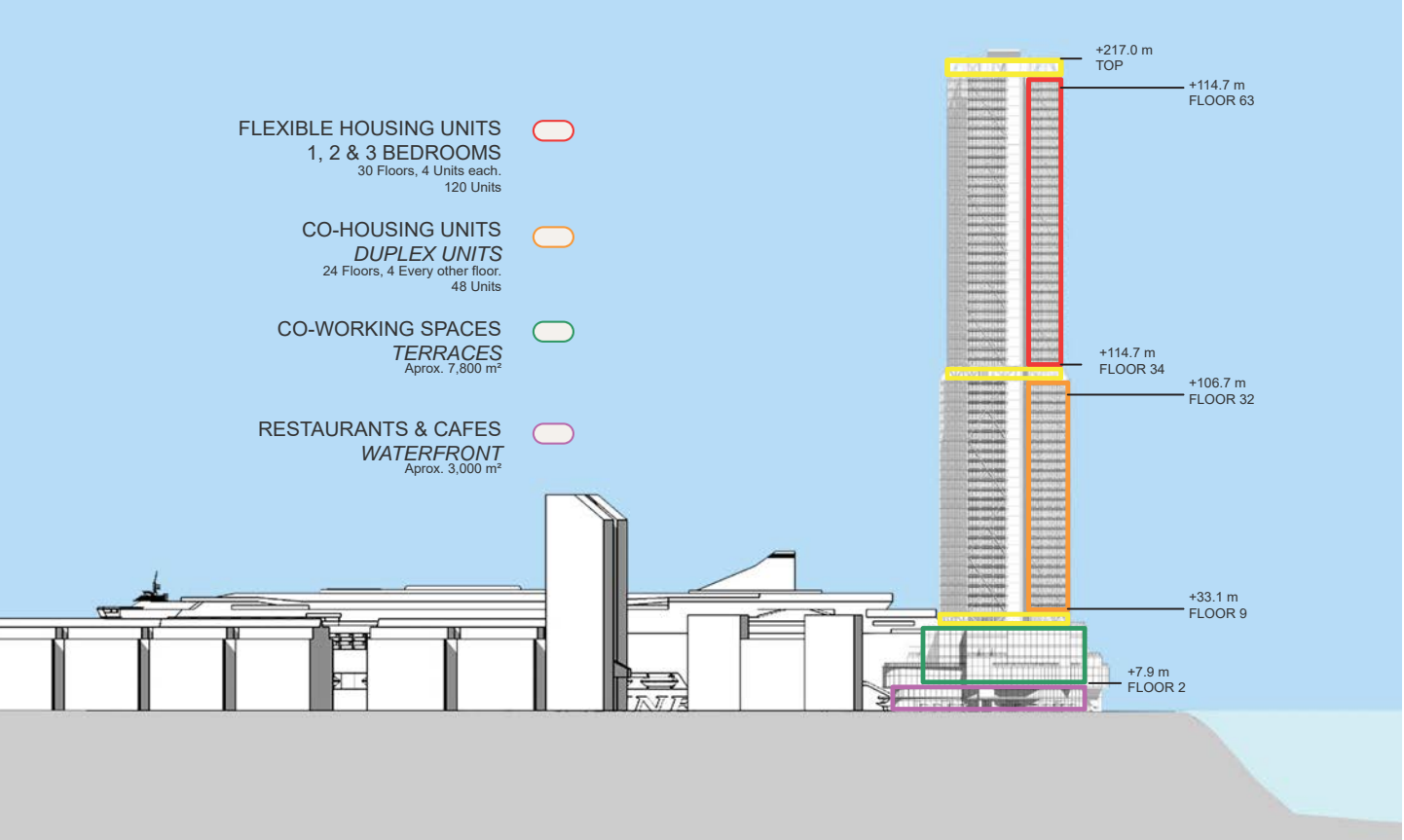
Summarizing, the building's program will have:
At the ground floor level and including the possibility to have a mezzanine, approximately 3,000 m2 for commercial use, restaurants and cafes towards the east and south facing the waterfront.

For the podium and from levels two up to level seven, there will be over 7,800 m2, designated for co-working spaces. In addition, terraces and inset balconies will be available for their members.

Three technicals floors will be located in the building. The first will be at the end of the podium and the beginning of the tower, the second will be at floor 34 and the last one at the top of the tower, at level 64.

The lower portion of the tower, between the first and second technical floors, will be for the duplex units. In total 24 floors with 4 units, every other floor will count for 48 duplex units. Each unit could have up to six single and one double bedroom, hence hosting around 384 persons.

The last portion of the tower setbacks. Even though the area of this units is smaller, I tried to keep the layout flexibility. For this portion of the building, I have decided to design one floor apartments for both a single person, and young couples as well as two and three bedrooms apartments. Moreover, I have explored the possibility to have a single floor co-living units with four large bedrooms and a fair common area. Here we have 30 floors with 4 units per floor, that in total counts for 120 housing units. And if we have on average 3 persons per unit this section will host 360 persons.



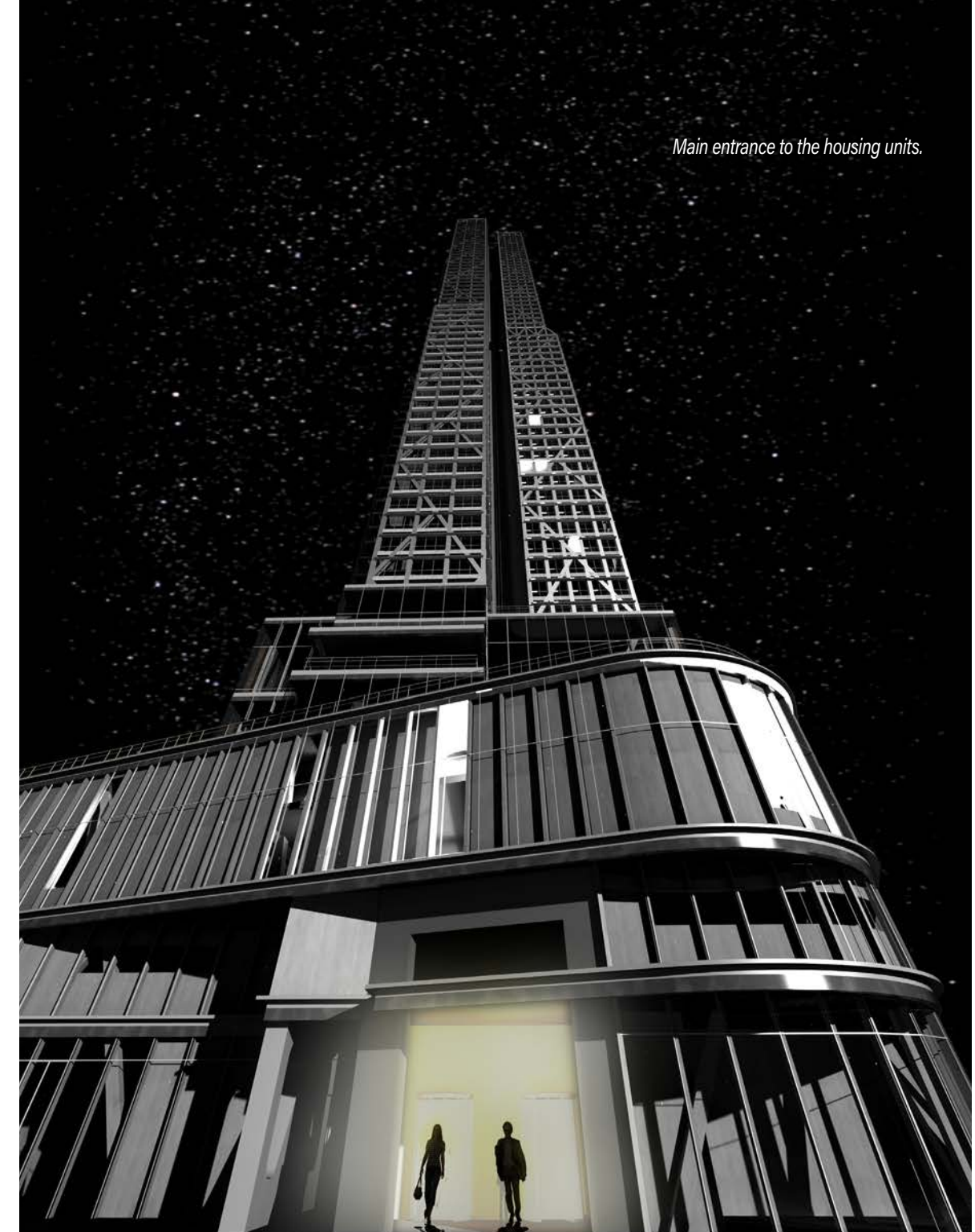
The building's program includes housing (co-housing and 1,2 and 3 bedrooms), co-working, restaurants and cafes.

The Design

In a tall building, there are many issues to tackle from the design point of view. The coordination between structure and architecture plays a very important role and even more if the objective is to obtain a flexible layout. Because CLT panels have a great bi-directional strength, I wanted to use them as a shear wall. Since early stages, I took the decision to focus on the design of flexible housing units, and here I found the challenge: How to design a shear wall system for a tall building and at the same time having flexible units?

Additionally, I wanted to provide a vibrant ground floor that could not only make a smooth transition from the city to the building but also become an attractive hub of activity at the 'edge' of the eco-district. In between, and not less important, are the coworking spaces. Here the challenge was to articulate the ground floor and the tower, providing attractive and inspiring working areas with generous communal areas and a lot of natural lighting.

Main entrance to the housing units.



Height Analysis

After studying the site's history and the future plans that the City Council has envisioned, I started to do an analysis of the building height. Within the Stockholm Royal Seaport, there is a design by 'Herzog & de Meuron' to build a housing tower of 170 meters height. Considering, that this building will be located on a site that is about 20 meters higher than my chosen site, my initial thought was to propose a building reaching to 200 meters height in order to make the most efficient use of the site. It wasn't an easy decision to take and even more taking into consideration the predominant building height in Stockholm, that ranges between 8 to 10 stories height. However later on a vision by one of the influential political parties in the city proposed increasing the density in the area of Loudden and included the construction of a number of tall buildings and one that promises to be the tallest building in Scandinavia.

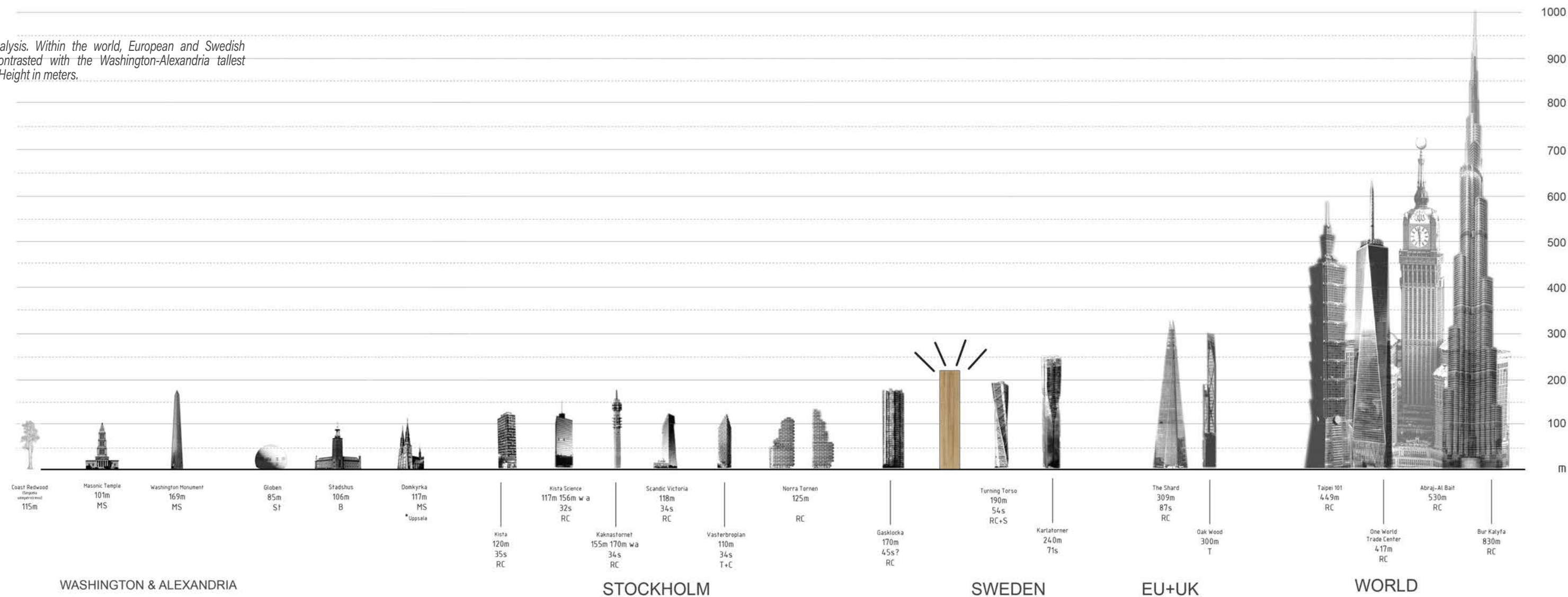
The research showed that in Sweden, the tallest building at the time is the Turning Torso and there is a project to build a 240 meters height building in Gothenburg. Within the international context the tallest building in Europe, the Shard (309m) in London, is just nine meters above the limit of the definition that the Council on Tall Buildings and Urban Habitat (CTBUH) has for a tall building. The CTBUH defines a tall building, if its height to the Architectural top is over 300 meters. And the Height to Architectural Top is measured: from the level of the lowest, significant, open-air, pedestrian entrance to the architectural top of the building, including spires, but not including antennae, signage, flag poles or other functional-technical equipment^[13].

The final design is a tower that reaches 217 meters height to the architectural top. I made a graphic comparison of the gross plot area, between the building footprints for conventional typologies of residential, office and retail and a tall building with a podium, that would include all of them. The analysis shows that by stacking all the program in a tower typology the footprint needed would be around 35 times smaller.



Fig. 42. The 'tall mass-timber building' surrounded by the buildings from Moderaterna's vision for Loudden in 2030, including the tallest building in Scandinavia.

Height analysis. Within the world, European and Swedish context contrasted with the Washington-Alexandria tallest buildings. Height in meters.

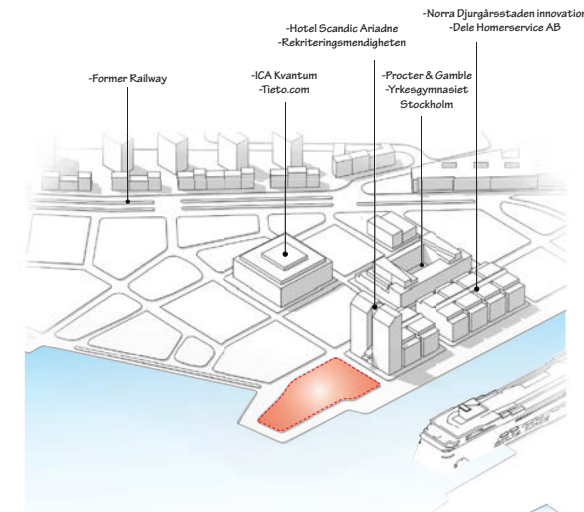


Design Development

I approached the design dividing it into two main components: The podium and the tower. For the tower, It was clear from the beginning that one of the main drivers was the intention to provide natural lighting as much as possible, specially because of the limited hours of sun light at this latitude. During early stages, I tried different configurations of a tower with a central core. At the same time, I studied alternatives of a 'bundled tubes' layout. One of the main structural challenges for the design of a tall building is to resist lateral forces, in this specific case due to the forces from the wind. As it was mentioned before, because the CLT mechanical properties, I attempted to address it by using a system of shear walls.

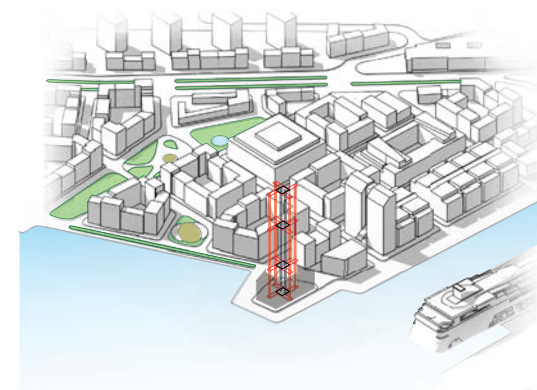
This input and the idea to have daylight in the main spaces lead the project to become like a pinwheel floor plan: four habitable wings rotated 45 degrees and arranged around a central core that provides stability and allows vertical transportation.

For the podium, the idea was to create transition from the public realm to the more private component of the program, co-living, and co-working spaces. The height of this volume reaches 8 stories, that is the average height for the winning proposal for the master plan presented by AIX Arkitekter. Following this master plan and in order to enhance the public vocation of a long waterfront, I wanted to create a destination for people to eat, have 'fika', to have a bath in summer and contemplate the beginning of the gorgeous Stockholm's archipelago.



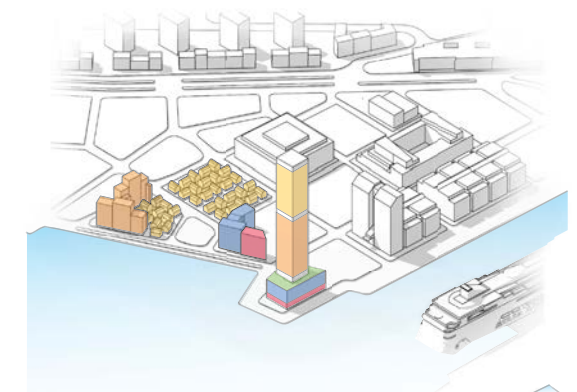
Existing buildings and proposed street + blocks layout

Not at scale



Core and Structure as Architecture

Trying to minimize the core area, but at the same providing strong stability against lateral loads, a cross like structural distribution of paired shear walls are conceived. The structure also works as a mean of vertical transportation of utilities and in some cases as a built in furniture.



Stacking it up!

A visual comparison between the building foot prints for conventional typologies -residential (houses and apartments), office and retail- and a tall building

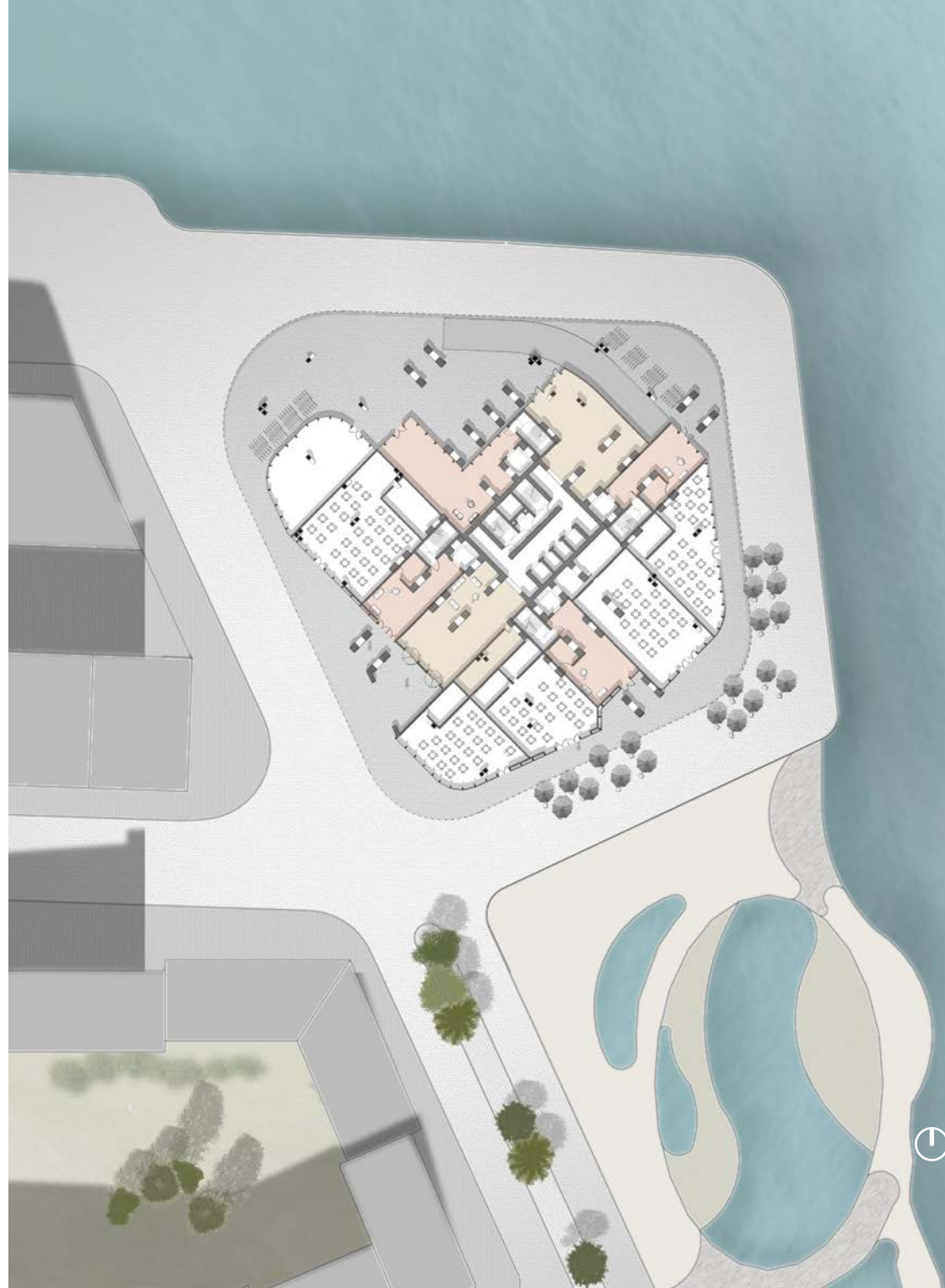


Footprint comparison
*Gross lotsize areas



A public swimming area

At the street level, the building articulates one of the most vibrant areas within the development, a public facility for swimming! All the activities generated at the podium level get an extension to the harbour promenade.



Ground Floor Plan.



In addition to the restaurants and cafes, located mainly to get the sun from south and east orientation, the ground floor provides independent access to the tower and to the higher levels of the co-working spaces in the podium. The main entrance for the housing is located in the southwest corner and the service entrance is accessible from the opposite northeast corner. The underground level has a vehicular ramp access towards the north. The co-working areas are also divided in for sections and each one has its own mean of egress as well as it elevators.

The podium volume relates directly to the planned surrounding buildings as well with the ships docking to the new Ferry Terminal 'Värtaterminalen' located north across the water. Aligned with the drivers for the design of the eco-district, the surrounding surface is pedestrian friendly. The restaurants will count with two indoor levels and they could extend its area towards the sidewalk when the weather allows it.

On the cafes and restaurants, the facade will be glassed and thin structural elements will provide not only the structural support but also the rhythm to the exterior. For the finishing of the floors as well as for the interior walls, when possible the proposed material is going to be wood.



Fig. 47.

The City Council encourages the use of public transportation, therefore most people would approach the building from the south along the boulevard by the waterfront.



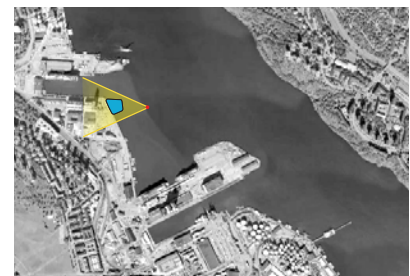
Getting to the building from the south, along the waterfront.



Looking at the waterfront, from a restaurant in the southeast of the podium.



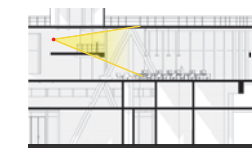
I also envisaged that during the warmer days of summer there will be many activities around the building. Children jumping into the water, kayaking, people taking a sunbath, riding a bike and also sailing in front of this vibrant hub. The prominent site of the building helps to create a protected and enclosed bath area.



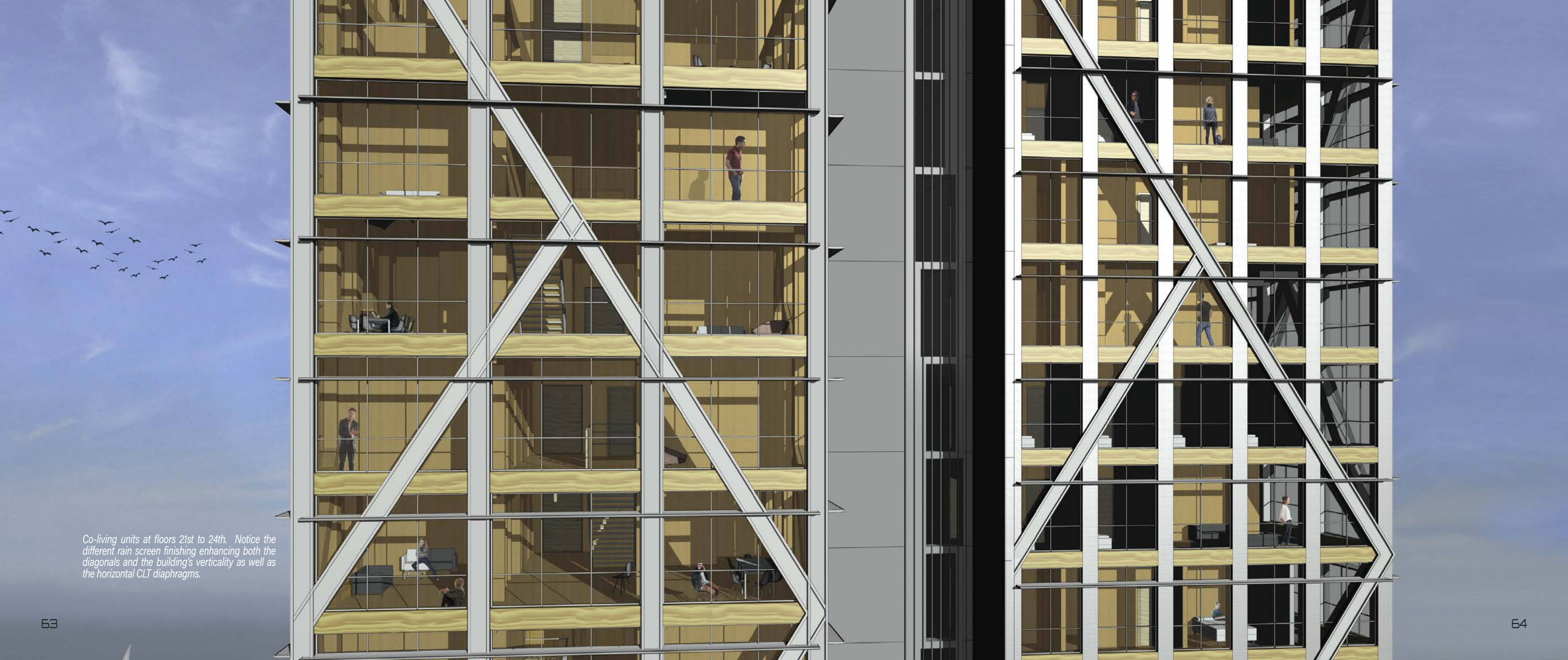
Sailing east from the building.



For the co-working spaces I wanted a design that is flexible and allows constant collaboration with individuals, creating a sense of community. The co-working areas are offering membership options like on demand, hot desk and dedicated desk. Some of them are more convenient if you are either a remote and part-time worker or if you are a startup or small agency. Even for individuals and freelancers having the need of some days per month. The share working stations are located in the double height spaces and the meeting rooms, as well as the more private offices, are closer to the core. In order to promote creativity and to propitiate social interaction, the main lounge areas have privileges views towards the archipelago.

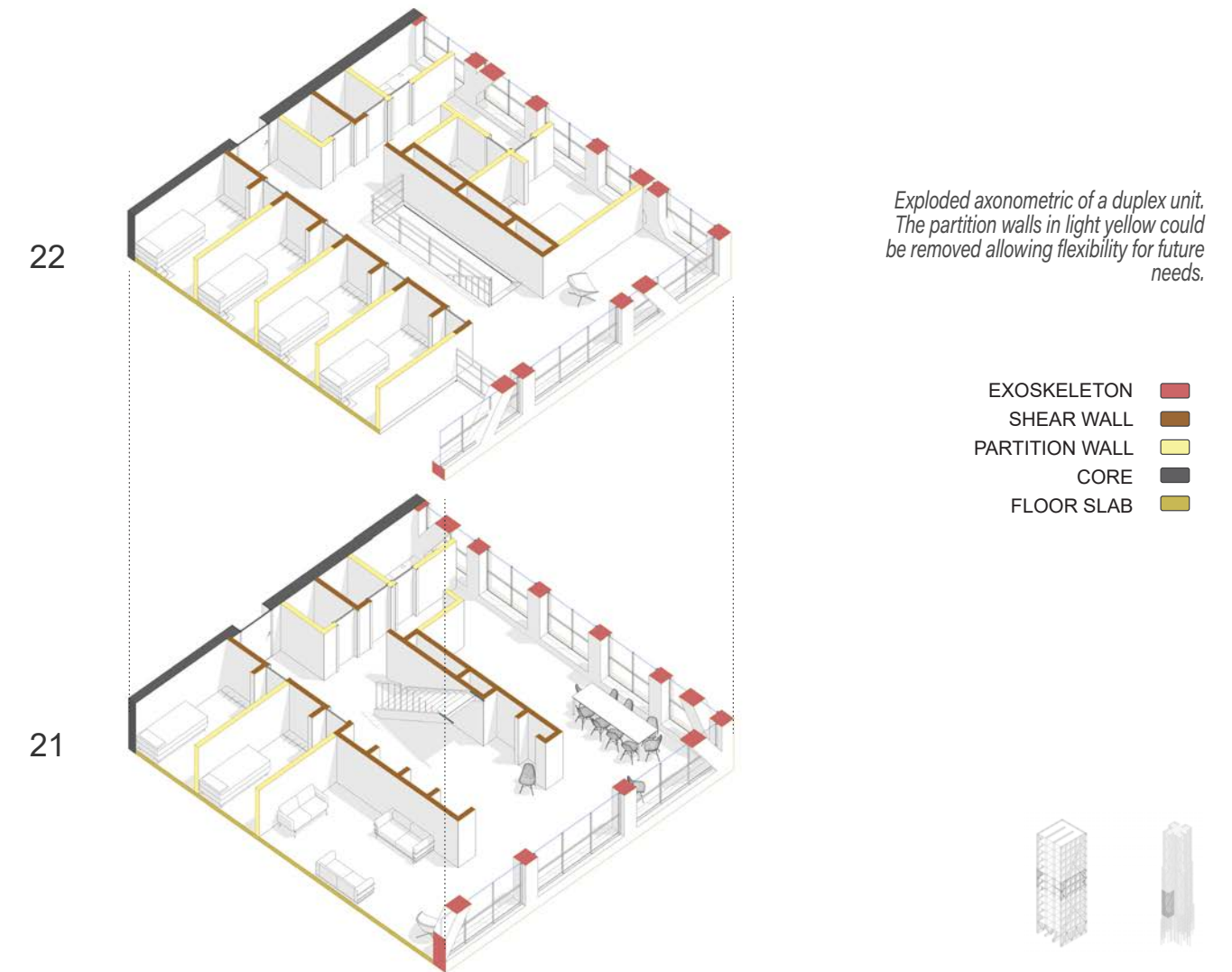


Interior of the southeast co-working space. Looking at the third floor from the fourth level.



Co-living units at floors 21st to 24th. Notice the different rain screen finishing enhancing both the diagonals and the building's verticality as well as the horizontal CLT diaphragms.

For the tower, it makes sense to suggest a bigger and a denser apartment layout on the first half of it. Therefore, from floor 9 to floor 32, we have duplex units with access on every floor. The challenge was to provide flexible housing units, so the tenant would be able to adjust the layout if the needs change over time. A straightforward ordering system, where the two doubled shearwalls not only provide space for inbuilt furniture and space for the utilities to run up and down but also encases the main circulation articulating the rooms and the communal areas. At one level, the main communal areas like the large open kitchen and the living room occupy the sides and the exterior corners. The other level has only bedrooms and a shared room that could be used to study, stretch or simply hang out. In addition, the common areas will have a double height space increasing the connection between floors. In both levels, the bathrooms and the kitchen are located towards the building core and attached to the doubled shear walls. Thanks to the simple structural system some of the partition walls could be removed, allowing the expansion of the bedrooms when needed. Along the circulation area, there is provision for storage of belongings that could be shared, like tools and any other thing. The interior walls as well the floor will expose the wood when it's possible.

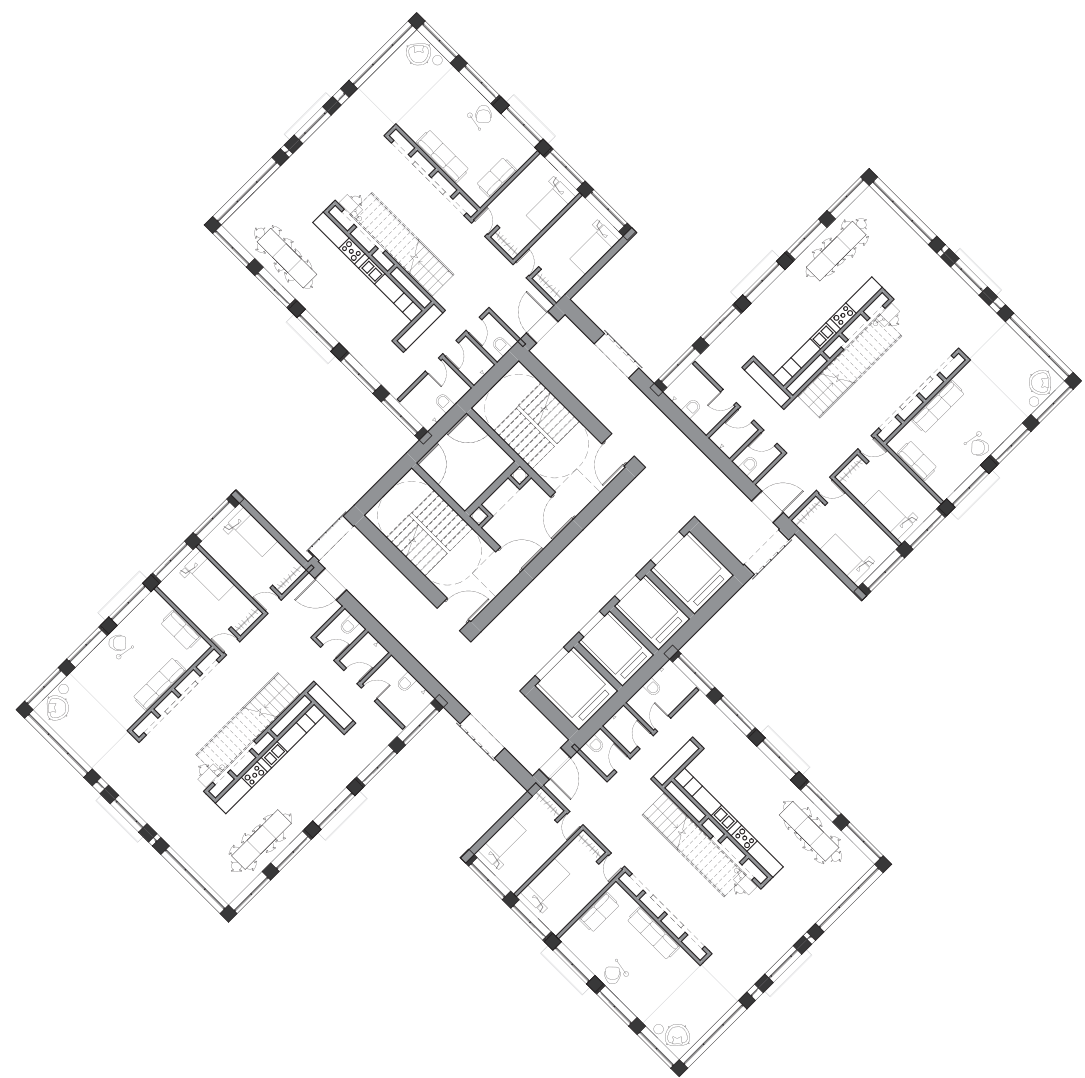




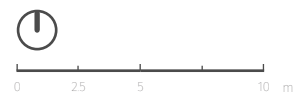
A sectional perspective of stacking duplex units, through the double height spaces.

After the technical floor at level 33, the volume of the building sets back. The units from floor 34 to floor 63, are dedicated to one, two or three bedrooms apartments in one single level. This section of the tower provides a more conventional way of living for either a single person, a young couple or a group of 3 friends. Additionally, I included a layout for a 4 bedroom unit, each with a private bathroom, that shares the kitchen and the living room.

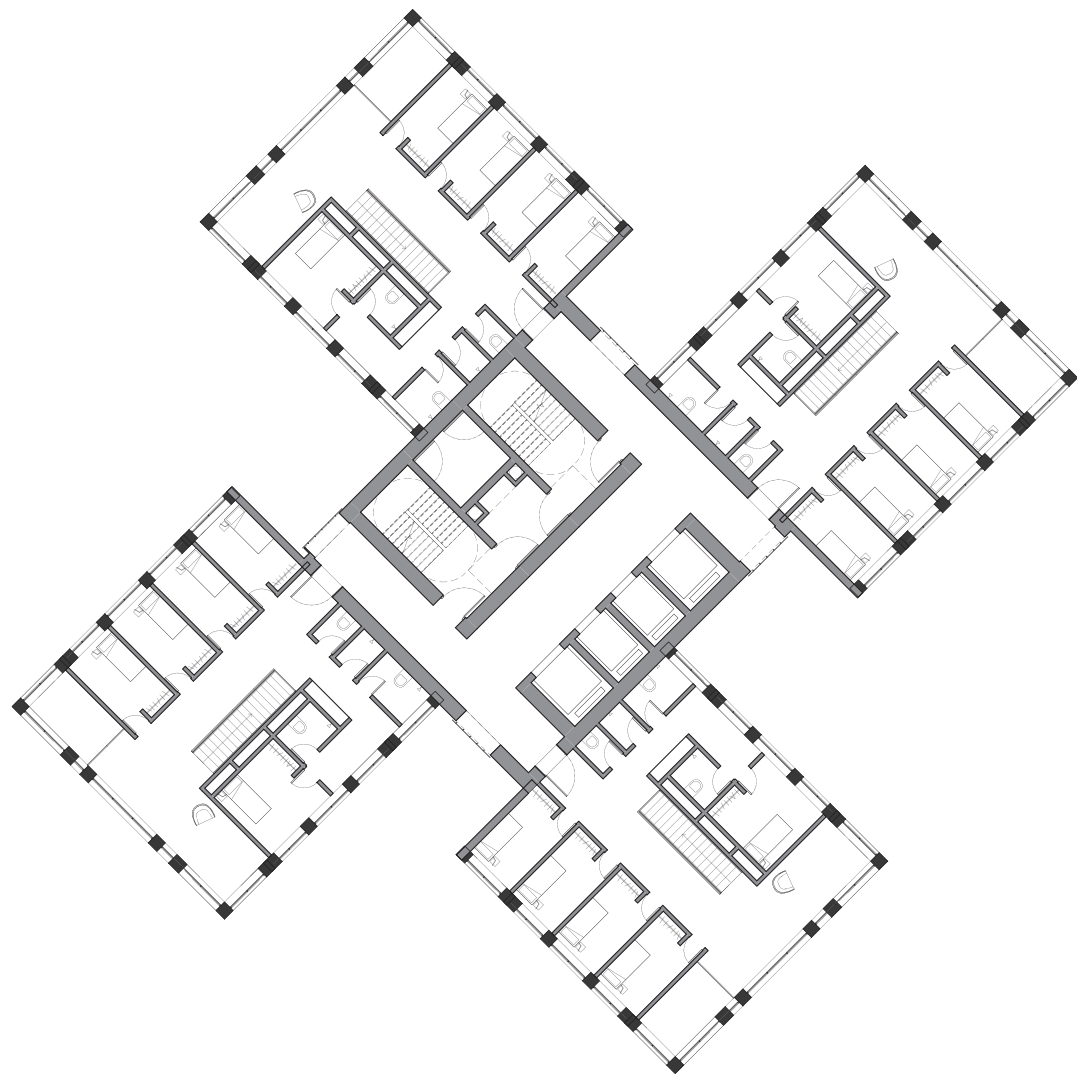
As for the lower part of the tower, the humid areas are attached to the doubled shear walls and the bedrooms are located around the shared areas. The concept of flexibility is once again present and the only limitation for the mirrored units is the necessary space for the apartment's entrance.



Typical floor plan for a duplex unit,
Lower level, with large common areas. Floor 9th to floor 32nd.



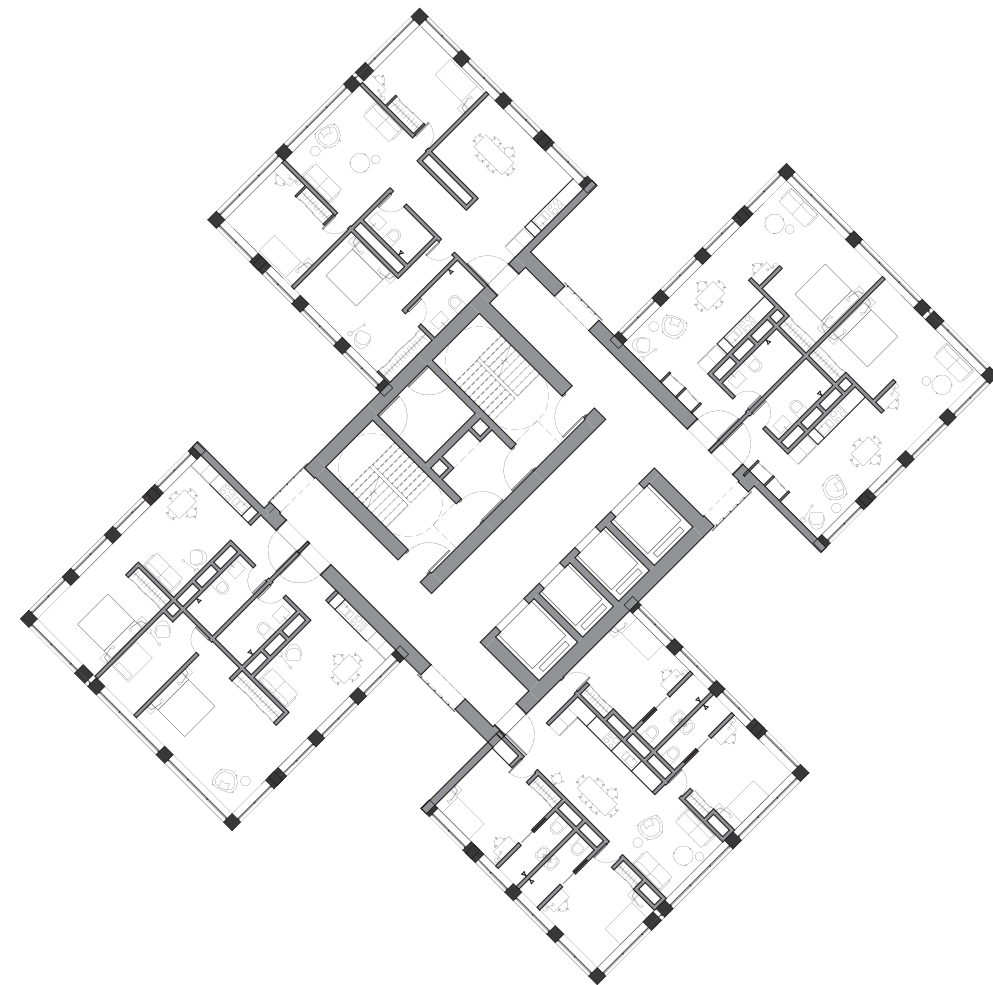
The common areas are located at the periphery and CLT is exposed on walls and ceiling.



*Typical floor plan for a duplex unit,
Upper level, private area. Floor 9th to floor 32nd.*



0 2.5 5 10 m



*Floor plan alternatives for 1, 2 and 3 bedroom units and a 4
bedroom shared unit. Floor 34th to floor 63th.*



0 2.5 5 10 m

Tectonics

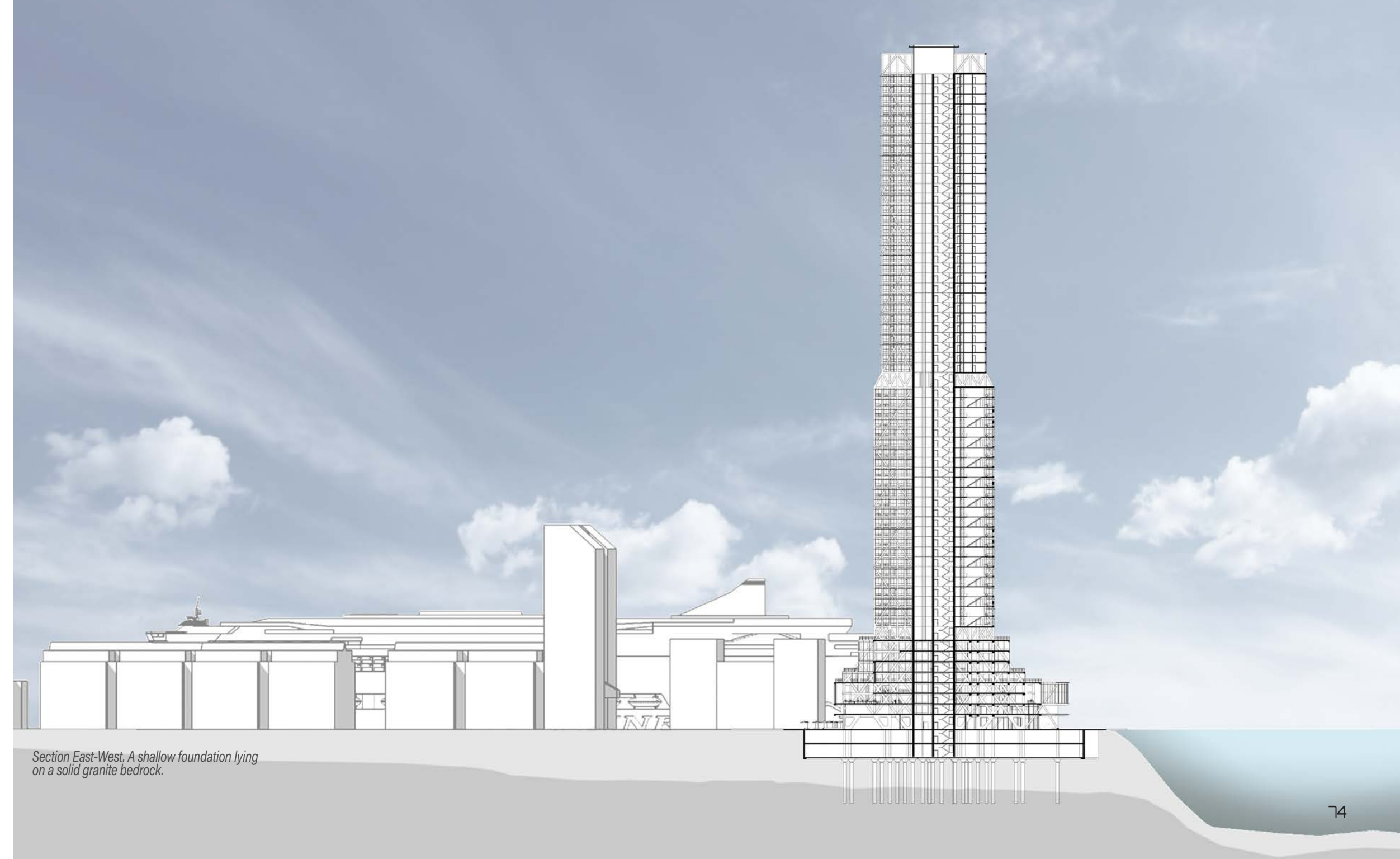
The structural design of a tall building is a complex task and even more so while trying to propose the use of a new building material. The structural design of this building is out of the scope of this project.

However, I have dedicated the time of an independent study with profesor Mehdi Setareh, to analyze some precedents and better understand the proposal for a tall timber building, the “Concrete Jointed Timber Frame”, by Skidmore Owings and Merrill (SOM). This study helped me to draw some conclusions and most importantly to propose a coherent structure using mainly CLT panels. Some of the conclusions are:

From the study, I found that there are two main ways to reduce the embodied carbon footprint of a building structure. First, by minimizing structural materials and second by using materials that is less carbon intensive such as timber.

Because timber is a low-density material, there could be significant savings in the materials required for the foundations

The material quantities required in the floor system of typical building counts for approximately 70% of all material used, therefore engineers ought to optimize the floor design.



Section East-West. A shallow foundation lying on a solid granite bedrock.

Using CLT panels spanning between rigid moment frames will stiffens the floor, which reduces deflections and vibrations. It also allows minimizing the thickness of the floor slab and consequently optimizing costs.

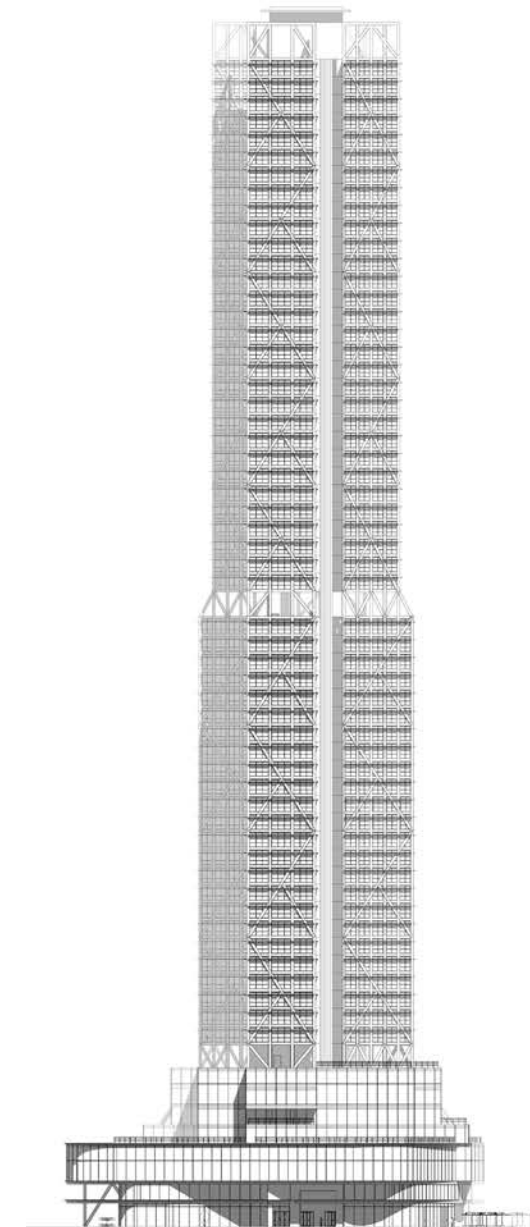
In order to minimize the potential of net uplift due to wind loads, we ought to maximize the amount of gravity loads that are supported by the lateral load resisting system.

Gravity and lateral loads need not be considered at their maximum values simultaneously.

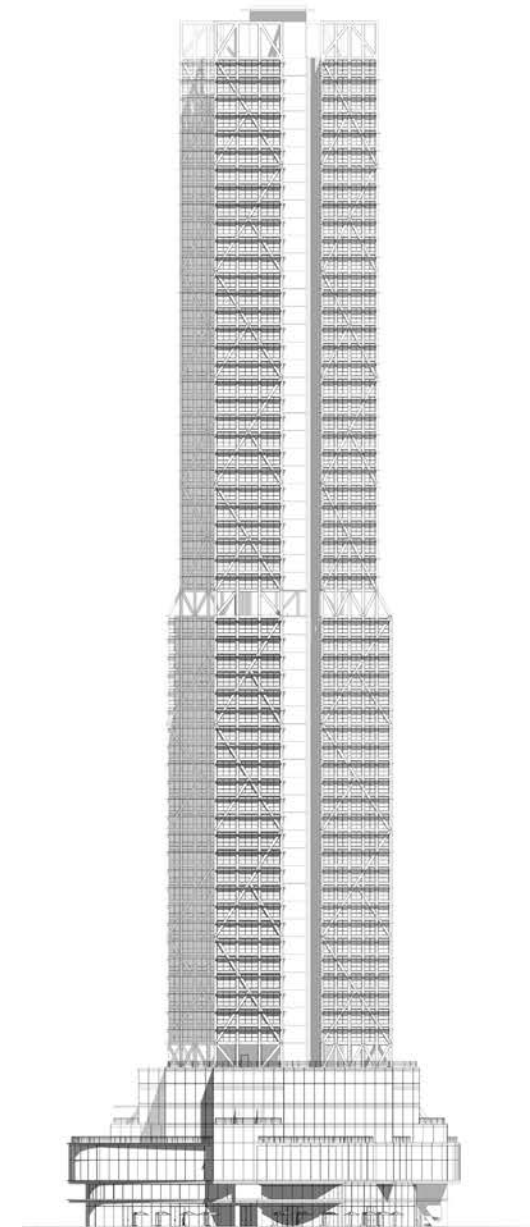
An efficient lateral load resisting system will have a large radius of gyration. If we consider our building as a vertical cantilevered beam, we can think about it, as trying to increase the moment of inertia of the 'beam' section.

Even though mass timber products have many advantages to offer, it makes sense for designers to combine different building material based on their respective strength.

The study and proposed design for the, "Concrete Jointed Timber Frame", suggests that mass timber is a viable structural alternative to reinforced concrete and structural steel for use in high-rise buildings.



South west Elevation



South east Elevation

For this thesis project, the proposed structural system is a composite system. It uses reinforced concrete, engineered timber, and steel for some connectors.

Due to the low density of timber as well as the shallow bedrock present in the site, the foundation is not deep compared with a building of a similar height.

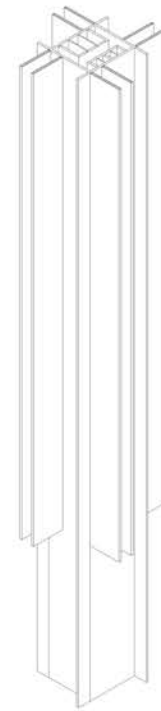
Reinforced concrete is the main structural material from the foundation and up to the ground floor, including it. The experience shows that for a timber construction it is a good practice to start the use of timber above a podium made of a more weather resistant material, like concrete.

The lateral resisting load system intends to be redundant and is composed of a core-shear wall system and an exoskeleton that transmits the lateral loads to the core through rigid diaphragms.

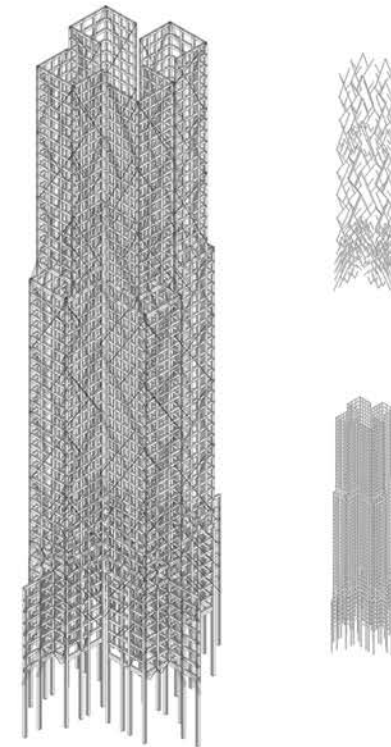
From the almost square core, a double system of shear walls extends from each of its sides to the exterior. The intent is to combine the structural function of the double-wall while providing the necessary space for some of the building utilities for running up and down as well as built-in furniture when it is possible.

A continuous shear-wall up to the top of the building is an effective way to support lateral loads, but it could limit the architectural layout. In order to provide flexibility to the housing units, the system is complemented with an exoskeleton. An outer modular grid made by layering cut CLT panels.

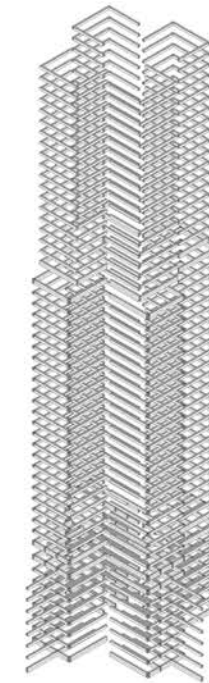
Finally, CLT floor panels act as a rigid diaphragm, transmitting loads from the outer shell to the concrete core.



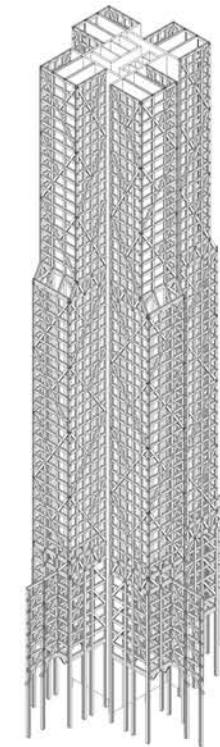
CORE + SHEAR WALLS



EXOSKELETON

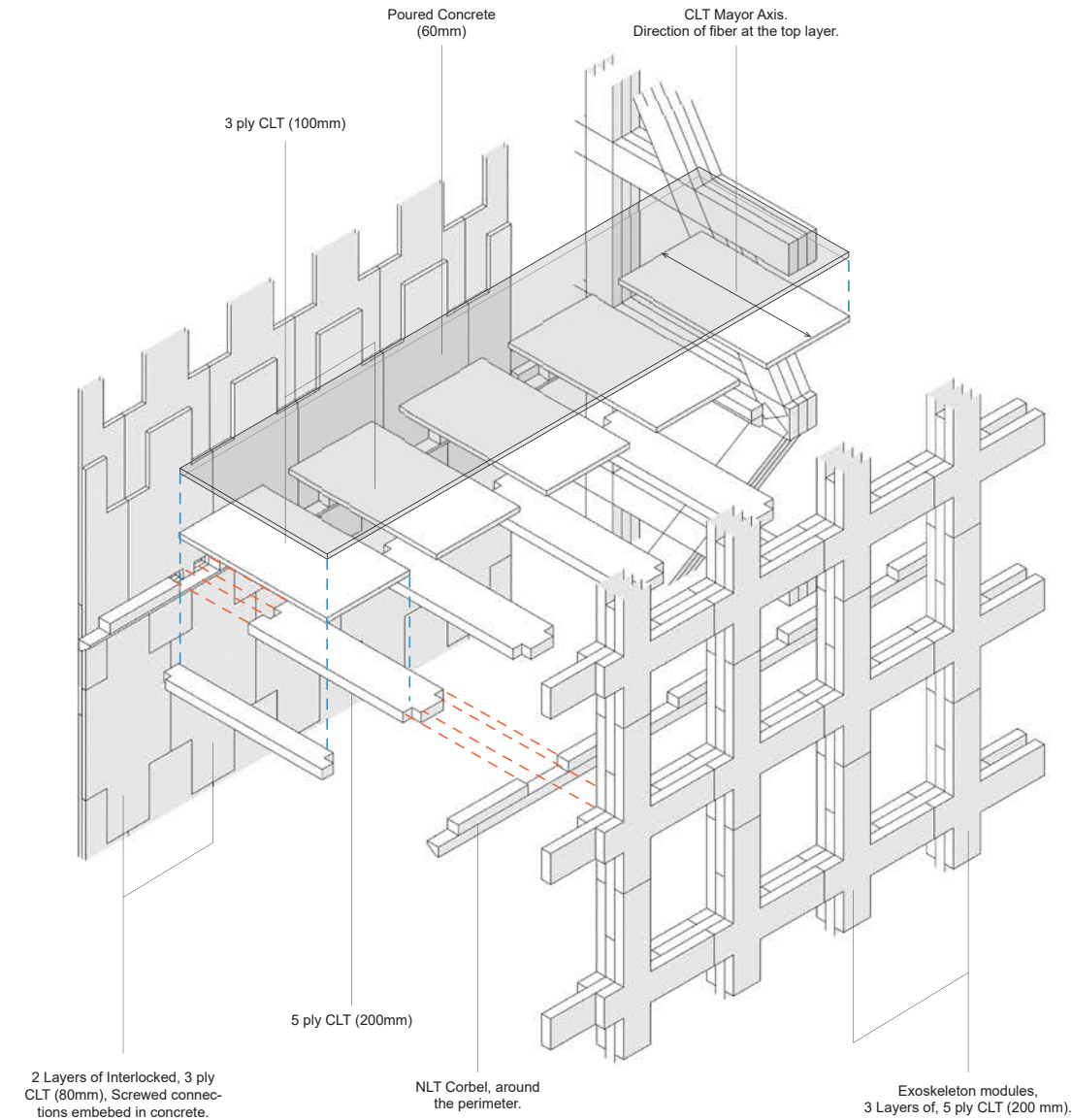
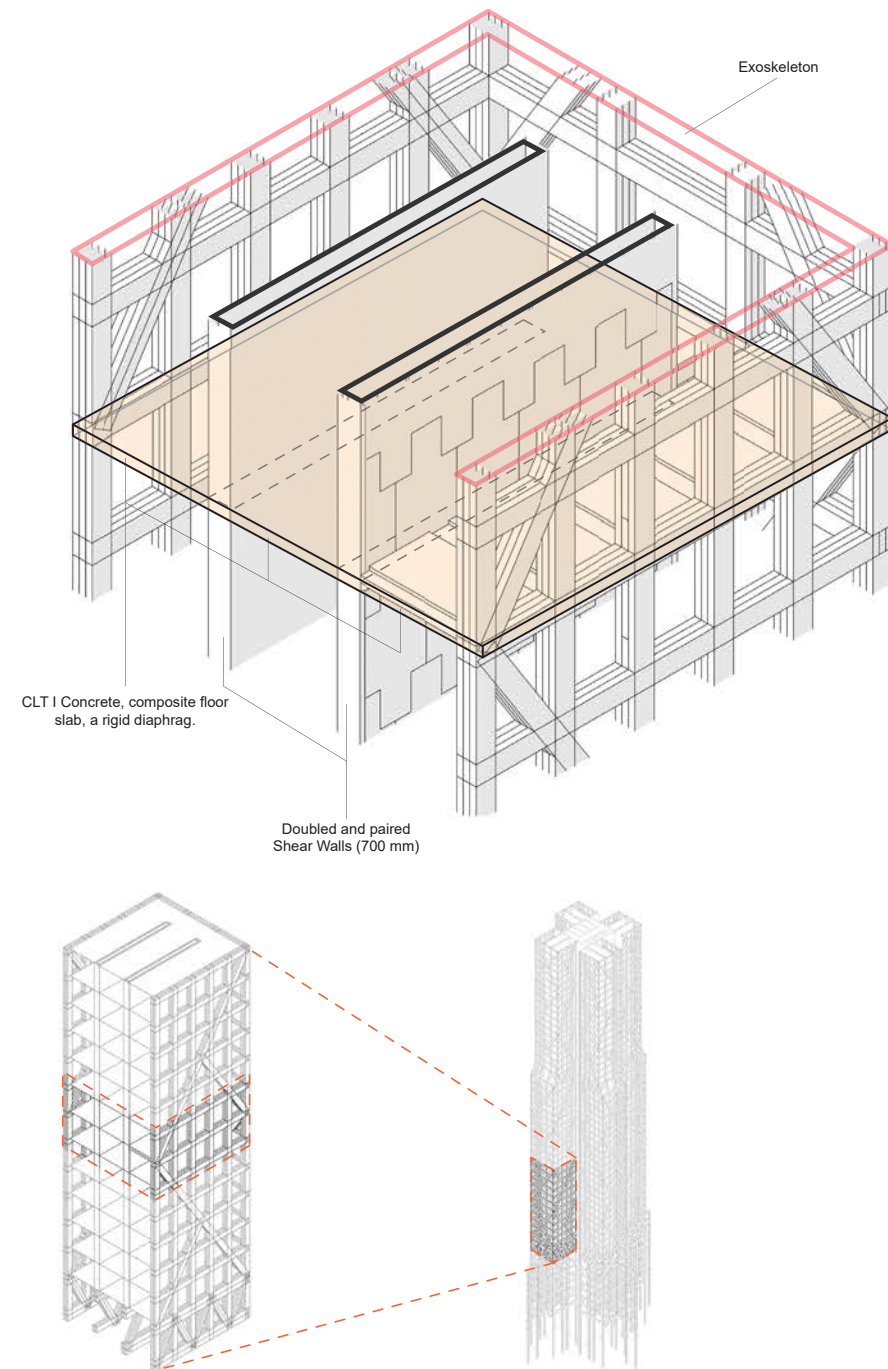


FLOOR SLABS



**COMPOSITE
STRUCTURAL SYSTEM**

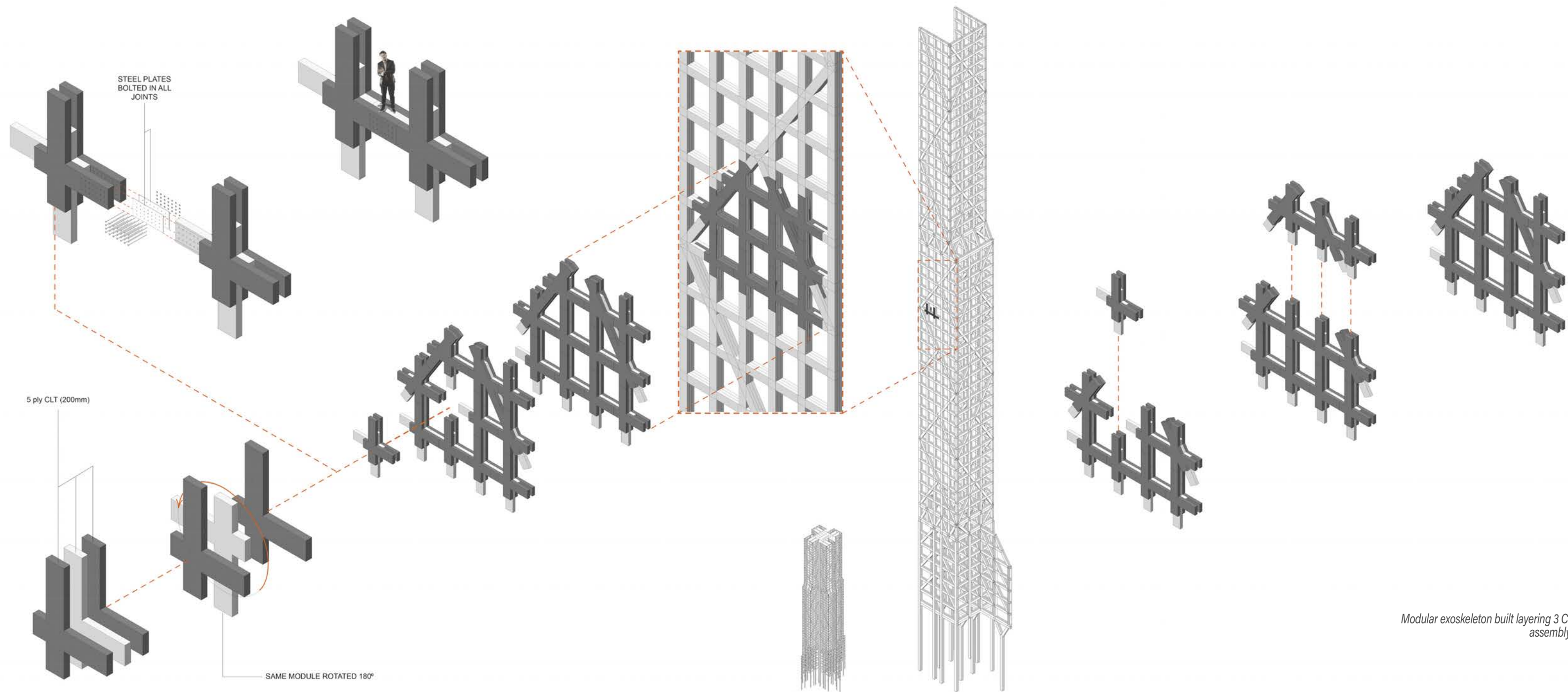
Structure diagram. A combination of a shear wall system and an exoskeleton articulated by the rigid floor slabs provides a steady structural system.



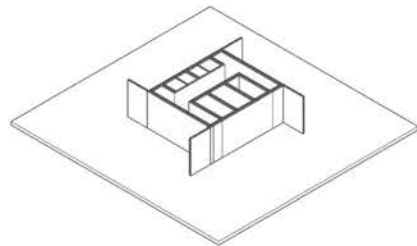
The gravity load system consists of two layers of CLT panels bearing in one direction. The 5 ply panels span at the exterior, between the exoskeleton and the double-shear wall at the interior. For the middle section of each unit, the CLT panels span between the doubled shear-walls. In order to minimize the use of material and at the same time providing space for lighting fixtures and most importantly create a sound barrier, there are two non continuous layers of CLT panels. A topping layer of mortar helps to increase the weight of the building and serves as a base layer for the wood finishing.

The shear walls are also made by layering and interlocking CLT modular panels. The idea here is to distribute the weakness of the connection surfaces as much as possible.

Shear walls, exoskeleton and diaphragms assembly diagram.

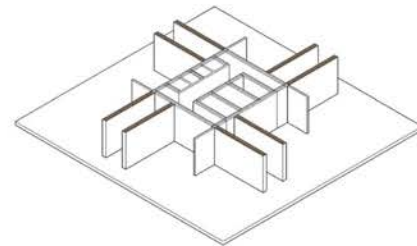


Modular exoskeleton built layering 3 CLT panels, assembly diagram.



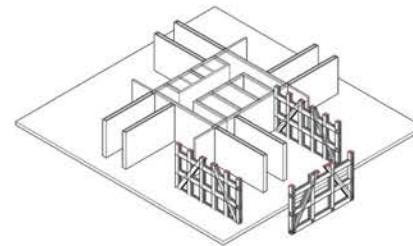
CONCRETE CORE

First, the reinforced concrete core is constructed. Steel connectors are put in place to attach the shear walls.



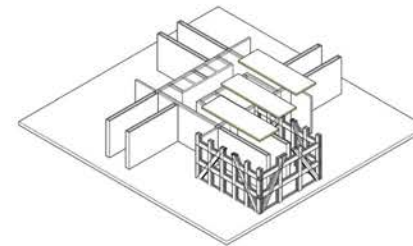
SHEAR WALLS

The shear walls are assembled and put in place.



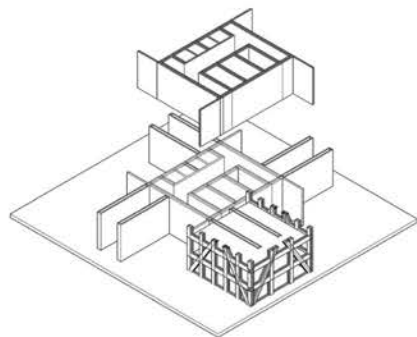
EXOSKELETON

The modular exoskeleton is assembled on ground, for two storeys high. Then, they are lifted and put in place.



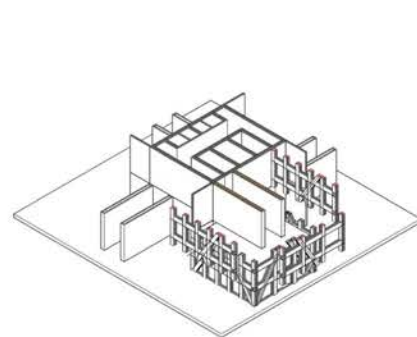
FLOOR DIAPHRAGM

The floor panels are installed, and all the utilities that run under and above as well.



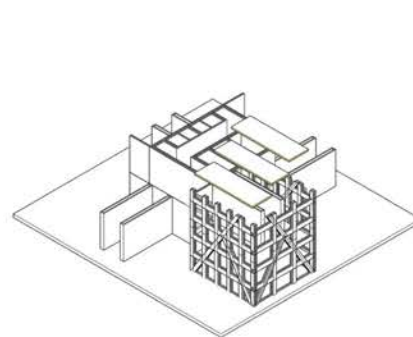
DUPLEX UNIT

A duplex unit is ready and a new concrete core can be constructed.



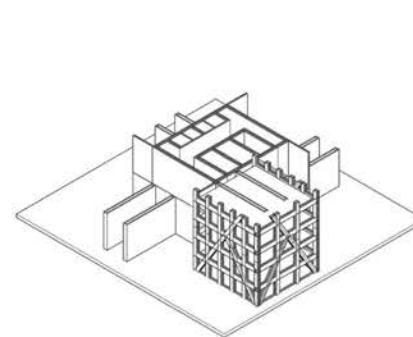
SHEAR WALLS + EXOSKELETON

The process is repeated again, first assembling and installing the shear walls and later lifting and installing the exoskeleton.



CONCRETE POURING

At the same time that the floor panels are installed at the top duplex unit, the concrete is poured on the lower levels.



'FOUR WINGS'

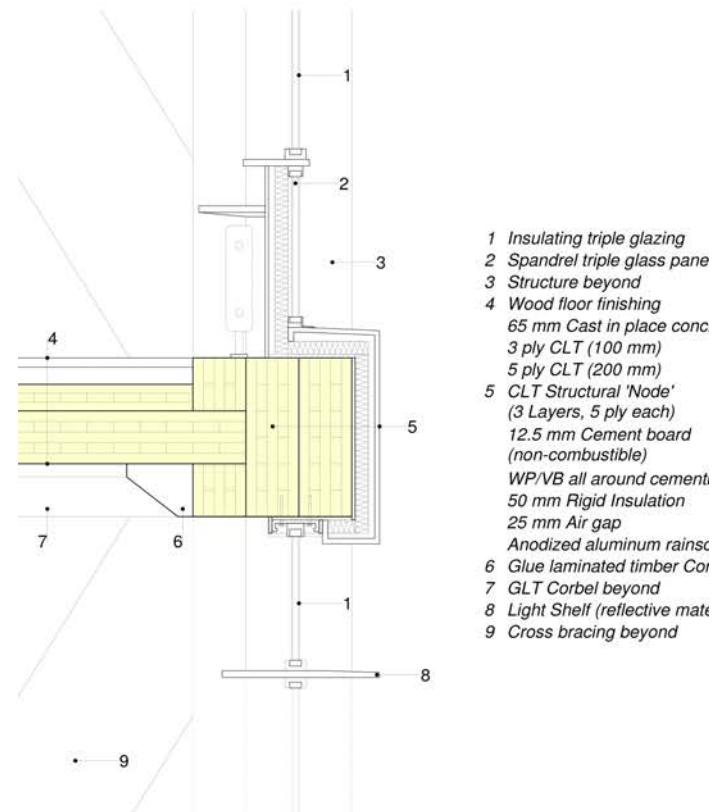
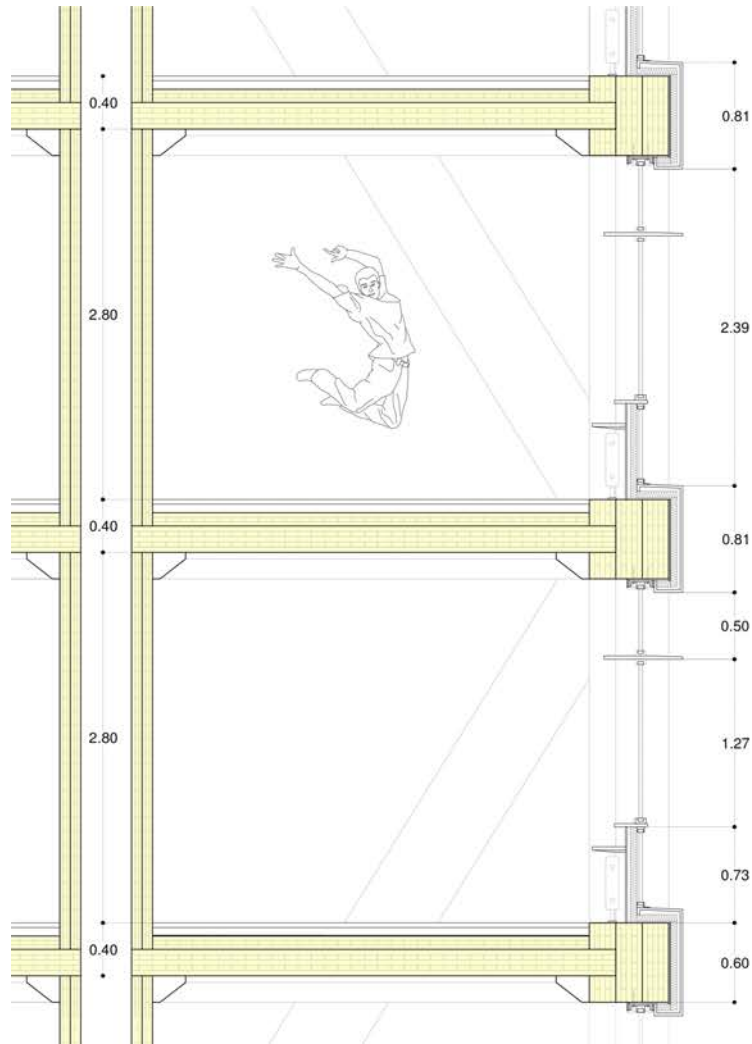
The four wings can be constructed in parallel.

One of the greatest advantages of the modular engineered timber construction is the speed of the assembling process. In addition, the site is cleaner and the construction crew is smaller than the one for a conventional steel or concrete construction.

The proposed concept for the construction sequence for the tower is explain in the diagram. There are four main steps: the erection of the concrete core, the shear walls assembling, the exoskeleton assembly and finally the installation of the floor diaphragms.

Those steps are repeated at each of the four wings of the building while the finishes are carrying out on the lower floors. The exoskeleton modular panels are prefabricated and they could be assembled one to one, or in order to speed the process, they could be assembled to complete an entire level and then be lifted to their place.

Construction sequence diagram, for the tower and each of its four wings.

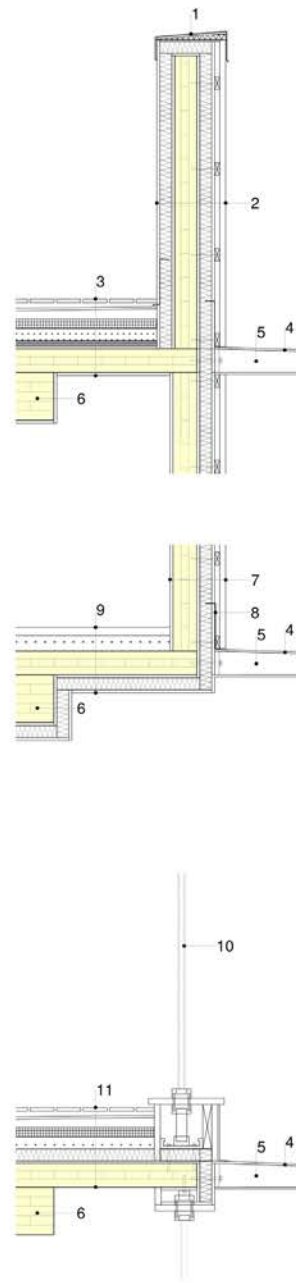
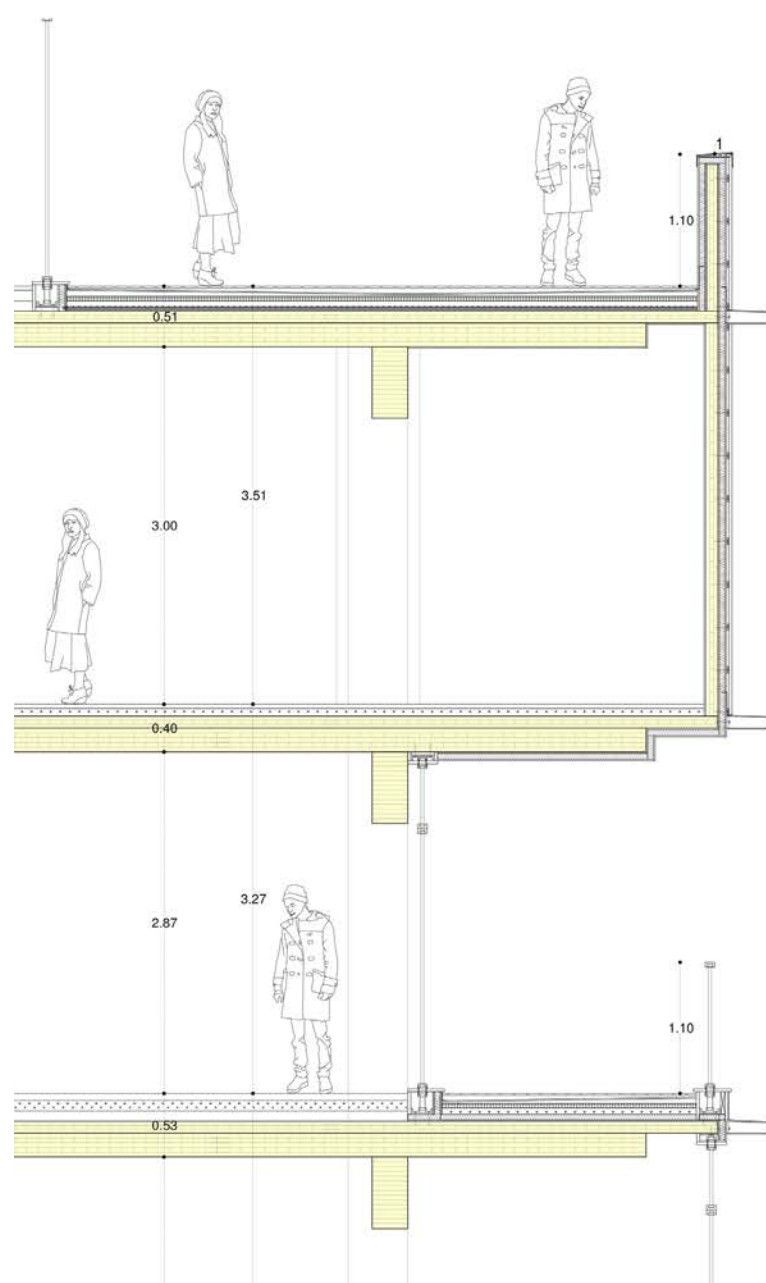


Typical wall section for the tower

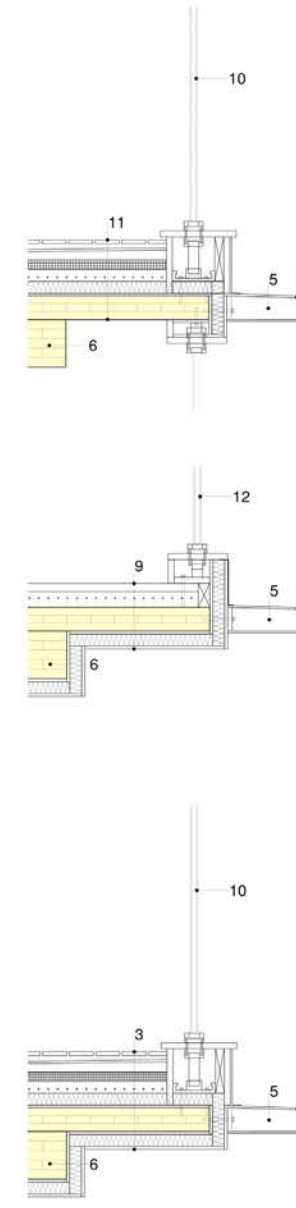
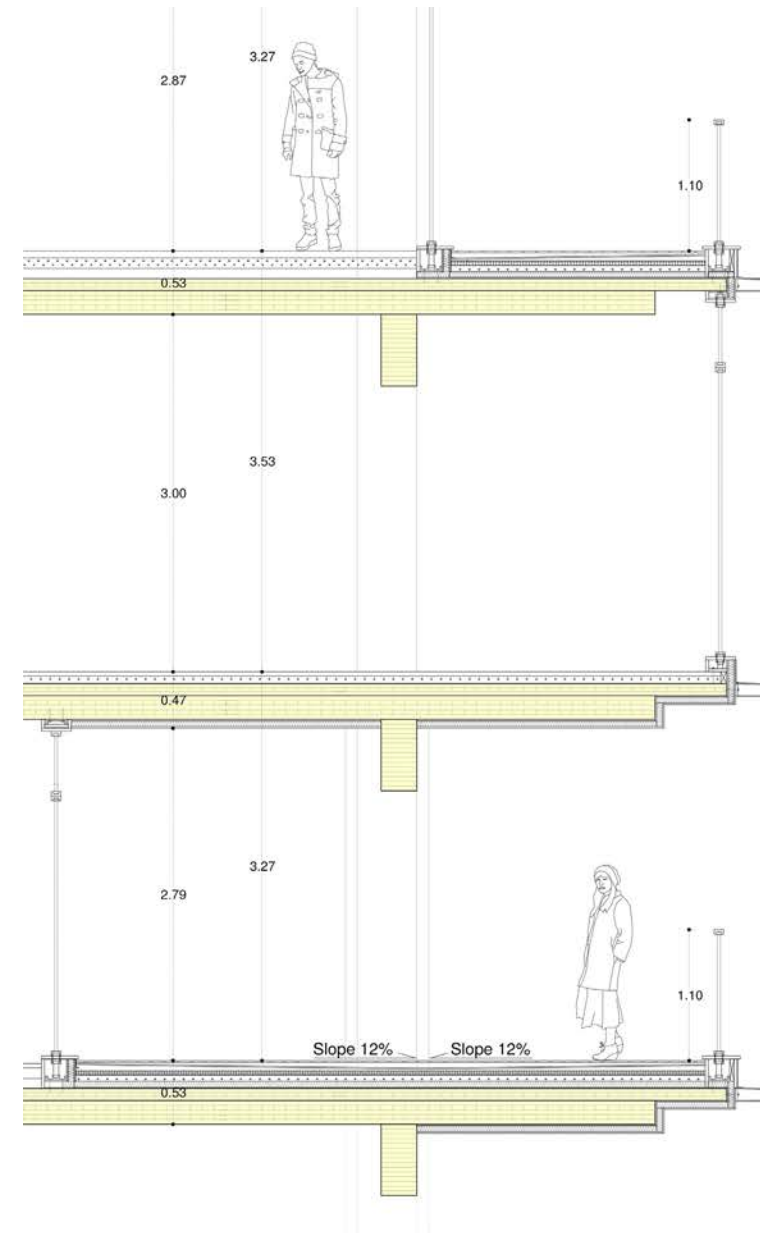
There is limited knowledge about how CLT panels ages while is being exposed to weathering and it will take some time to carry out tests and to collect information to predict its behavior. But because moisture and thermic insulation is needed at Stockholm's latitude and also to reach energy efficiency, it is necessary to protect the proposed exoskeleton.

First a layer of non-combustible cement board covers the CLT, then an air vapor barrier and a rigid insulation are installed. Finally, an aluminum rain-screen protects all the assembly. On the tower, the rain-screen has different finished surfaces because the idea is to highlight the verticality of the building.

For the podium levels, I have considered different wall sections because here the co-working spaces have terraces, double height balconies and either glazed or opaque facades. Here, I have applied the same principles as in the tower, protecting all the structural engineered timber that could be exposed to the weathering. Closer to the ground level I wanted the building to reveal its structural materiality, but because of technical reasons this wouldn't be possible, I decided to propose a timber cladding, waterproof painted to be predominant at the podium.



- 1 Aluminium flashing
- 2 Anodized aluminum rainscreen
- 50 mm Rigid Insulation
- 12.5 mm Cement board (non-combustible)
- 3 ply CLT (100 mm)
- 12.5 mm Cement board (non-combustible)
- WP/VB all around cementboard
- 50 mm Rigid Insulation
- 25 mm Air gap
- Attachment to CLT
- 50 X 20 mm Furring strips
- Timber cladding rainproof painted
- 3 Ipe decking or similar
- 50 x 50 mm treated timber bearers
- 40 mm Rigid Insulation
- Impermeable waterproofing + drainage material
- 50 mm topping slab 2°-3° slope
- 25 mm XPS acoustic break
- WP/VB all around cementboard
- 12.5 mm Cement board (non-combustible)
- 3 ply CLT (100 mm)
- Painted plasterboard ceiling lining
- 4 Anodized aluminium cover
- 5 Metal eave
- 6 5 ply CLT (200 mm)
- 7 Timber finishing screwed
- 12.5 mm Cement board (non-combustible)
- 3 ply CLT (100 mm)
- 12.5 mm Cement board (non-combustible)
- WP/VB all around cementboard
- 50 mm Rigid Insulation
- Attachment to CLT
- 50 X 20 mm Furring strips
- Timber cladding rainproof painted
- 8 Metal flashing
- 9 Wood floor finishing
- 65 mm Cast in place concrete
- 3 ply CLT (100 mm)
- WP/VB all around cementboard
- 12.5 mm Cement board (non-combustible)
- 50 mm Rigid Insulation
- 25 mm Air gap
- Anodized aluminum rainscreen
- 10 Glass & stainless steel handrail
- 11 Ipe decking or similar
- 50 x 50 mm treated timber bearers
- 40 mm Rigid Insulation
- Impermeable waterproofing + drainage material
- 50 mm topping slab 2°-3° slope
- 25 mm XPS acoustic break
- WP/VB all around cementboard
- 12.5 mm Cement board (non-combustible)
- Fully adhered membrane
- 3 ply CLT (100 mm)
- 12 Insulating triple glazing



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Typical wall section for the podium

Conclusion

If we want to address the increasing demand of housing in the cities and help to minimize the embodied carbon footprint of the buildings, in an effort to mitigate climate change, we should consider the use of timber as the main structural material for tall buildings. The building industry have already started to use engineered timber as a main structural material. Likewise, policy makers have started to focus efforts and allocate budget for the research and development of new technology to build tall with timber.

There are still some barriers to the realization of tall timber towers. These include additional required testing, lack of precedents and code provisions regarding fire engineering and construction technologies. Even though building codes have started to make provisions to include CLT and mass timber products, still there is a need to update them in order to include new compliant building systems.

In addition, there is a need for innovation in connections and the subsequent testing and research to validate their performance and development of design guidelines. So far, steel connections and long screws are the most used connections for mass timber framing.

In order to take full advantage of this less carbon intensive material and to overcome current challenges, there is a need for a platform to better share information and coordinate efforts from the industry, academy and practitioner designers.

In addition, I believe that to gain acceptance of the use of a new building material, the design and construction of an iconic tall building using mainly engineered timber would serve as an opportunity not only to gather technical knowledge but also as a vitrine to encourage the massive use of engineered timber globally.

I feel that this study has helped me to integrate my technical background and my interest in sustainability by using engineered wood that I strongly believe is the material of the future.

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Fig. 43. Bird's eye view of the tower from the east.
The National Royal Park on the left and the 'old town' in
the background.

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