TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Civil Engineering and Architecture

# TALL TIMBER BUILDINGS AS A CLIMATE CHANGE MITIGATION TOOL. 30-STORY TIMBER HIGH-RISE IN TALLINN

Puidust kõrghooned kui kliimamuutuse leevendamise vahend. 30-korruseline puidust kõrghoone Tallinnas

MASTER THESIS

Student: Sofya Smirnova

Student code: A131790

Supervisor: prof. Kimmo Lylykangas

Tallinn 2021

**AUTHOR'S DECLARATION**

Hereby I declare, that I have written this thesis independently.
No academic degree has been applied for based on this material.
All works, major viewpoints and data of the other authors used in this thesis have been referenced.

"......."................... 20…..

Author: .............................
/signature /

Thesis is in accordance with terms and requirements

"......."................... 20….

Supervisor: …..........................
/signature/

Accepted for defence

"......."...................20… .

Chairman of theses defence commission: .................................................
/name and signature/

Non-exclusive Licence for Publication and Reproduction of GraduationTthesis[1]

I, ____________________________ (name of the author) (date of birth: ……………… ) hereby grant Tallinn University of Technology (TalTech) a non-exclusive license for my thesis

________________________________________________________________________________

________________________________________________________________________________

_______________________________________________________________________________,

*(title of the graduation thesis)*

supervised by

_______________________________________________________________________________,

*(Supervisor's name)*

reproduced for the purposes of preservation and electronic publication, incl. to be entered in the digital collection of TalTech library until expiry of the term of copyright; published via the web of TalTech, incl. to be entered in the digital collection of TalTech library until expiry of the term of copyright.

I am aware that the author also retains the rights specified in clause 1 of this license.

I confirm that granting the non-exclusive license does not infringe third persons' intellectual property rights, the rights arising from the Personal Data Protection Act or rights arising from other legislation.

[1] Non-exclusive Licence for Publication and Reproduction of Graduation Thesis is not valid during the validity period of restriction on access, except the university's right to reproduce the thesis only for preservation purposes.

______________ (signature)

______________ (date)

**Department of Civil Engineering and Architecture**
**THESIS TASK**

**Student:** ……………………………………………………………………........…. *(name, student code)*

**Study programme,**
**main speciality:** ……………………………………………….............................…. *(code and title)*

**Supervisor(s):** ……………………………………………………......………. *(position, name, phone)*

**Consultants:** ………………………………………………….................……………. *(name, position)*

………………………………………………………………………………....... *(company, phone, e-mail)*

**Thesis topic**
*(in English)*: TALL TIMBER BUILDINGS AS A CLIMATE CHANGE MITIGATION TOOL. 30-STORY TIMBER HIGH-RISE IN TALLINN

*(in Estonian):* PUIDUST KÕRGHOONED KUI KLIIMAMUUTUSE LEEVENDAMISE VAHEND. 30-KORRUSELINE PUIDUST KÕRGHOONE TALLINNAS

**Thesis main objectives**

1.

2.

3.

**Thesis tasks and time schedule**

| No | Task description | Deadline |
|---|---|---|
| 1. | | |
| 2. | | |
| 3. | | |

**Language:** English
**Deadline for submission of thesis:** “.......”.........2021

**Student:**

“.......”…………....................2021

*/signature/*

***Supervisor:***

“.......”......................2021

*/signature/*

**Consultant:**

*“.......”......................2021*

*/signature/*

**Head of study programme:**

“.......”......................201.a

*/signature/*

*Terms of thesis closed defence and/or restricted access conditions to be formulated on the reverse side*

**ACKNOWLEDGMENT**

Throughout the writing of this master thesis, I got a lot of assistance and support, and I would like to share my sincere thankfulness to all people who have contributed to this work.

I would first like to express my deep gratitude to my supervisor, Professor Kimmo Lylykangas, for the continuous support of my research and design part, invaluable advice and constructive criticism. Thank You for the positive attitude that has inspired and encouraged me during this entire period and for the time devoted to my thesis. I am grateful for all specialists You found and involved to this work. You guidance helped me to brought my work to a higher level.

Extremely helpful to this master thesis was the contribution of architect, professor Harry Edelman. I would like to acknowledge You for sharing unique information about prestudy research at Tampere University on a 30-floor prefabricated timber development (Nordic Tower). Your recommendations were beneficial for the realistic design of my project part. My grateful thanks are also extended to Anni Oviir. Thank You to be very kind in guiding me through the One Clik LCA software and explanation of the problematic parts of the life cycle assessment (LCA). I would like to recognize the efforts of professor Alar Just for the constructive advice about timber structures and for his help in designing the structural part of the project.

Special thanks to Kadi Saluoks - hotel manager of Original Sokos Viru Hotel, and Kaie Luik - marketing assistant of Radisson Blu Hotel Olümpia, for providing an opportunity to take photos of the site from the hotel rooms.

I cannot leave my family and friends without mentioning and expressing my gratitude for their patience and support. I would like to thank my friend Jana Pärn for stimulating discussions and help with different software. In addition, one particular thanks to my beloved cat Semyon who systematically unceremoniously laid down on my laptop to give me a break and who was my stress reliever.

Sofya Smirnova,
Tallinn, May 2021

**ABSTRACT**

In the coming decades, urbanization and climate change may be the two main challenges humanity will face and need to solve. These two megatrends increase the pressure on our planet's resources and have a tangible impact on people, the built environment, and the natural environment.

While most of the World's population, 70%, lived in rural areas only a century ago, World Urbanization Prospects 2018 estimates that more than half of the planet's nine billion people will live in cities, megacities, and other urban areas by 2050. The urbanization trend continues to grow, along with the world population, causing an increasing demand for resources and new housing. As we cannot spread our cities endlessly, compact city thinking which focuses on building dense urban environment, is thought to be a consensus solution to fulfill human needs and mitigate resource depletion.

However, the growing trend in the construction industry will also harm the natural environment and human beings. The Global Status 2020 report shows that building stock is already the most significant contributor to the greenhouse gas (GHG) emissions among other industries due to material extraction and energy-related carbon dioxide (CO2) emissions. Carbon dioxide, the most common GHG compound has the most considerable impact on climate change causing global warming and is produced mainly by human activities. The building sector is responsible for 38% (28% operational energy and 10% materials) of the total annual global energy-related CO2 emissions. Many efforts have been made to reduce energy consumption during building operation, but materials such concrete and steel are very carbon-intensive during extraction and manufacturing. These two materials also shaped our modern cities as they proved their indispensable ability to build multi-story and tall buildings.

In recent years, sustainability has become a common challenge in all aspects of human life and, not surprisingly, also affects the construction industry. Building regulation is constantly developed to meet the new sustainable development requirements. The Paris Agreement outlined the urgent need to decarbonize the building sector leading it to "nearly zero-energy building stock" by 2050 in order to keep the temperature increase limited within on 1.5 degrees to avoid the serious impacts of climate change.

As the high-rise typology is expected to be dominating future cities there has been an emerging trend towards more sustainable designs and choice of materials in high-rise buildings. Until the 21st century, it was just a dream to use renewable resources in large-scale construction. Innovative technologies in the design, manufacture, and construction of engineered wood products drove the growing interest in using wood and wood-based materials in high-rises. The awareness of environmental benefits was also an essential factor. Without engineering, the dimensions of wood components will still be limited by the tree trunk size. The opportunities of engineered timber initiated the race for the tallest timber building, and the height limits for timber high-rises are constantly extending.

During the last two decades, the timber industry has experienced tremendous growth due to increased engineered wood production. This new material is categoty to have versatile structural and environmental potential. Engineered wood challenges conventional concrete and steel in many respects: strength, durability, fire safety, construction speed, and in some cases, cost. Of these three, timber is the only renewable resource. Wood emits less CO2 during the extraction and manufacture than concrete and steel and stores sequestered CO2 removing it from the atmosphere until final disposal. Engineered wood proponents advocate that the buildings with timber frame structure could serve as giant sinks for CO2, and the increased use of timber in the future will reduce the carbon impact of the construction industry, consequently contributing to the mitigation of climate change.

This work aims to examine the potential environmental benefits of using new engineered wood products in high-rises as a solution for reducing greenhouse gas (GHG) emissions and addressing the climate change problems by replacing conventional high-rise building materials with timber structures. This work describes the research whose purpose was to calculate and compare the environmental impacts of three different structural designs for high-rise buildings: mass timber, traditional reinforced concrete, and hybrid timber-concrete. The life cycle assessment (LCA) methodology was used to quantify the potential harmful emissions for each design separately during the whole life cycle of a building - from raw material extraction and manufacture through construction, use phase to the end of life. The study hypothesized that timber high-rise has a lower carbon footprint than alternative reinforced concrete.

## LÜHIKOKKUVÕTE


Võimalik, et järgnevatel aastakümnetel on linnastumine ja kliimamuutus kaks peamist väljakutset, mida tuleb inimkonnal käsitleda ja lahendada. Need kaks populaarset trendi suurendavad survet meie planeedi ressurssidele ja avaldavad märgatavat mõju inimestele, ehitistele ja looduskeskkonnale.

Kui veel sajand tagasi elas suurem osa maailma elanikkonnast, 70%, maapiirkondades, siis World Urbanization Prospects 2018 hinnangul elab 2050. aastaks üle poole planeedi üheksast miljardist inimesest linnades, suurlinnades ja muudes linnapiirkondades. Linnastumise trend kasvab jätkuvalt koos maailma elanikkonnaga, põhjustades kasvavat nõudlust ressursside ja uute elamispindade järele. Kuna linnade levik ei saa olla lõpmatu, arvatakse, et kompaktse linna idee, mis keskendub tiheda kõrghaljastusega linnakeskkonna ehitamisele, on inimeste vajaduste rahuldamiseks ja ressursside ammendumise leevendamiseks sobiv lahendus.

Ehitustööstuse kasvutrend kahjustab aga ka loodus- ja elukeskkonda. Aruandest The Global Status 2020 selgub, et hoonete ehitus on juba praegu teiste tööstusharude seas kõige suurem kasvuhoonegaaside (KHG) tekitaja, mis tuleneb ressursside kaevandamisest ja energiatarbimisega seotud süsinikdioksiidi ($C0_2$) heitkogustest. Süsinikdioksiid on üks kasvuhoonegaasidest, millel on kõige märkimisväärsem roll globaalset soojenemist põhjustavates kliimamuutustes ja mida toodab peamiselt inimtegevus. Ehitussektor on vastutav 38% (28% kasutatav energia ja 10% materjalid) aastasest ülemaailmsest energiatarbimisega seotud $C0_2$ heitkoguse eest. Ehitussektoris on energiatarbimise vähendamiseks rakendatud mitmeid meetmeid, kuid materjalid nagu betoon ja teras on kaevandamisel ja töötlemisel ikka veel väga saastavad. Need materjalid on ka meie kaasaegsete linnade kujundajad, just oma asendamatute omaduste poolest, mis võimaldavad ehitada mitmekorruselisi kõrghooneid.

Viimastel aastatel on jätkusuutlikkust rakendatud kõikides eluvaldkondades, sealhulgas ei jää puutumata ka ehitussektor. Uutele jätkusuutliku arengu nõuetele vastamiseks karmistatakse ehitusstandardeid pidevalt. Pariisi lepingus rõhutati kiireloomulist vajadust ehitussektor dekarboniseerida, et saavutada 2050. aastaks “liginullenergia hoonestik”, mis hoiaks temperatuuritõusu piiri 1,5 % tasemel ja hoiaks seega ära tõsiseid kliimamuutuste mõjusid.

Kuna kõrghoonetüüp on tulevastes linnades eeldatavasti domineeriv, on kõrghoonete puhul näha suurenenud vajadust jätkusuutlikuma disaini ja materjalivaliku järele. Kuni 21. sajandini oli taastuvate ressursside kasutamine suuremahulises ehituses vaid unistus. Innovaatilised tehnoloogiad insenertehniliselt töödeldud puidust toodete projekteerimisel, valmistamisel ja ehitamisel suurendasid huvi puidu ja puidupõhiste materjalide kasutamise vastu ka kõrghoonetes. Oluline tegur oli teadlikkus puidu keskkonnamõjudest. Ilma projekteerimiseta on puitdetailide mõõtmed ikkagi piiratud puutüve suurusega. Insenertehniliselt töödeldud puit tekitas võistlusmomendi kõrgeima puitehitise nimel ning andis hoogu kõrghoonete kõrguspiirangute pidevale suurenemisele.

Viimase kahe aastakümne jooksul on puidutööstus  tänu insenertehniliselt töödeldud puidu tootmise suurenemisele tohutult kasvanud. Usutavasti on sellel uuel materjalil mitmekülgne struktuuriline ja keskkonnaalane kasutusvõimalus. Insenertehniliselt töödeldud puit on tavalisest betoonist ja terasest mitmes mõttes parem: tugevus, vastupidavus, tuleohutus, ehituskiirus ja mõnel juhul ka maksumus. Samuti on puit ehitusmaterjalidest ainus taastuv ressurss. Puit eraldab kaevandamise ja tootmise ajal vähem $C0_2$ kui betoon ja teras ning säilitab eraldatud $C0_2$, eemaldades selle atmosfäärist kuni lõpliku kõrvaldamiseni. Insenertehniliselt töödeldud puidu pooldajad väidavad, et puitkonstruktsiooniga hooned võivad olla hiiglaslikud $C0_2$ sidujad ning puidu suurem kasutamine tulevikus vähendab ehitussektoris süsinikdioksiidi heitkoguseid, aidates seega positiivselt kaasa kliimamuutustele.

Käesoleva töö eesmärk on uurida uue insenertehniliselt töödeldud puidu kasutamise võimalikku kasutegurit kõrghoonetes, et vähendada kasvuhoonegaaside (KHG) heitkoguseid ja kliimamuutustega seotud probleeme, asendades tavapärased kõrghoonete ehitusmaterjalid puitkonstruktsioonidega. Käesolevas töös kirjeldatakse uuringuid, mille eesmärk oli arvutada ja võrrelda kolme erineva kõrghoonete konstruktsiooni keskkonnamõju: puitkomposiit, traditsiooniline raudbetoon ning puidu ja betooni hübriid. Olelusringi hindamise (LCA) metoodikat kasutati selleks, et kvantifitseerida potentsiaalsed kahjulikud heitkogused iga projekti puhul eraldi kogu hoone elutsükli jooksul – tooraine kaevandamisest ja tootmisest, ehitamisest, kasutusetapist kuni eluea lõpuni. Uuringus püstitati hüpotees, et puidust kõrghoonetel on väiksem süsiniku jalajälg kui alternatiivsel raudbetoonil.

**CONTENTS**

# PART I. THEORY

## 1. INTRODUCTION

### 1.1 Problem definition

In the coming decades, urbanization and climate change may be the two main challenges humanity will face and need to solve. These two megatrends are closely connected to each other. Population growth leads to increased consumption of the Earth's resources and energy, which raises depletion of the planet and increases the greenhouse gas (GHG) effect (Chan, 2017). GHGs like methane $CH_4$, nitrous oxide $N_2O$, water vapor $H_2O$, carbon dioxide $CO_2$ are the main drivers of global warming. Among others $CO_2$ is mostly produced by human's activities and has largest contribution to climate change. Increasing amount of $CO_2$ will continuously rise the plants average temperature, multiply or create new risks for nature and people environment. (Pachauri, R.K and Meyer L.A. 2017)

### 1.2 Urban situation and prospects

Since 1950, the World's population has increased at a high-speed rate. Around 70% of the World was rural in the mid-19th century. However, now by the second decade of the 21st century, more than half of the total population, or 4.2 billion people, inhabit urban areas. According to the World Urbanization Prospects 2018 report, the urbanization trend will continue in all World regions, however, at different rates. Today the total number of inhabitants on Earth is about 7.6 billion people, and another 2.1 billion will join them over the next 30 years. The urbanization rate will rise from 55% in 2018 to 68 % by 2050. The most significant population growth will occur small-to-medium-sized urban areas in developing regions and concentrate mainly in three countries: China, Nigeria, and India. In contrast, the more developed regions as Europe and North America will have reducing population rate. (United Nations)

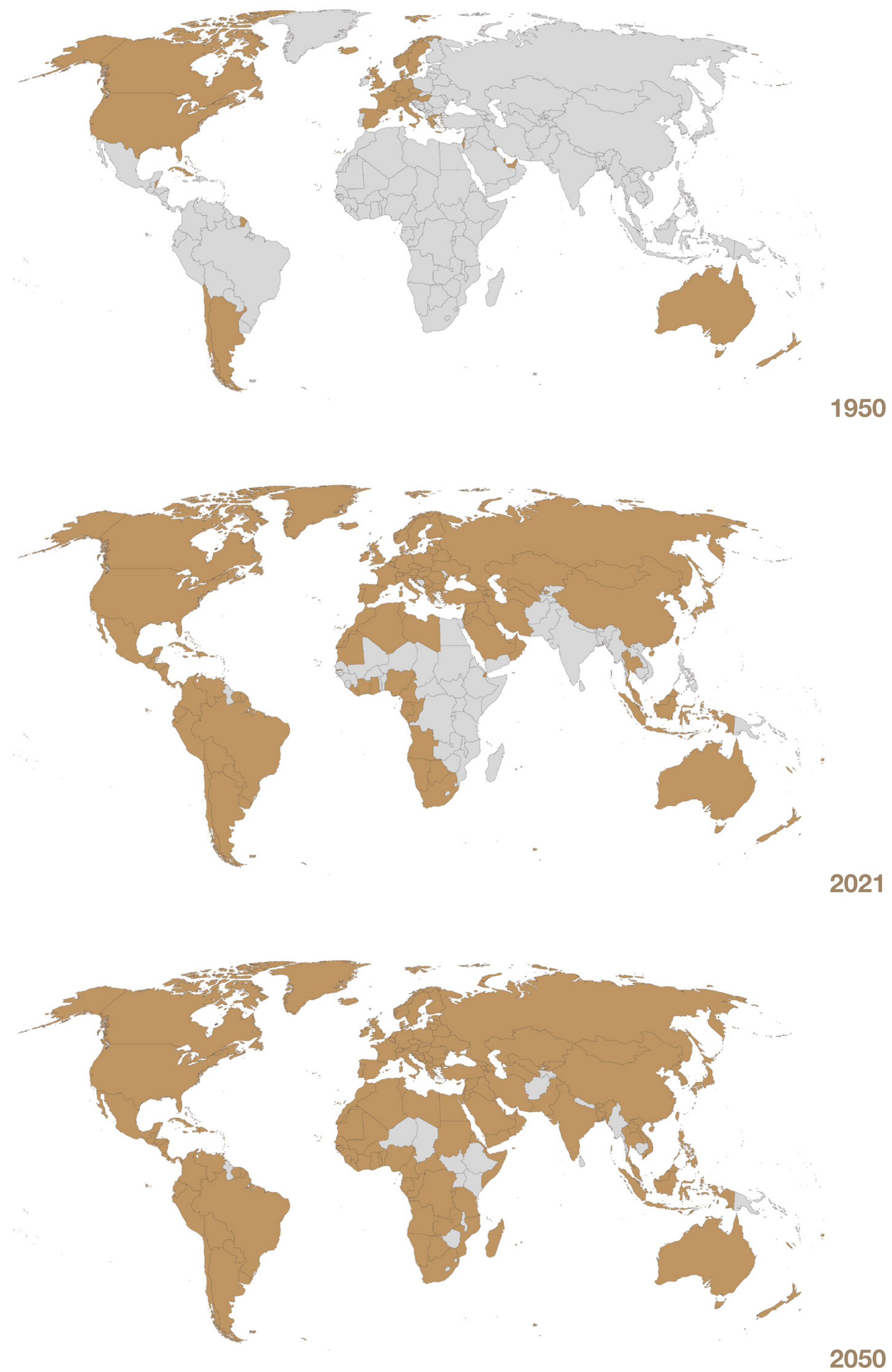



*Figure 1. World urbanization trend*

### 1.3 Environment and building sector
### Sector overview

Building stock impacts the environment in the forms of material extraction and energy-related CO2 emissions. While energy demand remains high, it has stabilized within recent years due to the transition to eco-fuels. Based on the 2020 Global Status report for building and constructions, the industry is responsible for 35% of the total global final energy consumption. Building operation and construction energy-related $CO_2$ emissions opposite hit their maximum in 2019, accounted for 38%, and tend to grow within the following years.

The annual global amount of energy-related $CO_2$ emissions (38%) consists of operational emissions (with the energy for cooling, heating, and power systems) resulting in 28% and 10% of emissions released from construction and materials. (United Nations Environment)

For a long time, the construction sector's focus has been on reducing operational emissions and making buildings more energy efficient. In contrast, the problem of embodied carbon caused mainly by the extraction and manufacturing of construction materials was not in the spotlight. Fortunately, the number of operational emissions may decrease over time, for example, due to renewable energy use. However, after the material creation and the end of building construction, embodied carbon emissions are locked in and cannot be affected by any other activities. (Pak, A., 2019) Global status report 2020 states that the amount of embodied carbon is influenced mainly by cement and steel. These materials use much energy for extraction and polluting at the manufacturing stage. (United Nations Environment)

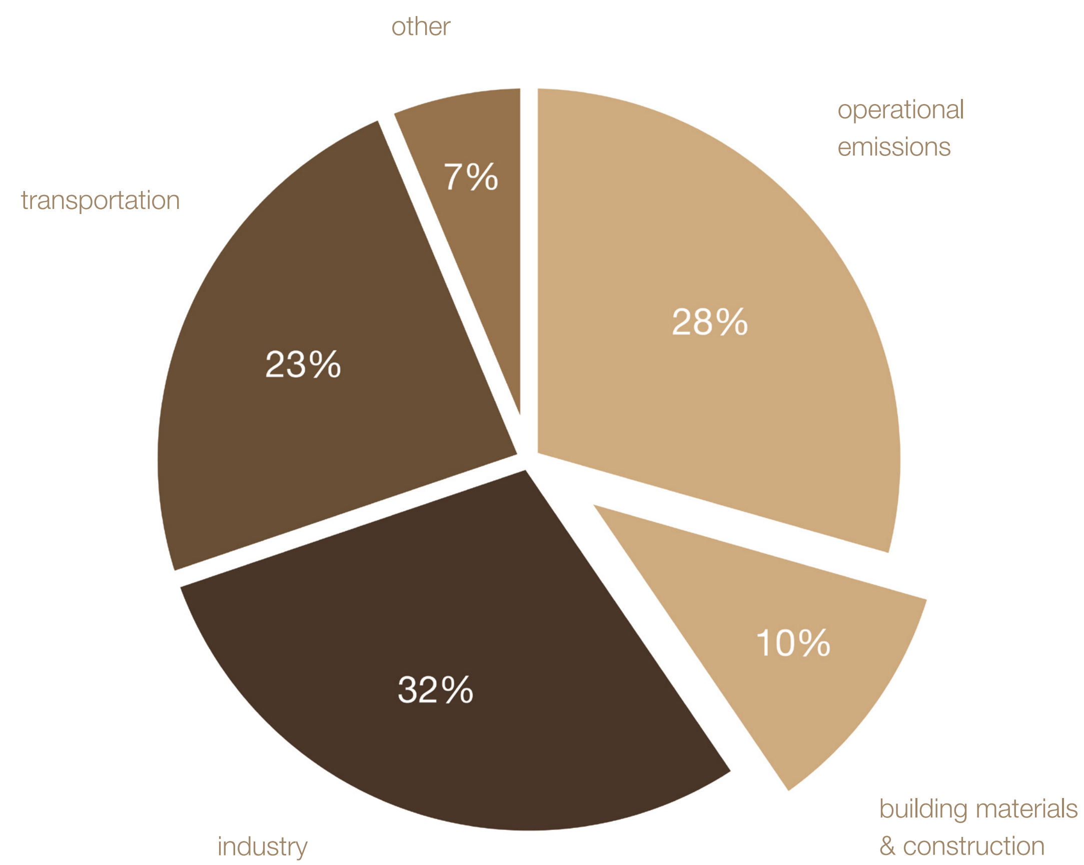



*Figure 2. Building sector $CO_2$ emissions*

### Concrete

Concrete has a large footprint and is responsible for 5% of total world $CO_2$ emissions. (United Nations Environment) Many factors influence the environmental impact of concrete, but the most significant is cement production. In cement production, almost half of the carbon dioxide emitted comes from the limestone calcination process, in which limestone is burnt at extremely high temperatures to produce cement clinker. The rest of the emissions comes from fuel combustion. However, the negative effect of concrete can be overestimated since concrete can bind carbon dioxide over time, just like trees. The absorption of carbon dioxide by concrete is called carbonization. The carbonization process is slower during the building use phase and accelerates when the concrete is demolished or crushed. During one year, concrete structures absorb about 0.5% of the total national carbon dioxide emissions or up to 30% over 100 years for the Nordic countries. (Kjellsen K. O., et al.)

### Steel

According to World Steel Association, the production of steel accounts for 6% of the total global $CO_2$ emissions. (United Nations Environment) The chemical reaction of coke and coal (carbon) with iron ore in a blast furnace produces $CO_2$. This method is known as iron ore reduction, and it results in the production of hot metal (near-pure iron) that is then processed into steel. (World Steel Association, 2019) The steel recycling rate is very high. Over 97% of steel products and co-products used on-site are already recycled products that may lead the steelmaking sector to nearly zero-waste production. (World Steel Association, 2020) The need for recycled steel is high, but scrap availability depends on past steel production. The amount of recycled steel meet sector needs as steel production stabilizes. (Skullestad JL)

### The role of tall buildings in environmental sustainability

Concrete and steel, due to their strength and durability, are essential structural materials for tall buildings in urban areas. As the population continues to grow, the demand for housing will rise, and the continued use of concrete and steel can be crucial for our planet's health as the amount of released $CO_2$ will also continue to increase. As a result, selecting environmentally friendly building materials is particularly critical for taller structures. (Michael Green Architecture)

### Building sector sustainable goals

The EU2050 strategy set a goal to reach «nearly zero-energy building stock » to meet the requirements of the Paris Agreement for a greener building stock and keep the global temperature rise below 1,5 ° C. This strategy aims to achieve a 80%-100% reduction in $CO_2$ emissions in the construction sector by 2050. (Publications office of the European Union, 2019) Within different global efforts to achieve a sustainable sector, The Global Status 2020 report highlights the reduction in the use of high carbon footprint materials. Biomaterials that require less energy to produce, which can act as a carbon storage and decompose at the end of their life without harming the environment could be an alternative material to concrete and steel and an essential decision to turn the construction sector into one part of the solution to climate change. (United Nations Environment Programme)

## 2. HISTORY OF ENGINEERED WOOD PRODUCTS FOR LOAD BEARING STRUCTURES

Wood is one of the oldest resources people use as a building material. Even though timber constructions were mid-rise during the last centuries, primarily (ARUP), the idea of tall timber buildings is not something new invented. One of the most outstanding examples from the history is Sakyamuni Pagoda (1056; 67, m high) located in China (Ciyun Z., 2015) or polish The Gliwice Radio Tower (1935, 118m high). (European rote of industrial heritage) However, in the late 18th and 19th centuries, the invention of reinforced concrete structures dramatically decreased mass production of large-scale timber constructions until present days. (ARUP)

*Figure 3. Sakyamuni Pagod*

*Figure 4. The Gliwice Radio Tower*

## 2.1 Composite wooden structures and mass timber

The last decade of 20th century bring a new conception for treating traditional timber and presented the composite with tightly bonded crosswise layers or cross-laminated timber (CLT). Since 1990, the idea of CLT has been actively developed by scientists from three countries Germany, Austria, and Switzerland. However, laminated timber structures have been used and tested in some projects before, for example, for aircraft hangars in Russia in the late 19th century and in the 60s of the last century for the exhibition hall in Dortmund. From 1970 to 1990, many studies of cross-laminated timber structures and their characteristics appeared. (Grasser K. K., 2015) However, the most significant contribution to the creation of a scientific and technical base for the development of CLT material was made by the Austrian scientist G. Schickhofer, (Gigler, B.) who defended his thesis in 1994 on the topic “Rigid and flexible composition in area-covering laminated wood structures.” In 1998, two companies, Austrian KLH Massivholz GmbH and German Merk-Holzbau GmbH CO KG, received official national product accreditation and became certified CLT suppliers. Since the 2000s, other materials have also been developed on the principle of glued timber, and CLT material has become widespread in Europe in the construction of private and multi-story buildings. In 2002, based on the dissertation of G. Schickhofer, Austria compiled the first national guidance on the use of CLT. In 2006, the CLT received the European Technical Approval (ETA), and in 2008, work began on the European CLT Standard. ( Grasser K. K., 2015)

Today the more general definition of “mass timber” is a new term to categorize wood products. The most significant difference between light small-scale constructions and mass timber products is the oversized dimensions of the last. Mass timber applies engineered wood panels - thick, compressed layers of wood formed through lamination, fasteners, or adhesives creating vital, structural load-bearing elements. (Mass Timber in North America.)  Mass timber includes cross-laminated timber (CLT), dowel-laminated timber (DLT), nail-laminated timber (NLT), glued-Laminated Timber (Glulam), laminated veneer lumber (LVL) and other similar products. (Jackson, R. et. al., 2017) The dimensions of panels can vary and among others CLT panels can be from any thickness. (Michael Green Architecture) These products are suitable for designing load-bearing and non-load bearing constructions as floors, exterior and interior walls, roofs, elevators and stair shafts; (Mass Timber in North America) Mass timber no inferior in acoustic, fire, construction efficiency, material stability and structural performance to concrete and steel. (Michael Green Architecture)

**Cross-laminated timber (CLT)**

CLT panels consist of several stacked and glued lumber layers. Usually, the number of layers is three, five, or seven. Lumber boards glued at a 90-degree angle to each other using finger joints and adhesives. (Mass Timber in North America)

**Glued-laminated timber (Glulam)**

Glulam includes individual wooden lumbers glued along the grain with moisture-resistant adhesive. Glulam is suitable for all load-bearing constructions but typically used for columns and beams. (Mass Timber in North America)

**Nail-laminated timber (NLT)**

NLT panels represent several lumber layers connected in one direction together by nails. (Mass Timber in North America)

**Laminated veneer lumber (LVL)**

LVL product consists of 3 mm thick layers of veneers that are glued together under heat and pressure. Veneers are made of rotary-peeled softwood.( Kerto® LVL., n.d)

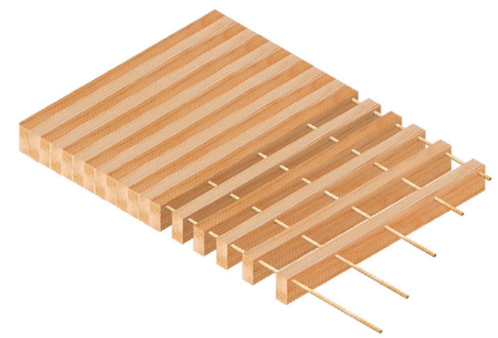
**Dowel-laminated timber (DLT)**

DLT panels present softwood lumber boards stacked together and bounded with hardwood timber dowels. Other materials such as concrete or mechanical elements could be integrated as a part of DLT design between the single lumber boards to reduce cross-section and better acoustic. (WoodWorks and Think Wood, 2021)

*Figure 5. Cross-laminated timber*
*Figure 6. Glued-Laminated Timber*
*Figure 7. Nail-laminated timber*
*Figure 8. Laminated veneer lumber*
*Figure 9. Dowel-laminated timber*





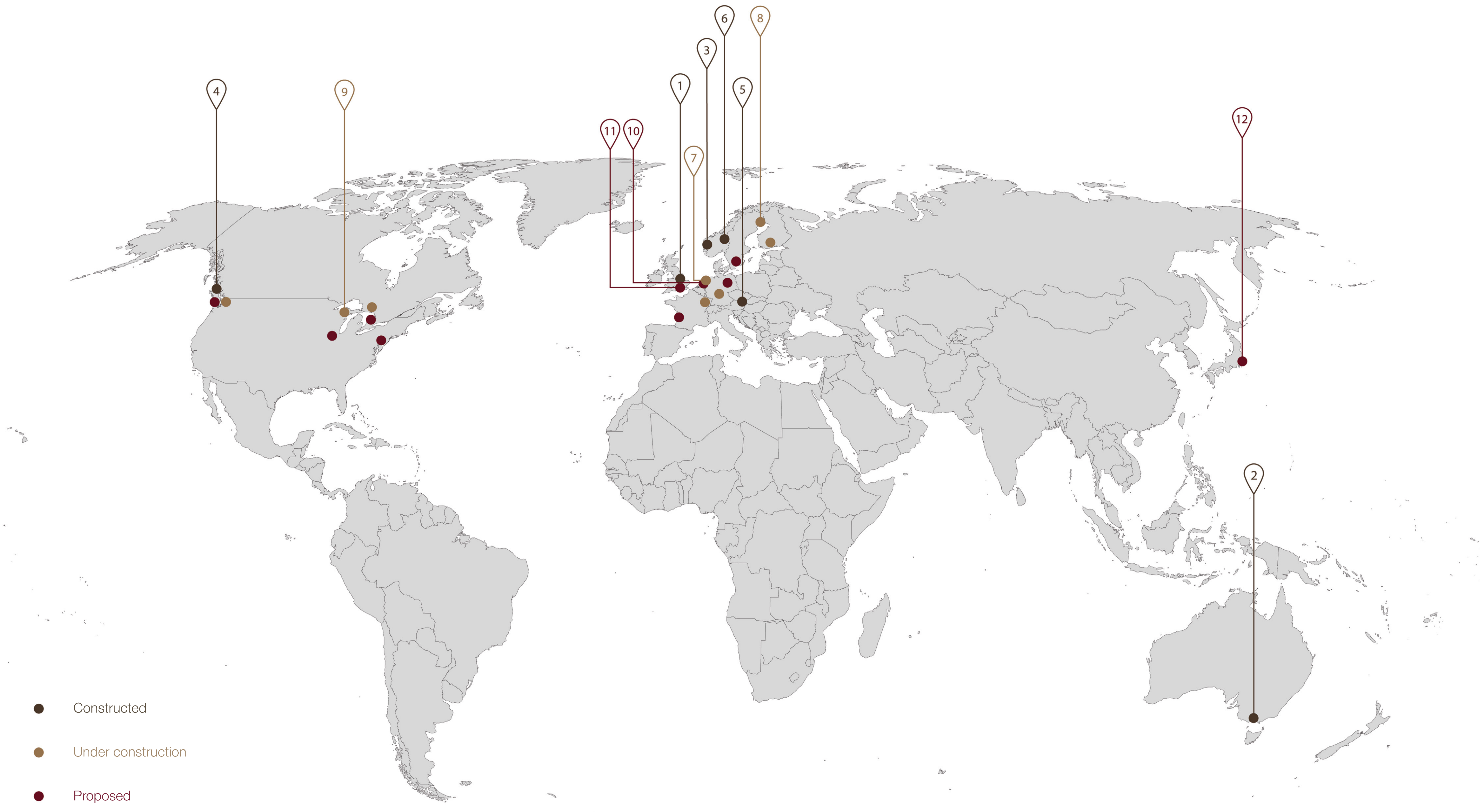


New technologies, innovations of engineered wood products, and the appreciation of wood's environmental benefits stimulated the growth of interest in the use of wood, especially for the construction of high-rise buildings, and sparked a worldwide race to construct taller wood structures. (Michael Green Architecture) Without engineering, the dimensions of wood components are limited by the size of the tree trunk.

The first timber-framed building with nine stories (30m), Murray Grove, was completed in London in 2009. After that, other timber high-rise buildings gradually began to appear in different parts of the World, with each new project trying to beat the previous one's height. The Murray Grove record hit at 2013 10 floors (32m) of Forte Living building in Melbourne, two years later was Treet in Bergen with 14 stories (49m), the race continued Brock Commons with its 17 floors (53m) in Vancouver finished in 2017. Vienna also presented its timber high-rise HoHo with 24 stories (84m) in 2019. However, until 2019, all constructed buildings were still composite and used concrete structures. Mjøstårnet building completed in March 2019 in Norway, Brumunddal, was the first to be built 18 floors (85,4m) entirely of wood. (De Giovanni, G., & Scalisi, F., 2019) In 2021 there already several buildings under construction like Haut tower in Amsterdam (73 m) or Ascent tower Milwaukee, USA (86 m) that will beat the Mjøsa tower record in nearest years. Also a lot of promising proposals are done for future. The more detailed timeline of timber high rises development can be found in Figure 11. Constructed, under construction and future proposed tall timber buildings.

*Page 30:*
*Figure 10. World map of tallest timber buildings*

*Page 30-31:*
*Figure 11. Constructed, under construction and future proposed tall timber buildings*



1
2
3
4
5
6
7
8
9
10
11
12
Constructed
Under construction
Proposed

1 2009 **29m**

Murray Grove
Waugh Thistleton architects
UK, London

2 2013 **32,2m**

Forte Living
Andrew Nieland architect
Melbourne, Australia

3 2015 **49m**

Treet
Artec architects
Bergen, Norway

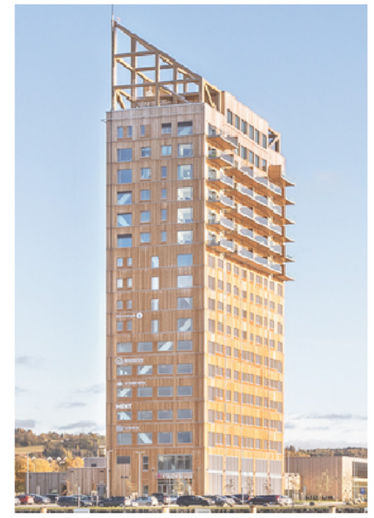
4 2017 **54m**

Brock Commons
Acton Ostry Architects
Vancouver, Canada

5 2019 **84m**

HoHo
RLP Rüdiger Lainer + Partner, Architects
Vienna, Austria

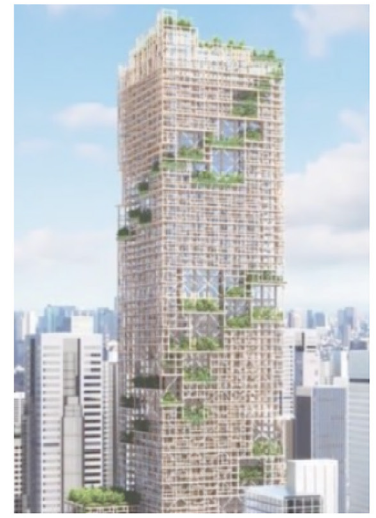
6 2019 **85,4m**



Mjøstårnet
Voll Arkitekter
Brumunddal, Norway

| STRUCTURAL CHARACTERISTICS | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Program | Residental | Residental/Retail | Residental | Student housing | Mix-use | Mix-use |
| Construction | Prefabrecated panels | Prefabricated panels | Prefabricated modules | Prefabricated panels, columns, walls | Prefabricated panels, columns, walls, beams | Prefabricated panels, columns, walls |
| Floors above ground | 9 | 10 | 14 | 18 | 24 | 18 |
| Concrete/timber floors | Ground/1-9 | 1/2-10 | 1/2-14 | 0-1/2-18 | 1/2-24 | 1/2-18 |
| Floor to floor height | ≈2,8 m | ≈3,2 m | ≈2,9 m | ≈2,81 m | ≈3,5 m | ≈3,5 m |
| Floor surface | - | - | ≈483 m2 | ≈840 m2 | ≈1270 m2 | ≈629 m2 |
| Floor plans measure | - | - | ≈23x21 m | ≈15x56 m | ≈55x40/20 m | ≈17x37 m |
| Structural system type | Hybrid (timber+concrete) | Hybrid (timber+concrete) | Hybrid (timber+concrete) | Hybrid (timber+concrete+steel) | Hybrid (timber+concrete) | Hybrid (timber+concrete) |
| Load bearing elements | Panel system | Panel system | Post and Beam + diagonal truss work + two intermediate strengthened levels | Post and Beam | Post and Beam | Post and Beam + diagonal truss work |
| Beam | not used | not used | Glulam | Floors act like beams | Glulam (side beams concreate) | Glulam |
| Columns | not used | not used | Glulam | Glulam | Glulam | Glulam |
| Walls | CLT panels | CLT panels | CLT panels | CLT panels | CLT panels | CLT panels |
| Floors | CLT panels | CLT panels | CLT panels; 5,10 floor-concrete | CLT panels+concrete | CLT panels | Timber; Ground,12-18 concrete |
| Core | CLT panels | CLT panels | CLT panels | Concrete | Concrete | CLT panels |
| Roof | CLT panels | CLT panels | Concrete | Steel | - | CLT panel |
| Fire System | Mass timber | Mass timber, encapsulation | Mass timber, encapsulation | Mass timber, encapsulation | Mass timber, encapsulation | Mass timber, encapsulation, sprinkles |
| Lateral force system | - | - | Diagonal glulam trusses, concrete podium | Concrete core, concrete podium | Concrete core | Glulam truss work, CLT core |
| Lateral core position | - | - | Center | Side | Center | Side |
| Fassade | - | - | - | - | - | - |

Constructed

| ⑦ 2021 **73m** | ⑧ 2021 **76m** | ⑨ 2022 **86m** | ⑩ **100/130m** | ⑪ **300m** | ⑫ **350m** |
|---|---|---|---|---|---|
|  |  |  |  |  |  |
| Haut<br>TEAM V Architecture<br>Amsterdam, Netherlands | Kulturhus<br>White Arkitekter<br>Skellefteå, Sweden | Ascent<br>Korb + Associates Architects<br>Milwaukee, USA | The Dutch Mountains<br>Studio Marco Vermeulen<br>Eindhoven, Netherlands. | Oakwood Tower<br>PLP Architects<br>London, UK | W350 Project<br>Nikken Sekkei architect<br>Tokyo, Japan |

| STRUCTURAL CHARACTERISTICS | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|
| Program | Residental | Mix-use | Mix-use | Mix-use | Mix-use | Mix-use |
| Construction | - | Prefabrecated modules | - | Prefabricated elements | - | - |
| Floors above ground | 21 | 19 | 25 | 38 | 80 | 70 |
| Concrete/timber floors | 1-2/3-21 | - | 1-5/6-25 | - | - | - |
| Floor to floor height | ≈3 m | ≈2,9 m | - | - | - | - |
| Floor surface | ≈600 m2 | ≈600 m2 | - | - | - | - |
| Floor plans measure | ≈40x26 m | ≈50x21 m | - | - | 40x40 m | 80x80 m |
| Structural system type | Hybrid (timber+concrete) | Hybrid (high part - timber; low part timber+concrete or steel) | Hybrid (timber+concrete) | - | - | Hybrid (timber+steel) |
| Load bearing elements | Post and Beam | Post and Beam | Post and Beam | - | Post and Beam + diagonal truss work | Post and Beam |
| Beam | Glulam | Glulam | Glulam | - | | Mass Timber |
| Columns | Glulam | Glulam | Glulam | Mass Timber | Glulam | Mass Timber |
| Walls | CLT panels | Data not found | Mass timber | - | Glulam | Mass Timber |
| Floors | Timber+concrete | Mass timber | CLT panels | Mass Timber | CLT panels | Mass Timber |
| Core | Concrete | CLT panels | Concrete | - | Mass Timber | Mass Timber |
| Roof | - | - | - | - | Mass timber | Mass Timber |
| Fire System | Partial encapsulation | - | - | Mass Timber | Mass Timber | - |
| Lateral force system | Concrete core, two share CLT walls | CLT core | Concrete core | - | - | Steel brace tube structure |
| | | | | | Mega truss | |
| Lateral core position | Center | - | - | - | | Side |
| | - | - | - | - | Center | - |
| | | | | | - | |

Under construction (7–9) — Proposed (10–12)

## 2.2 Estonian timber structure examples

Wood as a building material has also been known to Estonians since ancient times. The oldest timber building in Estonia is considered the Ruhnu church in 1643-44. Over the centuries, people used wood structures for churches, lighthouses, railway stations, markets, and many residential buildings in different parts of Estonia. (K. Hallas, 1999)

Of the modern wooden architecture in Estonia, there are only two large-scale buildings today. The first is Viimsi School, designed by Architect 11 (Arhitect 11, n.d) architects, opened in 2018. The school has three floors, with the concrete ground floor, and two stories above have wooden structures made of CLT. (E. Luht, 2018) The building is 15,1 m high and has a floor area of 9136 m2. (Ehitusregister, 2006). The second building that has recently opened its doors in 2020 is the Estonian Academy of Security Science, designed by the 3 + 1 architectural bureau. The building already has four floors. Concrete structures form the ground floor, and above, there are three stories of CLT structures. (Sõmmer, S., 2020) The building's height is 15 meters, and the floor area is 3317 m2. (Ehitusregister, 2020) Architectural bureau Kavakava - the winner of the architecture competition for State Environment Building, presented a project with wooden structures. The complex consists of three parts, one of which, based on the proposed project, will be 24.8 meters high, making Environment Building the tallest timber building in Estonia since its construction. (Kavakava, n.d)

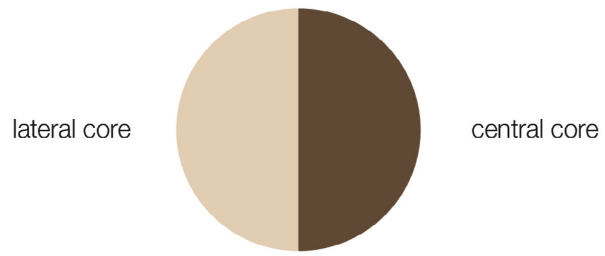
*Figure 12. Ruhnu church*
*Page 33 left: Figure 13. Viimis school*
*Page 33 right: Figure 14. Estonian Academy of Security Science*
*Page 34: Figure 15. Environment Building*

## 2.3 Findings

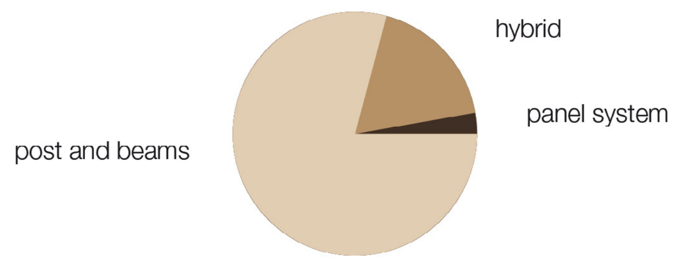
The structural system for timber high rises is typically post and beam system..
Beams presented in projects are made of glulam.
Columns can be mainly from mass timber materials or a hybrid system with steel inside. However, the primary material for columns remains glulam.
Floors are mostly made of mass timber elements. Commonly used CLT panels, but in some cases in buildings higher than 50 m to gain the mass, used hybrid structures (mass timber+concrete) or pure concrete floors.
The core of timber high-rise can be centralized or on the side. Only two buildings used concrete cores, and in other buildings, elevator shafts, and staircases were made of mass timber.
Foundations of all projects made of concrete and used to prevent moisture movement from soil to timber elements. Concrete ground floors are also preferred for retail spaces because they can be separated from timber structures above and give the higher floor to floor height and more freedom in architecture.
Lateral forces in case of not very high buildings can be mitigated using rigid core. However, to gain needed stiffness for buildings taller than 50 m, additional measures as shear walls, diagonal trusses, or a stiff facade can be applied. The cores of most of the buildings were made of mass timber that shows the timber's perfect ability to take lateral loads.
Facade in timber buildings plays an essential role in fire safety. Almost all of the timber high rises facade materials are non-combustible. As an additional fire protection measure, some of them have balconies.
Fire safety is ensured in most buildings by total or half encapsulation – additional plasterboard layers to all types of constructions. The charring method of over-dimensioned timber structures is also used to prove that the structure retains its bearing capacity for the required time.

*Figure 16. Author's drawings*

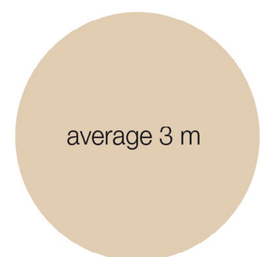
## CORE




## LOAD-BEARING SYSTEM



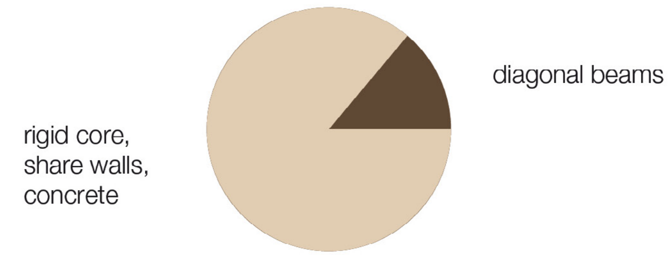

## FLOOR TO FLOOR HEIGHT



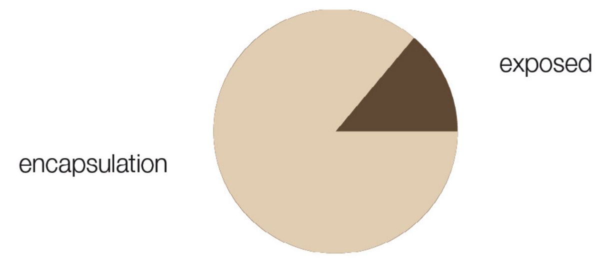

## STRUCTURE MATERIALS

foundations - concrete
**floors - mass timber**
columns beams - mass timber
walls - mass timber

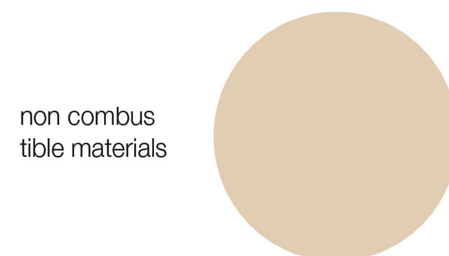
## LATERAL LOADS



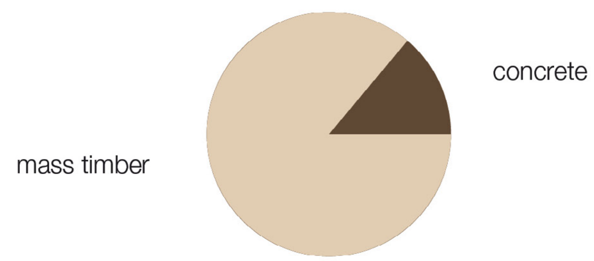

## FIRE SAFETY




## FASSADE MATERIALS




## CORE/ ELEVATOR AND STAIR SHAFTS MATERIALS



**2.3 Tall timber structure case studies**

Although the highest timber building today has only 18 floors, several investigations already started to test mass timber's possibilities to build even taller buildings.

In 'The Case for Tall Wood Buildings' published in 2012, Canadian architect Michael Green examined the possibility of building timber high-rise and made a proposal design for a tall timber building with 30 floors. The new construction model presented in the case study shows that using mass timber products can be beneficial in constructing timber high-rises and for environmental sustainability. (Michael Green Architecture)

A year later, in 2013, Skidmore, Owings & Merrill (SOM) architects released another Timber Tower Research Project. The study aimed to design based on existing concrete 42 stories building new structural system for tall timber building and find a solution to mitigate buildings carbon footprint. (Skidmore, Owings & Merril).

Two previous kinds of research were based on the projects for Western countries (Canada, USA). However, the most recent pre-study in Tampere University on a 30-floor prefabricated timber high-rise Nordic Tower NT conducted by Finnish research group Sami Pajunen, Janne Hautala, and Harry Edelman is especially important for Northern and Baltic countries. The findings of pre-study were published in March 2021, and the project concentrates on aspects for developing a timber high rise in Helsinki. The research's primary purpose is not to create a new solution to build taller timber buildings. The study concentrates on designing a standard load-bearing structural system of mass timber that allows flexible architectural design and could be applied to different building types: affordable housing, elite residential buildings, hotels. (H. Edelman, 2020)

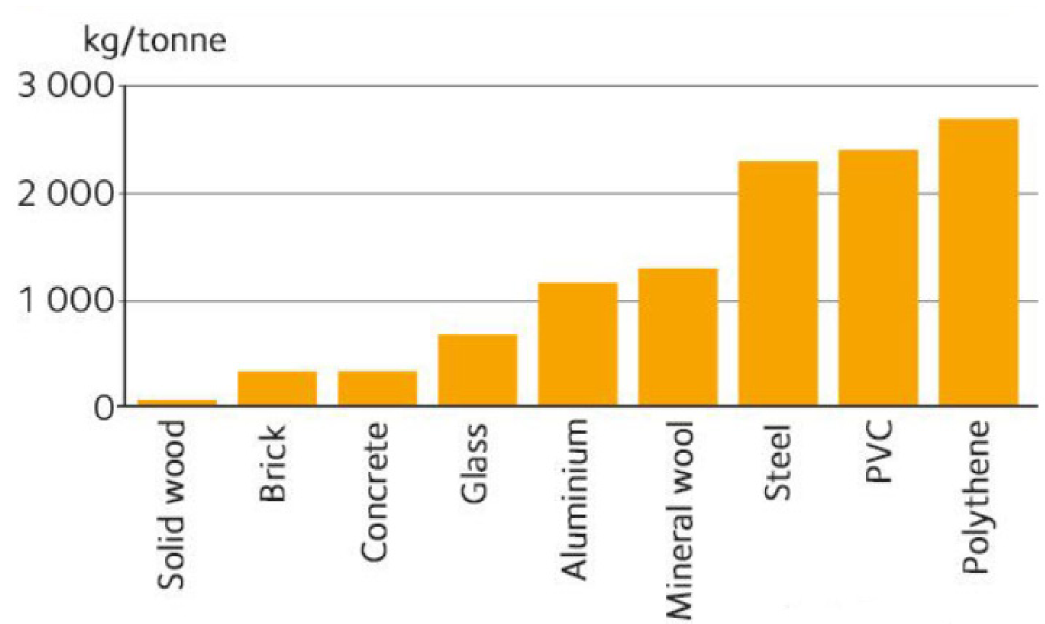
*Figure 17. „Nordic Tower" project*

**3. WOOD AS SUSTAINABLE MATERIAL**

### 3.1 Renewable resource

Construction material resources can be non-renewable and renewable. Non-renewable are those that can be harvested only once or form very slowly. Almost all common construction materials belong to non-renewable resources - iron ore, coal, sand, etc. ( Ruuska, A., Häkkinen T.) Due to the increasing demand for conventional materials like cement and steel, some resources may be at risk of depletion. For example, coal reserves based on BP's Statistical Review of World Energy report will account for 132 years based on 2019 production rates. (BP p.l.c.,2020) Pascal Peduzzi, the director of UNEP's Global Resource Information Database in Geneva, Switzerland, also shares his concerns about the risk of shortage of sand in the future. (Meredith, S. 2021)

Wood is the only naturally renewable building material resource. It is a resource that in some way stands apart as wood does not use (except soil) and deplete natural resources of the planet like other materials and can be cultivated and harvested time and again. (Martinez T., 2015) However, wood can be considered a sustainable construction material only when harvested from sustainably managed forests.




### 3.2 Carbon footprint

#### Carbon sequestration

Throughout the tree's whole life, photosynthesis takes place in it - a process in which the tree absorbs atmospheric carbon and produces oxygen. Carbon sequestration is a name for the process when atmospheric carbon dioxide is captured and stored in trees. Trees store absorbed carbon in all their parts - wood, leaves, roots, and soil for an extended period until complete decomposition or combustion as fuel. The carbon storage in the soil occurs through the interaction of tree roots and organisms in the soil. Accumulation of $CO_2$ occurs more actively in younger trees and slows down as trees become old. In sustainable forestry, cutting down trees maintains a balance between maximum carbon concentration and tree age. Both products made of wood and forests themselves serve as large carbon reservoirs. That is why it is essential to take care of aging forests and old trees that are not suitable for harvesting - to ensure carbon storage within forests. (Hill, CAS., 2019)

One cubic meter of wood retains a ton of carbon and has a lower carbon footprint compared to other materials.

#### Extraction and manufacturing emissions

The production of wood is easier than the production of cement or steel and therefore requires much less energy, which in turn results in less carbon dioxide emissions. In the production of wood, energy is spent mainly on mechanisms for cutting and processing wood and on transportation. (Bergman, R. et.al)

*Figure 18. Carbon emissions from manufacture of construction materials*

### The end of life

At the end of life wood products can be reused or recycled. Other options are landfill decomposition or combustion as fuel for energy instead of fossil fuels. In the first two cases, atmospheric carbon will remain stored further in the wood products; in the event of decomposition and burning, all the stored carbon will return back to the atmosphere. (Hill, CAS., 2019)

The question is how to evaluate the return of carbon back to the atmosphere - whether it has a positive or negative effect. From one hand, Michael Green, a Canadian architect, wonders if we are just delaying climate change by creating prolonged delay in carbon dioxide emissions. (Michael Green Architecture) Together with wood waste, paints, adhesives, and impregnations used to produce wooden product can form toxic and hazardous compounds during combustion. (ARUP) Wood for recycling is likely to have a tedious process of removing old paints, adhesives and applying new ones - this will lead to additional energy consumption and $CO_2$ emissions. ( Is reclaimed wood toxic?) In landfills, carbon stored in wood during decomposition can form into methane - a more vital greenhouse gas than carbon dioxide.

On the other hand, recycled wood products help to prolong the time of storage of $CO_2$. Burning wood as a renewable source could be an alternative to reduce the depletion of fossil fuels. (Hill, CAS., 2019) The Environmental Protection Agency EPA in U.S also declared burning wood as „carbon neutral ". The reason for this is when wood is burned as source of fuel and releases $CO_2$ back to the atmosphere another three can be grown to re-absorb this released $CO_2$ back. Based on this statment life cycle of tree doesnt increase the amount of $CO_2$ and keep it in balance.

Hovewer, there are those who argue about wood carbon neutrality. First of all, it takes a decade or more time to grow a tree that could store the same amout of $CO_2$ that was released while burning and all this time unabsorbed $CO_2$ will negatively impact our climate. Secondly, according to Sami Yassa, senior scientist at the Natural Resources Defense Council, cutting trees also affect soil, (Daley, J., 2018) that store twice much $CO_2$ than forest. ( D'Amore, D., Kane, E., 2016A)

Therefore, it is preferable to keep forest stay and use wooden elements and transfom them to another for as long as possible to prevent stored carbon from being released back into the atmosphere. (Hill, CAS., 2019)

## 3.2 Sustainable forestry

The growing interest in the medium to tall timber construction will consequently increase the demand for timber in the future. The question is whether there will be enough reserves of the World's forests to meet the growing needs because we already constantly hear about how a large number of forests disappear every year. There is a big difference between deforestation and sustainable harvesting.

Deforestation is the permament removal of trees and changing land-use for other needs, such as agriculture. As soon as the forests are removed, there is no replanting after. Sustainable harvesting provides a constant supply of wood resources followed by re-planting a forest that maintains or increases the population over time. Sustainably managed forestry focuses on keeping natural forests standing, ensures the distribution of the diversity of trees different species and ages across the landscape, density, and distribution, and monitors the age and height of regenerating trees. (Michael Green Architecture)

Two widely recognized certification systems for assessing sustainable forest management are The Forest Stewardship Council FSC and Program for the Endorsement of Forest Certification PEFC. These certifications confirm that forest is being managed in a balanced way regarding natural, social, and economic sustainability. (Waugh Thistleton Architects, 2018)

Nearly 35% of Europe covers forests, and almost a half of them have PEFC or FSC certification. Over the previous years, European forest stock has increased, and forest area expanded, according to the State of European Forests 2020 report. Every year forests in Europe sequester about 10% of CO2 emission released in other sectors. (Forest Europe, 2020) In Austria and Germany - large producers of CLT products - forest grows fast enough within 1 hour to produce 4,5 m3 of wood. On this scale, forests produce every 20 seconds enough timber for the average dwelling of 30 $m^3$. (Waugh Thistleton Architects, 2018)

### Notes on Estonian forests

Estonian forests account for 51 % of the total area, of which 70% are certified. (H. Välja, 2018). In Estonia State Forest Management Centre RMK gives the right to cut growing forest or forest-related products only according to PEFC and FSC standards. (State Forest Management Centre (RMK))

## 3.3 Health and wellbeing

The environmental benefits of wood extend not only to the planet's health but also to people's well-being. A study carried out in 2015 by the Australian non-profit organization Planet Ark showed that the presence of wood elements in the interior has a beneficial effect on the quality of work of office workers, the study of students, and the recovery of patients. The exposed wood has a beneficial effect on both the physical and psychological state. It contributes to reducing stress levels and improving a person's emotional state. (Waugh Thistleton Architects, 2018)

## 4. CHALLENCHES OF TALL TIMBER BUILDINGS

There are several challenges for timber building that need to be considered in early design especially in tall timber high-rise buildings.

### 4.1 Fire safety

Wood buildings are not stable in case of fire since wood is a combustible material. Small dimensions of wooden elements in lightweight timber structures cause their rapid-fire and premature destruction of construction. However, due to deliberately oversized dimensions, mass wood materials do not behave this way when the fire occurs.

Charring method is used for oversized mass timber to proof fire resistance. The charring process is predictable, and the laboratory can measure its charring rate. With this knowledge, it is possible to calculate the minimum thickness for the load-bearing layer of wood and the so-called sacrificial coal layer thickness to obtain the required fire resistance level. Alternative method is the "encapsulation" method that involves adding two extra layers of fire-rated gypsum board to all building parts, such as floors, walls, and roofs, providing 2-hour fire-resistance.

### 4.2 Acoustic

Good sound insulation between building elements has a beneficial effect on people's emotional state especially in residential buildings. (Michael Green Architecture)

The main factors affecting sound insulation are mass and thickness. The larger they are, the stronger the sound attenuation occurs. Lightweight timber structures may not perform as good acoustic results as more dense concrete constructions. In addition, a large number of joints between floors, ceilings, walls, and other parts in timber structures result in flanking paths through which sound can pass uncontrolled.

The use of CLT panels will improve acoustic performance as its crosswise layers are denser that regular timber structures and it helps to prevent passing sound. Additional layers of wood and increased thickness will also help to gain better acoustics. In the case of a floor, making a composite material and adding to the wood base a thin layer of concrete 50-70 mm would also be one solution. A suspended ceiling can also reduce sound transmission due to the air layer. (Preager, T., 2019)

### 4.3 Moisture movement and shrinkage

One of wood properties is absorb moisture from the environment and release it back under suitable conditions. When the moisture level changes, the timber element shrinks or expands, which leads to deformation of the structures (Just E., Just A., 2015) and multiply shrinkage over the height. (Michael Green Architecture) Due to the timber fibers' different directions, the structure deforms unevenly. Changes can become critical during the building's construction and its further operation. Excessive moisture also reduces the timber's strength and promotes harmful living organisms' reproduction. (Just E., Just A., 2015)

Mass wood has an advantage over the unengineered timber because its moisture level is already initially less about 8-10% for mass wood versus 15-19% for light wooden structures. This fact significantly minimizes possible structural deformations and shrinkage. (Michael Green Architecture) Constant contact of wood with the ground can also provoke moisture movement from the ground into the constructions. The use of concrete elements at ground level and level above separates timber structures from the soil and prevents possible deformations. (Skidmore, Owings & Merril.)

### 4.4 Lateral loads

Lateral loads are horizontal loads mostly caused by wind and seismic forces. Wind-induced effects as vibrations and oscillations can make people feel uncomfortable inside a building. Also, wind load puts limitations on the number of stories in high-rise buildings. The higher the building, the more pronounced the parameters listed above.

Three factors affecting the dynamic stability of building are mass, stiffness, and vibration damping. In the case of timber buildings, mass plays a critical role. Compared to massive concrete, timber structures are lighter consequently less stable and more susceptible to wind provokes' vibrations.

The increase of the buildings' structural mass could help mitigate wind effects. This approach generally includes adding concrete. (A. Alalwan, 2019) In the Mjøstårnet building in Norway, concrete floors on the top stories give an additional mass. HoHo building in Austria uses a concrete podium, and Brock Commons in Canada uses both concrete platform and concrete core to gain mass and minimize lateral (horizontal) forces that comes from wind. (Hamburg, P., et. al)

The systems of the core, perimeter moment frames and share walls are used to gain needed stiffness for building and take lateral loads. This system can be used separately or combined. (Michael Green Architecture)

## 5. FUTURE OF TIMBER STRUCTURES

There are two main strategies for developing mass timber in the future. One concerns its structural characteristics and another timber environmental benefits. (Robbins, J., 2019)

Canadian architect Michael Green, possibly the most well-known mass timber designer working today, believes that wood construction technology is critical for solving affordable housing crises in the future. The more urban world will demand more high-rise buildings. Wood structures will become one of the essential materials in constructing tall buildings. (Michael Green Architecture) The reason is that modern mass timber surpasses conventional concrete and steel in many respects. Using new engineered wood can benefit in strength, durability, fire safety, construction speed, and in some cases, cost. (Robbins, J., 2019) Several serious researches (see chapter 2) have already examined structural characteristics and successfully demonstrated that timber high-rise are technically feasible. Examples of constructed buildings, such as HoHo and Mjøsa towers (see chapter 2), also prove Green's theory. Does this mean that wood will displace concrete and steel from the market? Michael Green states that the future is more likely to be hybrid wood-concrete and wood-steel structures. (Michael Green Architecture)

Green also advocates that MT will be a climate change strategy solution and helps dramatically reduce $CO_2$ emissions in the future. Timber emits less $CO_2$ during extraction and manufacture than concrete and steel and stores sequestered $CO_2$ removing it from the atmosphere until decomposition. Based on these statements, Green also advocates that MT will be a climate change strategy solution and helps dramatically reduce $CO_2$ emissions in the future. (Michael Green Architecture) However, there are severe doubts and debates about how sustainable the new wood really if we look on a big scale. The MT can be a promising material only if its life cycle is fully sustainable. Since the life cycle analysis is complex and some of the required data is missing or insufficient, not a single thorough study has yet been carried out to understand how much carbon dioxide will release mass timber release into the atmosphere at different stages of its life - explains Beverly Law, professor of Forest Ecosystems & Society college, USA. There are just not enough studies to prove that timber can be an effective climate change solution. (Robbins, J., 2019)

Another concern is how increasing MT production will impact forest management. In the critical article "Mass Timber in the Age of Extinction," architect Alexander Hardly worries that the popularization of MT can be used by investors as a fashion brand to attract customers and make big money and not be driven by environmental considerations in the long run. As a result, such an industrial approach to forestry and a rapid surge in demand for wooden structures can lead to the deforestation and extinction of its inhabitants. (Hadley A., 2021). Used fuels for logging equipment, manufacture, and transport of wood products also a question to be considered. To conclude all the above, it is clear that we need to provide strict regulations for forest management and be sure that MT support sustainable forestry; otherwise, the use of MT will lose all its benefits.



Additional topics to consider are how long wood will be in use and how to store or re-use timber elements without decomposing and releasing sequestered $CO_2$ back to the atmosphere after building dismantling. (Robbins, J., 2019)

Timber has the potential to be a part of the solution in solving global problems, but further study is still needed to find more standardized applications and sustainable solutions that will enable timber to be introduced as a viable material in high-rise building and as climate mitigation tool.

*Figure 19. David Chipperfield installation of tree trunk columns in Mies van der Rohe's Neue Nationalgalerie*

## 6. METHODOLOGY OVERVIEV

### 6.1 Life Cycle Assessment

While life cycle assessment (LCA) has been used to evaluate building environmental performance since the late 1980s, it has only recently become a popular research method.

LCA - is governed by a family of international standards ISO 14000 method that helps to understand the potential environmental significance of a building or its parts. LCA identifies and quantifies all relevant energy and materials used and pollutants emitted into the air, water, and soil during the building's entire life cycle or particular life stage. The standard life cycle of a building consists of raw material extraction, manufacture of construction products, the construction process stage, use stage, demolition, and reuse or recycling processes. (Bayer C., et. al)

**The five life cycle stages of the building:**

The product stage concerns the extraction of natural resources, transportation of them to manufactures, and transforming them into simple building materials such as timber elements, steel, cement.

The construction stage includes the transportation of building materials from factories to the construction site, the use of these materials,  the installation of structures, and the building's completion.

The usage stage covers the building's occupation period during its lifetime and includes replacement and repair processes. This stage considers processes to maintain the building's operation, such as heating, cooling, ventilation, electricity supply, etc.

At the end of life stage, considered the impact on the environment during the building's dismantling. The building's demolition includes the dismantling of building structures into components and transportation obtained solid waste to landfills and appropriate materials for subsequent processing.

The reuse or recycling stage includes all the consequences of recycling or reusing materials after the building's dismantling. This part is out of system boundaries and has to be reported separately according to the EN 15978:2011 standard. (Simonen, K., et. al)

Each stage, in addition to the unique processes included in it, also considers the influence of the energy used, other resources, transport,  and additional materials necessary for carrying out various activities at each stage and those required for the operation of specialized equipment. The impact of the generated waste is also included in each step. (Bayer C., et. al), (Simonen, K., et. al), (Birgisdóttir, H., ), (Bruce-Hyrkäsa, T.) For the last three stages, it is necessary to choose the scenario for using the building, its operation, and method of carrying out the dismantling process. (Bruce-Hyrkäsa, T.)

*Figure 20. The life cycle stages of the building*

### Benefits of LCA

It indicates hotspots where materials, processes, or a whole life stage are more crucial to the environment, helping decision-makers find ways to make their products more sustainable.
Assessment helps to achieve environmental requirements set by regulations and standards on local, national, and international level.
The analysis supports making more sustainable decisions between alternative designs.
It helps to reduce cost of a product identifying hotspots where materials or energy sources can be replaced for alternative or improved for better cost performance.
LCA can increase product and company competitiveness and value as more developers, sponsors and clients are concerned about the eco-friendliness of the products they support, product or use.

### Challenges of LCA

The method is time and cost consuming. Poorly scheduled LCA results in out-of-date information; databases and experts' long-term work are expensive, which also increase the product's final price.
Gaps in material properties databases and lack of experienced experts to conduct an LCA assessment.
Standardization problems. There is a lack of generally agreed manuals how to assess diferent products and those that exist provide different approaches on same activities. (Bruce-Hyrkäsa, T.) ISO standards do not provide sufficient information. (DEAT)
Level of model boundaries and sophistication affects reliability of results. Complicated and simplyfied methods both can be either very reliable from a large amount of data and less truthful from a large number of predictions. (Bare, J. C et. al)

## 6.2 Methodological framework of LCA

The process, requirements, and methods of LCA assessment presented in this chapter and followed in the research part based on the following standards (Simonen, K. et. al):

ISO 14040: 2006 Environmental Management - Life Cycle Assessment - Principles and Framework.
ISO 14044:2006 Environmental management - Life cycle assessment -Requirements and guidelines.
EN 15978:2011 Sustainability of construction works - Assessment of environmental performance of buildings – Calculation method
ISO 21930:2017 Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services



EN 15804:2012+A1:2013 Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products

The standard ISO 14040 divides LCA into four compulsory stages: Goal and Scope Definition, Inventory Analysis, Impact Assessment, and Interpretation.

### Step 1: Goal and scope

This step is the first and most important part of the research since it forms the whole study. The goal defines the purpose of the research, motivation for the assessment, and target audience whom the results will be delivered. The scope should deliver an information about what kind of product will be studied, its functions, time and data limits, the functional unit, assumptions and limitations and impact categories:

| LCA IMPACT INDICATOR UNITS<br>Use | CML2012<br>Europe/ EN Standards |
|---|---|
| Global warming potential | $CO_2e$ |
| Ozone depletion potential | CFC-11-eq |
| Acidification potentional (land) | SO2e |
| Eutrophication potential (fresh water) | PO43e |
| Formation of tropospheric ozone<br>(photochemical oxidant formation) | C2H4e |

*Table 1. Indicators describing environmental impacts.*

### Step 2: Inventory analysis

This phase consists of data collection and calculation parts. The data collection section covers all the inputs (something that is taken of the environment and put into product or system like energy and materials) and outputs (waste and releases to the air, water, and soil caused by product or system) from all single processes the system's boundary. The data calculation part generates the total results of the collected data.

### Step 3: Impact assessment

Impact assessment phase examines defined in goal and scope product or system from an environmental perspective using category indicators. The calculated data from the inventory analysis phase is translated to functional units of impact categories defined in goal and scope.

### Step 4: Interpretation

This step summarizes results for the entire study, compares the results with the set goal and scope, identifies the significance of gained impacts on the environment, and makes conclusions and recommendations for the target audience following the goal's definition and the results' intended application. It is also necessary to evaluate an assessment itself - check availability and completeness of data, the accuracy of results, assess the compatibility of the goal and scope with the chosen method.

It is essential to highlight that the research results are relative and express the potential impact and contribution of the product to factors that affect the environment. The study results are not actual predictions of implications for the environment.

LCA is an iterative method. During the entire study, each stage's actions can be repeated multiple times as information that we did not know at the beginning of the study appear. New details may cause changes and modifications in each stage's initial data. (ISO 14044:2006)

## 7. LIFE CYCLE ASSESSMENT

The conducted LCA with the necessary information, explanations and conclusion presented in Appendices 1. *Life cycle assessment.*

## 8. CONCLUSION

This work aimed to study the environmental benefits of wood and assess how realistic it is to promote wood as a solution to the climate problem. Some of the hypotheses were confirmed; however, the negative aspects of using wood in construction were also revealed.

The popularization of wood products looks pretty one-sided, highlighting only the positive qualities and keeping silent about the possible negative ones, which, if taken into account, may probably outweigh the positive effects. For example, such factors include toxic adhesives used in engineered wood. What impact will they have when the wood product is burned? Also, the growing "wood is good "trend seems to advisedly demonize concrete and steel so that wood looks in the best possible light. However, these two materials already made significant improvements to decrease their carbon footprint.

Based on this work LCA results, it is clear that the adverse environmental effects of wood in building constructions are less severe than cement and steel. The ability of wood to store carbon and the lower energy consumption during the manufacturing of wood products contributes to a lower carbon footprint than other materials. The popularization of wood also contributes to more sustainable forestry.

Despite the positive results of research, the benefits of wood can be overestimated and speculative. The assessment of wood products' contribution to environmental sustainability is too complex, including many derivatives on which the final result depends. The research carried out in this paper is a very simplified model of the life cycle of a wood product. It has many assumptions and missing information. However, this is not a problem of specific study but a typical thing for all researchers that try to assess the impact of the production and use of wooden structures on the environment. As we do not have research covering every aspect of the wood product life cycle, the wood environmental benefits are still under question.

The conducted LCA also showed that eliminating two underground parking floors in concrete structures design helps to reduce around 5% of emissions. Based on this data, reducing the number of parking spaces can be a starting point in decreasing the high carbon intensity of high-rise buildings.

The building sector plays an essential role in climate change. The choice of construction materials has consequences. Wood products have a good environmental potential. However, the simple transition from reinforced concrete to wood structures does not solve the climate change problem. Still, it can be a part of a complex solution and significantly reduce the total global amount of carbon dioxide caused by the building sector.

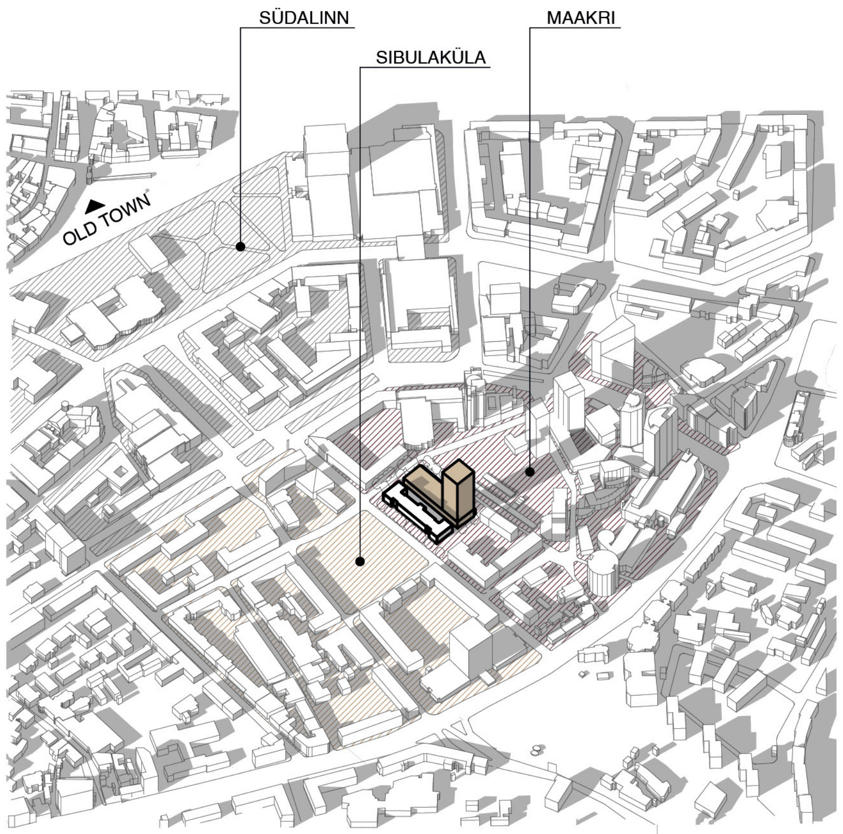
# PART II. PROJECT

## 1. INTRODUCTION

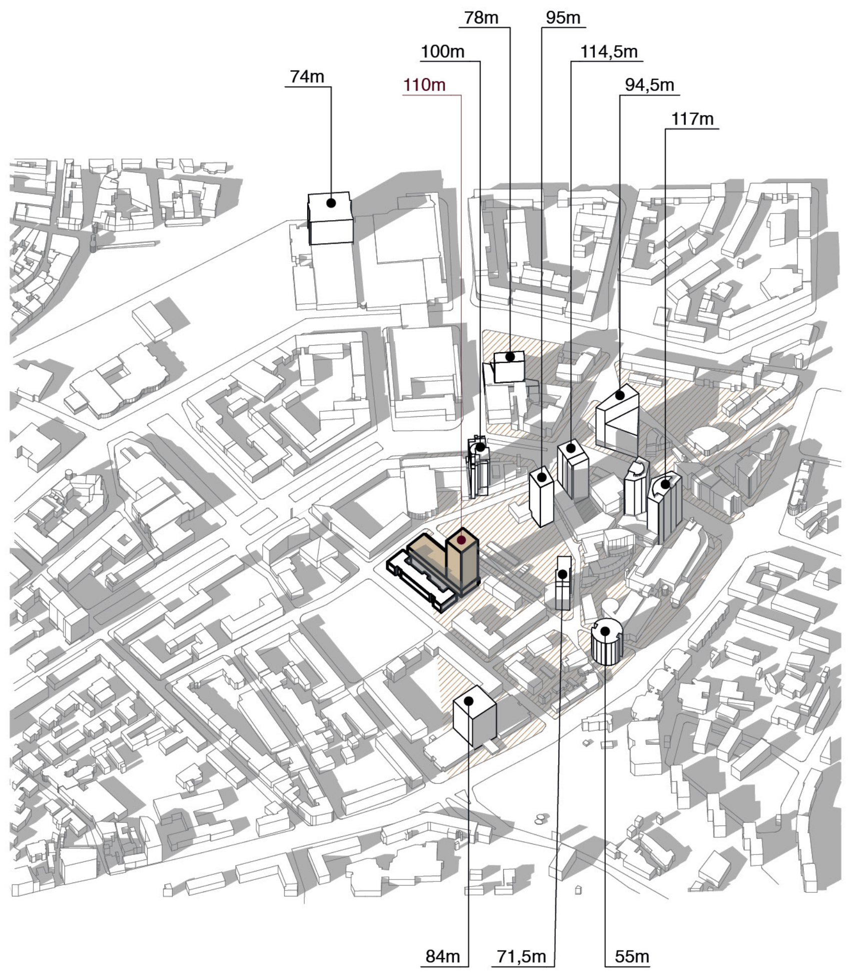
The project is based on the architectural competition for Estonian Business School that took place from November 2019 to July 2020. The object of the competition is multifunctional high-rise up to 30 storeys. The project's design followed the competition brief requirements with some changes. The competition brief can be found in Appendices 2. *Competition brief and exception sheet.*

**The project designed according to the following Estonian standards:**

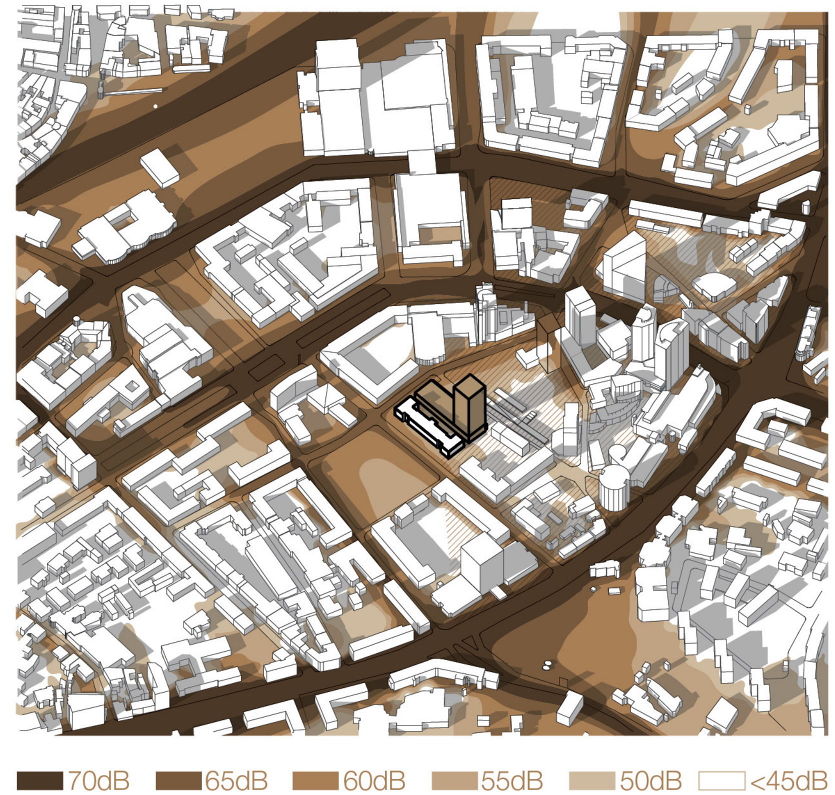
Hea ehitustava ET-10207-0068;
Nõuded ehitusprojektile (Majandus- ja kommunikatsiooniministri 17.07.2015 määrus nr 97);
EVS 932:2017 Ehitusprojekt;
EVS 865-1:2013 Ehitusprojekti kirjeldus, Osa 1: Eelprojekti seletuskiri
Siseministri 30.03.2017 määrus nr 17 „Ehitisele esitatavad tuleohutusnõuded ja nõuded tuletõrje veevarustusele. "
Olmejäätmete sortimise kord ning sorditud jäätmete liigitamise alused (Keskkonnaministri 16.01.07 määrus nr 4).



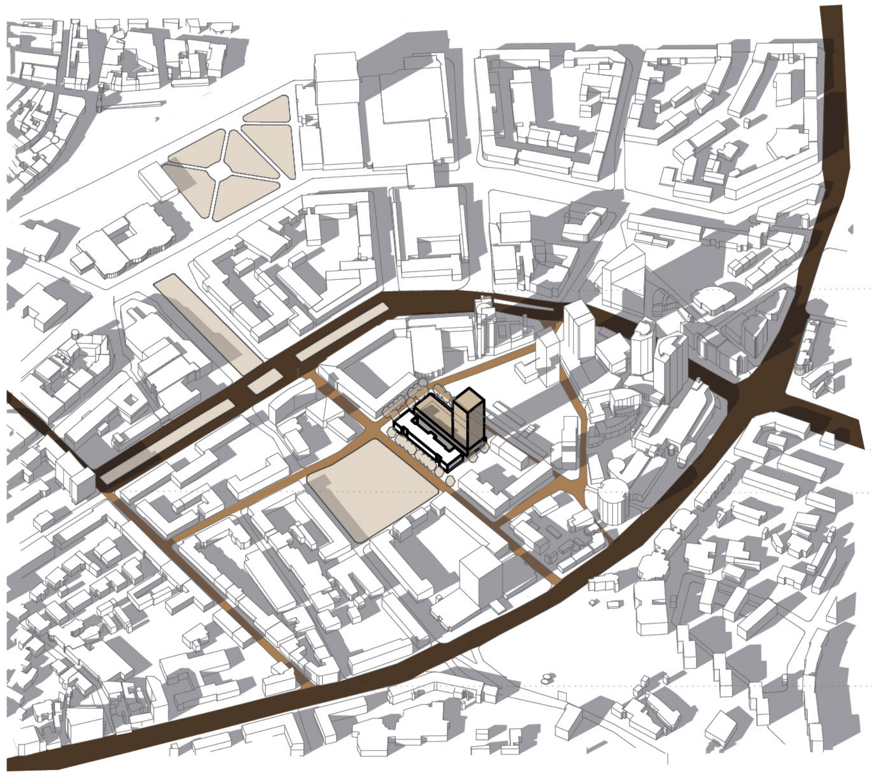

Location

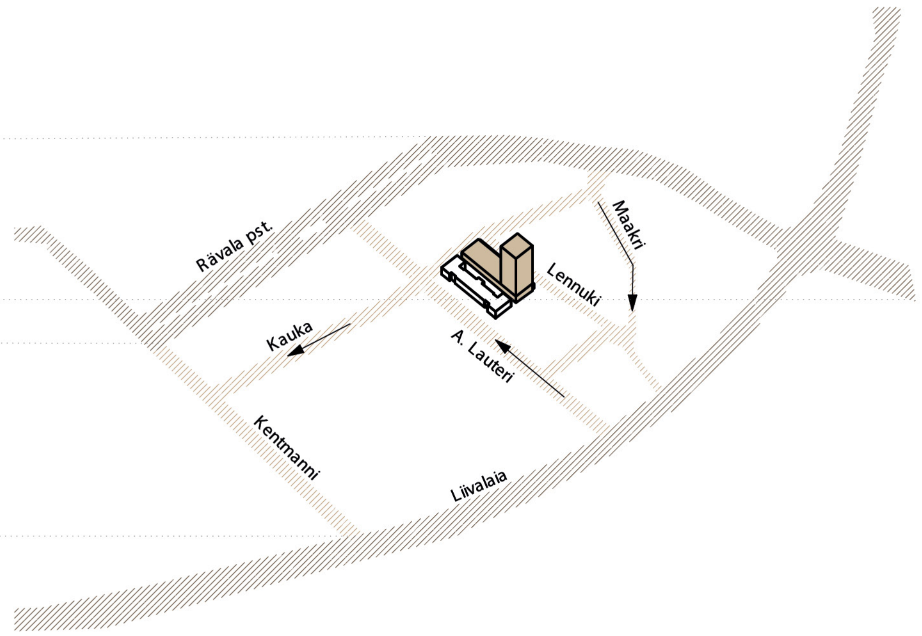


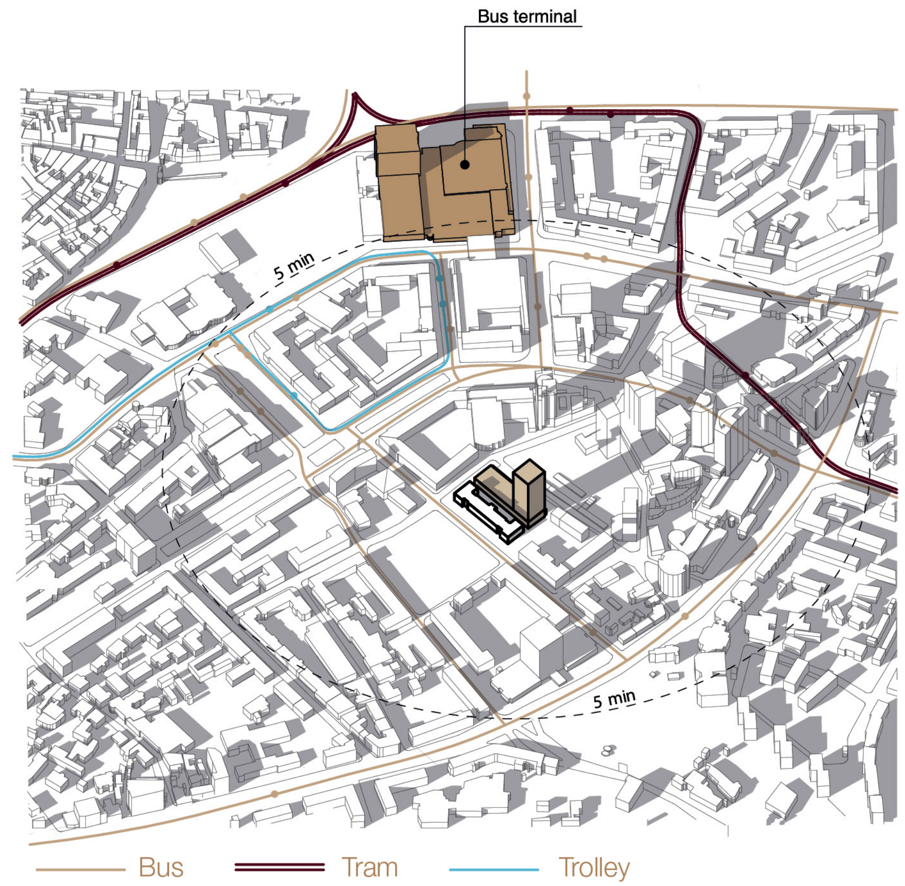

Tallinn high-rise area




Noise map





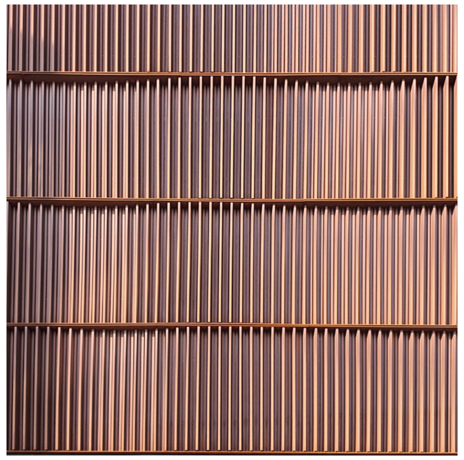



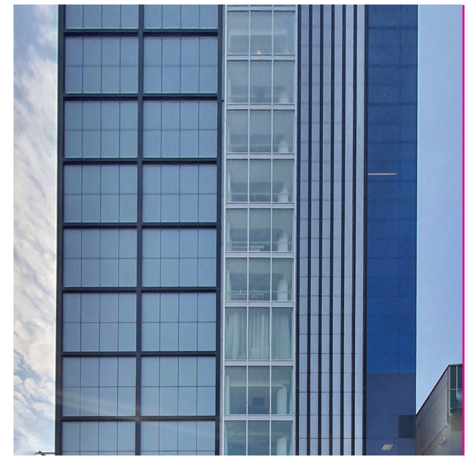

Main roads and green areas

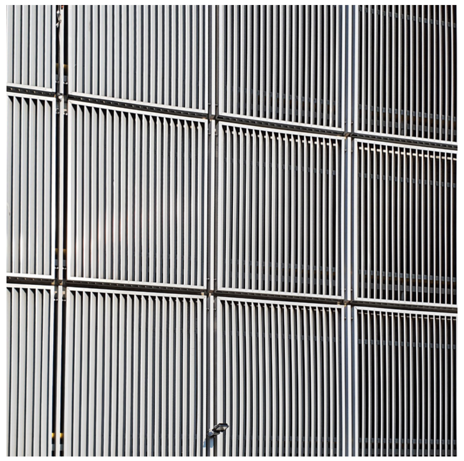
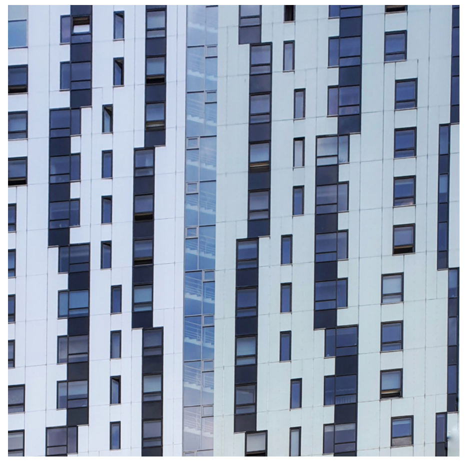
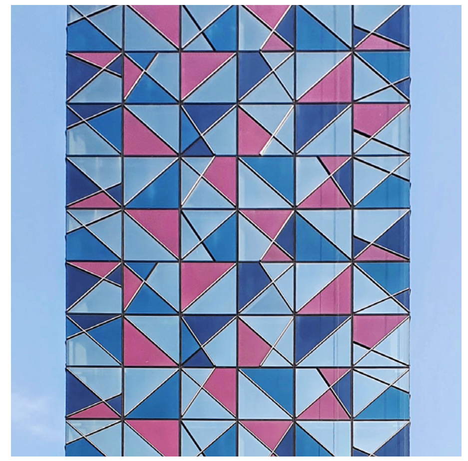
Public transport


ULTIMA THULE
PECORINO
ABLOY

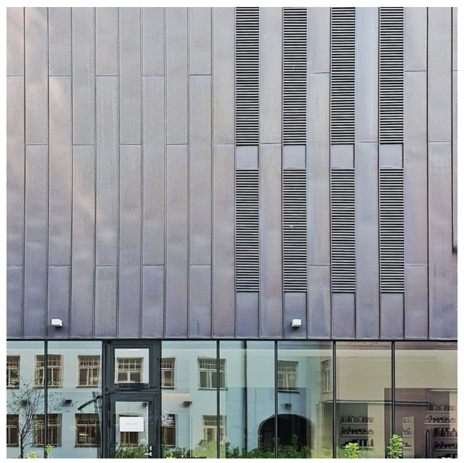
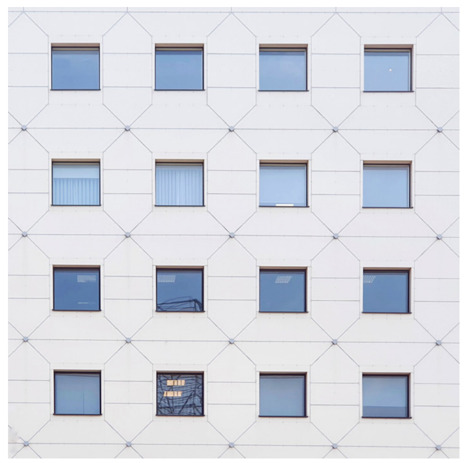
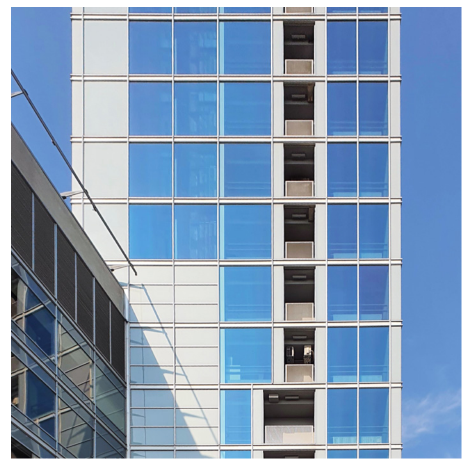






SEB

## 2. THE SITE

### 2.1 Site analysis

The project is located in Tallinn, Estonia. The site refers to the Kesklinn area, discovers on Maakri and Sibulaküla's border and belongs to Maakri district. Kuke, Lennuki, Maakri, and A. Lauteri streets surround the project area. There are two large main roads Liivalaia and Rävala nearby, but according to the noise map the site remains in quiet zone. The access to the site is possible from Lennuki and A. Lauteri streets. Currently, the site represents private on the ground parking and has a decrease of ground from Lauteri Street's side towards Lennuki Street. The difference between heights is 2,6 meters. Public transport is well developed in this area. There are several bus and trolleybus stops near the site. There is also a bus terminal and a tram line nearby. Deciduous trees grow along the site's perimeter however, the surrounding area's vegetation is scarce. The only park Lembitu Park locates opposite the site along Lauteri Street. Surrounded area of the site is primarily multifunctional. In the immediate vicinity, there are various grocery stores, services, business areas, apartments, various entertainment venues such as cinemas, theaters, concert halls, spa and sports clubs. The project area is on the border of two different housing development. On the southwest of the site prevails low building development with perimetral buildings up to 5-6 floors. Buildings in the Stalinism style date back to 1950s. On the northeast formed a modern high-rise area of Tallinn. The area has vide diversity of different façade types that presented in Figure 27. Maakri quarter facades.

*Figure 21. Situation scheme*

*Pages 48-49, from left to right:*
*Figure 22. Location*
*Figure 23. Tallinn high-rise area*
*Figure 24. Noise map*
*Figure 25. Main roads and green areas*
*Figure 26. Public transport*

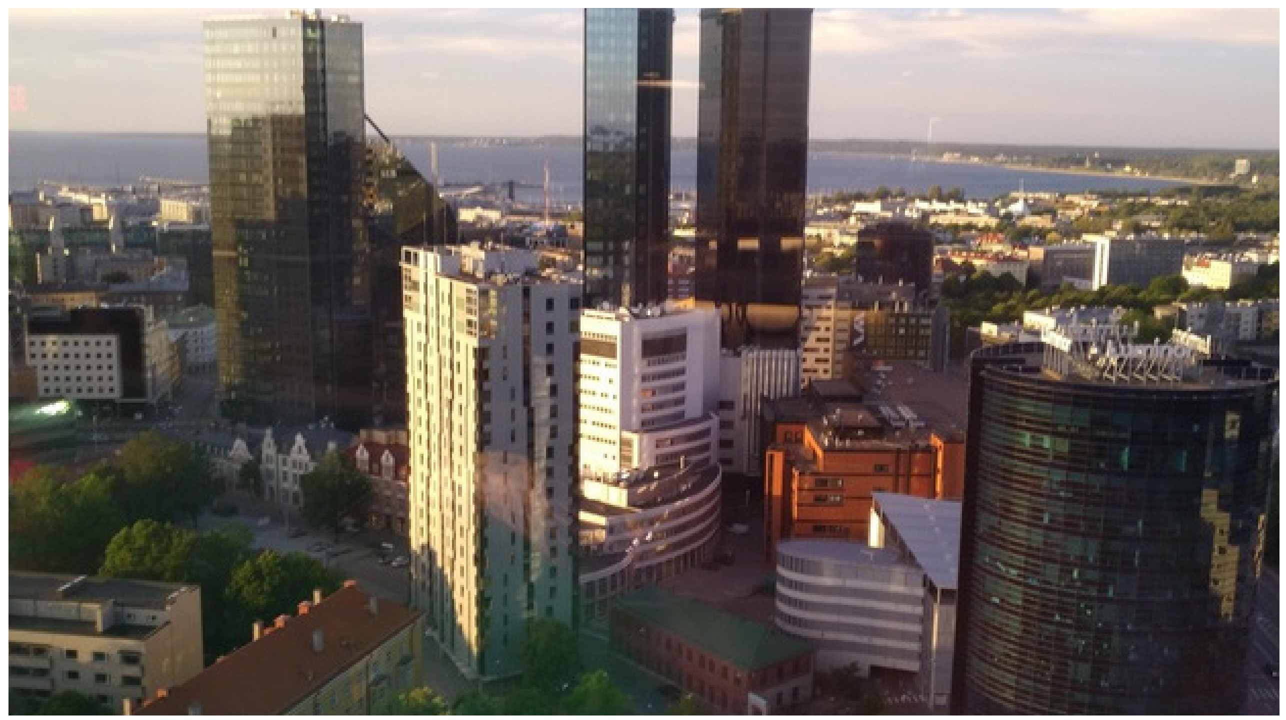
*Pages 50-51: Figure 27. Maakri quarter facades.*

In the Middle Ages, on the quarter's site was the suburb of Kivisilla. (Tallinna Linnamuuseum) The first mention of the area dates to the 13th century and is associated with a Jaani almshouse's construction. (Pärmann, S., 2019) At that time, the Haryapea River ran parallel to today's Maakri Street. The river flowed out of Lake Ülemiste and poured into Tallinn Bay. The 4.5 km long river (Juske. J., 2019) was one of the most exploited rivers in Tallinn. (R. Veski) The river's mills laid the foundation for a large part of Tallinn's industries. By the end of the 17th century, more than eight mills operated on the river banks. Among them, flour, paper, copper processing, gunpowder, and leather tanning mills. (Pärmann, S., 2019 In the Maakri Quarter, located leather mill (Välja, L., 2018) and Jaani mill. (Nerman, R., 2007) The river supplied water to mills and ditches around Tallinn, but people also used it to drain wastewater. Therefore, by the beginning of the 20th century, the river was heavily polluted (Suurkask, H., 2013) and then partially covered with wooden boards In 1914. The river was finally closed to the tunnel collector in the mid-1930s. (Juske. J., 2019)

*Figure 29. View from the EBS school point towards the site in 1950.*

*Top left: Figure 30. Johanson paber fabric.*
*Bottom left: Figure 31. View of the city centre of Tallinn and the building of Maakri Street 1979.*
*Bottom: Figure 32. View of the city centre of Tallinn and the building of Maakri Street 2018.*

*Page 55: Figure 33. Modern Maakri quarter.*



From the 13th century, the Jaani almshouse was the largest building complex in the Kivisilla suburb. It included a hospital, a chapel, a water mill, staff houses, a blacksmith's stable, and a bath. During the Livonian War, the entire complex was destroyed. Soon the almshouse was rebuilt. (Tallinna Linnamuuseum) However, during the Great Northern War (1700-1721), the region's territory was damaged again. (Pärmann, S., 2019) Information about the almshouse buildings' exact location and constructions has not survived. There is evidence that the bath and the lavatory were made of stone. (Gaimster, D., 2011) Despite the consequences of the wars, the restoration of industrial buildings began after a while. In 1877, Theodor Grünwaldt founded the largest leather factory in Estonia. (Pärmann, S., 2019)

Initially, the complex structures were wooden, but they were replaced by stone at the beginning of the 20th century. (Kultuurimälestiste register 1105.) The opening of the paper factory took place ten years later. At the beginning of the 20th century, a synagogue (Nerman, R., 2007), dry cleaning and dyeing gild (Kultuurimälestiste register 8164.) and, E. Lender Girls' Private Gymnasium (Nerman, R., 2008) appeared in the area. Maakri street received its architectural appearance in 1909–1912 [12] according to the Jacques Rosenbaumi Baltic German architect project. (Pärmann, S., 2019) The constructed buildings have elements of such styles as Neo-Baroque, Jugend, Historicism, Neo-Renaissance (Kultuurimälestiste register 1105). [13] In the March 1944 bombing, almost all the buildings were destroyed (Nerman., R., 2008). Buildings along Maakri street were preserved.

## 3. ARCHITECTURE

### 3.1 Spatial program

The designed high-rise complex is an extension of the existing EBS school. The new multifunctional building operates 24/7. The building functions are offices, business, accommodation, residential, shared spaces, and IT school.

### 3.2 Design conception

The multifunctional complex consists of a lower part with four floors and a higher part with 30 floors. Bridges connect the old and the new part on four floors. Between the old and new parts, there is a courtyard. Inside the new building, a big atrium goes through all floors of the lower part. The atrium gives additional light for the internal spaces. Also, the atrium is a space where presented constructions of exposed wood. For the structural design was chosen the modular system, and it also affected an architectural design. The site was divided into a grid with different size modules. Around this modular system was build the whole complex. Modularity impacted floor plans design, contributing to each floor's clear and smooth structure. Inner spaces were also designed following the sizes of modules. The reason for choosing the prefabricated modules system is that Estonia is one of the largest producers of prefabricated timber modular houses. An Estonian firm even participated in constructing the Mjøsa tower in Norway, the World's tallest timber tower. However, Estonia does not have a single outstanding example of a tall wooden building. The high timber rise made of prefabricated modules in the center of Tallinn could be a significant landmark and represent the power of the Estonian wooden construction industry.

### 3.3 Floor plans

#### Ground floor

There are three main entrances into the high-rise complex—two from Lennuki street – one to the lower part, and one to the high-rise. The separate entrance is devoted to tower residents from the south of the building. On the ground floor, there are two business areas along Lennuki street. There is a big canteen with shared space in the middle of the floor.

#### Floor 2

The second floor is fully occupied by IT school rooms. Here is IT school teacher staff rooms under the high-rise part of the complex. In the lower part locates four classes. Three big classes can be divided into smaller by folding wall if necessary. Here is also a big auditorium for 300 students. In from of the big auditorium there is an open shared space and under the auditorium more private space for individual and group study.

#### Floor 3-4

Three floors are devoted to offices of different sizes. There is also a shared space for office workers on each floor.

#### Floor 5-7

This floor slocates only under the high-rise part and is entirely devoted to the big open-office with a total area of 655 $m^2$. The big office can be divided into smaller offices if needed.

### Floor 8-15

Seven floors are devoted to the hotel apartments. Each floor has ten hotel units with an average unit area of 23 $m^2$. Two bigger apartments – 30 $m^2$ and suitable for disabled people. There are also a shared space and a big kitchen on the floor for hotel residents.

### Floor 17-21, 26-30

Smaller apartments accommodate floors from 13 to 21. On each floor, there are eight apartments – four apartments with three rooms, two studio apartments, and two two-room apartments. The area four three-room apartments with an area - 62 $m^2$, two studio apartments – 30 $m^2$, and two two-room apartments -36 $m^2$.

### Floor 22-25

The big apartments accommodate floors from 21 to 30. On each floor, there are five apartments – 3 big apartments with four rooms, one single-room apartment, and one apartment with three rooms. The area of big apartments from 95 - 100 $m^2$. Big apartments have a master bedroom with a separate bathroom and cabinet.

### Garbage and technical rooms

The garbage room locates on the ground floor on the south corner of the building. There is one big technical room in the lower part of the complex. The high-rise technical room locates on the 16th floor and serves the tower upper and lower part. The area for the technical rooms was calculated based on 5-10 percent of the total floor area.

### Parking

Access to the underground parking is from A. Lauteri street. There are two floors of underground parking with 40 parking lots on each floor. Also, there are 20 parking lots on the ground floor between the EBS and new building and 18 on the ground parking lots along Lennuki street in front of the new building. There is one parking lot for disabled people on each underground floor and one on the ground parking lot in front of the new building. The total amount of parking lots 118.

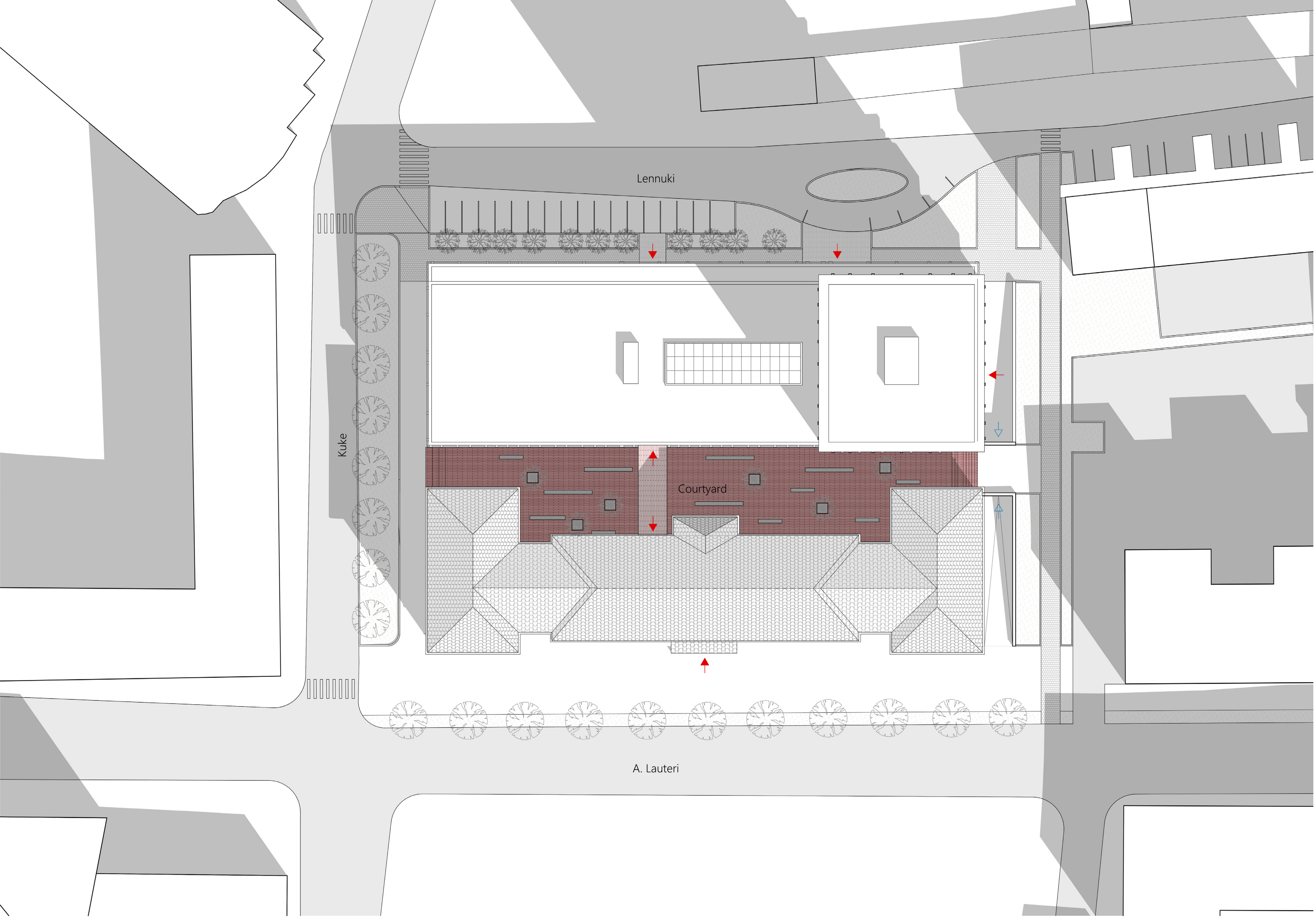
### Elevators

There are six elevators in the complex. Two locates in the lower part of the building and four in the high-rise part. The high-rise part two elevator is devoted only to office workers and hotel residents and the other two to tower residents. One fire-safe elevator in the high-rise part can be accessed from all tower floors.

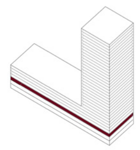
## 3.4 Facade design and materials

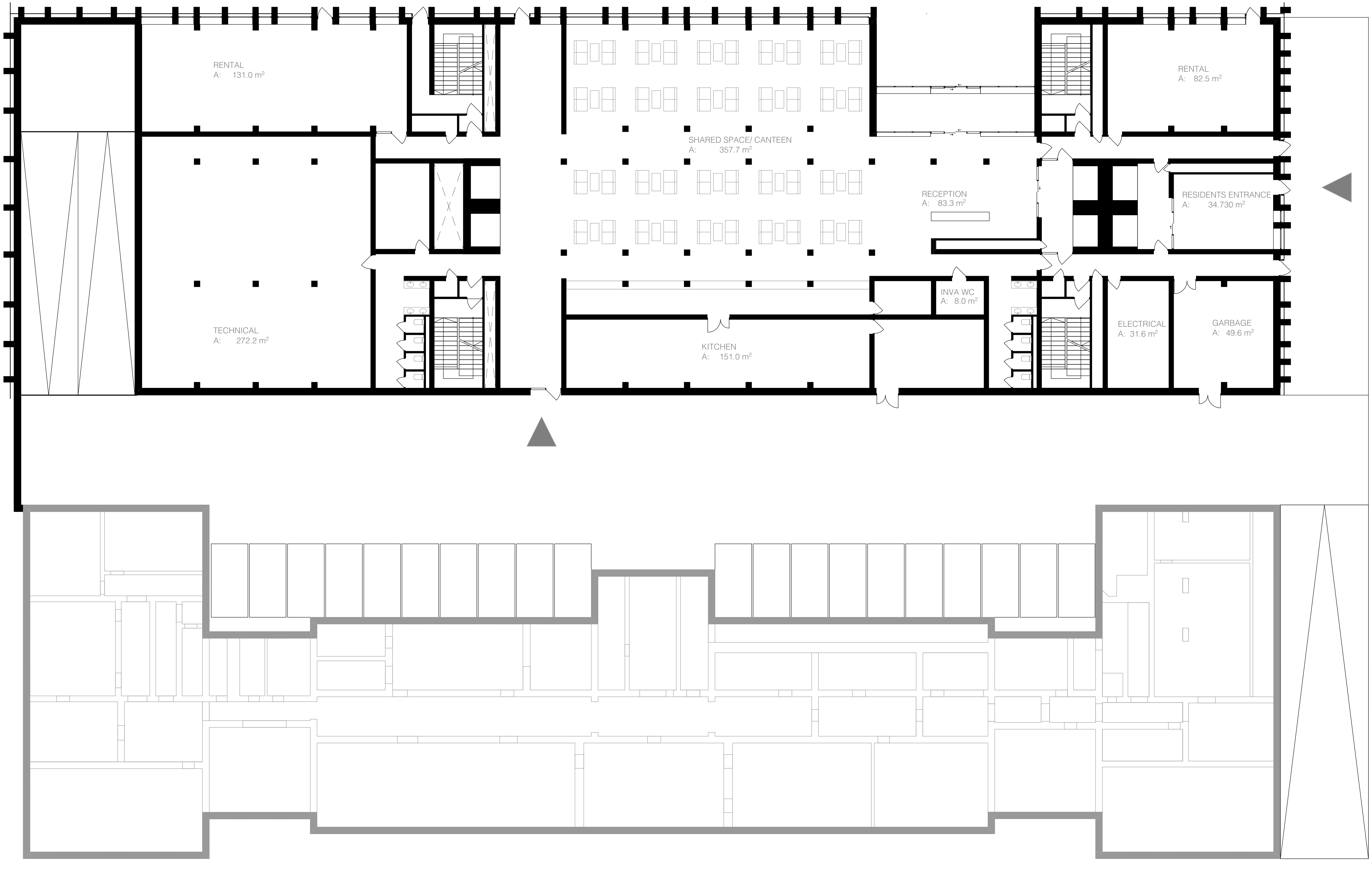
The wood material itself inspires the idea of the exterior shape of the building. The building is divided into parts and resembles piled timber. The alternation of different facade patterns is associated with a change in the functions of the building. The double skin facade system was used for energy efficiency. For the facade material was chosen ceramic facad. The ceramic facade is made of natural materials, sustainable and durable. The natural color of ceramic louvres also resembles wood from a big scale.

## SITE PLAN

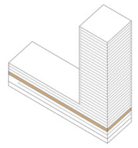

Lennuki
Kuke
Courtyard
A. Lauteri

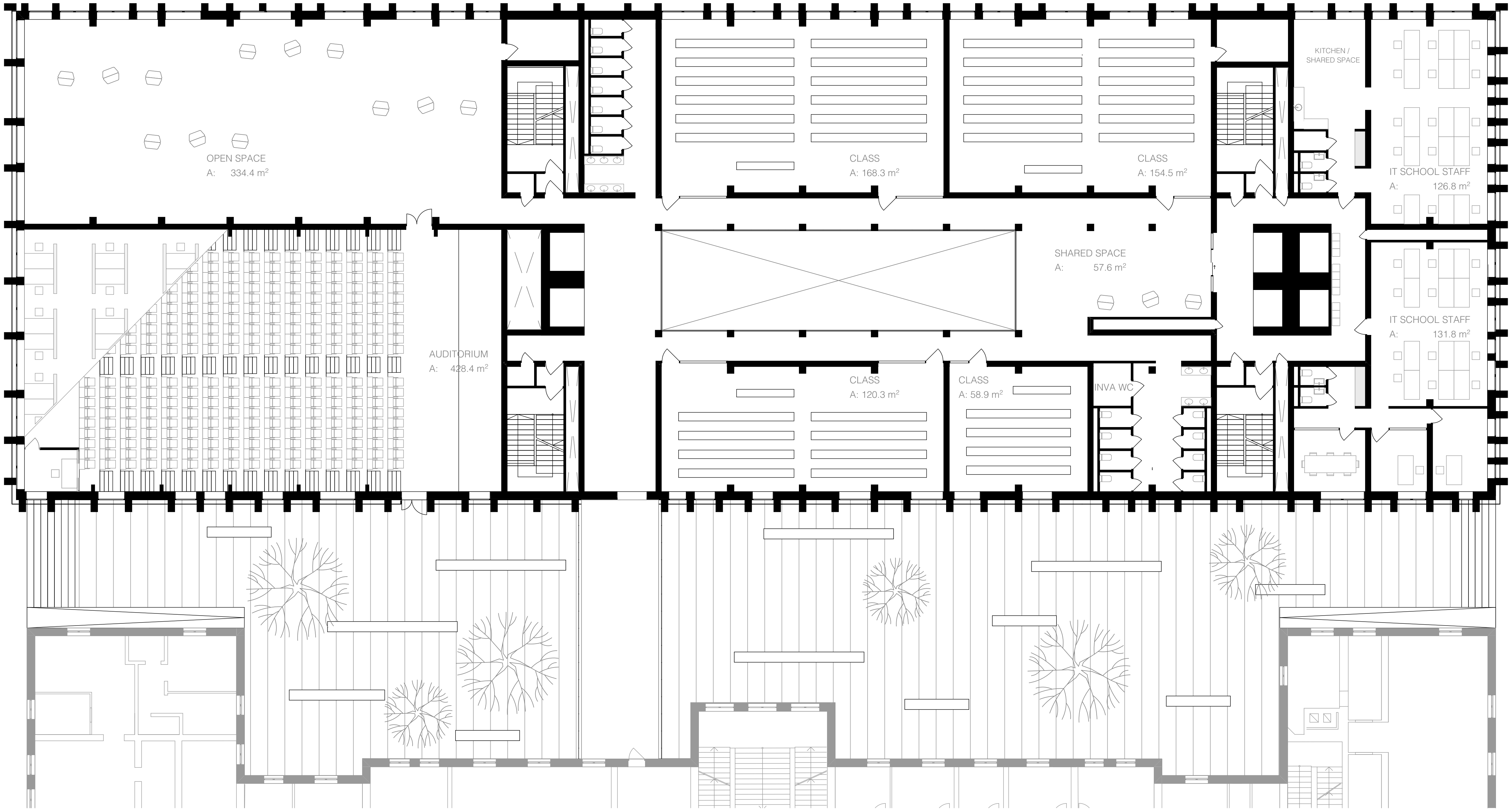
**GROUND FLOOR**



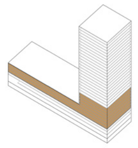


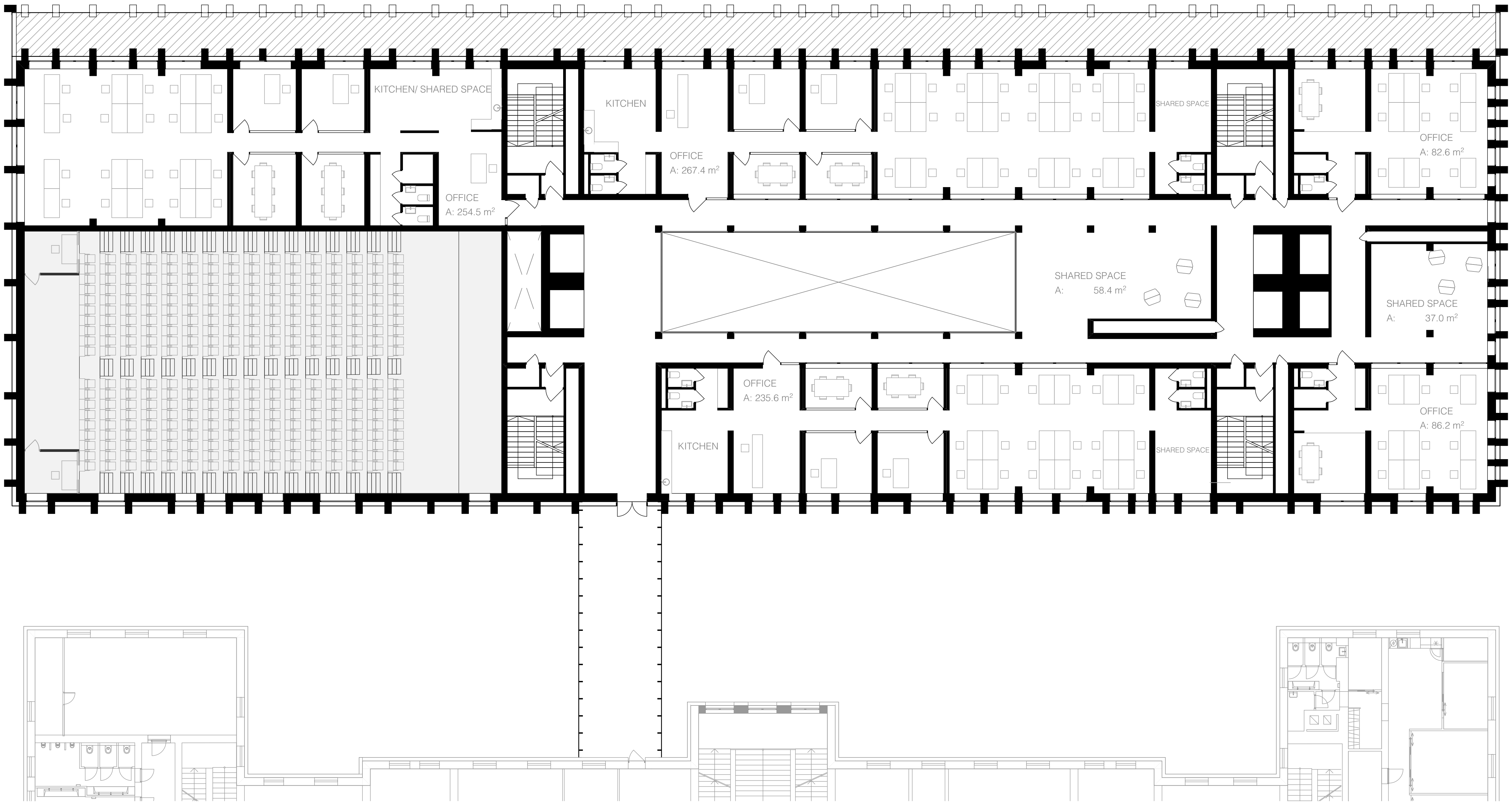
## IT SCHOOL I FIRST FLOOR



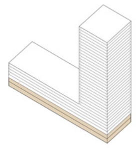


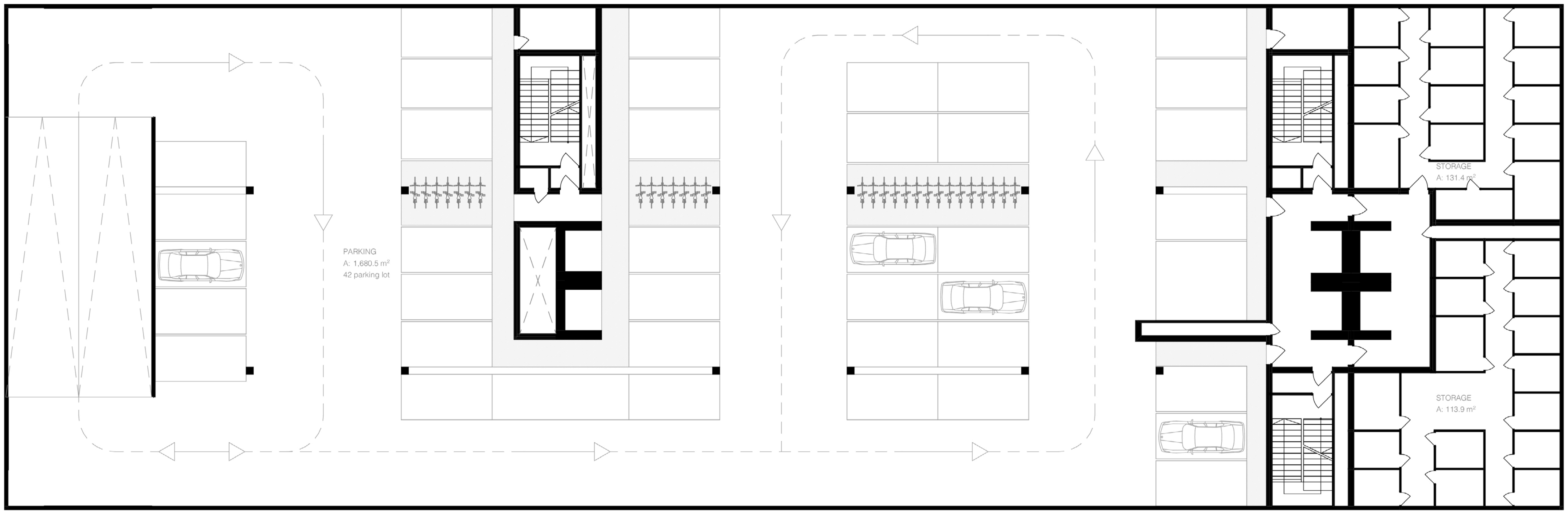
**OFFICES I FLOOR 2-3**



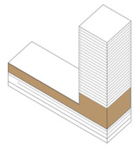


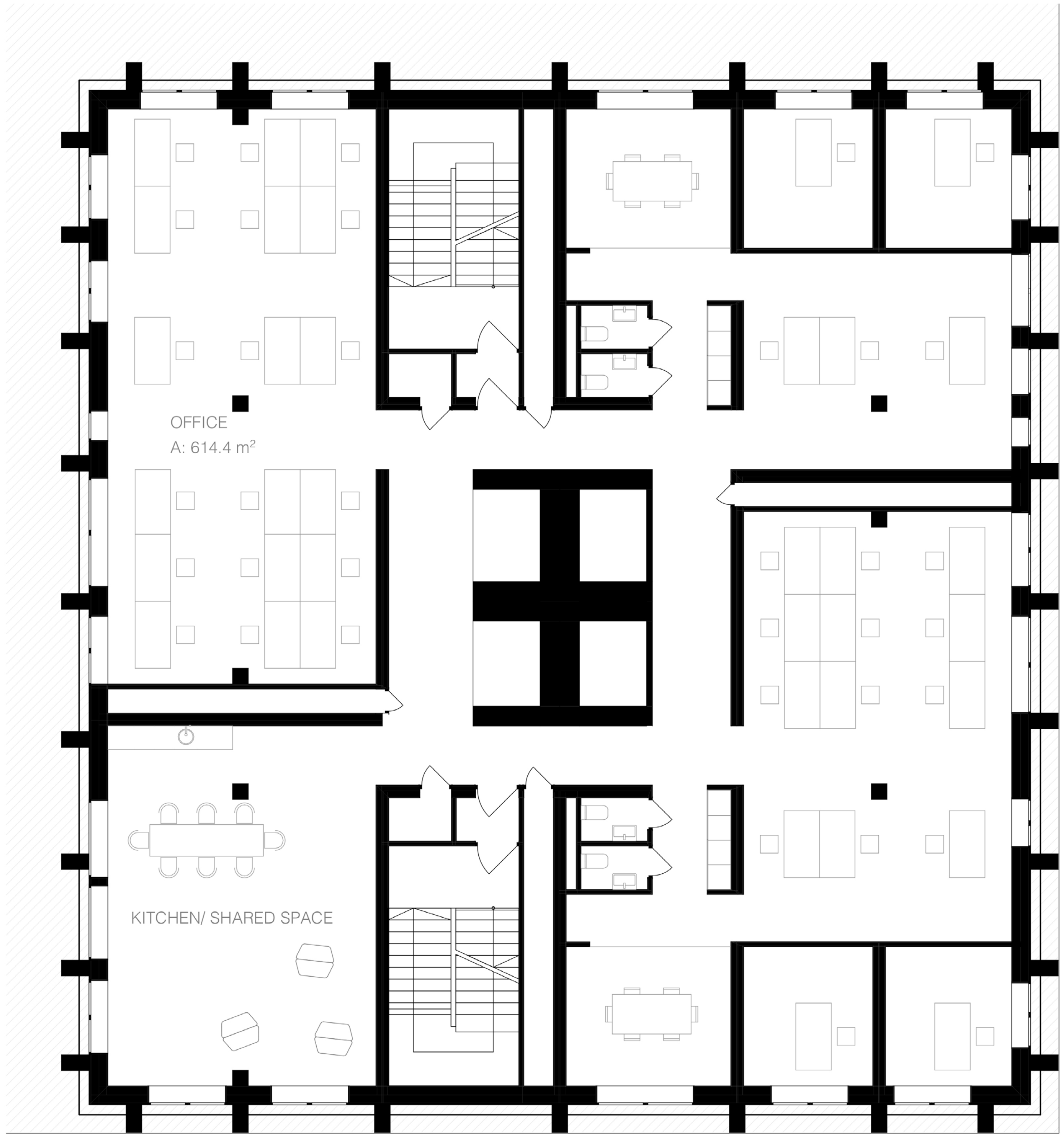
## PARKING I FLOOR -1-(-2)



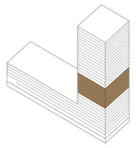


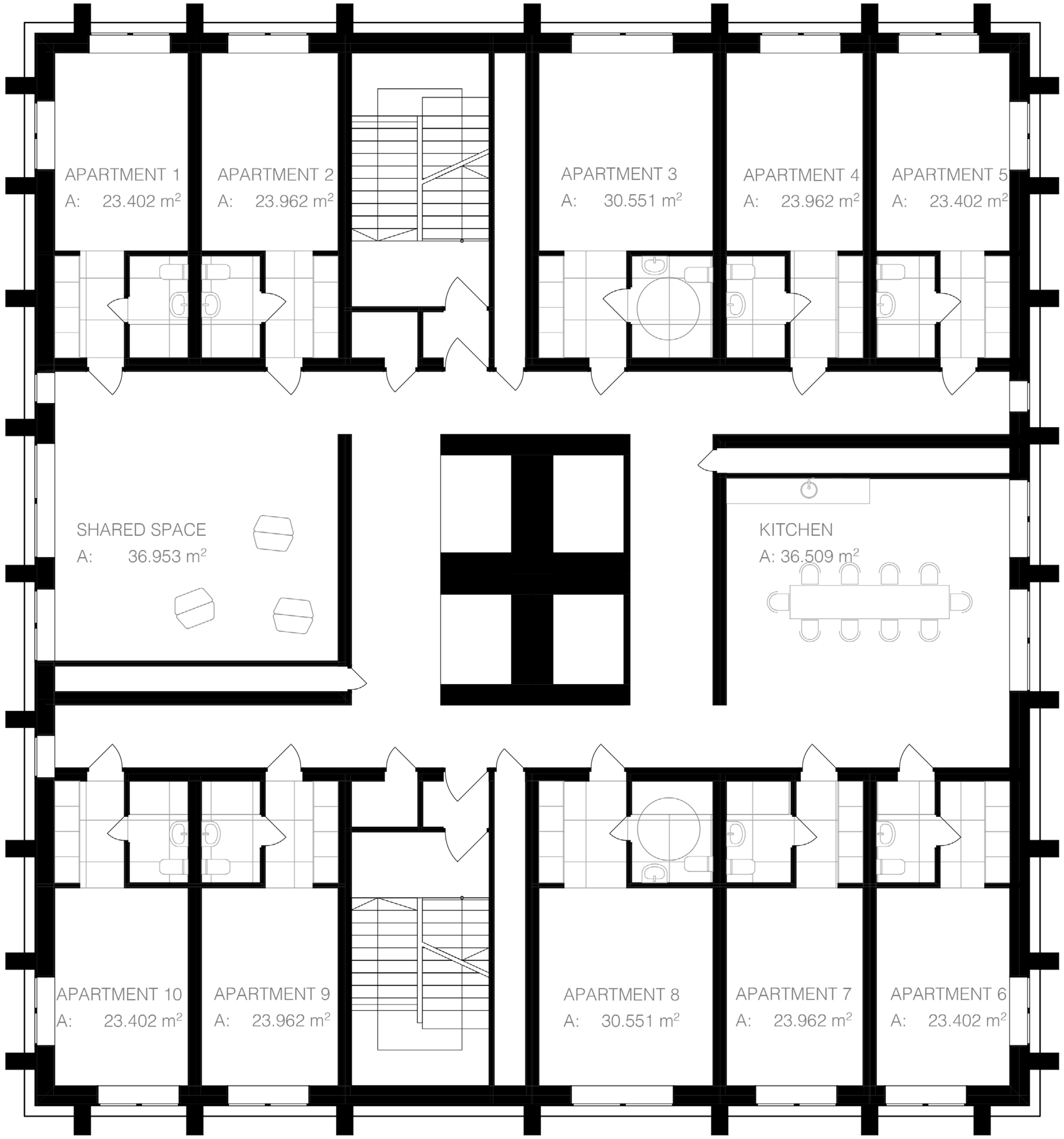
**OFFICES I FLOOR 5-7**



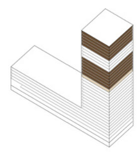


**HOTEL I FLOOR 8-15**





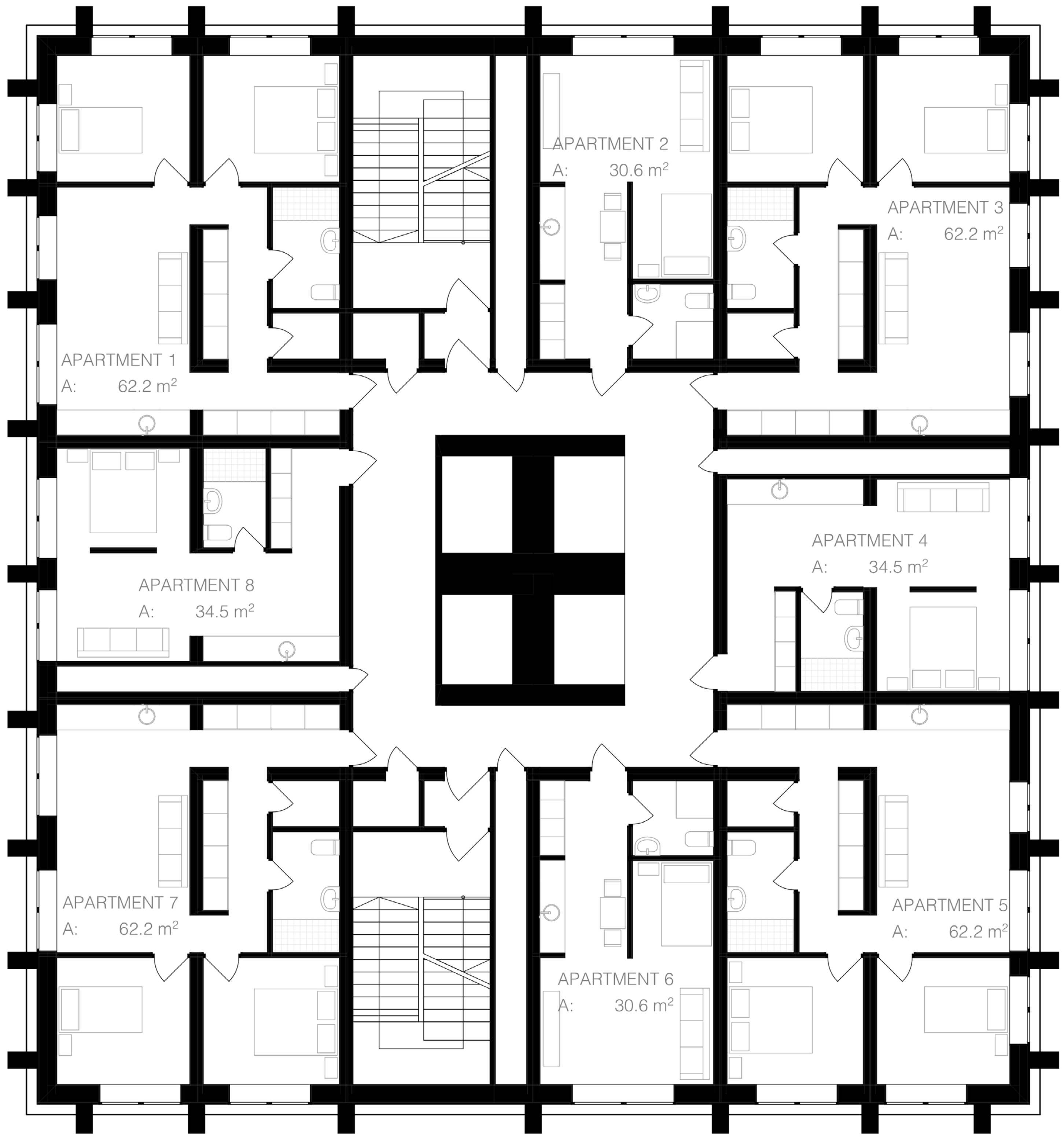
**SMALL APARTMNETS I FLOOR 17-21, 26-30**



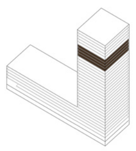
Small apartments

2 - room

1 - room



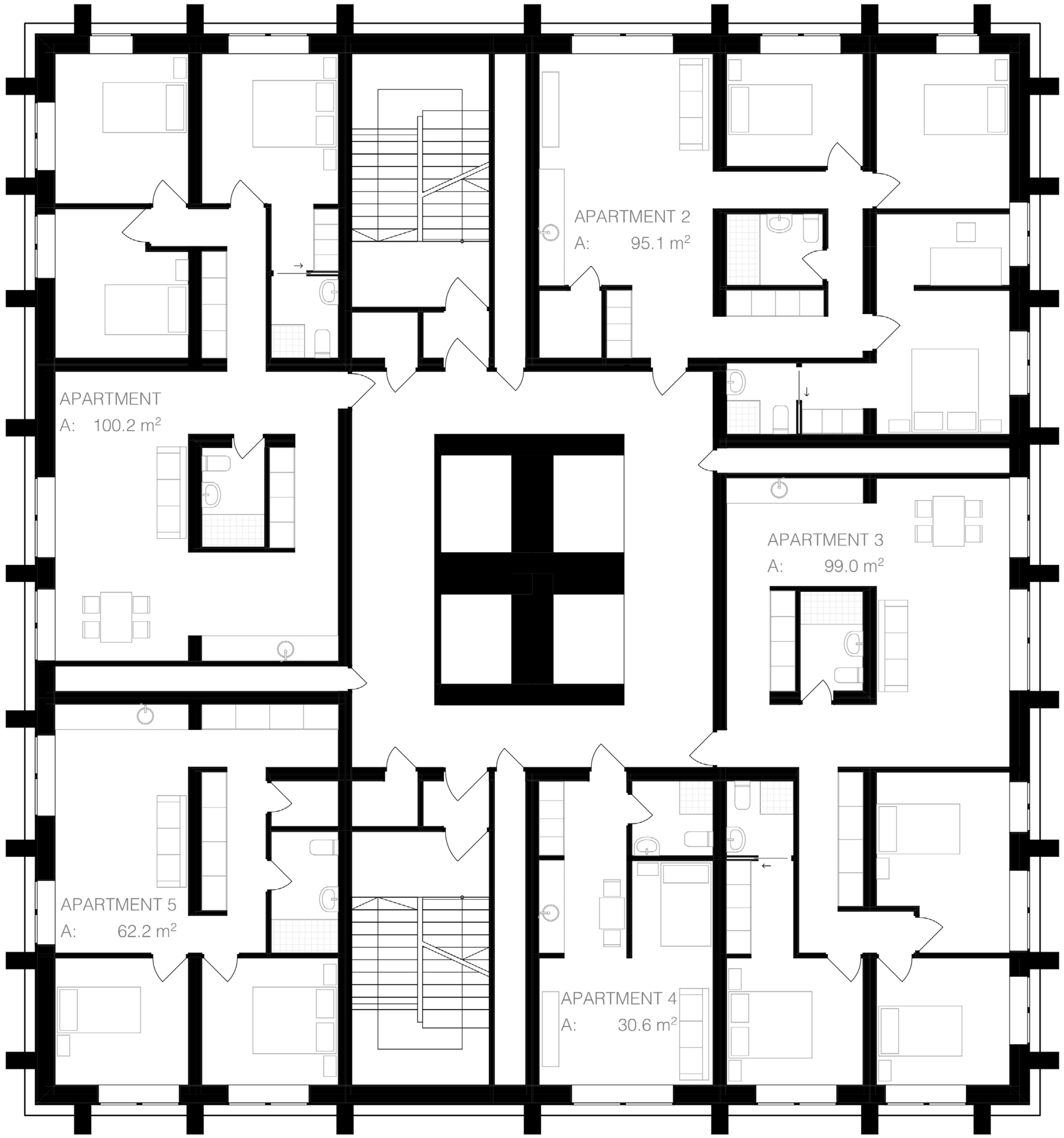
## LARGE APARTMENTS I FLOOR 22-25



Large apartments

4 - room

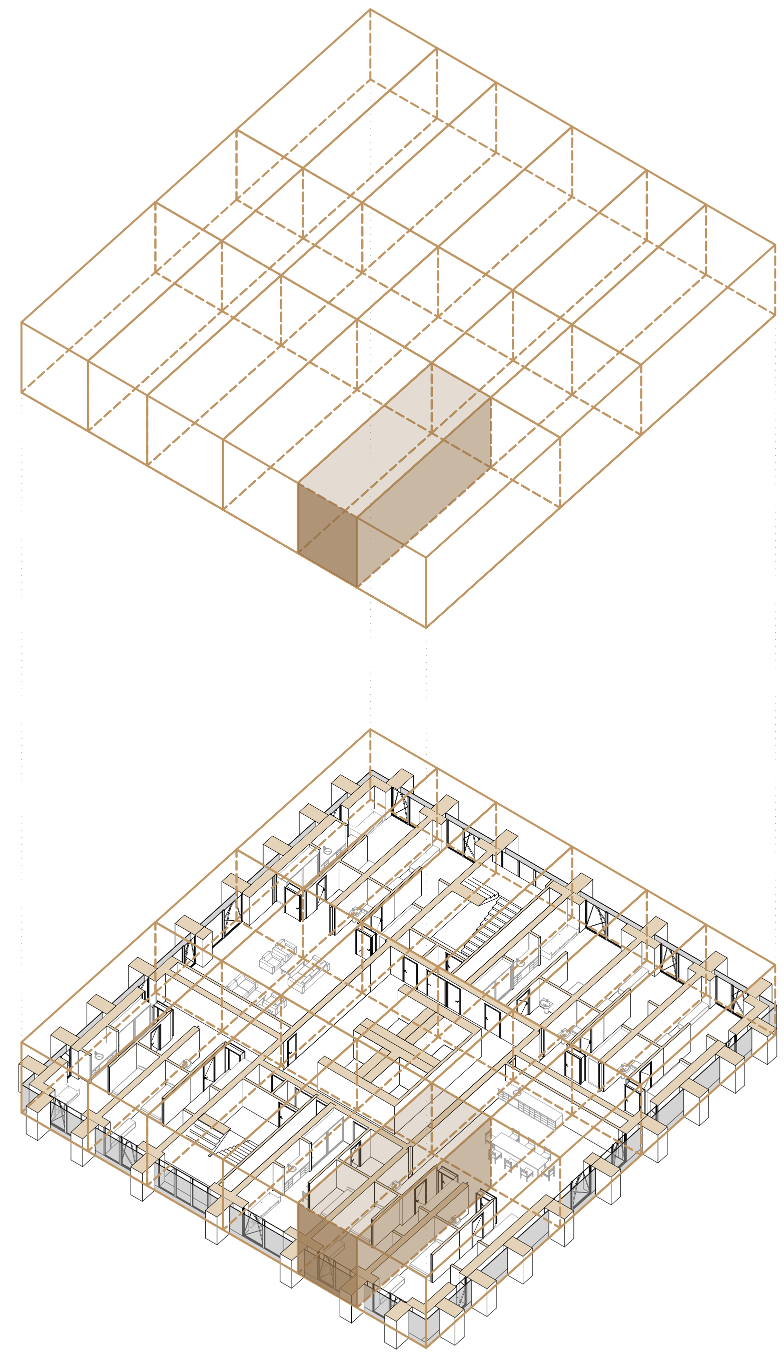
3 - room



## 5. CONSTRUCTIONS

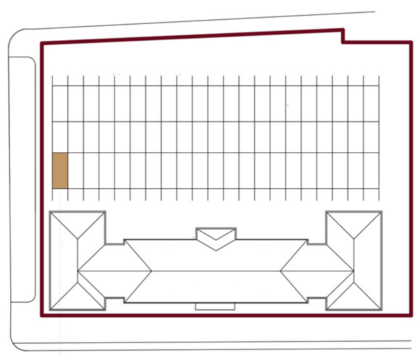
### 5.1 Structural system

The high-rise complex rests on a RF concrete foundation that prevents moisture movement from the soil to wooden structures above the concrete. Above the RF concrete foundation, the main body of high-rise complex consists of prefabricated modules. The modular system allows modules bear themselves. The stability of high-rise part gained by core and four shafts connected to the core. Inside the shafts there are tension diagonals to mitigate horizontal loads. Modules connected to the core and shafts, stacked on each other and can bear themselves. The same load-bearing structure was used in Nordic Tower research. (H. Edelman, 2020) External and internal walls, floors, roofs are made of CLT panels, beams and columns above the ground floor made of glulam. Also, all stairs and elevator shafts are made of wood. Elevator shaft wall thickness is 0,5 m. Two underground parking floors are made of concrete and thick layer of concrete was also used in intermediate floors for better acoustics and additional mass. More detailed load-bearing and non-load bearing constructions presented on Section I-I and Section II-II.



### 5.2 Acoustic

Massive CLT floor and wall panels due to their dense structure, provide good acoustic comfort for people in office spaces, educational rooms and apartments. In educational part of the building also used sound rated plasterboard. In shared spaces and more private parts used acoustic furniture and additional acoustic panels.



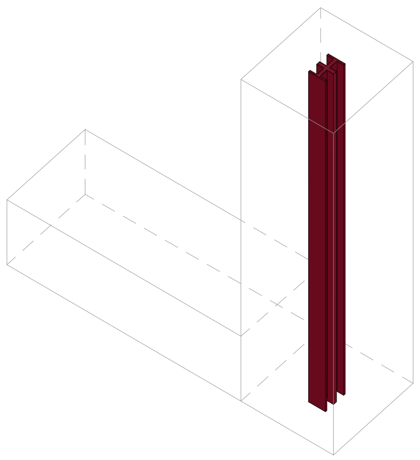
Module 1
4,2X 7,9 m
offices

Module 2
3,6 X 7,9 m
stairs

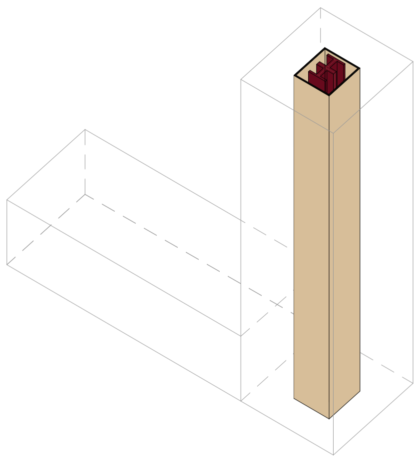
Module 3
3,6 X 7,9 m
offices, apartments, hotel

### 5.3 Fire safety

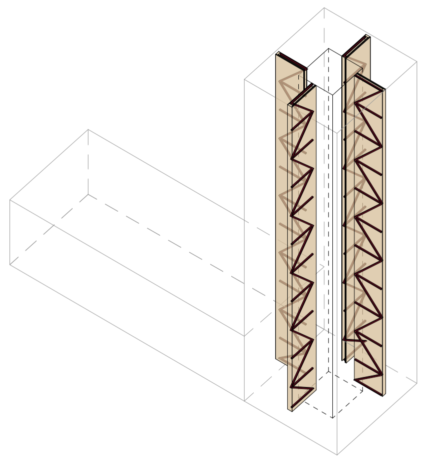
Almost all timber elements have an additional protective plasterboard 18 mm layers to achieve fire safety requirements. Some of the columns and beams are exposed in the middle of the building. In this case over-dimensioned timber structures contribute to elements fire safety as they have protective charring layer. The high-rise part has a fire safe elevator. The facade of the low and high part is made of non-combustible materials.



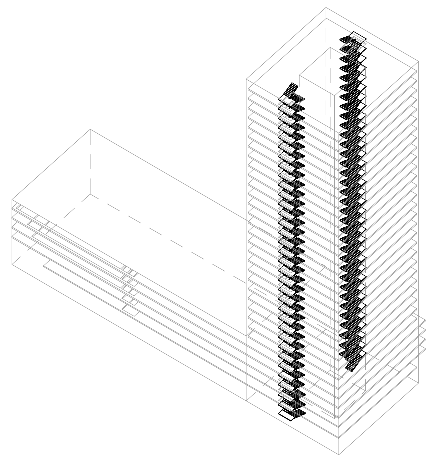
Elevator shafts 500 mm



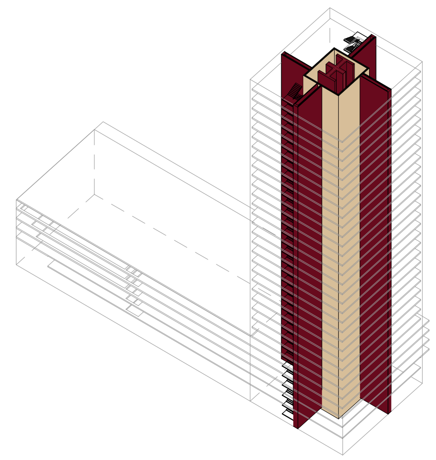
Mass timber core



Four shafts with t
ension diagonals bars



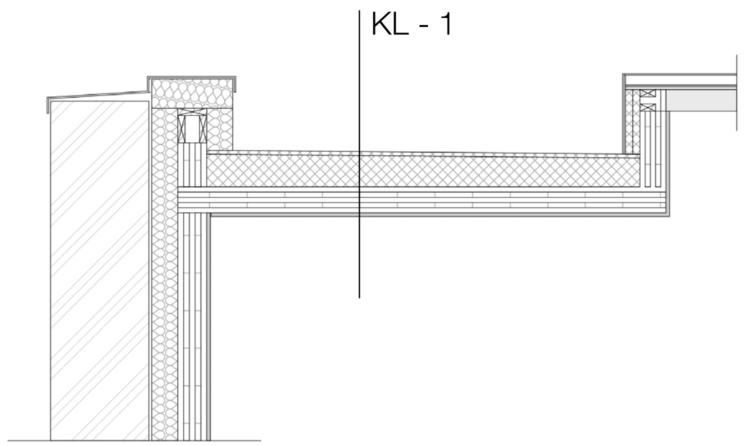
Mass timber stairs



Shafts connected to
core

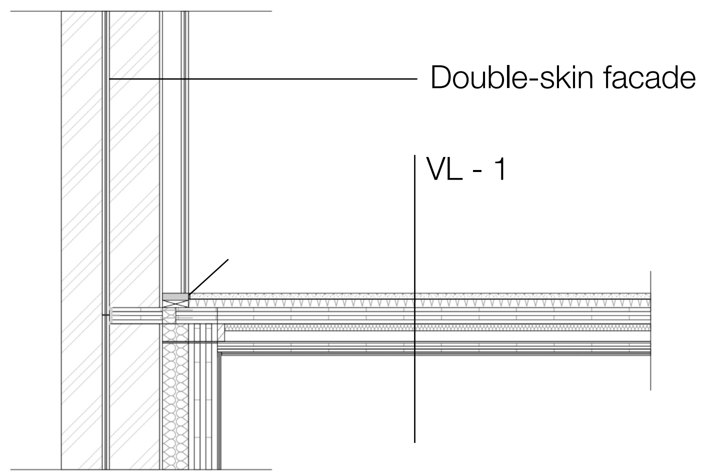
**DETAILS**

## Roof to external wall



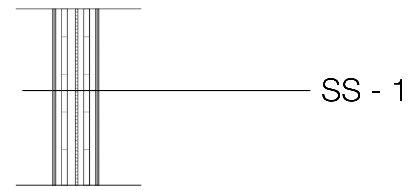

KL-1
bitumen sheet
18 mm plywood board
30 mm rockwool with insulation channel
200 mm polyurethane insulation board
moisture barrier
180 mm CLT panel

## Intermediate floor



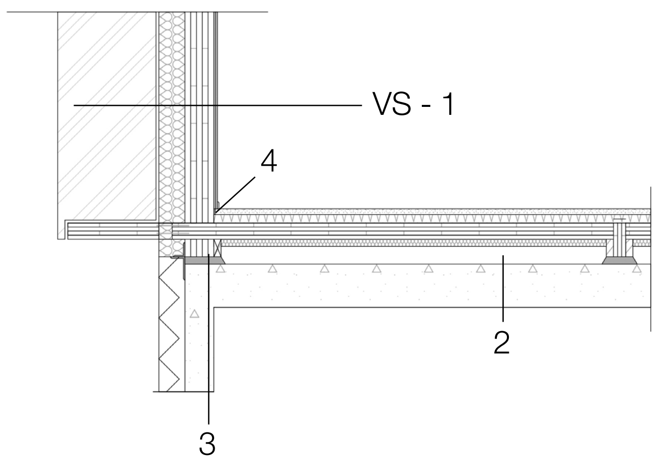

VL-1
40 mm floating concrete slab
30 mm impact sound insulation
140 mm CLT panel
135 mm air gap + insulation (50 mm)
80 mm CLT pan

## Internal load-bearing wall




SS-1
15 mm gypsum plasterboard
15 mm gypsum plasterboard
120 mm CLT panel
30 mm air gap + insulation
120 mm CLT panel

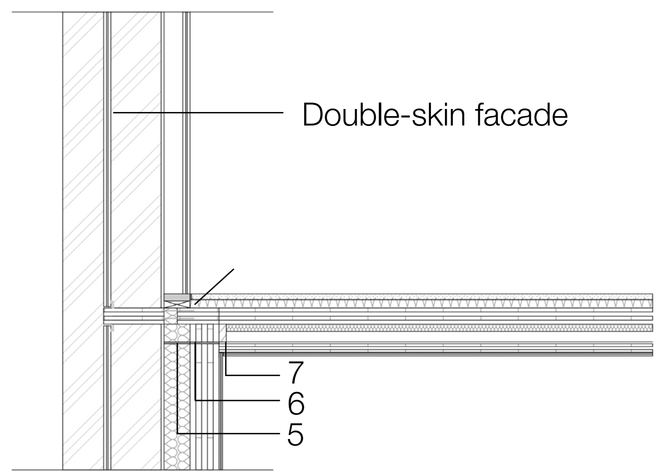
## Ground floor wood module to concrete slab




VS-1
200 mm insulation
moisture barrier
200 mm CLT panel
15 mm gypsum plasterboard

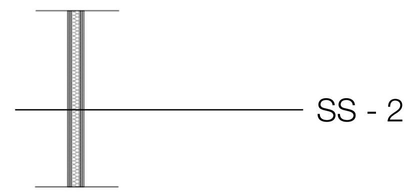
1 - infill cast (0-50 mm)
2 - moisture under the module from site operation needs to be ventilated

## Roof to external wall



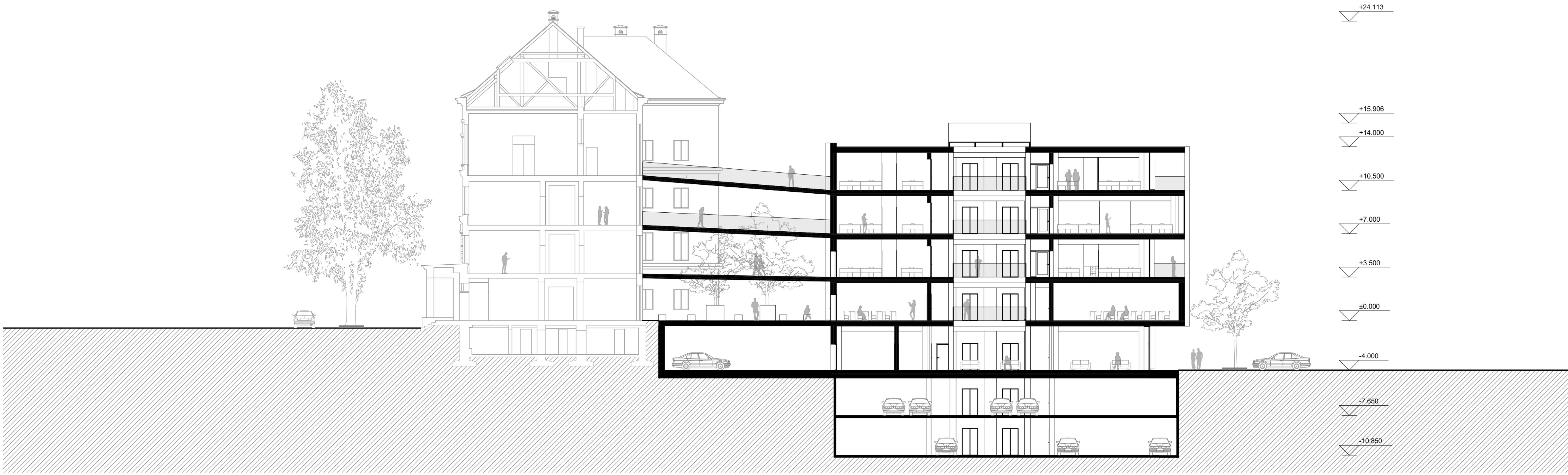

4 - separation strip for moisture and sound isolation
5 - mineral wool
6 - vibration isolation pad
7 - EPDM rubber sealant (soft)

## Partition wall

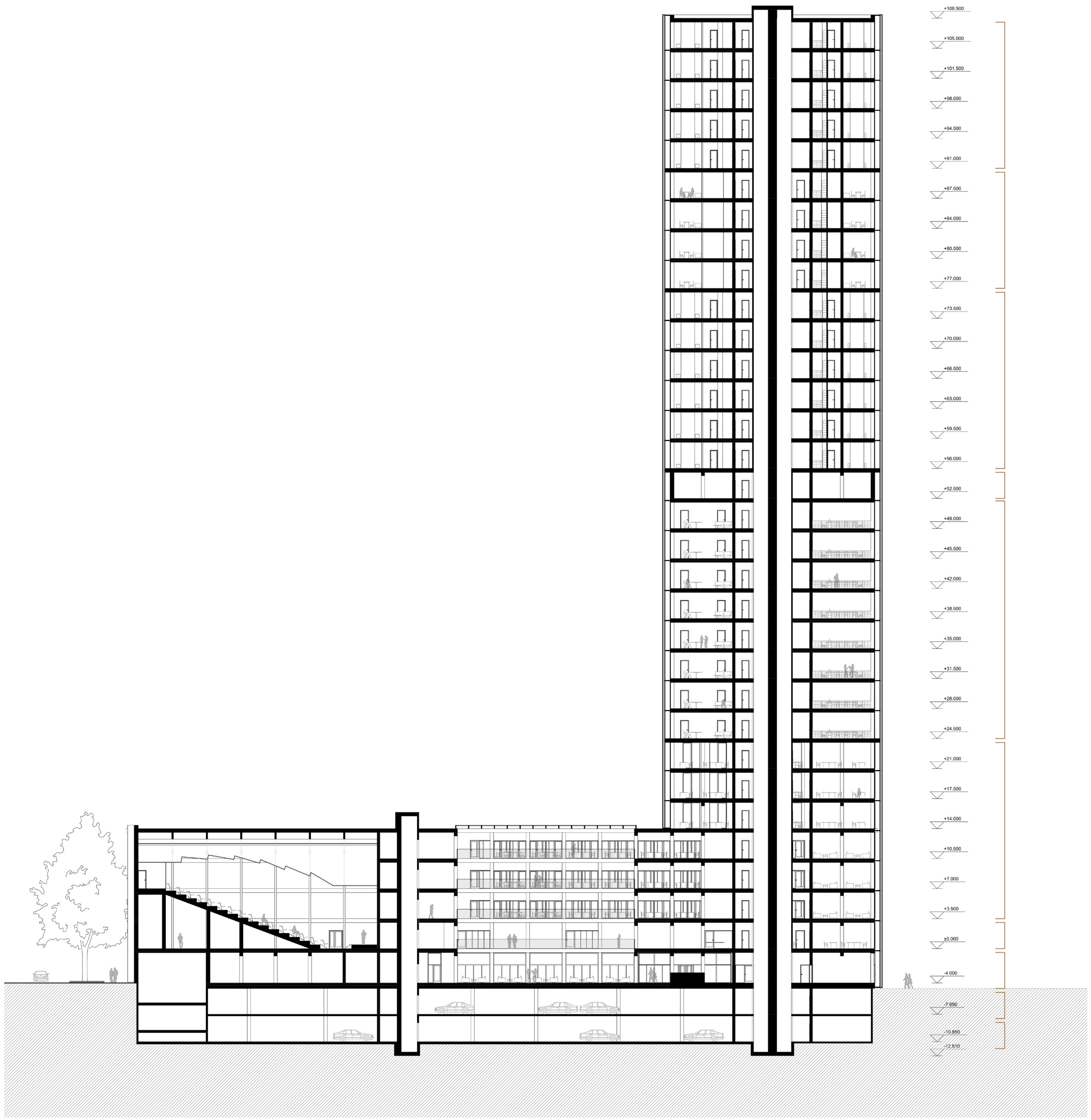



SS-2
15 mm gypsum plasterboard
15 mm gypsum plasterboard
66 mm timber frame + insulation (50 mm)
15 mm gypsum plasterboard
15 mm gypsum plasterboard

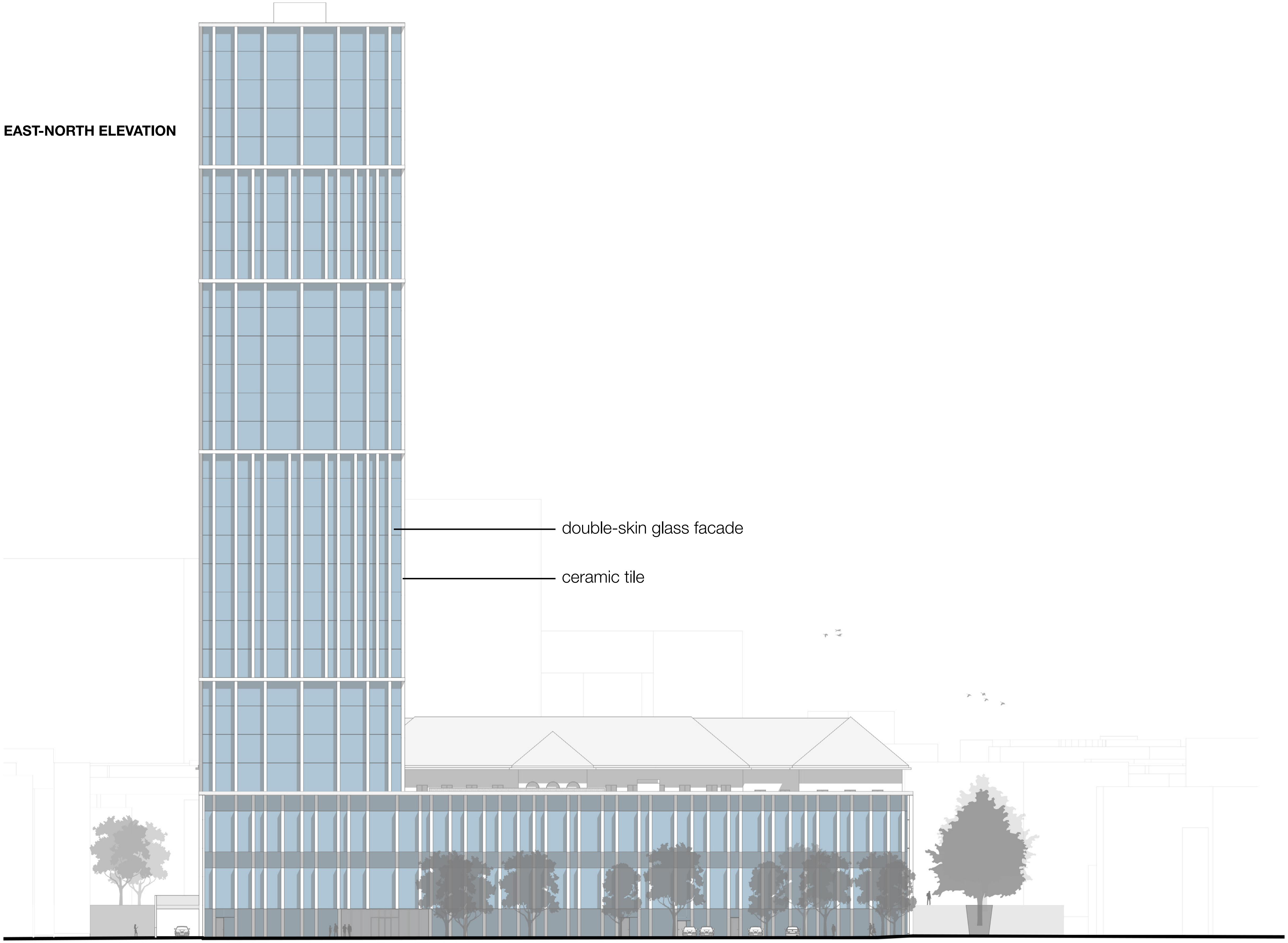
## SECTION I-I



## SECTION II-II



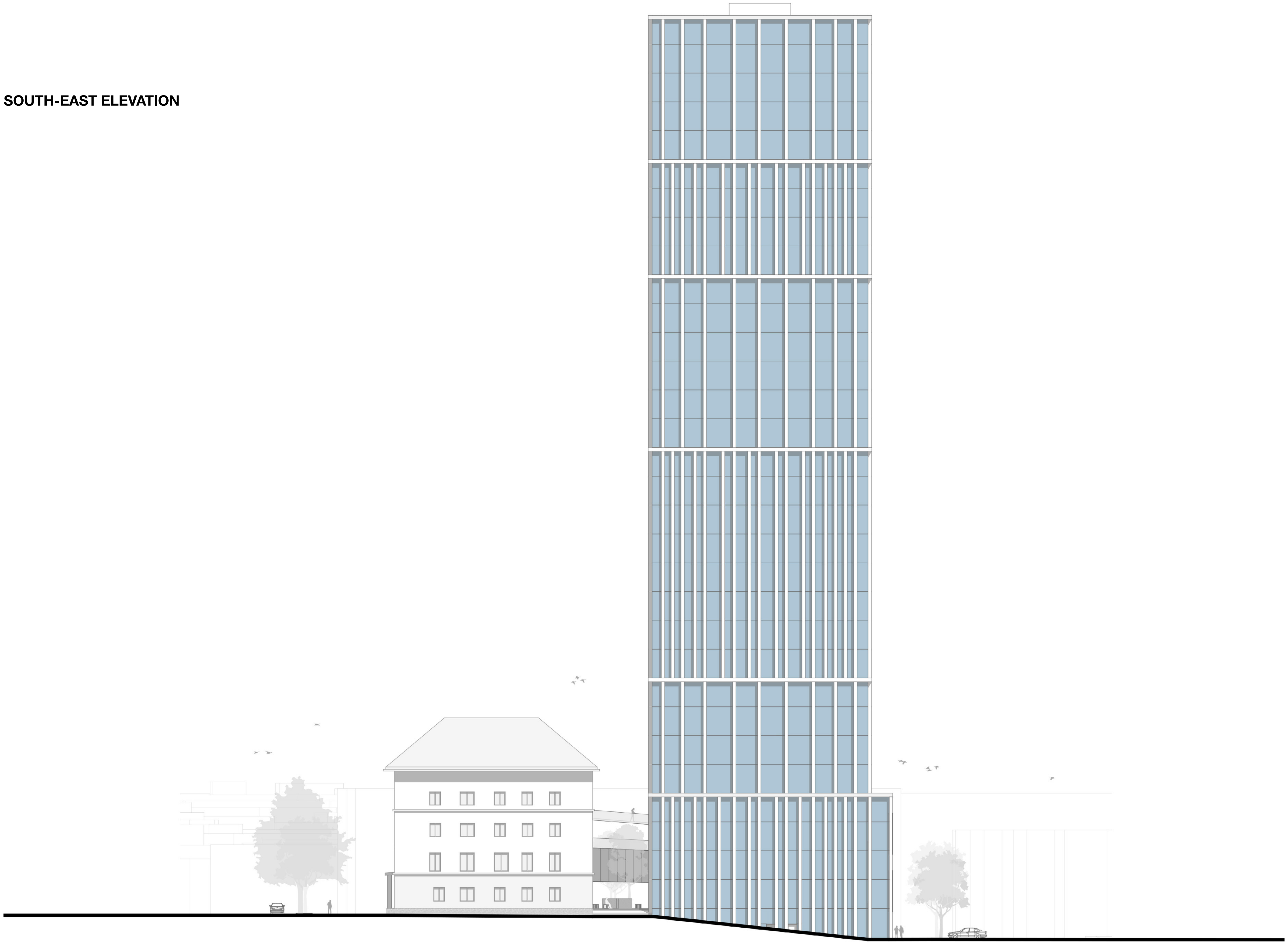
EAST-NORTH ELEVATION



## SOUTH-WEST ELEVATION

# WEST-NORTH ELEVATION

SOUTH-EAST ELEVATION




SKYON
SEB

**LIST OF TABLES**

**LIST OF DRAWINGS**

## List of drawings



## Drawings sources

Figure 1. Ritchie H., Roser M. (2018). Urbanization. https://ourworldindata.org/urbanization

Figure 2. United Nations Environment Programme (2020). 2020 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector. Nairobi

Figure 3. China.org.cn. (April 9, 2012). The Sakyamuni Pagoda of Fogong Temple. http://www.china.org.cn/travel/2012-04/09/content_25094031.htm

Figure 4. UAB In Your Pocket. (September 2, 2020). Radio Station Gliwice. https://www.inyourpocket.com/katowice/radio-station-gliwice_73449v

Figure 5. WoodWorks and Think Wood. (2021). Mass Timber Design Manual.

Figure 6. WoodWorks and Think Wood. (2021). Mass Timber Design Manual.

Figure 7. WoodWorks and Think Wood. (2021). Mass Timber Design Manual.

Figure 8. Source:

Figure 9. WoodWorks and Think Wood. (2021). Mass Timber Design Manual.

Figure 10. Author's drawing.

Figure 12.

1. Murray grove
Dewar, L. (n.d.). Mass Appeal: Mid-Rise Solid Timber Buildings in the UK. Eurban. https://wood-works.ca/wp-content/uploads/5-Dewar-EURBAN-UK-Experience-in-Mid%E2%80%90Rise-Solid-Timber-Buildings.pdf
Cross-Laminated Timber: A Revolution in Timber Construction. (2014). KLH Massivholz GmbH. https://bct.eco.umass.edu/wp-content/uploads/2014/10/KLH_Company-presentation_UMass-Amherst.pdf
Liddell, C. (2010). Stadthaus, 24 Murray Grove, London: Eight storeys of apartments featuring cross-laminated timber panels. TRADA Technology. https://eoinc.weebly.com/uploads/3/0/5/1/3051016/murray_grove_case_study.pdf
Picture:
Pryce, W. (2009). Stadthaus, 24 Murray Grove [Photo]. https://www.e-architect.com/sustain-

gaps for construction of high-rise timber buildings : Sustainable High-Rise Buildings Designed and Constructed in Timber (Hi Timber). Tallinna Tehnikakõrgkool. https://www.digar.ee/viewer/et/nlib-digar:421322/358768/page/46
Brännström, M.E. (2021). Welcome to Sara Kulturhus in Skellefteå. Skellefteå AB. https://www.visitskelleftea.se/en/sara/
Salvadori, V. (2017). The Development of a Tall Wood Building. Politecnico Milano.
Picture:
White Arkitekter. (2017). A CLT high-rise to bring a community together. Katus.eu [render] https://katus.eu/learn/news/clt-high-rise-brings-community-together
Ascent
Gibson, S. (2019). 21-Story Mass Timber Building Proposed in Milwaukee. Green Building Advisor. The Taunton Press, Inc. https://www.greenbuildingadvisor.com/article/21-story-mass-timber-building-proposed-milwaukee
Peronto, J. (2020). Designing the World's Tallest Mass Timber Building. Thornton Tomasetti. https://www.thorntontomasetti.com/project/ascent
Picture:
Korb + Associates. (2019). ASCENT. [render] http://www.kaa-arch.com/php/page-projectLoader.php?project=135
The Dutch mountains
Brouwers, B. (2019). 'Dutch Mountains' get a Place in New Station Area Eindhoven. Innovation Origins. https://innovationorigins.com/dutch-mountains-get-a-place-in-new-station-area-eindhoven/
Parkes, J. (2021). Studio Marco Vermeulen designs cross-laminated timber Dutch Mountains skyscrapers. Dezeen. https://www.dezeen.com/2021/02/18/studio-marco-vermeulen-designs-cross-laminated-timber-dutch-mountains-skyscrapers/
Picture:
Studio Marco Vermeulen. (2019). The Dutch Mountains. [render] https://innovationorigins.com/dutch-mountains-get-a-place-in-new-station-area-eindhoven/
The Oakwood Tower
Hamburg, P., Lellep, K., Kiisa, M. (2018). International study on best practices and knowledge gaps for construction of high-rise timber buildings : Sustainable High-Rise Buildings Designed and Constructed in Timber (Hi Timber). Tallinna Tehnikakõrgkool. https://www.digar.ee/viewer/et/nlib-digar:421322/358768/page/47
Ramage, M., Foster, R., Smith, S., Flanagan, K. (2017). Super Tall Timber: design research for the next generation of natural structure. The Journal of Architecture 22(1):1-19. https://doi.org/10.1080/13602365.2016.1276094
Picture:
PLP Architecture. (2017). The Oakwood Timber Tower. Centre for Natural Material Innovation, Cambridge University. [render] https://urbannext.net/oakwood-timber-tower/
W350



Lynch, P. (2018). Japan Plans for Supertall Wooden Skyscraper in Tokyo by 2041. Archdaily. https://www.archdaily.com/889142/japan-plans-for-supertall-wooden-skyscraper-in-tokyo-by-2041
Harada, H., Fukushima, T., Hatori, T., Hajime, A. (2020). W350 - The Roadmap Of Super High-Rise Timber Building. Council on Tall Buildings and Urban Habitat. https://global.ctbuh.org/resources/papers/download/4375-w350-the-roadmap-of-super-high-rise-timber-building.pdf
Picture:
Nikken Sekkei. (2018). Japanese builder unveils plans for world's tallest timber skyscraper in Tokyo. Inhabitat. https://inhabitat.com/japanese-builder-unveils-plans-for-worlds-tallest-timber-skyscraper-in-tokyo/
Figure 12. Eesti kirikud. (n.d). Ruhnu püha Magdalena kirik. http://kirikud.muinas.ee/?page=3&subpage=1135

Figure 13. Blaat. T. (2020). Viimsi kooli 8. klasside õpilased saadeti ennetavalt distantsõppele. https://www.delfi.ee/artikkel/91274359/viimsi-kooli-8-klasside-opilased-saadeti-ennetavalt-distantsoppele

Figure 14. Tunnel T., Õunasaar E. (2020). Sisekaitseakadeemia Narva õppekeskus. https://www.tajuruum.eu/projektid/sisekaitseakadeemia-narva-oppekeskus

Figure 15. Kavakava. (2019). Keskonnamaja. http://www.kavakava.ee/project/keskkonnamaja/

Figure 16. Author's drawings.

Figure 17. Edelman, E. (March 3, 2020). Nordic Tower. Accessed: May 5, 2021. [Online]. Available: https://www.linkedin.com/pulse/nordic-tower-harry-edelman/

Figure 18. BNP Paribas. (2028). Wood is the new concrete. https://cib.bnpparibas/wood-is-the-new-concrete/

Figure 19. Becker., D. (2014). David Chipperfield installation of tree trunk columns in Mies van der Rohe's Neue Nationalgalerie. https://www.dezeen.com/2014/10/02/david-chipperfield-sticks-and-stones-tree-trunks-installation-neue-nationalgalerie-mies-van-der-rohe-berlin/

Figure 20. Simonen, K., Huang, M., Rodriguez, B.X., Todaro, L. (2019). Life Cycle Assessment of Buildings: A Practice Guide, Version 1.1. The Carbon Leadership Forum Department of Architecture University of Washington.

able-timber-architecture
2. Forte living
Hamburg, P., Lellep, K., Kiisa, M. (2018). International study on best practices and knowledge gaps for construction of high-rise timber buildings : Sustainable High-Rise Buildings Designed and Constructed in Timber (Hi Timber). Tallinna Tehnikakõrgkool. https://www.digar.ee/viewer/et/nlib-digar:421322/358768/page/40
LendleaseGroup. (2013). The Making of Forte, Victoria Harbour, Melbourne. [video] https://www.youtube.com/watch?v=QR8Z-5cyzrI
Think Wood. (2013). Forte` - Creating the World's Tallest CLT Apartment Building. [video] https://www.youtube.com/watch?v=pHpthNBiYqE
Forte Living. (n.d.). Forest and Wood Products Australia Ltd. https://www.woodsolutions.com.au/inspiration-case-study/forte-living
Forte by Lend Lease. (2014). Architecture & Design. https://www.architectureanddesign.com.au/projects/multi-residential/forte-by-lend-lease
Picture:
Cross, E. (2014). Forte by Lend Lease. Architecture & Design. [photo] https://www.architecture-anddesign.com.au/projects/multi-residential/forte-by-lend-lease
3. Treet
Malo, K.A., Abrahamsen, R.B., Bjertnæs M.A. (2016). Some structural design issues of the 14-storey timber framed building "Treet" in Norway. Springer. https://www.researchgate.net/publication/298906052_Some_structural_design_issues_of_the_14-storey_timber_framed_building_Treet_in_Norway/link/5fb6eafc299bf104cf5f48da/download
Guajardo A.E.M. (2016). Carbon Footprint of the Tallest Timber Building. Universitat Politècnica de València. https://riunet.upv.es/bitstream/handle/10251/78052/Mansilla%20Guajardo%2C%20Alonso%20E_Huella%20de%20Carbono%20del%20edificio%20m%C3%A1s%20alto%20de%20estructura%20de%20madera.pdf?sequence=5&isAllowed=y
Picture:
Tomba, M. (2016) Building services for the World's tallest wooden building designed using MagiCAD. [photo] https://www.magicad.com/en/case/building-services-worlds-tallest-wooden-building-designed-using-magicad/
Brock Common
University of British Columbia. (n.d.). Brock Commons Tallwood House: The advent of tall structures in Canada. https://cwc.ca/wp-content/uploads/2019/03/CS-BrockCommon.Study_.23.pdf
Lau, W. (2016). The University of British Columbia's Brock Commons Takes the Title of Tallest Wood Tower. The Journal of the American Institute of Architects. Hanley Wood Media. https://www.architectmagazine.com/technology/the-university-of-british-columbias-brock-commons-takes-the-title-of-tallest-wood-tower_o#:~:text=Designed%20by%20local%20firm%20Acton,%2C%20concrete%2C%20and%20steel%20components.
Picture:
Elkan, M. (2017). Brock Commons Tallwood House Acton Ostry Architects & University of British Columbia. [photo] https://line.17qq.com/articles/cllckggoov_p2.html
HoHo
Infanti, T., Jeitler, G. (2020). HoHo Vienna: A case study for the construction of an 84m tall hybrid-timber tower. WoodSolutions. [video] https://www.youtube.com/watch?v=rGOlr37uhbw&t=1619s
Salvadori, V. (2017). The Development of a Tall Wood Building. Politecnico Milano.
Picture:
SIGA Swiss. (2019). HoHo Wien, Austria. https://www.siga.swiss/global_en/projects/hoho-wien
Mjøsa
Abrahamsen, R. (2017). Mjøstårnet - Construction of an 81 m tall timber building. 23. Internationales Holzbau-Forum IHF 2017. https://www.moelven.com/globalassets/moelven-limtre/mjostarnet/mjostarnet---construction-of-an-81-m-tall-timber-building.pdf
Salvadori, V. (2017). The Development of a Tall Wood Building. Politecnico Milano.
Picture:
Ricardo Foto. (2020). Mjøstårnet The Tower of Lake Mjøsa. ArchDaily. [photo] https://www.archdaily.com/934374/mjostarnet-the-tower-of-lake-mjosa-voll-arkitekter/5e5435c76ee67e943b000076-mjostarnet-the-tower-of-lake-mjosa-voll-arkitekter-photo
Haut
Amsterdam to build 21 storey wooden building, Arup provides consulting. (2016). Consultancy.uk. https://www.consultancy.uk/news/12351/amsterdam-to-build-21-storey-wooden-building-arup-provides-consulting
Vola, M., Verhaegn, R., Jong, J. (2020). Haut - A 21-storey Tall Timber Residential Building. International Journal of High-Rise Buildings Volume 9 Number 2. https://global.ctbuh.org/resources/papers/download/4361-haut-a-21-storey-tall-timber-residential-building.pdf#:~:text=Haut%20is%20a%2021%2Dstorey,in%20the%20world%20upon%20completion.
Salvadori, V. (2017). The Development of a Tall Wood Building. Politecnico Milano.
Picture:
TEAM V Architecture. (2016). Amsterdam to build 21 storey wooden building, Arup provides consulting. Consultancy.uk. [photo] https://www.consultancy.uk/news/12351/amsterdam-to-build-21-storey-wooden-building-arup-provides-consulting
Kulthurus
Lott, K. (2020). A CLT high-rise to bring a community together. Katus.eu. https://katus.eu/learn/news/clt-high-rise-brings-community-together
Gibson, E. (2016). White Arkitekter selected to build timber-framed high-rise in Sweden. Dezeen. https://www.dezeen.com/2016/06/07/kulturhus-i-skelleftea-white-arkitekter-cultural-centre-hotel-sweden-wooden-timber-frame/
Hamburg, P., Lellep, K., Kiisa, M. (2018). International study on best practices and knowledge

Figure 21. Author's drawing.

Figure 22. Author's drawing.

Figure 23. Author's drawing.

Figure 24. Author's drawing.

Figure 25. Author's drawing.

Figure 26. Author's drawing.

Figure 27. Author's drawing.

Figure 28. Harjapea river placed on modern map of Tallinn. https://jaakjuske.blogspot.com/2013/06/kust-voolas-tapselt-harjapea-jogi.html?view=flipcard

Figure 29. Esop. R. (1950), View from the EBS school point towards the site in 1950. https://ajapaik.ee/map/photo/157306/?mapType=roadmap&lat=59.43217515806491&lng=24.755936513896454&zoom=18&photoModalOpen=1&limitToAlbum=0

Figure 30. Eesti Arhitektuurimuuseum. (1939). Johanson paber fabric. https://ajapaik.ee/map/photo/247119/?mapType=roadmap&lat=59.43214765807644&lng=24.759841864344285&zoom=18&photoModalOpen=1&limitToAlbum=0

Figure 31. Eesti rahva muuseum. (1979). View of the city centre of Tallinn and the building of Maakri Street 1979. https://ajapaik.ee/map/photo/17880/?mapType=roadmap&lat=59.430763511651875&lng=24.757482287446496&zoom=18&photoModalOpen=1&limitToAlbum=0

Figure 32. Annus, T. (2018). View of the city centre of Tallinn and the building of Maakri Street 2018. https://ajapaik.ee/map/photo/17880/?mapType=roadmap&lat=59.430763511651875&lng=24.757482287446496&zoom=18&photoModalOpen=1&limitToAlbum=0

Figure 33. Klada, K. (2021). Modern Maakri quarter. https://www.kaupokalda.com/portfolio/maakri-aerikvartal-kogu-pikkuses/



**LITERATURE**

Chan, N.W. (2017). Urbanization, Climate Change and Cities: Challenges and Opportunities for Sustainable Development. Keynote Paper Presented at the Asia-Pacific Chemical, Biological and Environmental Engineering Society International Conference, School of Humanities, Universiti Sains Malaysia, Penang, Malaysia.

Pachauri, R.K and Meyer L.A. (eds.) (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva: IPCC, 151 p.,2014.

United Nations, Department of Economic and Social Affairs, Population Division (2019).

World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420). New York: United Nations.

United Nations Environment Programme (2020). 2020 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector. Nairobi

Pak, A. (2019, March 11). Embodied Carbon: The Blindspot of the Buildings Industry. https://www.linkedin.com/pulse/embodied-carbon-blindspot-buildings-industry-anthony-pak/

Kjellsen K. O., Guimaraes M., Nilsson Å. (2005) The CO2 Balance of Concrete in a Life Cycle Perspective. Danish Technological institute.

World Steel Association. (2019). Climate change mitigation.

World Steel Association. (2021). Steel and raw materials.

Skullestad JL, Bohne RA, Lohne J. (2016, November 21). High-rise timber buildings as a climate change mitigation measure—a comparative LCA of structural system alternatives. SBE16 Tallinn and Helsinki Conference; Build Green and Renovate Deep, Tallinn and Helsinki

Michael Green Architecture. (2017). The case for tall wood buildings. 2ed.

Publications office of the European Union. (2019). Going climate-neutral by 2050. https://ec.europa.eu/clima/sites/clima/files/long_term_strategy_brochure_en.pdf

ARUP. (2019). Rethinking Timber Buildings.

Melton, P. (2018). The Urgency of Embodied Carbon and What You Can Do about It. https://www.buildinggreen.com/feature/urgency-embodied-carbon-and-what-you-can-do-about-it

European rote of industrial heritage. (n. d). Gliwice radio station. https://www.erih.net/i-want-to-go-there/site/gliwice-radio-station

Ciyun Z., (2015). Shanxi pagoda world's oldest wood tower. https://archive.shine.cn/sunday/now-and-then/Shanxi-pagoda-worlds-oldest-wood-tower/shdaily.shtml

Grasser K. K., (2015). Development of Cross Laminated Timber in the United States of America. University of Tennessee, United States.

Gigler, B. (2019). TU Graz researcher Gerhard Schickhofer awarded prestigious Marcus Wallenberg Prize. https://www.tugraz.at/en/tu-graz/services/news-stories/planet-research/singleview/article/tu-graz-forscher-gerhard-schickhofer-erhaelt-hochdotierten-marcus-wallenberg-preis0/

Mass Timber in North America. (2016). Architectural Record.

Bayer C., Gamble M., Gentry R. , and Joshi S. (2010). AIA Guide to Building Life Cycle Assessment in Practice.

Simonen, K., Huang, M., Rodriguez, B.X., Todaro, L. (2019). Life Cycle Assessment of Buildings: A Practice Guide, Version 1.1. The Carbon Leadership Forum Department of Architecture University of Washington.

Birgisdóttir, H., Rasmussen, F.N. (2016) Introduction to LCA of Buildings, 1st ed. Danish Transport and Construction Agency

Bruce-Hyrkäsa, T., Pasanena, P., Castro, R. (2018). Overview of Whole Building Life-Cycle Assessment for Green Building Certification and Ecodesign through Industry Surveys and Interviews. 25th CIRP Life Cycle Engineering (LCE) Conference, 30 April 2018, Copenhagen, Denmark

DEAT. (2004). Life Cycle Assessment, Integrated Environmental Management, Information Series 9. Department of Environmental Affairs and Tourism (DEAT), Pretoria.

Bare, J. C., Pennington, D. W., Udo de Haes, H. A. (1999). Life Cycle Impact Assessment Sophistication. The International Journal of Life Cycle Assessment Vol. 4, No. 5, article nr. 299

International Organization for Standardization. (2006). Environmental management — Life cycle assessment — Principles and framework. (ISO 14040:2006)

International Organization for Standardization. (2006). Environmental management — Life cycle assessment — Requirements and guidelines. (ISO 14044:2006)

Pärmann, S. (5 June, 2019). Linnaruum. Maakri kvartal. Tõus Tallinna tippu. Edasi. [Online] https://edasi.org/41773/linnaruum-maakri-kvartal-tous-tallinna-tippu/ (May 5, 2021)
Tallinna Linnamuuseum. (n.d.) Ajalugu. Tallinna Linnamuuseum Jaani seek. [Online] https://www.linnamuuseum.ee/jaani-seek/lugemiseks/seegi-ajalugu/ (May 5, 2021)

Juske, J. (22 May, 2019). Linnaretk Jaak Juskega | Kadunud Härjapea jõgi ärkab ellu. Maaleht. [Online] https://maaleht.delfi.ee/artikkel/86286343/linnaretk-jaak-juskega-kadunud-harjapea-jogi-arkab-ellu (May 5, 2021)

Veski, R. (2021). Juske : Härjapea jõgi tuleb Tallinna linnaruumis paremini eksponeerida. https://www.postimees.ee/1204992/juske-harjapea-jogi-tuleb-tallinna-linnaruumis-paremini-eksponeerida

Välja, L. (2018). Piiride kompamise kunst Maakri kvartalis. Muinsuskaitse aastaraamat 2018. Tallinn: Tallinna Raamatutrükikoja Osaühing. pp. 20-24

Nerman, R. (5 February, 2007). Jaani seegil aitasid elus püsida mitmed külad, jahuveski ja kõrts. Postimees. [Online] https://www.postimees.ee/1626853/jaani-seegil-aitasid-elus-pusida-mitmed-kulad-jahuveski-ja-korts (May 5, 2021)

Suurkask, H. (15 December, 2013) Kunagine Härjapea jõgi - kas sa ikka tead, mis su jalge all voolab. Forte. https://forte.delfi.ee/artikkel/67437400/kunagine-harjapea-jogi-kas-sa-ikka-tead-mis-su-jalge-all-voolab ( May 5, 2021)

Gaimster, D., Russow, E. (2011). The Monkey Code on a Tallinn Breaking the and the Shoe: Stove-Tile.

Kultuurimälestiste register 1105. (1995). Tootmishoonete kogum Maakri tänaval ja kus a. 1908-1921 asus Tallinna Jaani koguduse kool. https://register.muinas.ee/public.php?menuID=monument&action=view&id=1105 ( May 5, 2021)

Kultuurimälestiste register 8164. (1997). Keemilise puhastuse ja värvimistööstuse hoone Maakri t. 23, 20. saj. algus. [Online] https://register.muinas.ee/public.php?menuID=monument&action=view&id=8164 (May 5, 2021)

Nerman., R. (12 February, 2008). Kivisilla eeslinn kujunes tähtsaks kultuuripaigaks. Postimees. https://www.postimees.ee/1757853/kivisilla-eeslinn-kujunes-tahtsaks-kultuuripaigaks

Robbins, J. (9 April, 2019) As Mass Timber Takes Off, How Green Is ?is New Building Material? https://e360.yale.edu/features/as-mass-timber-takes-off-how-green-is-this-new-building-material

Hadley A., (5 April, 2021). Mass Timber in the Age of Mass Extinction. [Online] https://failedarchitecture.com/mass-timber-in-the-age-of-mass-extinction/

Preager, T. (2019). Understanding the acoustical challenges of mass timber buildings. [Online] https://www.constructioncanada.net/understanding-the-acoustical-challenges-of-mass-timber-buildings/

Just E., Just A., (2015). Puitkonstruktsioonid.

Skidmore, Owings & Merril. (2013). Timber tower research project.

A. Alalwan, J. Larsson. (2019). Stability and Dynamic Properties of Tall Timber Structures A parametric study of the structural response due to wind action. (Master thesis) Chalmers University Of Technology, Department of Architecture and Civil Engineering, Gothenburg, Sweden

Hamburg, P., Lellep, K., Kiisa, M. (2018). International study on best practices and knowledge gaps for construction of high-rise timber buildings : Sustainable High-Rise Buildings Designed and Constructed in Timber (Hi Timber). Tallinna Tehnikakõrgkool. https://www.digar.ee/viewer/et/nlib-digar:421322/358768/page/47

Ruuska, A., Häkkinen T., (2014). Material Efficiency of Building Construction.

BP p.l.c. (2020). Statistical Review of World Energ. 69th ed.

Meredith, S. (5 March, 2021). A sand shortage? The world is running out of a crucial — but under-appreciated — commodity. https://www.cnbc.com/2021/03/05/sand-shortage-the-world-is-running-out-of-a-crucial-commodity.html ?



Martinez T. (21 August, 2015). Sustainable building: Why wood is our most valuable resource. https://www.usgbc.org/articles/sustainable-building-why-wood-our-most-valuable-resource

Hill, CAS. (5 october, 2019). The Environmental Consequences Concerning the Use of Timber in the Built Environment. Front. Built Environ. 5:129

Is reclaimed wood toxic? (5 June, 2019). https://non-toxic-home.org/f/is-reclaimed-wood-toxic

Daley, J. (24 April, 2018). The EPA Declared That Burning Wood Is Carbon Neutral. It's Actually a Lot More Complicated. Smithsonian Magazine.

D'Amore, D., Kane, E. (2016). Climate Change and Forest Soil Carbon. U.S. Department of Agriculture, Forest Service, Climate Change Resource Center. www.fs.usda.gov/ccrc/topics/forest-soil-carbon
Waugh Thistleton Architects. 2018. 100 Projects UK CLT.

Forest Europe. (2020). State of Europe's Forests 2020.

State Forest Management Centre (RMK). (n.d). cetificate FSC, PEFC https://www.rmk.ee/sale-o/sale-of-t/sertificate-fsc-pefc 1/3

H. Välja, (2018). Metsatööstus on üks Eesti majanduse alustaladest. Riigikogu toimetised 37, 75-85

Edelman, E. (March 3, 2020). Nordic Tower. Accessed: May 5, 2021. [Online]. Available: https://www.linkedin.com/pulse/nordic-tower-harry-edelman/

K. Hallas, (1999). Eesti Puitarhitektuur = Estonian Wooden Architecture.

Arhitekt 11. (n.d). https://www.architect11.com/ru/portfolio/viimsi-kool/

E. Luht, (2018). Viimsi Gümnaasium – esimene puidust kool üle saja aasta. https://ehitusest.ee/uudis/2018/10/16/viimsi-gumnaasium/

Ehitusregister. (2006). Hoone 120269882 / Ehitis. ://ehr.ee/app/w/page?4

Sõmmer, S. (2020) Narvas avati pidulikult Sisekaitseakadeemia ning Tartu Ülikooli ühine õppe- ja majutushoone. https://www.ut.ee/et/uudised/narvas-avati-pidulikult-sisekaitseakadeemia-tartu-ulikooli-uhine-oppe-majutushoone

Ehitusregister. (2020). Hoone 120873124 / Ehitis. https://ehr.ee/app/w/page?610

Kavakava. (n.d). Available:http://www.kavakava.ee/project/keskkonnamaja/

Kerto® LVL. (n.d). Laminated veneer lumber (lvl) – Kerto® LVL. https://www.metsawood.com/global/Products/kerto/Pages/Kerto.aspx

WoodWorks and Think Wood. (2021). Mass Timber Design Manual.

De Giovanni, G., & Scalisi, F. (2019). PRO-INNOVATION : PROCESS PRODUCTION PRODUCT. (PROJECT. ESSAYS AND RESEARCHES). Palermo University Press.

Jackson, R., E.I., Luthi T., Voyle I. (January, 2017). Mass Timber: Knowing Your Options. Structure. https://www.structuremag.org/?p=10916

Bergman, R., Puettmann, M., Taylor, A., Skog, K.E., 2014. The carbon impacts of wood products. Forest Products. 64, 220–231.

## APPENDICES

# TALL TIMBER BUILDINGS AS A CLIMATE CHANGE MITIGATION TOOL. 30-STORY TIMBER HIGH-RISE IN TALLINN

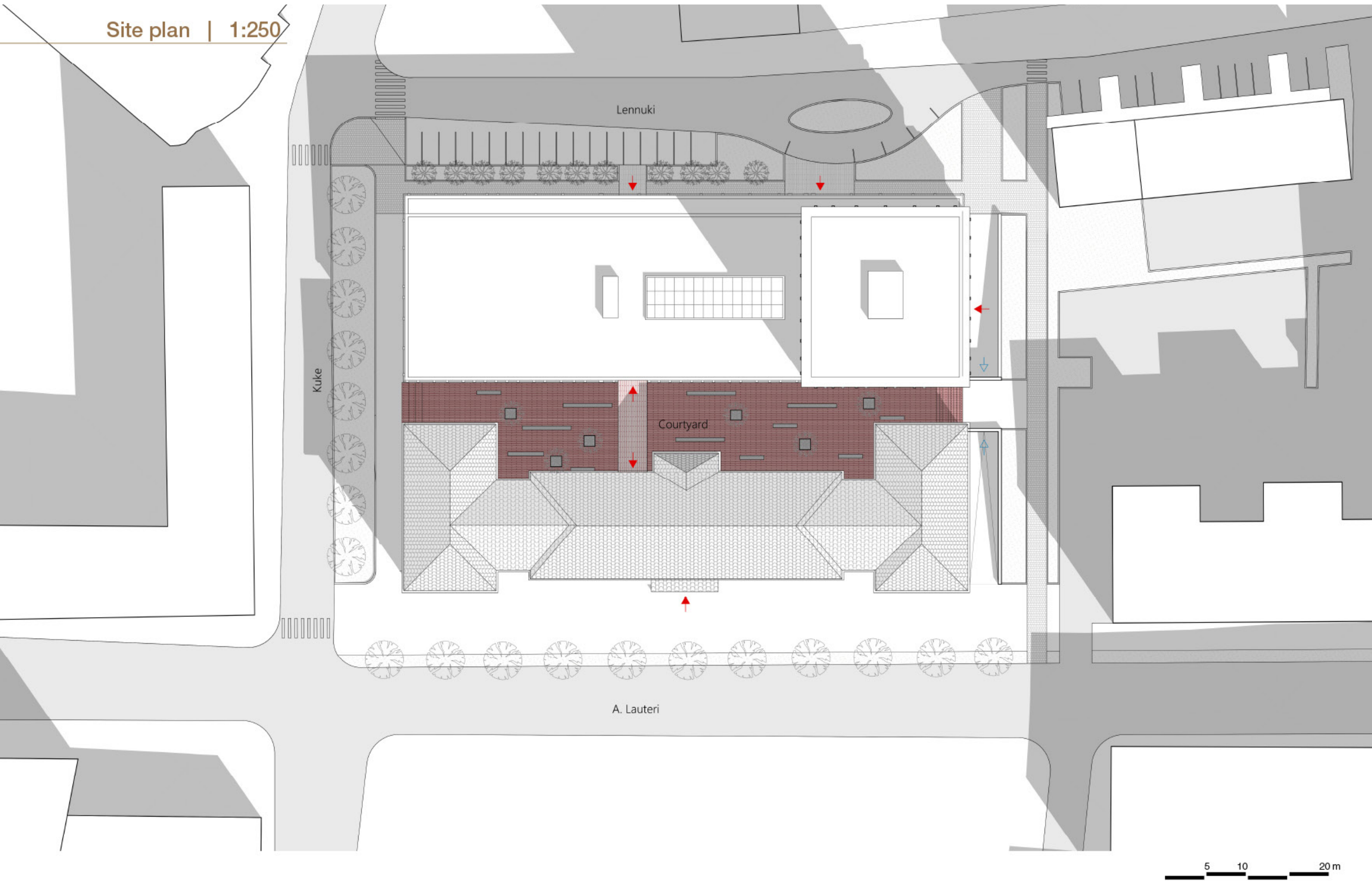
Sofya Smirnova
Supervisor: prof. Kimmo Lylykangas

The building sector plays an essential role in climate change as it is responsible for the largest share of carbon emissions into the atmosphere. The choice of construction materials has consequences. Production of conventional concrete and steel is very carbon-intensive during extraction and manufacturing. The urbanization trend continues to grow, along with the world population, causing an increasing demand for resources and new housing. As we cannot spread our cities endlessly, compact city thinking which focuses on building dense urban environment, is thought to be a consensus solution to fulfill human needs and mitigate resource depletion. Tall buildings are an integral part of highly urbanized cities, and most of them built of concrete and steel. As vertical cities are a part of a solution for land scarcity, the demand for these materials will consequently rise in the future and can be crucial for our planet's health. The amount of released $CO_2$ will also continue to increase using concrete and steel. As a result, selecting environmentally friendly building materials is critical for taller structures.

During the last two decades, the timber industry has experienced tremendous growth due to the invention of engineered wood - thick, compressed layers of wood formed through lamination, fasteners, or adhesives. This new material category has versatile structural and environmental potential. Engineered wood challenges conventional concrete and steel in many respects: strength, durability, fire safety, construction speed, and in some cases, cost. Of these three, timber is the only renewable resource. Wood emits less $CO_2$ during the extraction and manufacturing than concrete and steel and stores sequestered CO2, removing it from the atmosphere until final disposal. Engineered wood proponents advocate that the buildings with timber frame structures could serve as giant sinks for $CO_2$. The increased use of timber in the future will reduce the carbon impact of the construction industry, consequently contributing to the mitigation of climate change.

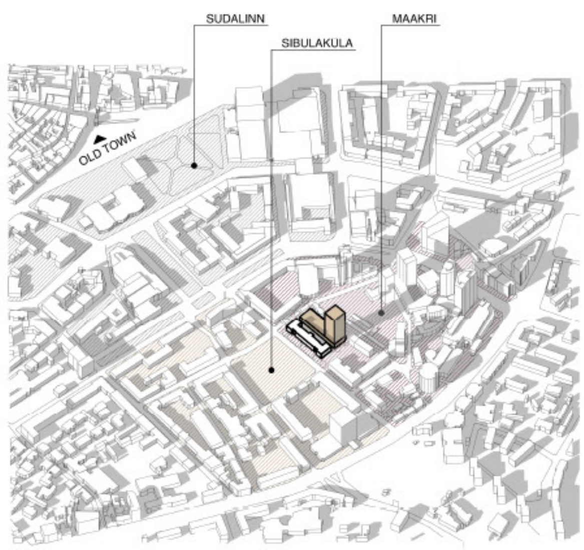
This work aimed to examine the potential environmental benefits of using new engineered wood products in high-rises to reduce greenhouse gas (GHG) emissions and address climate change problems by replacing conventional high-rise building materials with timber structures. The conducted life cycle analysis (LCA) evaluated and compared two material choices for high-rise building load-bearing structures: timber structures and reinforced concrete structures. The motivation for analysis was to find out which type of structure has the highest impact on the environment during the building's whole life cycle period. LCA results proved that the adverse environmental effects of wood in building constructions are less severe than cement and steel. The ability of wood to store carbon and the lower energy consumption during the manufacturing of wood products contributes to a lower carbon footprint of a building than other materials.

## Site plan | 1:250

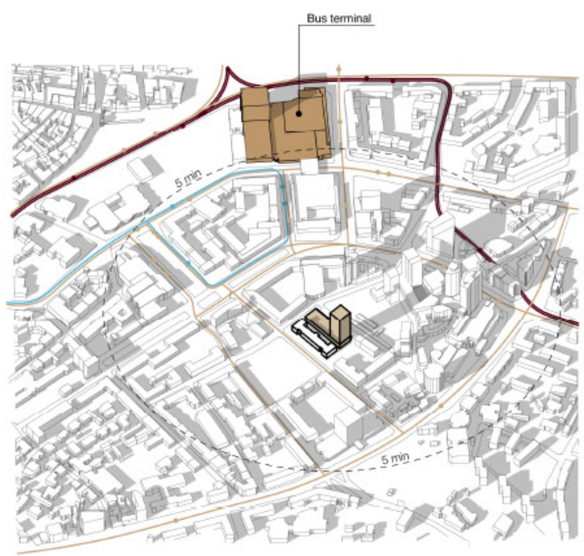



## Site analysis

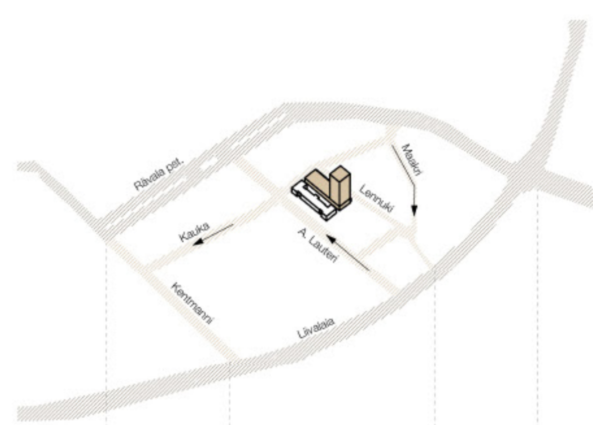
### Location

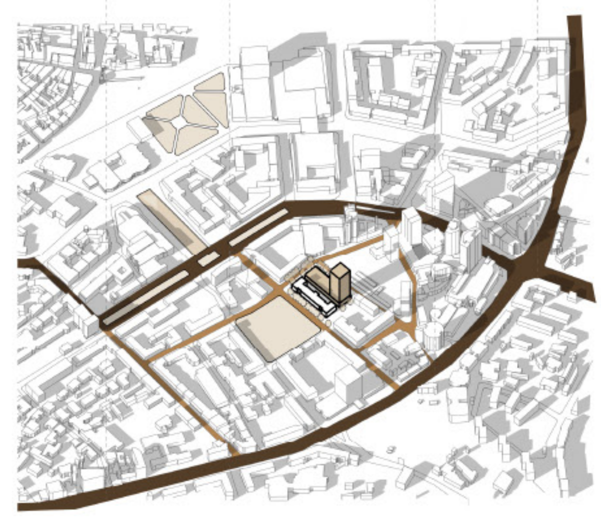



### Public transport

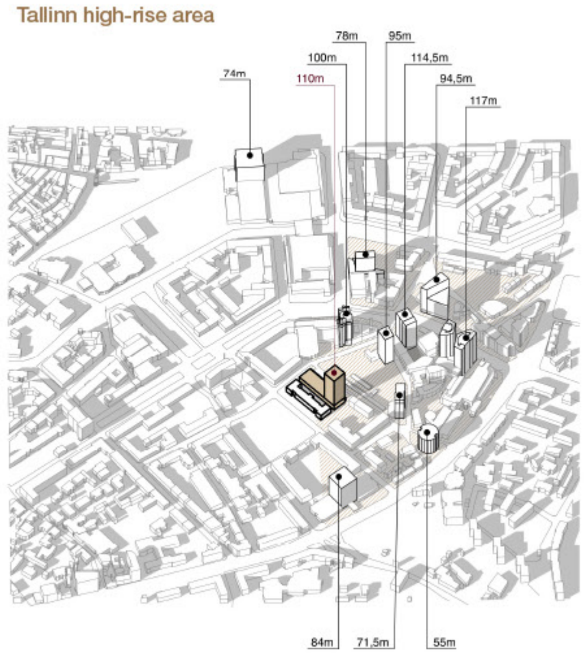



### Main roads and green area



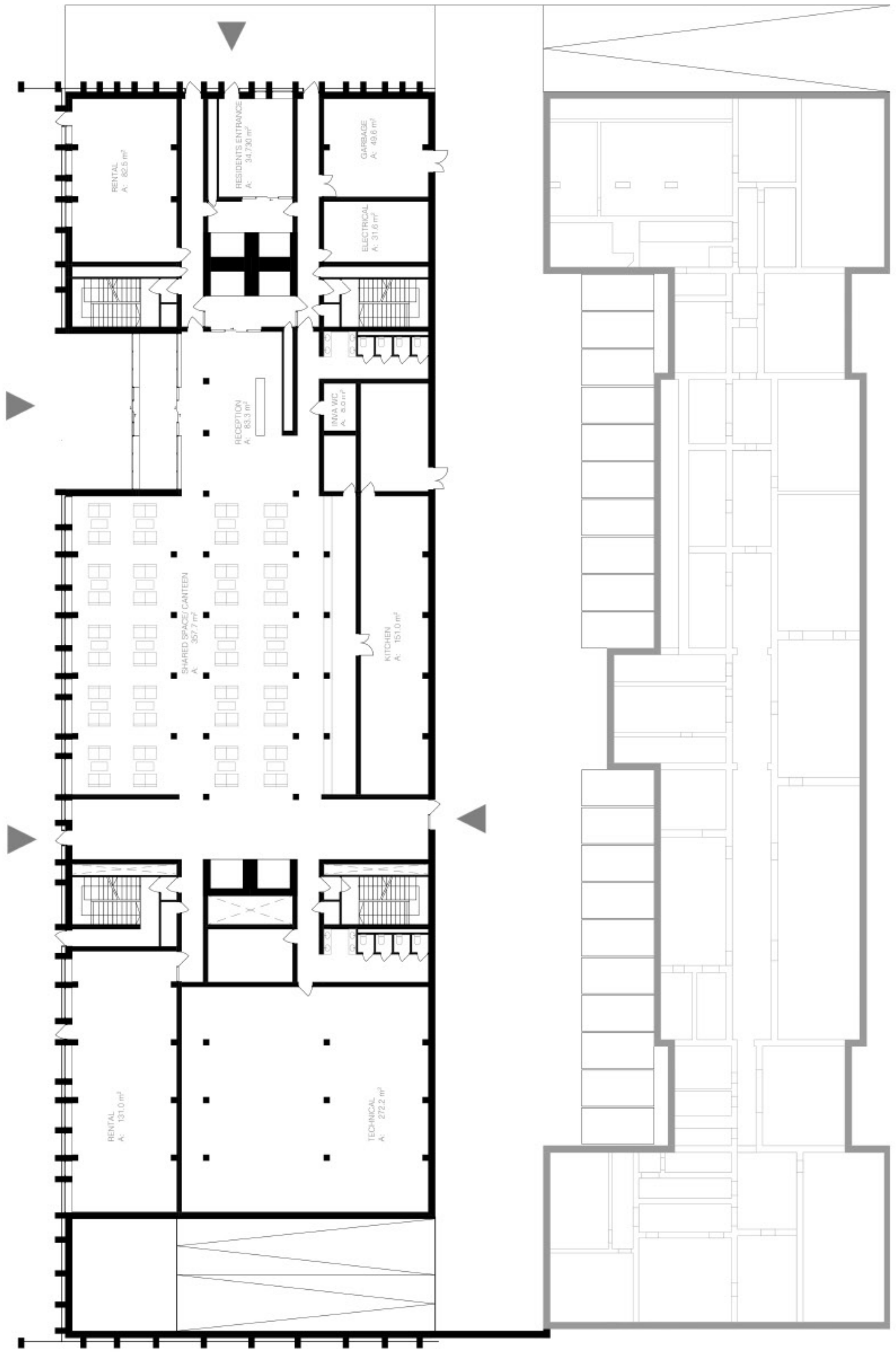
### Tallinn high-rise area



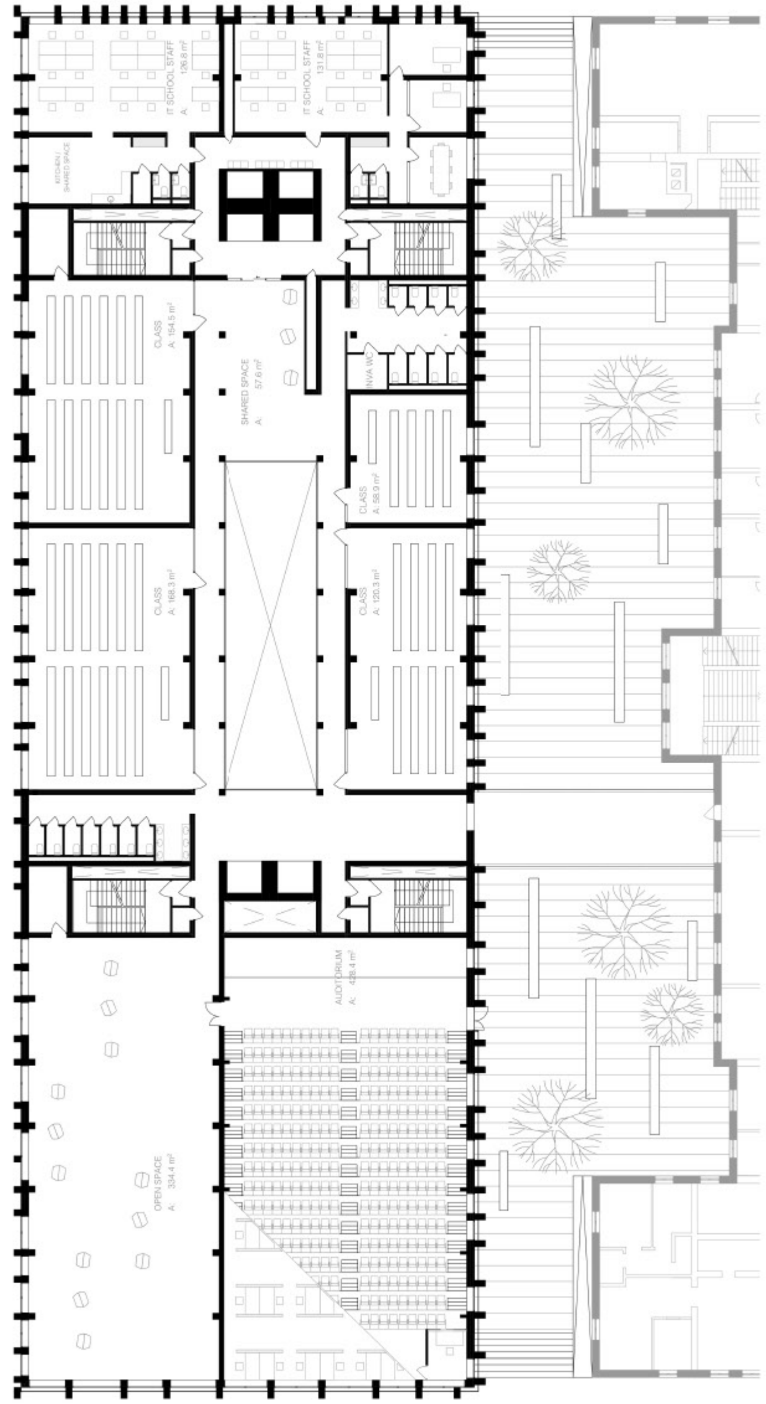

### Noise map

**TALL TIMBER BUILDINGS AS**
**A CLIMATE CHANGE MITIGATION TOOL.**
**30-STORY TIMBER HIGH-RISE IN TALLINN**

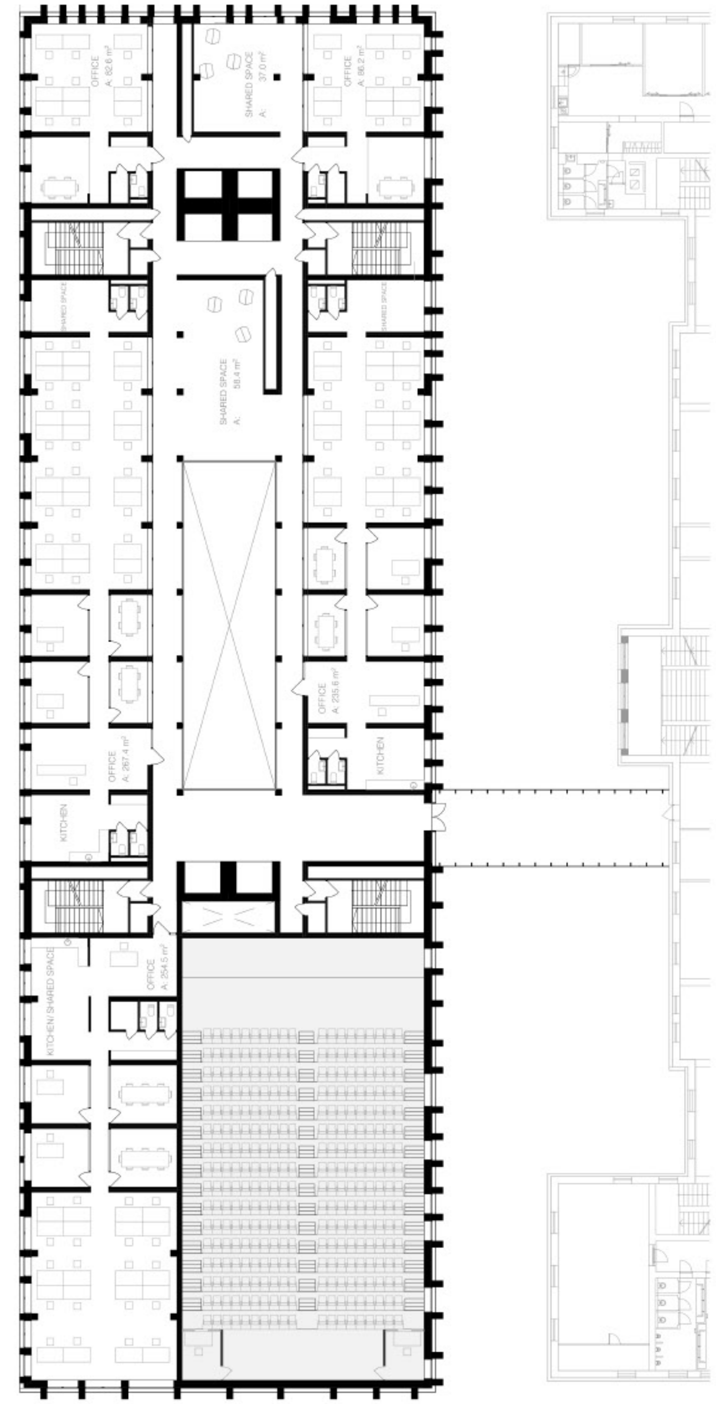
Sofya Smirnova
Supervisor: prof. Kimmo Lylykangas



Ground floor | 1:200



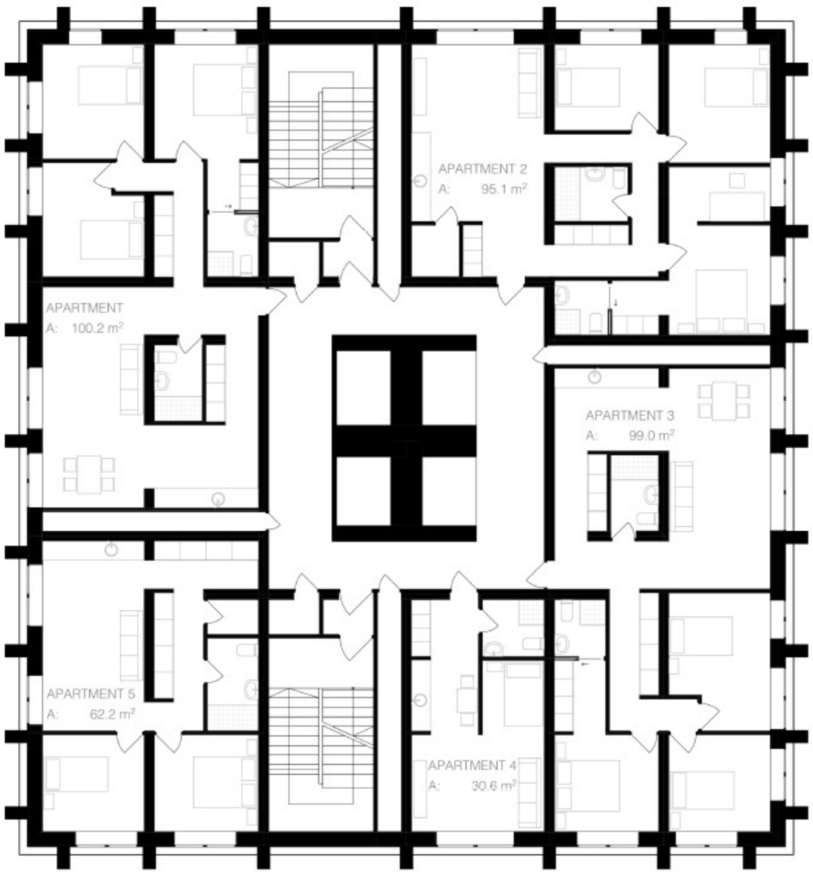
First floor | 1:200



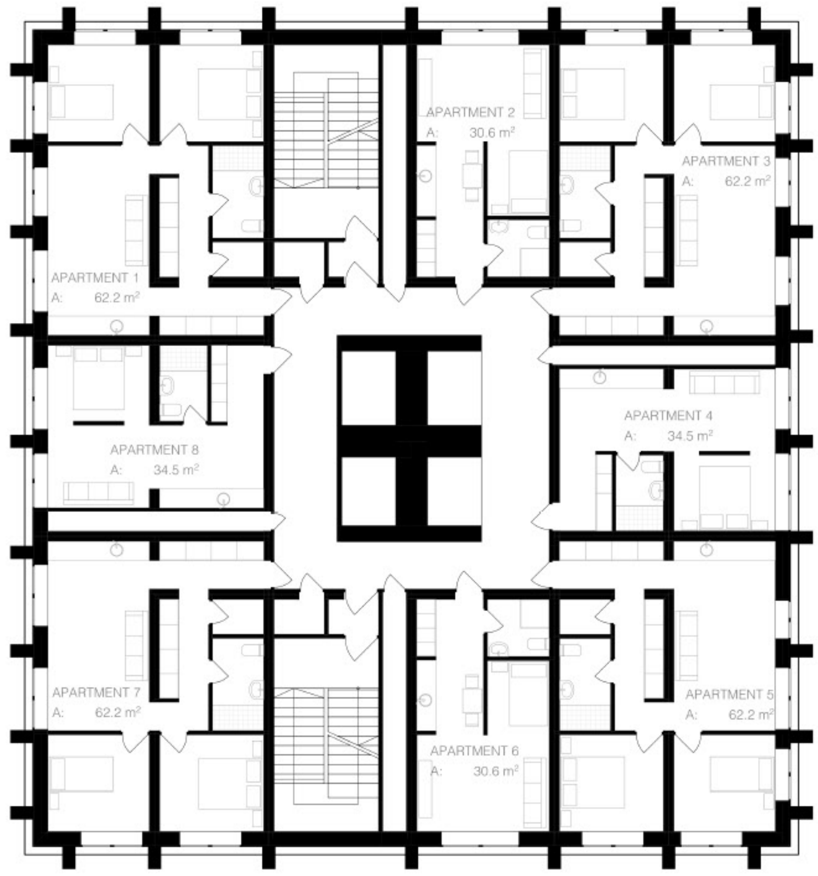
Second and third floor | 1:200

TALL TIMBER BUILDINGS AS
A CLIMATE CHANGE MITIGATION TOOL.
30-STORY TIMBER HIGH-RISE IN TALLINN
Sofya Smirnova
Supervisor: prof. Kimmo Lylykangas

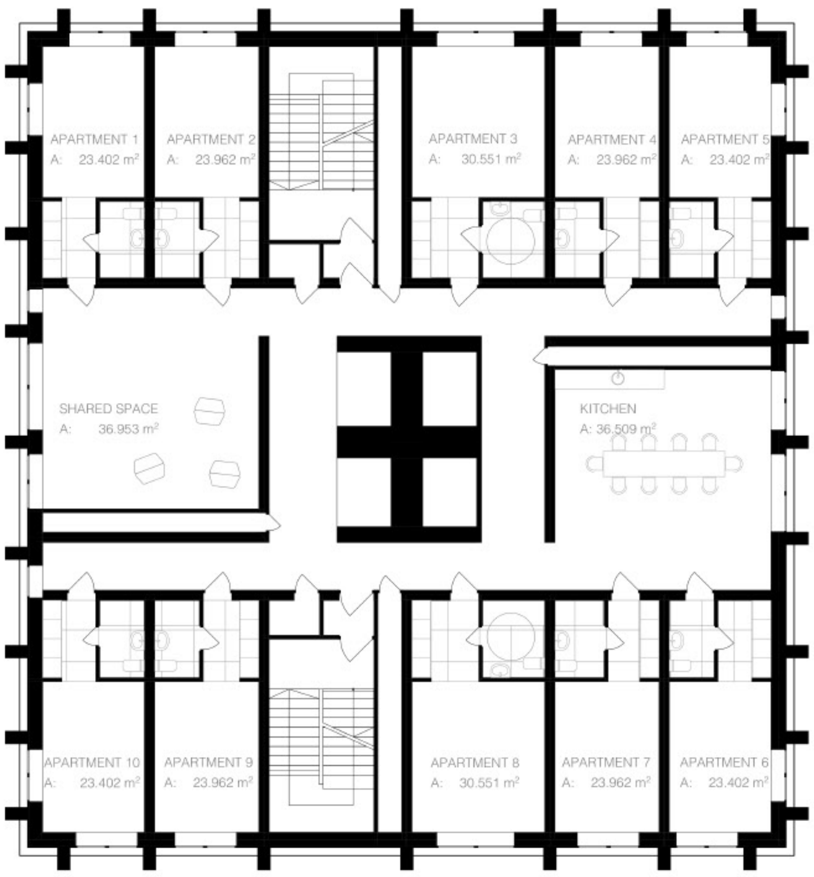
## Small apartments
## Floors 17-21, 26-30 | 1:200



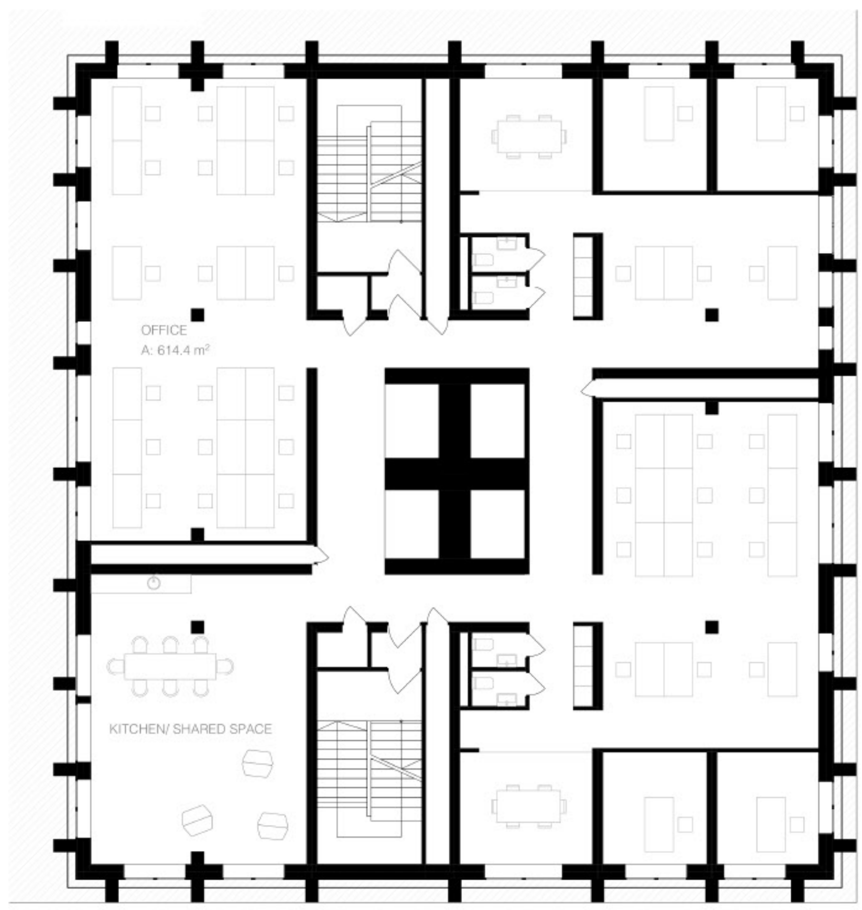

## Large apartments
## Floors 21-25 | 1:200



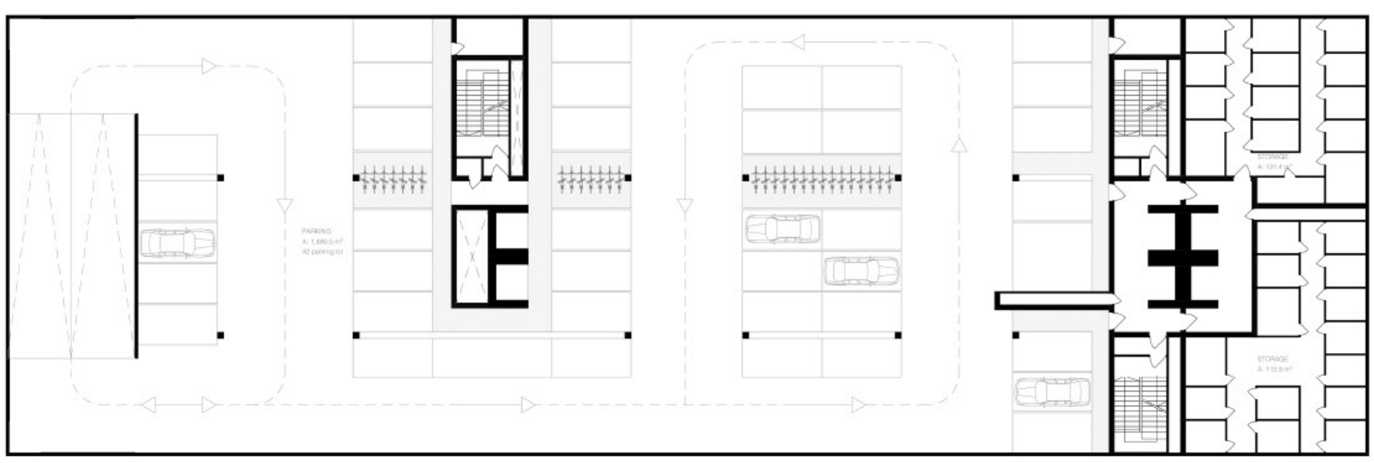

## Hotel
## Floors 8-15 | 1:200



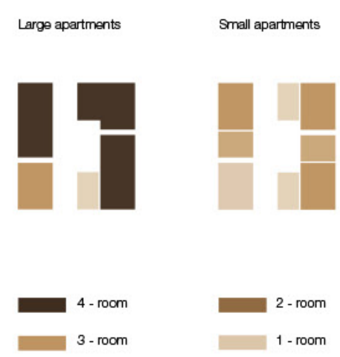

## Office
## Floors 5-7 | 1:200




## Parking
## Floors -1-(-2) | 1:400

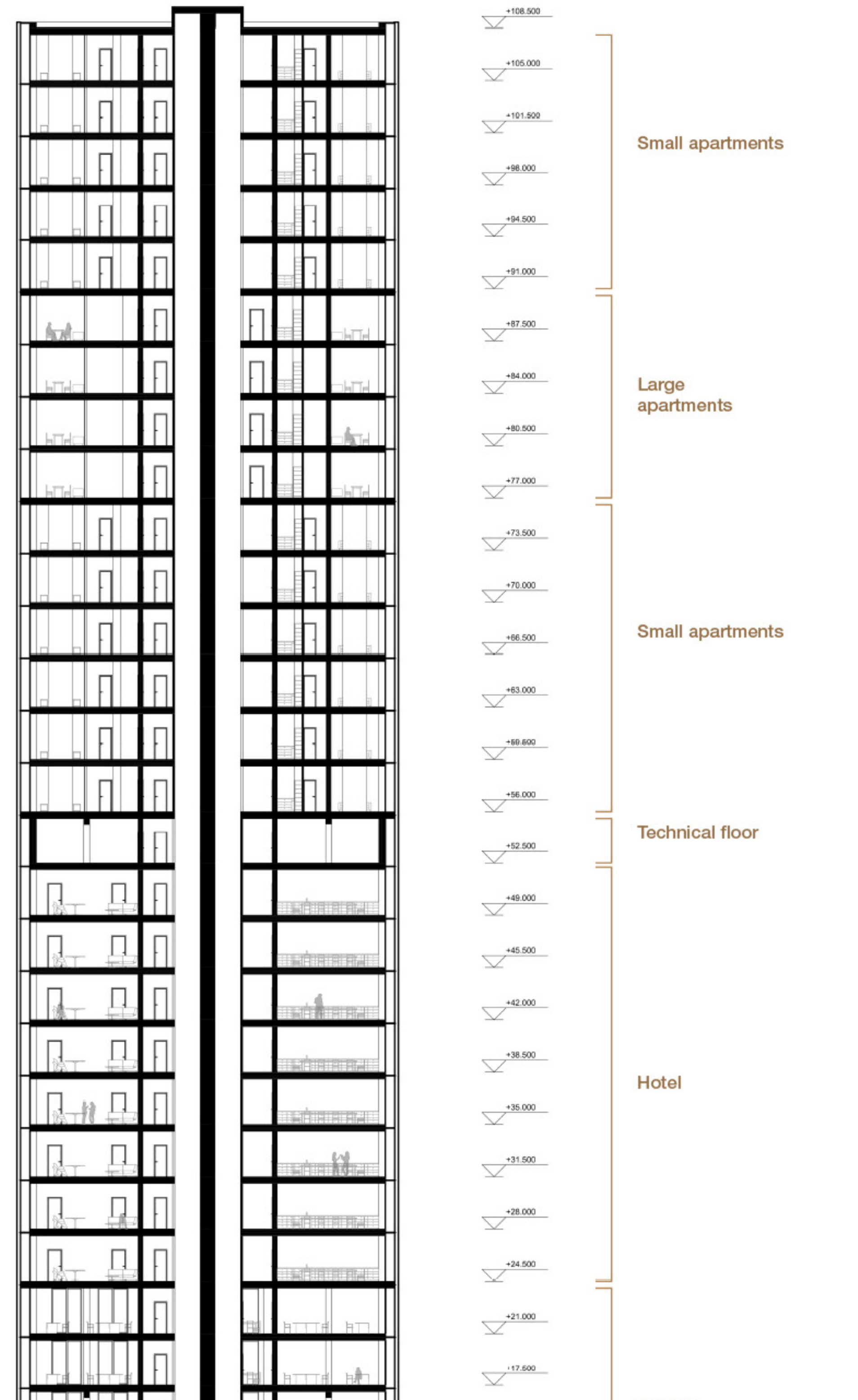


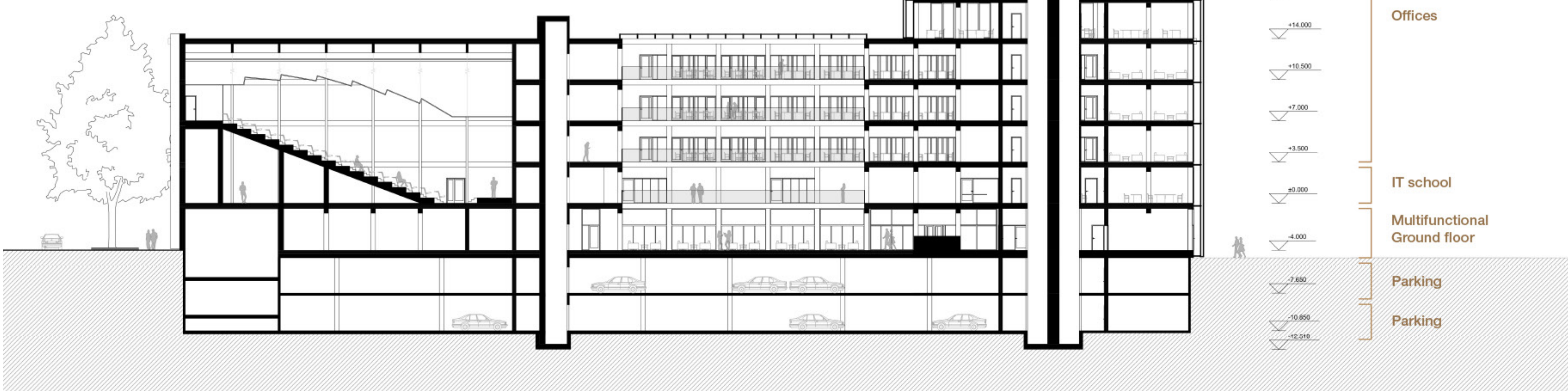
## Apartment schemes




TALL TIMBER BUILDINGS AS
A CLIMATE CHANGE MITIGATION TOOL.
30-STORY TIMBER HIGH-RISE IN TALLINN
Sofya Smirnova
Supervisor: prof. Kimmo Lylykangas

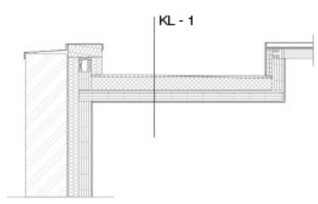
# Section II-II | 1:200



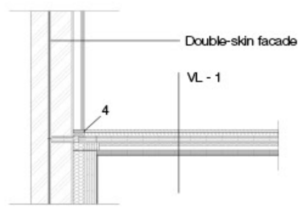

# Details | 1:30

### Roof to external wall



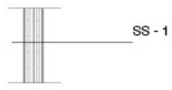

KL-1
bitumen sheet
18 mm plywood board
30 mm rockwool with insulation channel
200 mm polyurethane insulation board
moisture barrier
180 mm CLT panel
15 mm gypsum plasterboard
15 mm gypsum plasterboard

### Intermediate floor



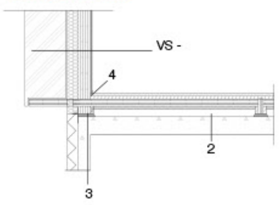

VL-1
40 mm floating concrete slab
30 mm impact sound insulation
140 mm CLT panel
135 mm air gap + insulation (50 mm)
80 mm CLT pan
15 mm gypsum plasterboard
15 mm gypsum plasterboard

### Internal load-bearing wall




SS-1
15 mm gypsum plasterboard
15 mm gypsum plasterboard
120 mm CLT panel
30 mm air gap + insulation
120 mm CLT panel
15 mm gypsum plasterboard
15 mm gypsum plasterboard

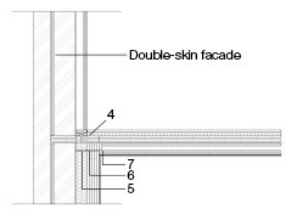
### Ground floor wood module to concrete slab




VS-1
200 mm insulation
moisture barrier
200 mm CLT panel
15 mm gypsum plasterboard
15 mm gypsum plasterboard

1 - infill cast (0-50 mm)
2 - moisture under the module from site operation needs to be ventilated
3 - bitumen felt between wood and concrete

### Roof to external wall




4 - separation strip for moisture and sound isolation
5 - mineral wool
6 - vibration isolation pad
7 - EPDM rubber sealant (soft)

### Partition wall


SS-2
15 mm gypsum plasterboard
15 mm gypsum plasterboard
66 mm timber frame + insulation (50 mm)
15 mm gypsum plasterboard
15 mm gypsum plasterboard

# Section I-I | 1:200

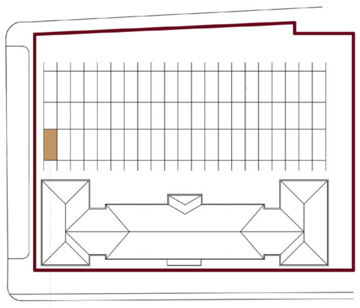

**TALL TIMBER BUILDINGS AS A CLIMATE CHANGE MITIGATION TOOL. 30-STORY TIMBER HIGH-RISE IN TALLINN**


Sofya Smirnova
Supervisor: prof. Kimmo Lylykangas

## Structural system

For the structural design was chosen the prefabricated modular system. The site was divided into a grid with different size modules. Around this modular system was build the whole complex. The reason for choosing the prefabricated modules system is that Estonia is one of the largest producers of prefabricated timber modular houses. An Estonian firm even participated in construction of the Mjøsa tower in Norway - the World's tallest timber tower in 2021. However, Estonia does not have it's own outstanding example of a tall wooden building. The timber high-rise made of prefabricated modules in the center of Tallinn could be a significant landmark and represent the power of the Estonian wooden construction industry.

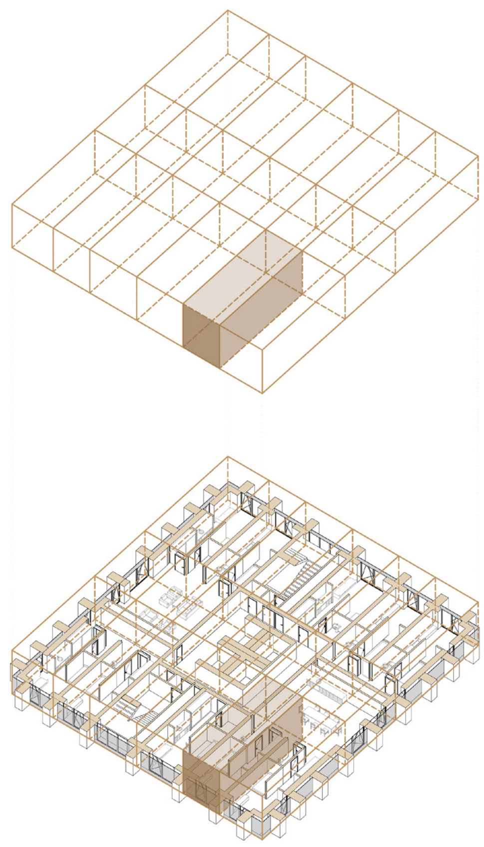
The high-rise complex rests on a RF concrete foundation that prevents moisture movement from the soil to wooden structures above the concrete. Above the RF concrete foundation, the main body of high-rise complex consists of prefabricated modules. The modular system allows modules bear themselves. The stability of high-rise part gained by core and four shafts connected to the core. Inside the shafts there are tension diagonals to mitigate horizontal loads. Modules connected to the core and shafts, stacked on each other and can bear themselves. External and internal walls, floors, roofs are made of CLT panels, beams and columns above the ground floor made of glulam. Also, all stairs and elevator shafts are made of wood. Elevator shaft wall thickness is 0,5 m. Two underground parking floors are made of concrete and thick layer of concrete was also used in intermediate floors for better acoustics and additional mass.



Module 1
4,2X 7,9 m
offices

Module 2
3,6 X 7,9 m
stairs

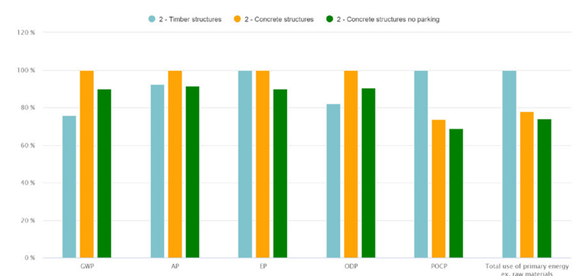
Module 3
3,6 X 7,9 m
offices, apartments, hotel



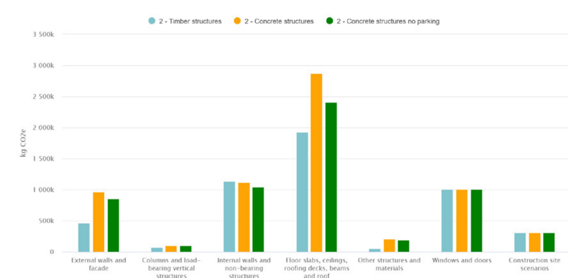
## Lify cycle assessment (LCA)

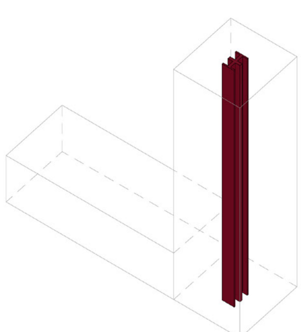
A Life cycle assessment (LCA) is a method to calculate the potential environmental impact of a product over its entire life-cycle. Building life cycle stages: material extraction and production, construction process, use stage and end of life – (deconstruction, disposal, recycle)

Life-cycle assessment, EN-15978 - All impact categories.

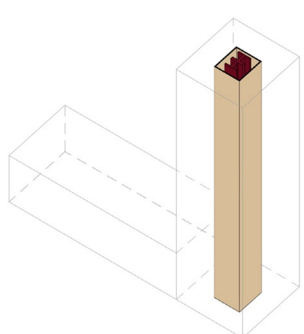


Life-cycle assessment, EN-15978 - Global warming, kg CO2e - Compare elements

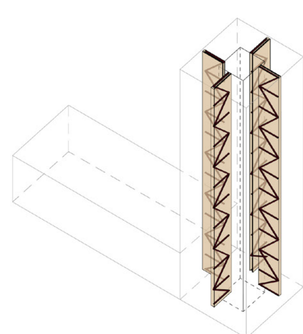




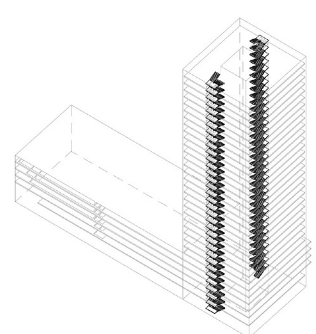
Elevator shafts 500 mm



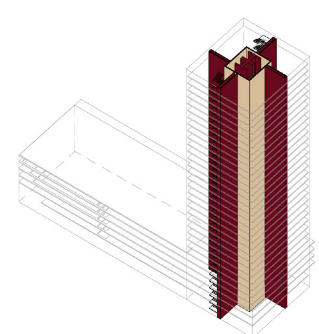
Mass timber core



Four shafts with t ension diagonals bars



Mass timber stairs

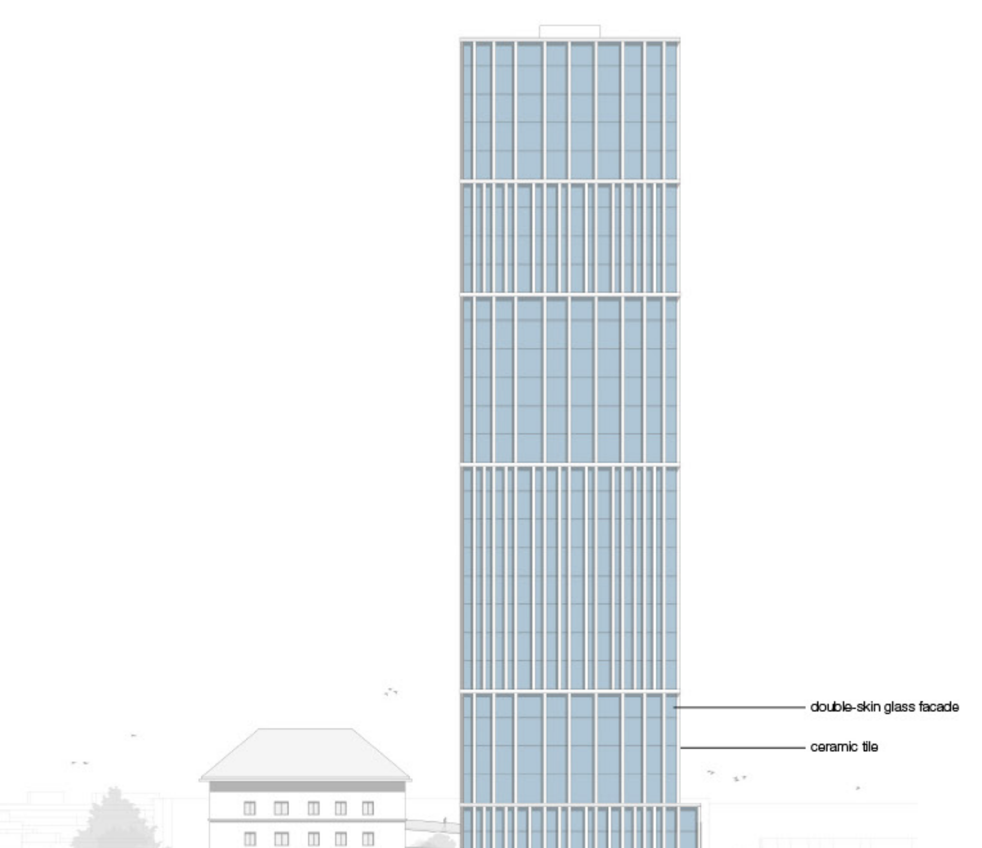


Shafts connected to core

TALL TIMBER BUILDINGS AS
A CLIMATE CHANGE MITIGATION TOOL.
30-STORY TIMBER HIGH-RISE IN TALLINN

Sofya Smirnova
Supervisor: prof. Kimmo Lylykangas

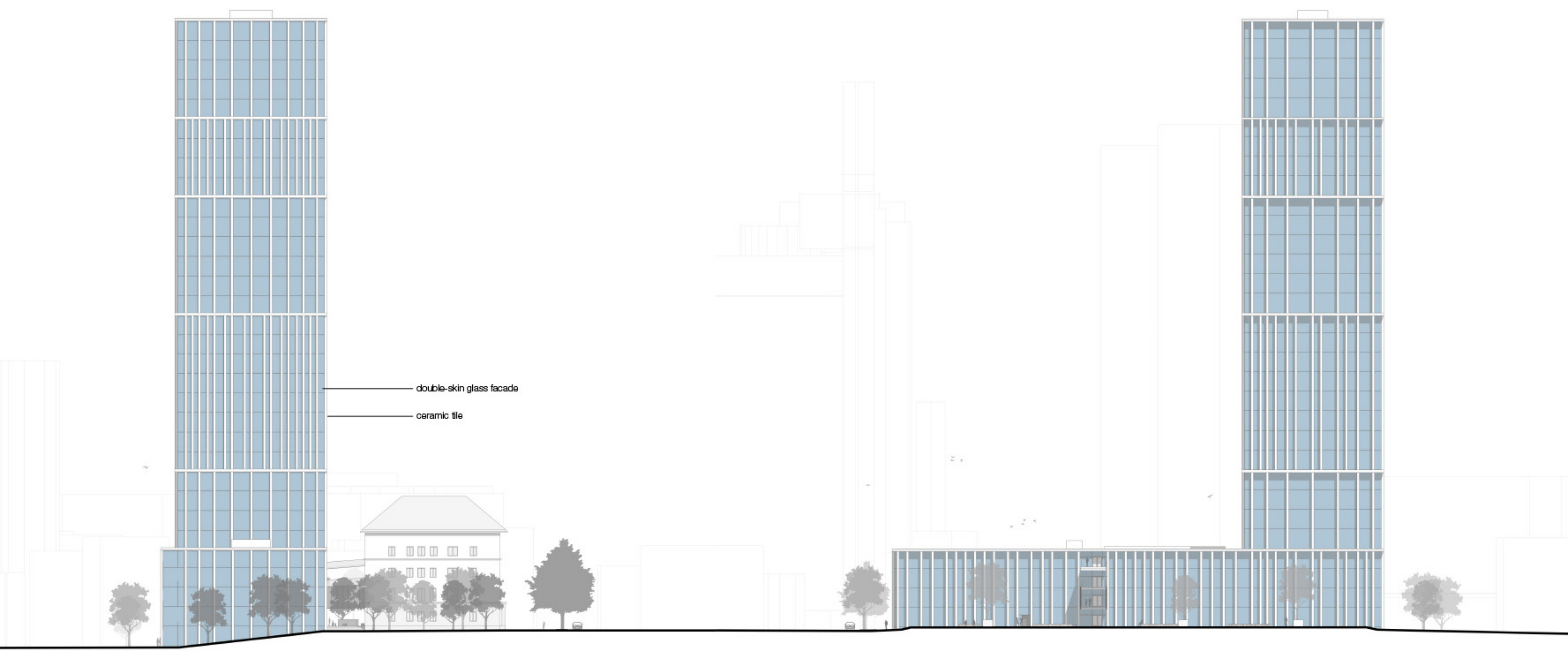
South-East elevation | 1:200




East-North elevation | 1:200

West-North elevation | 1:200

South-West elevation | 1:200




TALL TIMBER BUILDINGS AS
A CLIMATE CHANGE MITIGATION TOOL.
30-STORY TIMBER HIGH-RISE IN TALLINN

Sofya Smirnova
Supervisor: prof. Kimmo Lylykangas