The highrise of timber: feasibility of timber structures

Dynamic Response for timber structures with CLT and Concrete Core implementation

Author:

Santiago Lozano Rincon
5559561
June 23, 2023

First mentor:

Stijnn Brancart - Structural design & Mechanics

Second mentor:

Marcel Bilow - Building product innovation

TU Delft

Table of Content

Table of Content

Table of Content

1.0

Introduction

Abstract

As a threatening reality to the planet's stability, climate change has forced the building industry to develop sustainable techniques and materials to fulfil the constant demand for infrastructure. Timber, as a biobased material, appears like a promising option for constructing highrise structures, a typology that, before the creation of engineered wood products (EWP), was impossible due to technical limitations. Today, buildings with timber as macrostructure are being built worldwide, redrawing the skylines of many cities and revolutionizing the way the building is due to its low CO2 embodied carbon and reducing construction time. However, these new buildings still need to improve regarding circularity principles. Today, the timber industry is experiencing a flourishing, even tho timber highrises implement inefficient design constraints that limitate adaptability and durability and decrease their advantage of having a lower embodied energy than traditional construction materials. This investigation delves into the feasibility of timber highrise structures and examines various factors that must be considered when evaluating them. The study utilizes a parametric model to determine the crucial role of the core and the influence of structural components in the global stiffness of highrise structures and in potential strategies to maximize mechanical behaviour.

Introduction:

The building sector consumes a large amount of energy and natural resources during the building's lifetime; the design, construction, operation, and maintenance, hence they have a massive impact on the environment (Invidiata, A., Lavagna, M., & Ghisi, E. 2018). **Only the construction sector accounts for the use of 40% of the natural resources extracted in industrialized countries, the consumption of 70% of the electrical power and 12% of potable water, and the production of 45–65% of the waste placed to landfills** (Castro-Lacouture, Sefair, Flórez, & Medaglia, 2009; Franzoni, 2011; Pulselli, Simoncini, Pulselli, & Bastianoni, 2007). Additionally, they are responsible for a large amount of GHG emissions, accounting for 30% used during the operation phase and an additional 18% produced during material utilization and transportation (Umar, Khamidi, & Tukur, 2016). These negative environmental impacts of the building sector to the increasingly problematic climate change situation require a redefinition of practices and behaviors in the industry.

The Circular Economy (CE) appears as an opportunity to migrate from an extractivist and linear system to one more compact and resource-efficient one. (Geissdoerfer., 2017) defines the circular economy as: *"A regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through durable design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling".* From this definition, this paper will focus on three principles that will shape the criteria of the circular strategy: First, **Modularity** refers to the prefabrication and standardization of components that integrate the system efficiently. Second, **(Dis)ssembly** as a fundamental design requirement that allows the system and its components to be flexible and adaptable to different requirements and changes, making it easier to maintain and update. And the third, **Durability,** is the characteristic that will considerably reduce the need for reparation or replacement of components.

The circular economy strategy, shaped with the previous criteria, has the potential to decrease primary materials usage and environmental impacts (EMF & MCK, 2014). The annual global GHG emissions from key industrial materials, like cement, steel, plastics, and aluminum, will be reduced by 40% by 2050 (EMF, 2019) if the building industry implements circular production and design strategies.

Biobased materials like timber and other EW products facilitate the implementation of previously explained circular strategies. Implementing efficient and sustainable ways of production and consumption. The CE is an emerging process used by an increasing number of conscientious professionals; even so, it still has several considerations that have slowed down its development and implementation.

Adams., Osmani., Thorpe & Thornback (2016) state that the main challenges for the implementation in the building industry are: lack of interest due to the cost and insufficient incentives, awareness of stakeholders, fragmented supply chain, lack of consideration for the end of life and complexity of buildings.

This panorama shows that despite the considerable evolution that the industry is facing, much work should continue to be done to face these challenges and implement the CE processes. Additionally, the mechanical properties of timber must be understood to maximize their potential to be applied and understand its limitations in efficiently using the material.

Problem Statement:

Timber as a structural building material for highrises is rare. When it is used in many cases, it is complemented with hybrid systems that uses concrete, a material with high carbon footprint, decreasing its potential to be circular.

Concrete core is a component that many systems use as stabilizer despite having a high embodied energy, making impossible the option of design for disassembly, a pillar of the circularity principles.Currently, structures and their components still are built without considering an end-life panorama, designed as if they will never be taken down. This is needed, because most of the timber materials used in hybrid system as (Pastori et al. M., 2022) states: cannot be easily recycled or reused due to the non-reversible connections between the timber elements and the concrete. The application of deconstructable connectors enables the possibility of disassembly and reuse of timber materials at the end of life. It is fundamental to change how materials are joined together and how they are layered in a way that they are accessible and reversible (Boyd R.,2017).

On the other hand, Sara Kulturhus is an example of a project that uses only timber in the macro structure; even so, a solid individual modules system was implemented, generating a high technical complexity in the assembly process and a complete lack of flexibility. Similary, the connections between CLT components are not designed for disassembling, most of the joints are material-material without a connection element, with a high risk of damage if it is unjoined.

These factors show that despite the use of biobased material in the macrostructures, the high-rise timber buildings continue implementing static designs that enable the potential reuse and reconfiguration in the future, creating potentially future obsolete infrastructures. Today most of the waste of the building industry mainly comes from the demolition (CDW) of obsolete structures, accounting for more than a third of all waste generated in the EU and more than 2 billion tons each year (European Commission). This panorama is evidence that the building industry, despite the notorious innovation in techniques, materials, and management, still is not considering the variability of use and requirements of the space that individuals and cities have.

The cities are in constant transformation due to economic and social changing dynamics, so if the cities are not static, why still the buildings?

1.2 Research question:

How can modular timber systems lead to highrise buildings that are technically feasible and adaptable to future use scenarios?

Subquestions:

- To what extent is it possible to reduce the use of metal alloys in the joints of timber components?

- Its possible to replace the concrete core as a lateral stabilizer component?

- How do the wind loads affect the feasibility of a timber highrise?

Specifications:

The following list aims to specify the meaning of the terminology used in the Research question:

- Adaptable: lifetime extension of the macro structural system and components due to the ability to continue fulfilling a function even if the spatial and technical requirements of the building change.
- Future use: architectural programme can be transformed based on functional requirements during the lifetime of the building.

1.2.2. Objectives:

Key words:
Timber, Highrise, structures, modularity, adaptability, circularity.

The following objectives will guide the research and developing of the final product:

1. Design a **multifunctional** highrise timber building in a specific location in the Netherlands.
This objective aims to give specific design parameters to the structure like maximum height, spans, and horizontal and vertical loads.
2. Design an **adaptable structural system.**
The goal of this objective is to design the components required for the building: Columns, beams, trusses, connections, etc. and possibly a core in a sustainable material that allow global stiffness, following the circular principles of modularity and design for disassembly. As a hypothesis, it is assumed that the building must be able to increase the height and change uses as is required by hypothetical urban changing circumstances and completely disassembled in a future panorama of ending life cycle.
3, **Prove the technical and structural viability** of the design.
The goal is to indicate how the system works and that is realizable. Structural analysis of the system and its components is required to demonstrate that the design goals are possible. Similarly, the construction process of the system must show that it is technically possible and logical.

Specifications:

The following list aims to specify the meaning or objectives of the terminology used in the objectives:

- **Multifunctional:** architectural programme of the building consists in different uses that require specific spatial and technical requirements.
- **Circular principles:** Modularity, design for (Dis)assembly and durability (definition of each principle specified in the introduction).

1.2.3. Scope:

This thesis is under the supervision of two chairs: structural design & mechanics and building product innovation. This investigation is focused in the development of a structure and its components that can maximize the spatial flexibility and life span of a timber high-rise. The problem addressed is limited to load-bearing timber systems and stabilizing elements different from concrete. Material fire resistance characteristics is considered outside the scope, assuming the timber products comply with regulations and the highest standard.

The main focus of this investigation is sustainable structures; for that reason, a deep architecture program and climate design analysis will not take place, only will be considered specific factors as inputs to the project and developed to the level that affects the scope of the investigation. The Life cycle assessment will evaluate in a general approach the following factors: Raw Material Extraction, Manufacturing & Processing, transportation and Waste Disposal globally.

1.3 Methodology:

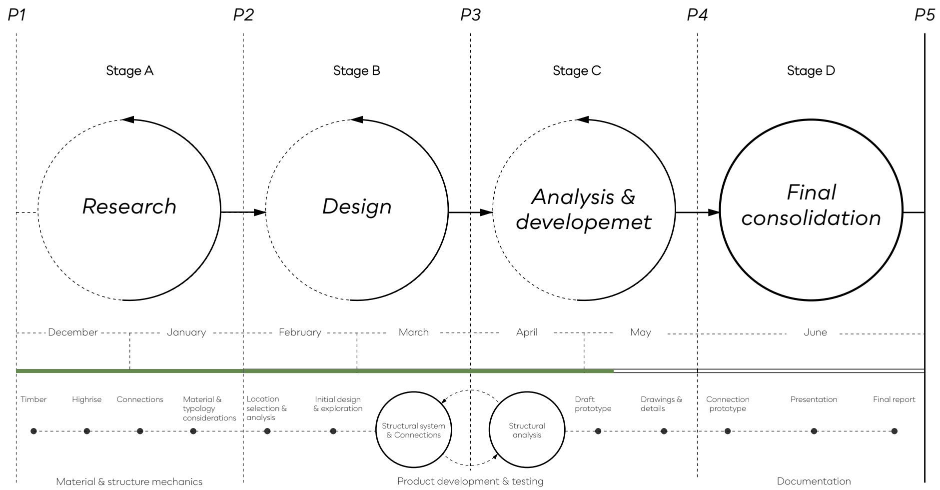


Fig 1: Research methodology preliminary schedule

The first part of the research is literature review and case studies. Stage A will be focused on the following sections of interest: Timber, Highrise, connections and materials & typology considerations. The investigation will provide insights into the current situation, limitations, and potentialities of these topics and the gaps that can be found to link them.

Stage B will continue with the initial design and project development; for that, a location must be selected, and a site analysis has to be made to understand the location's conditions and requirements.

The goal is to have the required knowledge and needs to establish the boundaries needed to develop the Highrise. Between Stage B and the beginning of stage C, two processes will take place and will be interdependent.

The initial design exploration of the structural system and the connections and structural analysis. The information and knowledge studied in the literature review will give to the project design parameters to develop and analyze a parametric model in grasshopper with a specific design criterion to be defined. In this stage, the methodology research by design will be implemented with simulations and analysis using the grasshopper plugin Karamba and prototyping, which will direct the system's development.

The design and analysis stages will operate as a circular process due to its interdependence and changes that can happen for findings, test results, or literature review. For P4, it planned to have a highly detailed preliminary design of the system and its components to have time to make modifications and improvements before P5, where the final concept, details, and prototype will be shown.

2.0

Literature Review

2. Literature Review:

2.1 Circularity

Building obsolescence, whatever the cause, is a problem for the building environment. The loss of value and the energy embodied in obsolete infrastructure represents a high environmental and capital cost (Machado, N., & Morioka, S. N., 2021). The circular economy (CE) emerges as an alternative for the replacement of the linear economy, aiming to extend the useful life of products, components and materials (N.M.P. Bocken, E.A. Olivetti, J.M. Cullen, J. Potting, R. Lifset., 2017 & F. Sariatli., 2017). Due to its added value and sustainable potential, the long-lasting concept is expanding to a macroscale level, including not only products but also construction systems and infrastructures, through the application of **Modularity**, **Durability** and **Design for Disassembly** concepts.

2.1.1. Modularity:

Refers to the product or process structure composed of modules that can be designed independently but works together in an integrated manner (C.Y. Baldwin, K.B. Clark., 1997). Modularity can be implemented in three dimensions: first, modularity in the product that is focused on the architecture and design project. Second, in production involving the assembly line. Finally, modularity in use is aimed at the consumer, allowing ease of use and customization (J. Pandremenos, J. Paralikas, K. Salonitis, G. Chryssolouris., 2009).

Implementing EWPs in the construction process accomplishes the goal of modularity in production, facilitating the design and manufacture of components and transforming the construction site into an assembly line. Modularity still needs to be applied to the design stage and user customization. Implementing these three stages will be a determinant factor in extending the useful life of infrastructure and, consequently, a potentially significant reduction of demolition and construction waste.

2.1.2. Durability:

It can be categorized into two groups: product quality, related to its ability to maintain its integrity, which will be explained in section 2.2.4 considerations, and durability, related to the ability to adapt to changing user demand, which this chapter will focus on. Durability is a quality incorporated in the design of buildings to ensure that a building can withstand various conditions that it will be exposed to over time, which can save costs and reduce the negative impacts related to building operation and maintenance (Chini, A., & Schultmann, F., 2001). Considering the possibility of change over time will make a building adaptable, allowing it to be versatile enough to accommodate the changing requirements of the physical environment within who it exists and the users which occupy it (Macozoma D S, 2001).

In a dynamic context of constant transformation of cities and users, the static configuration of architecture programs generates a direct confrontation between user needs and available and functional infrastructure. The impacts of the construction industry are mainly related to the generation of construction and demolition waste caused by obsolescence (R. Minunno, T. O'Grady, G.M. Morrison, R.L. Gruner., 2020) coming from homes, industrial buildings, roads, bridges, and others. They consist of different materials, such as concrete, bricks, ceramics, mortar, metal, wood, and plastic (H. Yuan, 2017). This is the result of decades of a system based on open loops, where the extraction, manufacture and disposal where the normal process without considering reuse or adaptability.

2.2.3. Design for Disassemble:

as a practice, allows existing and new building stock to serve as a primary material source for new construction, rather than harvesting resources from the natural environment. (Durmisevic, E., 2006.) This concept is directly related to the modular design, where the modules or components must to develop detachable interfaces that enable new product variations, assembly and simple disassembly to improve the product lifecycle (P. Gu, M. Hashemian, S. Sosale, E. Rivin., 1997).

Brand. (1995) developed the concept of a building as a mix of layers; this layer has different purposes and requirements that show the different transformation rates that the components of a building have.

The facade has an average of 50 years, the structure 30-300 years, services 15 - 20 years, the space plan 3 years, finishes 5-7years and stuff 3-2 on average. This permanent and different transformation of the building components shows the need to develop compatible building components that work and fulfil their individual and collective purposes but can also evolve or be replaced without affecting the integrity of all systems.

2.2 Timber

2.2.1. Renewable material:

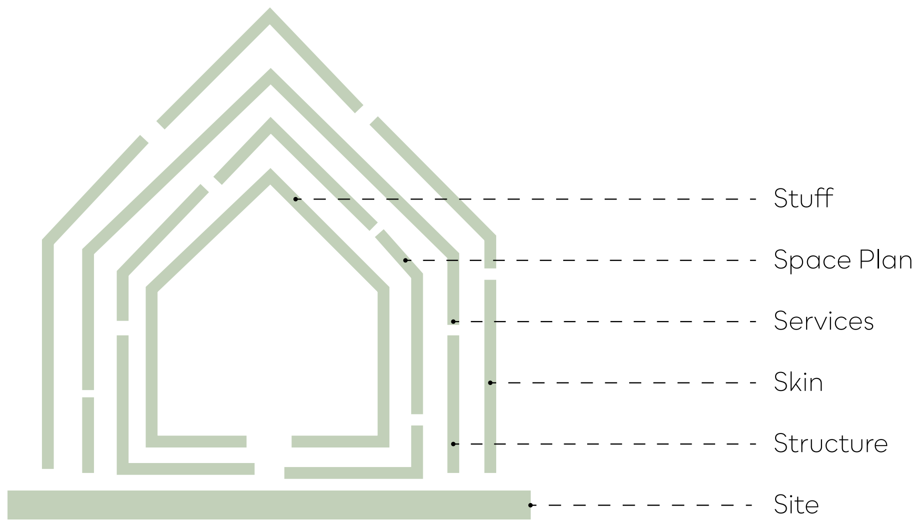


Fig 2: Building layers according to Brand – sharing layers of change (Brand 1995)

Masonry, concrete and steel, for decades, had built our cities, being the most common construction material worldwide but also very damaging in terms of environmental impact. On average, the Co_2 emissions by the energy production requirements are 288 and 8611 kg/m^3 of these two materials, respectively.

This situation makes us reconsider ways to continue building to fulfill the increasing demand for infrastructure while limiting the environmental impacts as much as possible. Wood was replaced by reinforced concrete as the primary construction material due to its mechanical properties limitations as strength and stiffness, despite being very sustainable. (Darby., 2013) states that forests are eco-system that naturally stores carbon dioxide from the atmosphere. If they are sustainably managed, the carbon store can be maintained constantly while the trees removed and converted into timber products will form an additional long-term carbon store.

Due to this, wood has become an up-and-coming option for the building industry. Even so, as Pastori S., Mazzucchelli S E., Wallhagen M. (2022) state, the real sustainability of using wood as a construction material depends on appropriate forest management, manufacturing methods, and site assembly, the distance required for transportation and use of adhesives.

2.2.2. Engineered wood products (EWP):

Timber emerges as a potential solution to the emissions of the building industry due to its low embodied carbon (M van

156Kg of CO^2/ m^3 | 288Kg of CO^2/ m^3 | 8611Kg of CO^2/ m^3

Fig 3: Average comparison of CO_2 emissions / m^3 of: concrete. Steel and timber without transportation.

Vliet.2018).

The engineered characteristics of current wood products (EWP) allow the creation of homogeneous components without considerable imperfections, making these products compared to traditional materials like concrete and Steel in terms of mechanical properties.

Similarly, EWP's industrial production has considerably reduced the technical limitations that biobased materials had before, like size and shape. Today many of the restrictions EWP have are mainly logistical and no technical, as transportation limitations of components, opening a new chapter in the long history of wood as a competitive construction material.

The following mass timber products that will be mentioned are the most relevant in the industry for structural purposes:

- **(CLT) Cross-Laminated Timber:**

it is a product made by gluing crosswise several layers of sawn lumber until a thick sheet is formed. The layering orientation alternation makes the product stiff and strong in orthogonal directions, suitable for load-bearing walls and slabs.

- **(DLT) Dowel-Laminated Timber:** (Wood Design & Building 2018):

it is a panel made from stacked softwood lumber boards using friction-fit together through hardwood dowels. The dowels hold each board side-by-side, forming a stiffer and stronger connection. Each board lamination in a DLT panel is finger-jointed, creating a stiffer and stronger panel that eliminates the board splices and butt joints. This product is used for flooring and roofing.

- **(Glulam) Glued Laminated Timber:**

consists of several layers of sawn lumber glued together and orientated in one direction with the wood grain; this allows to have higher strength than in perpendicular orientation, being appropriate for columns and beams.

Glulam products can also be manufactured in curved shapes, giving them a differential characteristic from other EWP products.

- **(LVL) Laminated Veneer Lumber:** (Design of timber structures: Structural aspects of timber construction., 2016)

it is made by gluing the wood veneer sheets together to form thick panels. The layers are oriented with the fiber direction in the same direction, generally in the long direction of the finished product. Gluing the sheets together creates a structural element of higher reliability and lower variability through defect elimination and distribution of defects, in the same way as for glulam. In general, LVL has high bending, tension, and compression strength, as well as high shear strength and a relatively high modulus of elasticity.

The industrial manufacture of EWP makes them competitive with other products; the fact that they are produced in factories makes it possible to produce uniform products without the imperfections that affect the mechanical performance, like knots or cracks.

The lightness of timber makes it easy to transport and assemble, considerably reducing the cost, time, and number of construction workers on a construction site. Similarly, the preciseness of the machinery that produces the EWP, reduces the waste of material considerably, and the production technique allows high flexibility in components shapes and sizes.

The numerous advantages of Engineered wood products make timber a material with enormous potential with a growing use tendency in the building industry.

2.2.3. Joints:

Timber joints can be classified into three groups: carpentry, dowelled and glued. In the case of timber construction, the dowelled joints are the group used as the macrostructure level. Due to wind loads, the high-rise joints are the most vulnerable factor to consider in terms of structural failure. Their load-bearing capacity depends on the timber elements' embedment strength and the steel fasteners yield moment, making the material's ductility the common reason for failure (Domański, T., & Kmiecik, K. 2019). The load-bearing capacity of timber structures is often limited by the resistance of steel connection between timber structural members (Domański, T., & Kmiecik, K. 2019). The transfer of loads between the EPW differs depending on the selected product, position and type of connection. The structural dynamic due to these accelerations makes the moment stiff connection fundamental to have a functional and safe structure.

2.2.3.1. Carpentry joints

Timber-to-timber joints consist of load transfer through friction and shear strength of components (Branco, J., Dietsch, P., & Tannert, T. 2022). This type of joint works mainly in compression and is considerably weaker in tension. Traditional timber framing connections are often variants of a mortise and tenon joints, where the tenon is retained in the mortise by one or more wood pegs (Sandberg, L. B., Bulleit, W. M., & Reid, E. H. 2000).

Most of the conventional carpentry joints can be classified in 6 main groups: simple half-lap splice (a), halved and tabled splice (b), scarf ©, heading (d), mortise-tenon (e) and step joints (f).

Branco, J., Dietsch, P., & Tannert, T. (2022) describe the characteristics of these five carpentry joints:

- **Tabled joints** can bear compressive, tensile and shear loads in

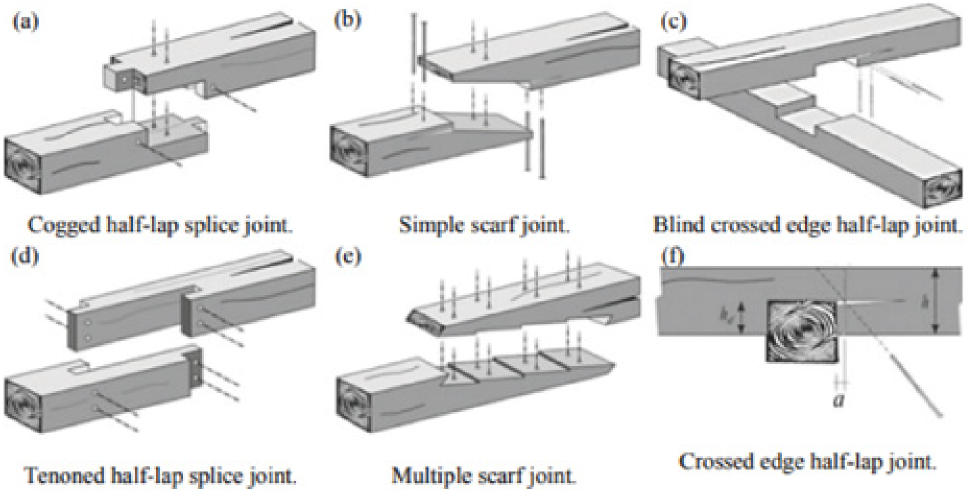


Fig 4: Traditional carpentry joints (Branco, J., Dietsch, P., & Tannert, T. 2022)

the axial direction of the members. A disadvantage of this type is the reduction of the member section at the joint area.

- **Scarf joints** are an end-to-end connection of two timber members through a sloping cut of overlapped surfaces. It carries compression, but it can carry tension and shear along the axial direction of the members. Wedges are used to ensure the tight fitting of the connected members.

- **Heading joints:** the components counteract in axial compression, parallel to the grain, and in axial tension, only when they are dovetailed or tenoned with a peg.

- **Mortise-tenon joint** are composed of two components; one is the tenon, which is an extrusion of a part, and the second one is the mortise, with is the opening in the other component that will receive the extruded part. This joint had a significant compressive strength of the butt contact surfaces.

Also, they feature some rotational stiffness and flexural capacity. Pegs, wedges or tusks can be inserted in such connections to resist moderate tensile loads to avoid axial and transverse displacements of the timber members.

- **Step joints** mostly work in compression at the contact surfaces and tension and shear along the grain at the end of the notched timber member. The geometry of the heel strongly influences the stiffness, and the load-bearing capacity of step joints is not enough to carry the shear forces, and out-of-plane displacements need to be reduced.

The mechanical properties and geometry of the joint component are the determining factors of failure in carpentry joints. Compressive crushing, shear cracks and tensile cracks are the three main failure mechanisms due to the high combination of shear stress parallel to the grain and tensile stress perpendicular to the grain (Lathuillière D, Bléron L, Descamps T, Bocquet J-F 2015). Lack of Tight fitting and proper contact between the assembled components is the more significant challenge, causing a non-uniform stress distribution worsened by the joint geometry and imperfections in the material that decreases its strength performance (Branco, J., Dietsch, P., & Tannert, T. 2022).

2.2.3.2. Dowelled joints

This type of joint involves nails, screws, dowels, nail plates and bolts. The characteristic of this group is the transfer of forces through shear in mechanical fasteners mounted at an angle to the force direction (Design timber structures., 2016). The utilization of high-strength steels (VHSS) with subsequent higher yield moments is promising to optimize joints and get high-performance joints due to the high-stress levels concentration (Vayas, I., Ermopoulos, J., & Ioannidis, G. 2018).

2.2.3.2.1. Steel to timber joint:

The use of steel for the connection component is due to its higher strength-to-weight ratio, which is much superior to timber. This connection is commonly realized with plates that work as the transition between the EWP and the dowels; this forms the plastic hinge at the interface of the materials, increasing the resistance capacity of the joint and generating fix support (Design timber structures., 2016).

- **Double shear;** is the most common steel-to-timber joint. Mainly are two ways of implementing this connection; one is through the use of nails at the end of the timber member, generating a single shear steel-to-timber joint, or it is also possible to have the dowel protrude all the way through the timber member and both steel plates (Design timber structures., 2016).

- **Slotted in steel plate:** consists of locating the plate inside the timber component; the number and location of the plates will depend on the thickness of the EWP and the mechanical requirements the component needs to fulfil.

This choice is becoming more used in timber construction for fire safety and aesthetic reasons. The encapsulation of the steel plate is a protection measurement that reduces exposure to combustion and is also commonly visual appealing.

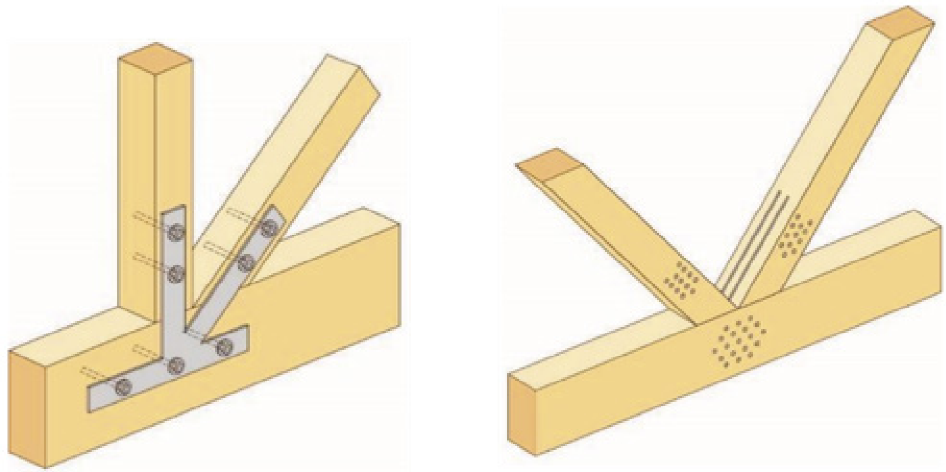


Fig 5: Double shear (A) and slotted in steel plate (B) joints (Crocetti, Roberto., 2016)

2.2.3.3. Glued Joints

Glued connections are regularly used in wooden constructions to connect new elements and reinforce existing members; there are several types of glued connections, such as structural finger joints and glued steel rods (Fonseca, E. M. M., Leite, P. A. S., Silva, L. D. S., Silva, V. S. B., & Lopes, H. M., 2022). This type of joint is challenging due to the need for controlled environmental conditions in the glueing process to ensure quality.

According to Feldt P., & Thelin A., (2018) the most important failure mode of glued-in rod connections was near the timber-adhesive interface. Similarly, the manufacture of EWP products like CLT or Glulam uses glue joints at the material scale level. Here, the stress distribution in the joint is non-uniform, even though the ends of the glue line are the ones with peak stresses and where the failure will start (Design timber structures., 2016).

2.2.4. Considerations:

2.2.4.1. Fire resistance

Fire has been the biggest threat to wood as a construction material in the record of human construction history. Ancient disasters such as the fire that devastated the Roman capital in 64 AD to most recent events like the Grenfell tower fire of 2017 in London show the high vulnerability of a city built with materials lacking fire resistance. These disasters and the disinformation regarding the fire probe characteristics of modern EWP are present in society and, by extension, in many legislation and regulation offices around the world, hindering the development of timber Highrise at its full potential. Even so can't be denied that Timber is still a combustible material and has risks and challenges that need to be taking into consideration.

(A. Law, L. Bisby 2020): defines fire resistance as the duration during which a structural member fulfills predefined criteria with respect to structural integrity, stability, and temperature transmission under monotonically increasing standardized fire conditions. A common approach to making fire prove combustible materials as timber, is the encapsulation method, which consists of applying an external low-combustible material layer that will control the expansion of the fire. Even so, (Philion, E., Chorlton, B., Gales, J., & Kotsovinos, P. 2022) states that: this method has significant drawbacks like the larger environmental footprint of the use of redundant layers covering the timber and the increasing time and cost of a construction project.These drawbacks are against many qualities of timber, like its environmental strength, the desire for exposed the material, and its rapid rate of construction.

To tackle the combustible nature of timber without affecting the qualities of the material, the EWP have controlled combustion properties that, in contrast to steel, for example, which has an uncontrollable behavior under high temperatures, Timber products have an intentional over size dimension known as “**sacrificial layer**” following the reduced cross-section method (RCSM), which considers the components cross-section reduction due to fire but maintaining the strength of the component for a certain period of time (Philion, E., Chorlton, B., Gales, J., & Kotsovinos, P. 2022). Despite the material improvements in the fire resistance, if the fire is not suppressed on time, timber can continue to combust and potentially fail long after a fire has been considered extinguished (Gernay 2021) due to the affectations made of mechanical properties in the decay phase. Temperatures can reach nearly 100°C in the centroid of glulam beams and columns in the cooling phase, resulting in an irreversible reduction of load-carrying capacity, additional deflections, and delayed failure (Gernay 2021). This is evident in the heat penetration shown in Fig 6., where the temperature distribution on a timber column happens in four stages after 59 min of fire exposure until failure in minute 230.

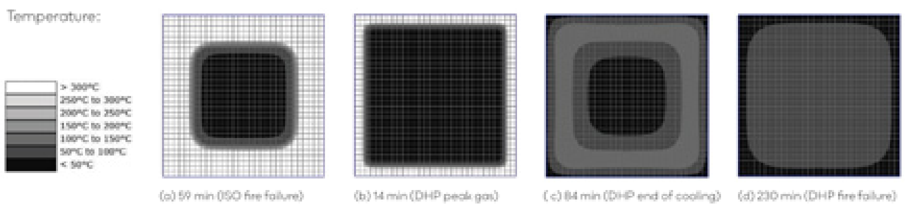


Fig 6: Temperature distribution in the cross-section of timber column H26A throughout the fire event and thereafter due to delayed heat transfer (Gernay 2021).

Connections and their non-linear load-deformation behavior considerably impact the deformation of timber structures and the stress distribution in statically indeterminate structures. (Sandhaas, C., Munch-Andersen, J., Dietsch, P. 2018.);

For that reason, it is important to remark how they are a relevant component to consider in the fire safety of timber structures. Previously was mentioned how the timber reacts to fire but also should be considered the high vulnerability that the connections have when exposed for long periods to fire and its potential contribution to failure. The connections of timber components are made mainly in steel, a metal that as (Pastori A S., Mazzucchelli E S., Wallhagen B M., 2022) mention: shows a substantial reduction of its mechanical properties at high temperatures; moreover, it is a conductive material that transports heat quickly into the interior parts of the wooden section causing the carbonization of the centroid.

This risk could be substantially reduced if the connections are encapsulated in the timber component, less exposed, and protected by the material layers. Considering the improvements and still existing challenges of timber as a primary structural material, is relevant highlight the importance of implementing a rapid detection that allows an early fire warning. An early stage will allow a safe evacuation and a rapid sectorization of the affected area, meaning timely containment and suppression. Equally active fire control systems like fire sprinkler systems must be implemented to prompt auto-extinction or controlled combustion until the emergency services arrive if an auto-extinction does not occur.

Finally, the implementation of compartmentalization will be a determining factor if a fire hazard occurs; the establishment of fire compartments will limit the fire's expansion and reduce the structures thermal exposure and potentially irreversible affectation.

2.2.4.2. Durability and protection

Fig 7: Durability challenges of mass timber in buildings and constructions (Ayanleye, S., Udele, K., Nasir, V., Zhang, X., & Militz, H. 2022)

Timber has three factors that generate its deterioration: first, the environmental degradation caused by weathering. The causes are rain, high humidity, or close contact between the material and streams. Secondly, it is biological degradation. Fungi and termites are the most common. And finally, safety concerns like fire hazards (Ayanleye, S., Udele, K., Nasir, V., Zhang, X., & Militz, H. 2022). Timber is a hygroscopic material that easily absorbs and holds water. This phenomenon makes the material can dimensionally absorb and release moisture, a determinant factor of the durability of timber buildings (Pastori S., Mazzucchelli S E., Wallhagen M., 2022), being especially vulnerable the material that is constantly exposed to high humidity concentrations.

Swelling and shrinkage are natural reactions of wood structural behavior, but either can cause damage if not adequately addressed in design and construction. These movements can potentially cause large tension stresses and damages in correspondence of the connection system (McLain, R., Steimle, D. 2019). Timber products can be treated in order to increase durability and improve materials characteristics, making them more resistant to the deteriorating factors previously stated. The most common wood treatment techniques are **Preservative Treatment (PT), Thermal Modification (TM), and Chemical Modification (CM)** (Ayanleye, S., Udele, K., Nasir, V., Zhang, X., & Militz, H. 2022).

Preservative treatment (PT):

This method involves applying chemicals to the wood, aiming to protect it against deteriorating agents like fungi and termites.

The servant can be applied brushing or spraying; the chemical agent will adhere to the material surface and penetrate through the external layers (Ayanleye, S., Udele, K., Nasir, V., Zhang, X., & Militz, H. 2022). Even so, this method is questioned for its potential environmental impacts.

Thermal modification (TM):

it is a technique that reduces the affinity of the material for moisture, blocking the cell walls by the penetration of the nanopores through the material exposure to high temperatures and reduced oxygen (Tjeerdsma, M. Boonstra, A. Pizzi, P. Tekely, H. Militz, 1998). The thermal modification increases the material resistance to degradation for weathering; even so, according to (B. Esteves, H. Pereira) it could affect strength properties, like stiffness and modulus of rupture.

Chemical modification (CM):

it is a technique that consists in replacing the functional group, hydroxy, from the wall cells of the wood that is responsible for the absorption of moisture. CM increases the durability of the material, protecting it from biological an environmental degradation (Ayanleye, S., Udele, K., Nasir, V., Zhang, X., & Militz, H. 2022); however, it is not as cost-effective as PT.

Complementing the preventive treatment, post-construction maintenance, moisture monitoring, and control must take place to achieve the EWP's long durability. It's important to remark that moisture control can't only be controlled with the material modification of its physical and mechanical properties, but also the architectural design and the construction process play an important role in its conservation.

Timber building requires correct detailing of facades, roofs, and foundations in order to have exterior components covered from wind and rain, the biggest weathering deteriorating sources. Similarly, the construction process is commonly a stage that it's not taken into consideration in the prevention face; but it plays an important role. (P. Morris., 2015) states that the transportation and storage of EWP are moments where timber is more exposed to high biological and environmental degradation situations, risking product integrity.

2.3 High Rise

The population growth projection will be 9.7 Billion by 2050, and 2/3 of the population will live in cities in the next 30 years (Roser, M., Ritchie, H., Ortiz-Ospina, E., & Rodés-Guirao, L. 2013) In developed countries the urban inhabitants with an increase from

2.7 to 5.1 billion in 2050 (J, 2015). This situation Will generate several sustainability and social challenges, mainly on infrastructure and the environmental impact (Akande, Cabral, Gomes, & Casteleyn, 2019; Bibri & Krogstie, 2017; Han et al., 2017; Steverson & Steverson, 2018).

The quick evolution of demographics is becoming visible in the deficit of dwellings and critical infrastructure in the principal urban centers. The exponentially growing demand decreases the available spaces for new construction developments and increases land costs considerably.

Hight rise as a densification strategy appears as one of the most efficient alternatives to develop proper land management, reducing the expansion of cities and infrastructures needed for its functioning, meaning a considerable reduction of the environmental impact that low-density systems don´t achieve. In many cases, the development of these projects saves thousands of km² of countryside and natural space that would be potentially urbanized, becoming an opportunity for consolidating compact urban centers and factors of urban renovation and revitalization.

Smith and Coull (1991) define a high-rise as a structure where wind or seismic forces govern the structural design; managing these forces is an essential factor in guaranteeing safety and comfort levels. The conventional design of a high-rise is governed by the strength and stability of its structural components.

However, in the case of timber high-rises, due to the material's properties, the reduction of accelerations is challenging. Variables like self-weight, global stiffness, height, natural frequency, and structural damping of this kind of structure became essential (Versteeg C J 2022) to achieve the serviceability of the building.

2.3.1. Gravity Loading:

The gravity loads are the vertical forces that stress a structure. They Can be categorized as Dead loadings, which consist of the weight of all materials of construction incorporated into the building, and live loadings, A load produced by the use and occupancy of the building or other structure that does not include construction or environmental loads (American Society of Civil Engineers, & Engineers, A. S. C. 2010).

The two primary types of vertical load-resisting elements of tall buildings are **columns** and **wall cores**.

The primary function of these components is to resist the gravity loading from the weight of the building and its contents (G van Oosterhout 1996). The structural system, through its components, will transfer the loads to the foundations, where they will be dissipated entirely to the terrain.

The structure must comply with structural integrity requirements, following stability, strength and stiffness standards to resist all stress combinations.

Load combinations can be calculated with:

$$1.1\left(1.35G + \sum_{i\ge 1} 1.5\varphi_{0.1}Q_{k,i}\right)$$

$$1.1\left(1.2G + 1.5Q_{k,i} + \sum_{i\ge 1} 1.5\varphi_{0.1}Q_{k,i}\right)$$

Equation 1: Load combinations applied for dimensioning on strength NEN-EN (2019)

2.3.2. Wind engineering:

The wind is a dynamic and random force in time and space that increases its velocity as the distance from the ground increase, making the structural performance of tall buildings be determined by the dynamic response caused by the horizontal load (C. Geurts., 1997).

In the case of the Netherlands, the wind is the most important factor to consider for its high average velocity and building considerable slenderness due to regulations of interior requirements of daylight.

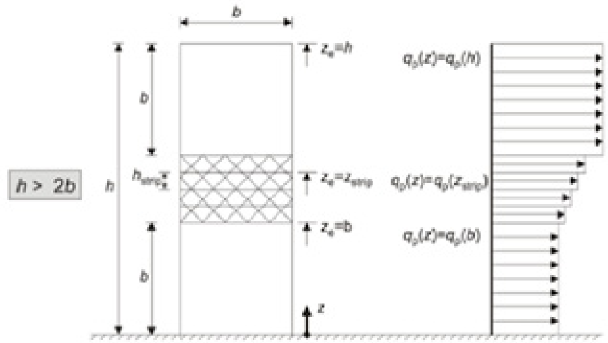


Fig 8: Wind pressure distribution over height according to NEN-EN 1991 (Felicita M., 2021)

- Wind induced accelerations:

The flow of air around a building induces pressures perpendicular to the surface of the building; the wind induces loads that can be categorized in three primary responses: along, cross and torsional (G van Oosterhout 1996).

The three different wind circumstances represent different challenges for high rise depending on the shape of the building. Along wind: represents a challenge to rectangular shape buildings this because of the high-pressure concentration per area on the windward facade.

- Cross-wind response: represents an adverse condition for cylindrical and square shape buildings; this is due to the vortex shedding generated when the air passes the building and Torsion-wind response: affects irregular shape buildings by inducing torsion (G van Oosterhout 1996).

Along wind acceleration can be calculated with:

$$a_{max}(y,z) = \sigma_{a,x}(y,z) \cdot k_p$$

$$\sigma_{a,x}(y,z) = c_f \cdot \rho \cdot I_v(z) \cdot {v_m}^2 \cdot R \cdot \frac{K_y \cdot K_z \cdot \phi(y,z)}{\mu_{ref} \cdot \phi_{max}}$$

Equation: Along wind acceleration (Oosterhout 1996).

Cross wind acceleration can be calculated with:

$$a_w = {n_{1,x}}^2 \cdot k_p \cdot \sqrt{b \cdot d} \cdot \left(\frac{a_r}{\rho_B \cdot k_p \cdot \sqrt{\xi}} \right)$$

$$a_r = 78.5 \cdot 10^{-3} \cdot \left[\frac{v_m(h)}{n_{1,x} \cdot \sqrt{b \cdot d}} \right]^{3.3}$$

Equation: Cross wind acceleration (Smith & Coull, 1991).

- Natural frequency: known as eigenfrequency is the frequency at which structure oscillates after being exposed by an external force (G van Oosterhout 1996), the magnitudes of the frequency on this paper will be directly related to the speed and turbulence generated by the wind.

Natural frequency can be calculated with:

$$n_{1,x} = f(\alpha h) \cdot \sqrt{\frac{q_w \cdot h}{\mu \cdot \delta_{max}}}$$

$$\alpha^2 = \frac{(GA)_{tot}}{(EI)_{tot}}$$

Equation: Natural frequency (Oosterhout 1996)

$0 \leq \alpha h \leq 1$

$$f(\alpha h) = \sqrt{\left[\frac{0.3131}{(\alpha h)^2} + 0.1148\right] \cdot \left[\frac{-1 - \alpha h \cdot sinh(\alpha h) + cosh(\alpha h)}{(\alpha h)^2 \cdot cosh(\alpha h)} + \frac{1}{2}\right]}$$

$\alpha h \geq 1$

$$f(\alpha h) = \sqrt{\left[\frac{0.2365}{(\alpha h - 0.3)^{1.22}} + \frac{1}{16}\right] \cdot \left[\frac{-1 - \alpha h \cdot sinh(\alpha h) + cosh(\alpha h)}{(\alpha h)^2 \cdot cosh(\alpha h)} + \frac{1}{2}\right]}$$

Equation: modal behaviour ratio to shear and bending stiffness (Oosterhout 1996).

- Damping: it is a property which influences vibration amplitudes under forced vibration and the rate of decay of vibration amplitudes under free vibration (Design of timber structures., 2016). The response to the resonances will take place through structural damping, and the components of the system will dissipate the energy until the accepted level of serviceability.

Even so, the energy dissipation its not the same and will be determined by the materials, type of structural system and connections used. Felicita M., (2021): For timber structures, total structural damping ratio ranges from 0.7-2.1%.

The use of lightweight materials, like timber, makes relevant the need of create strategies to face wind-induced dynamic behaviors for high rise. According to G. van Oosterhout (1996): Modal mass, global stiffness and the damping have shown being the most relevant parameters to respond to these accelerations.

Structure oscillation must be controlled to be under the comfort levels around 0.05 m/s^2 where is the velocity where humans cannot perceive motion according to the Eurocode standard parameters.

2.4. What is happening in the timber high rise industry?

Modern timber buildings are made of CLT (cross-laminated timber) and Glulam (glued laminated timber) as main load-bearing systems. This product has become an alternative to traditional construction materials due to its sustainable raw origin and time construction efficiency. The highly engineered properties made them competitive, complying with strict performance requirements related to strength, fire, and wind resistance.

Most of the tallest timber buildings have been built in the last decade, achieving similar heights of around 90m in the biggest example, thanks to the use of hybrid structural systems. The incorporation of other stabilizing materials increases the structure's self-weight and global stiffness (Felicita M., 2021),

Timber has a good strength-weight ratio and elasticity. However, its orthotropic behavior and lack of ductility make it necessary to complement its use with other materials to maximize structural performance. Hybridization, defined as the mixed use of materials, can take place at two scales: component, like columns or beams, and system, like vertical or horizontal structure (Pastori S., Mazzucchelli S E., Wallhagen M., 2022).

For timber, the most common hybridization is with concrete and steel, forming composites denominated TCC and STC, respectively. In Fig. 4. Are the four tallest timber buildings until December 2022, each of them uses different approaches in the construction process.

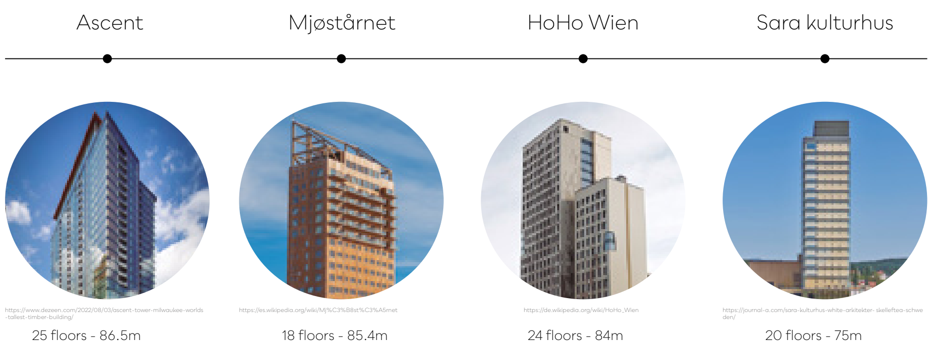


Fig 9: Floor and high comparison of tallest timber buildings until December 2022.

- Hybrid components:

Timber-concrete composite (TCC) is mainly applied for beams, walls, and floors. The beams are usually formed by a timber beam coupled with reinforced concrete in cross-section or longitudinal direction (E. Augeard, L. Michel, E. Ferrier, 2018 & S. Benkai, L. Weiqing, Y. Huifeng, 2021).

The floors are conformed by EWP panels connected to a reinforced concrete slab through shear connectors (Pastori S., Mazzucchelli S E., Wallhagen M., 2022). Moreover, walls can be a combination of some of the EWP like CLT, GLT, or LVL with a concrete layer that can be lightweight or high-performance (L.F.C. Jorge, S.M.R. Lopes, H.M.P. Cruz, 2011). The TCC hybridization optimizes the component through material complementation of properties; in this case, timber resists tension and concrete compression.

An example of the implementation of TCC was in the structural scheme of Mjøstårnet. The structural system of the building is made of a Glulam frame, façade trusses, and a central CLT core that transfer the loads vertically. The system is complemented in the last six levels with TCC floors, conformed of EWP flooring panels with a reinforced concrete layer each that contributes to increasing the self-weight of the structure, stabilizing the building against the horizontal loads caused by the wind.

Steel-timber composite (STC), components are used to increase the strength of engineered wood products by using metal components that supplement beams, columns, and walls.

An example of an STC is the Flitch beam; this structural element is made by layering the steel plate and mass timber. For the fitch beam case, the timber members provide restraint to lateral torsion buckling, and the steel bolts are used to transfer shear between the metal plate and timber members, increasing the strength of the beam (Pastori S., Mazzucchelli S E., Wallhagen M., 2022).

- Hybrid buildings:

The structural design of timber high-rise structures is governed by the structure's dynamic response when exposed to dynamic horizontal loads such as wind (Felicita M., 2021). For that reason, system hybridization it's a common design approach to tackle the deficiencies in stability that mono-material timber structures have. (Pastori S., Mazzucchelli S E., Wallhagen M., 2022): Hybrid systems can be grouped into four main categories, where timber is coupled with: steel framing, reinforced concrete and masonry walls, dissipating steel braces, and seismic protection devices. Implementing these categories makes possible the integrity of the structure and serviceability of the building.

Ascent is currently the tallest timber structure in the world, with 25 stories and 86.5m in height. The stability system consists of a glulam frame with CLT floor slabs complemented with a concrete core that stiffened the building; the strategy was to rely on the structure's stability in a hybrid system, compensating for the lack of self-weight of the timber macrostructure.

Another example is Sara Kulturhus, a tower of 20 stories and 75m in height constructed of premanufactured module units stacked between two cores made from CLT at each end of the building, stabilizing the structure. Felicia M., (2021) states that the cross-section of the structural elements, the stiffness of the connections, and the spans determine the global stiffness of this type of structure. The rotational stiffness of the connections is limited by the materials mechanical properties and the connectors capacity, concluding that Independent of the structural system used, the moment-resistant connection plays a crucial role in the integrity and stability of the system.

3.0

Joints analysis

Introduction:

This chapter will discuss the results of a pre-design analysis focused on the joint assessment criteria. This analysis aimed to identify the most suitable material and joint technique for the timber high-rises while ensuring that the construction process adhered to the design for (dis)assembly criteria. The analysis include an assessment of the mechanical properties of various materials in determining their structural performance and an evaluation of their embodied energy to ensure that the chosen material aligned with circular economy principles. The analysis aimed to strike a balance between the mechanical performance of the chosen material and its environmental impact throughout its life cycle.

3.1. Joints:

Timber has a reduced self-weight ratio compared to steel or concrete, demanding a much higher rotational stiffness of the joints for these structural configurations. The joints for timber high-rises play a significant role in the safety and serviceability of the building, being the components of the system that have higher responsibility in the resistance and dissipation of the external and dynamic forces applied to the structure; for that reason, the structural performance must fulfill rigorous criteria.

Additional to the safety and serviceability considerations, the joints also must consider other requirements that directly affect the qualities that the implementation of a timber structure in a project has compared to other materials, like the environment impact, for example, where the hybridization with pollutant agents or the increased use of unsustainable materials in specific components to compensate the deficiencies in the mechanical properties of timber is common. To select the most accurate joint type for timber Highrise, an assessment was made to compare the qualities and challenges of the following groups: carpentry, cold formed, dowelled, glued and screws.

Mailler N., (2020) propose an evaluation following four criteria: life cycle, exchangeability, re-use potential and structural performance. For the interest of this investigation, a list of 10 factors were integrated into these factors to analyse specific sustainability and structural viability characteristics. See FIG 15. The principles evaluated as the percentage of importance were established in this investigation to achieve a criteria selection based on a heterogenous background that doesn't overfocus on just one characteristic.

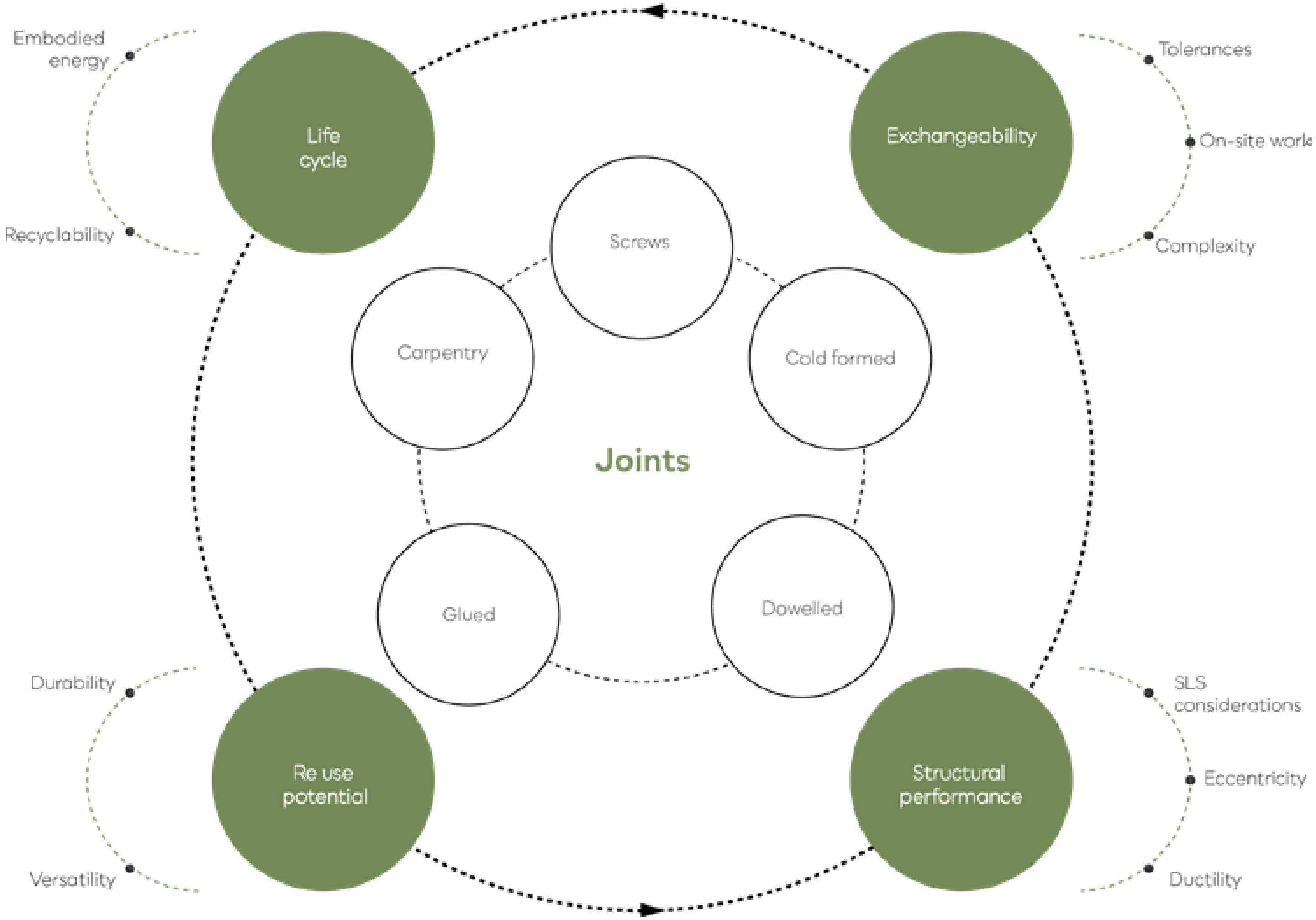


Fig 15: Joints assessment criteria, adaptation from (Mariller N., 2020).

The life cycle criteria will evaluate the material's embodied energy as its recyclability potential; this principle has a 20% load importance. Exchangeability considers the complexity of the connection in terms of installation and how much on-site work it demands. This principle has a 20% load importance.

The reuse potential evaluates the versatility of the component concerning its applicability in other parts of the system and the durability and resistance of the component to be reused multiple times. This principle has a 30% load importance. Structural performance evaluates the load-bearing capacity and SLS considerations like ductility and eccentricities. This principle has a 30% load of importance.

3.1.1. Carpentry:

Carpentry joints were a type of connection of particular interest in this investigation due to its implementation's almost neglected environmental impact, having an enormous potential for development in highrises. A preliminary structural component design was developed to analyze its performance and potential applicability to the project. The Fig 16 shows three components developed,column-column, truss, and core. All the carpentry joints can be seen in Appendix B: Joints design, B1 Carpentry Joints preliminary design.

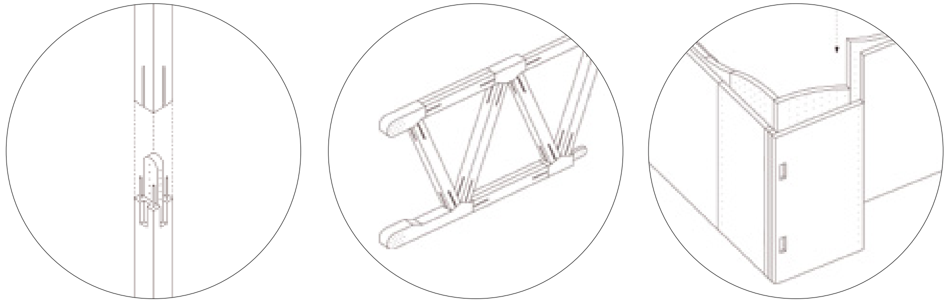


Fig 16: Carpentry joint: column to column, truss and core.

The design concept followed the traditional carpentry technique of tenon and mortise, using the interlocking characteristic of this type of joint as one of the main strategies for connecting different structural components. As a complement to the geometry interlocking, the components had pre-drilled holes for the steel screws in the nodes to ensure the tightness of the components avoiding eccentricity or dynamic behaviours. Even so, the carpentry joints showed much potential for implementation; the demanding mechanical resistance that joints for highrises demand made the feasibility of this type of joints complex. This type of preliminary design faced two main challenges: mechanical behaviour and manufacture. In mechanical behaviour, reducing the cross-section of components to create the interlocking significantly increased the risk of buckling and fracture.

Similarly, the geometrical configuration of components, like the nodes of the truss, could create stresses perpendicular to the grain of the material due to the structure's dynamic behaviour, being one of the mechanical weaknesses of the EWP used.

The manufacture also had many challenges popping out where the design was advancing; one was that the production of this type of component would considerably decrease the modularity potential of structural elements and increase the cost of production.

The interlocking created a series of different types of connections, becoming this design complex and requiring much in-site work by specified personnel.

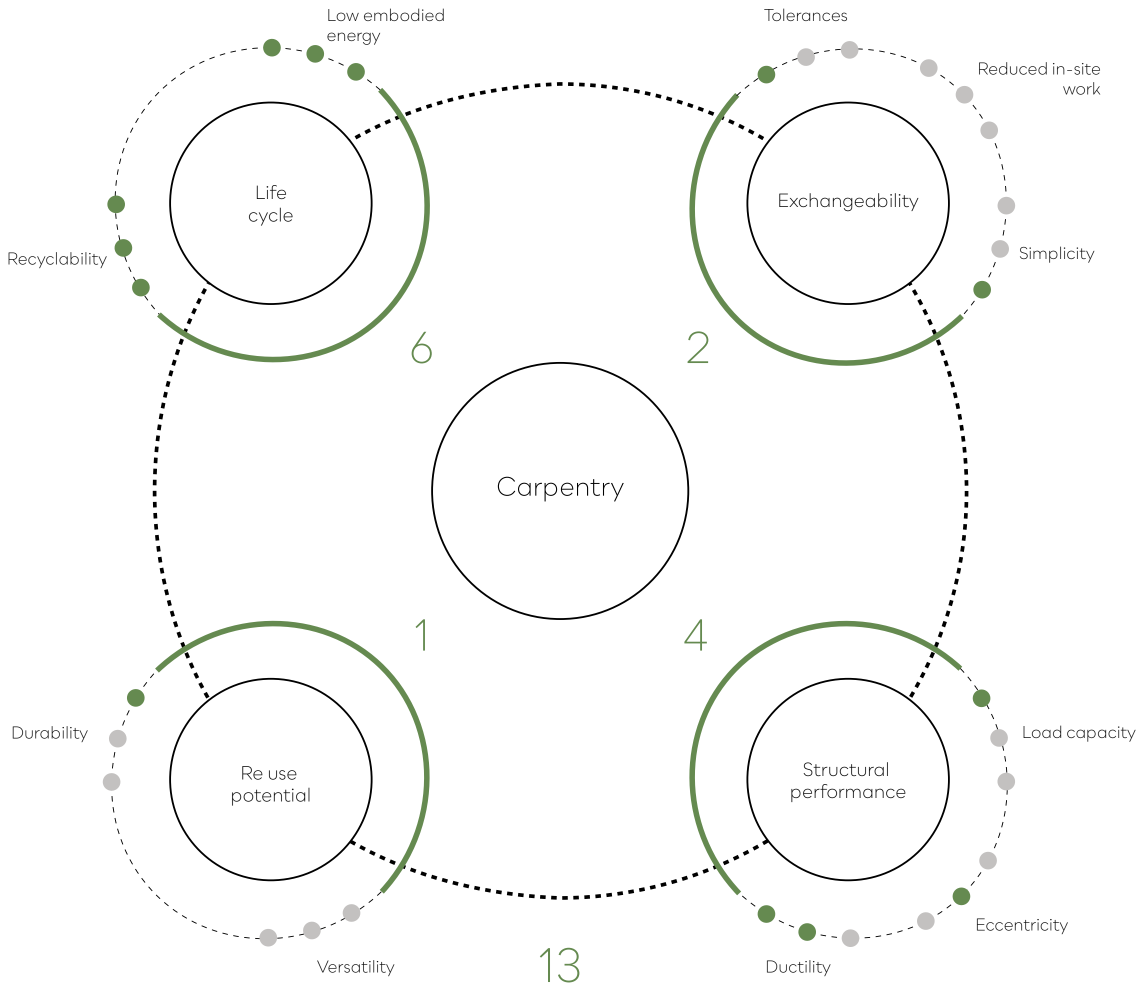


Fig 17: Carpentry joint assessment.

3.1.2. Cold formed:

Cold formed consists of the shaping and forming of solid structural components in metal. This type of joint has excellent structural performance, having a high strength-to-weight ratio and a uniform and predictable distribution of stresses (J.L. Miotto, A,A. Dias 2012).

The load-bearing capacity of these joints is high due to the mechanical properties of the material used, allowing high durability to resist long-term deteriorations and exchangeability stresses.

The lifecycle is a weakness and a potential advantage at the same time; the raw material has a high embodied energy but is entirely recyclable, so the existence and availability of material can be used from recyclable sources and urban mining.

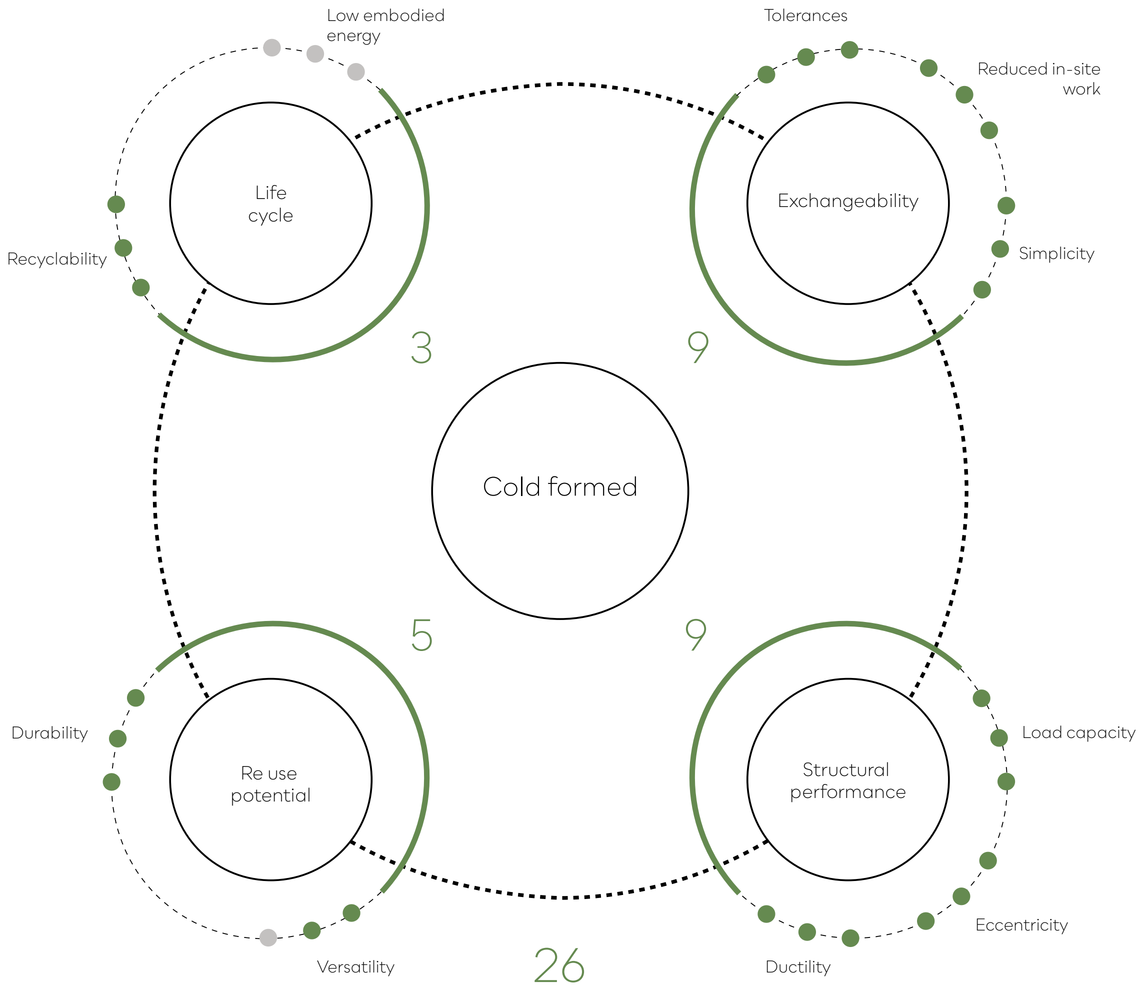


Fig 19: Cold formed joint assessment.

3.1.3. Dowelled:

This assessment is based on the complementary use of dowels and metal sheets. This type of joint can be implemented as, Slotted plates located in the geometric centroid of load-bearing components, allowing an excellent structural performance due to the high strength-to-weight ratio and a uniform and predictable distribution of stresses (J.L. Miotto, A,A. Dias 2012).

The slotted-in approach makes the metal covered by timber, protecting the metal from fire hazards or environmental degradation, making this configuration durable. The characteristic of the material and installation makes it resistant to multiple assemblies without affecting SLS considerations. As cold-formed joints, the lifecycle is a weakness and a potential advantage at the same time; the raw material has a high embodied energy but is entirely recyclable, so the existence and availability of material can be used from recyclable sources and urban mining.

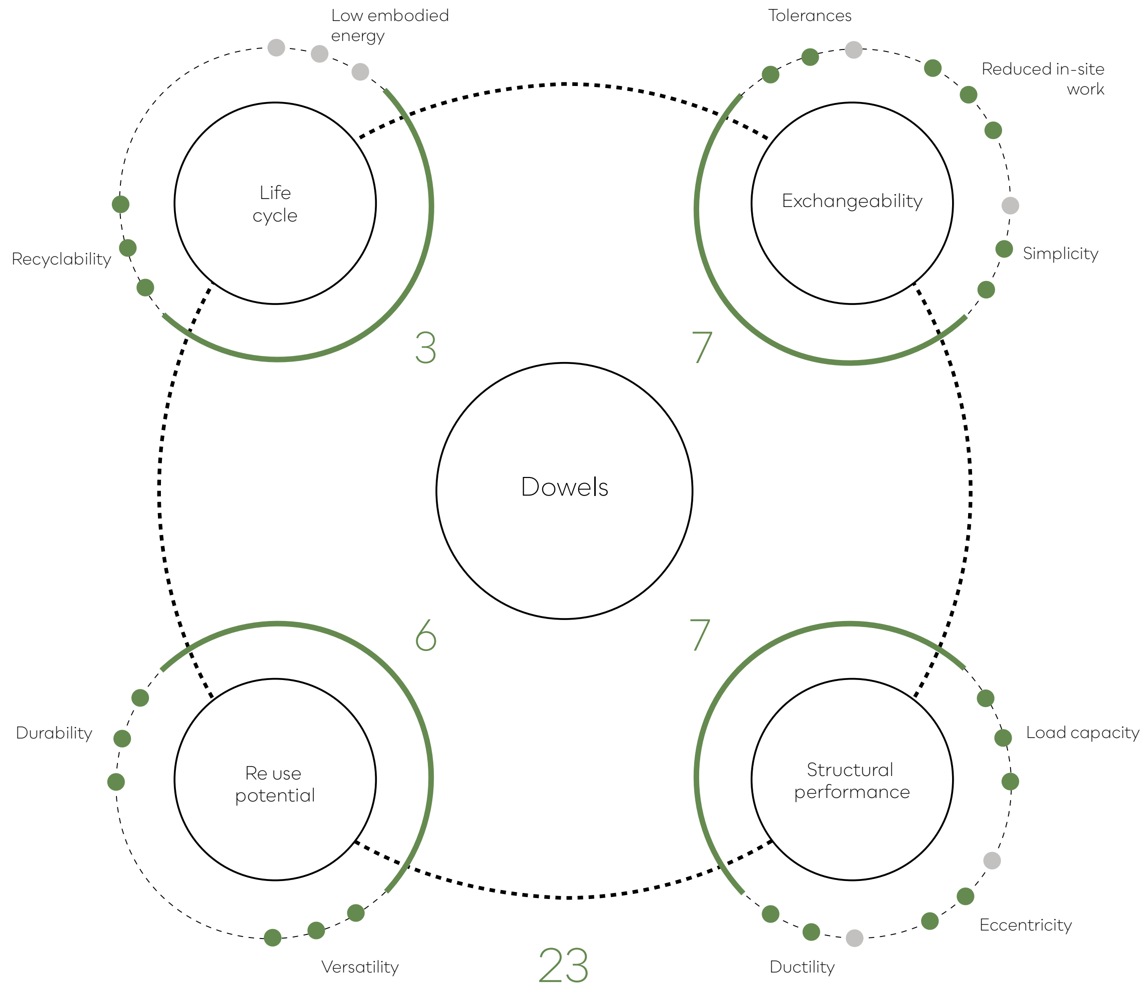


Fig 19: Dowelled joint assessment.

3.1.4. Glued:

Glued joints are commonly used to hybridize the structure in the component scale. The glue joins typically consist of metal rods inserted into the timber in the direction parallel to the grain; this makes the connection of the two materials strong and stiff (G. Youssef, L. Loulou, S. Chataigner, S. Car´e, A. Flety, R. Le Roy., 2014) making a general good structural performance.

On the other hand, the negative aspect of this type of connection is the life cycle and re-use potential; the most commonly used glues are polyurethane and epoxy-based substances, which, until today, use chemical agents that are a challenge to achieve sustainable manufacture.

The glue joints also create a permanent joint of components, as (Pastori S., Mazzucchelli S E., Wallhagen M., 2022) state: “Permanent connectors enable the disassembly and disassembly and recyclability of timber”.

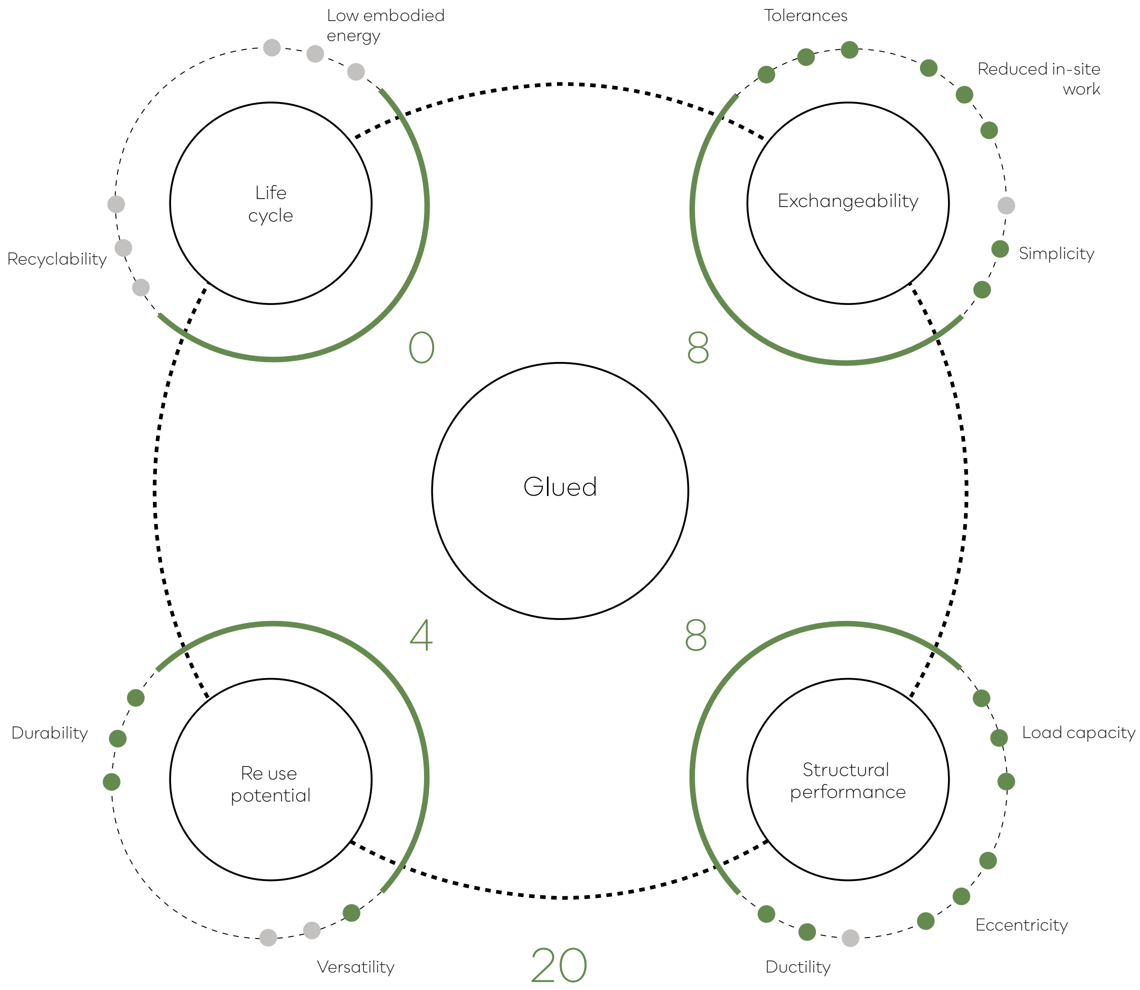


Fig 20: Glued joint assessment.

3.1.5. Screws:

Screw joints are often used to connect timber elements, not as a structural connection system.

They rely primarily on the strength provided by the threads of the screws, which create a strong axial rigidity. This rigidity is achieved by combining the biaxial strength and the depth of the screw's penetration into the timber (Mariller N., 2020), having, in general, a good structure performance.

The life cycle of this type of join is good due to the reduced amount of metal used and the possibility of being completely recyclable.

On the other hand presents challenges in the exchangeability and re-use-potential because its implementation is complete on-site, reducing the possibility of pre-construction site work; similarly, its relevant to remark that is completely demountable but reassembling it is challenging for the complexity of reusing the existing holes and screws, that can be damaged or deformed in the disassembly.

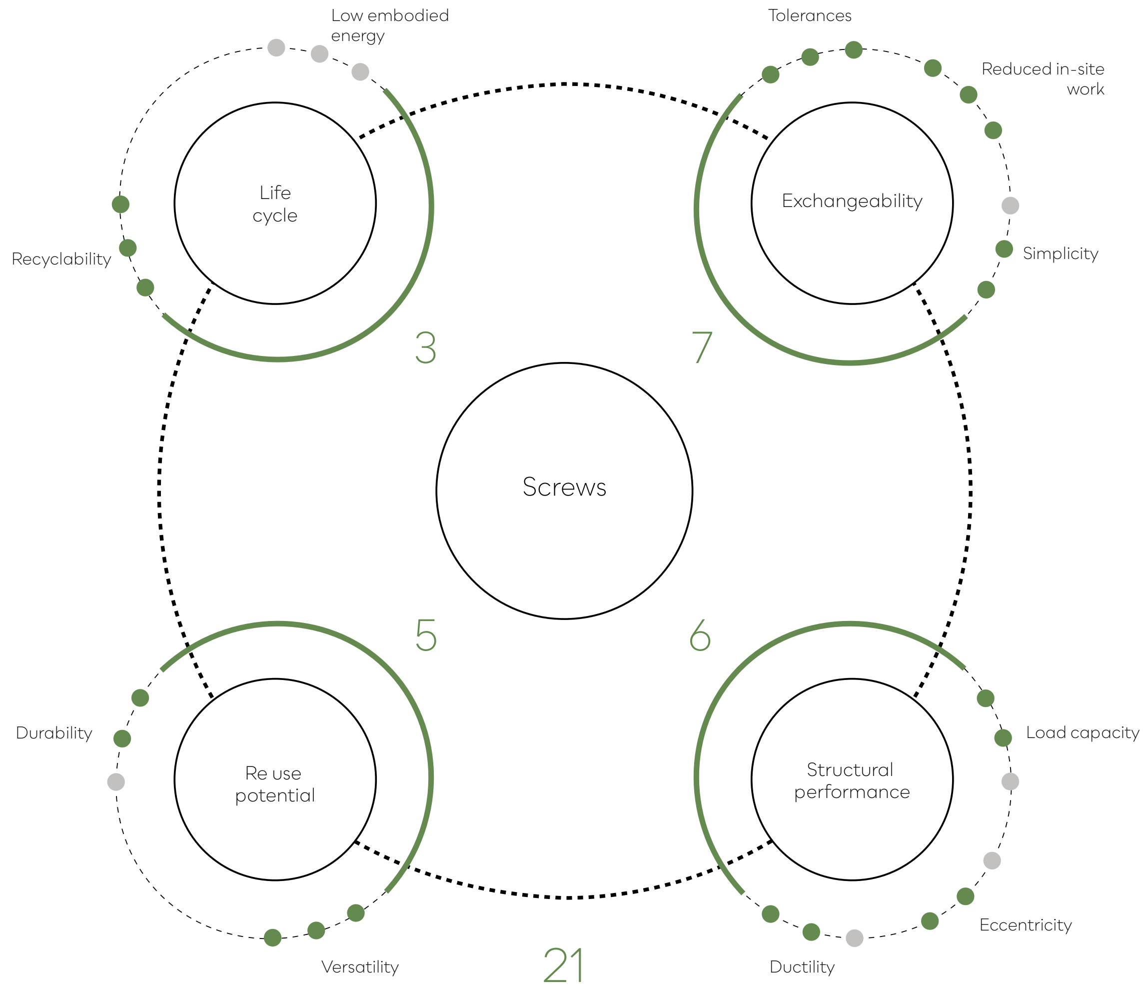


Fig 21: Screws joint assessment.

3.1.6. General results:

In conclusion, carpentry joints have enormous potential for implementation. However, high-rise buildings face significant challenges in terms of mechanical behaviour and modular manufacture due to the structure's dynamic behaviour.

Glued joints provide a high strength and stiff connection but face challenges regarding sustainable manufacturing and reuse potential. Screw joints provide good structural performance and have a good life cycle due to their reduced amount of metal and recyclability; however, their on-site implementation makes pre-construction site work difficult, and reassembling them can be complex.

Cold-formed joints as well the slotted-in plates used in dowelled joints, have the highest structural performance above all the joints due to their high strength-to-weight ratio and uniform stress distribution, making them the suitable options for moment resistance stiffness that timber highrises demand, in addition to that the manufacture characteristics of this two make them ideal for mass production and pre-site work, making the assembly process simpler and quicker.

The high embodied energy of the metals that can be applied can be compensated for the complete recyclability and potential acquisition of material from recycling sources. With this high performance in ¾ of the principals evaluated and the potential to have a circular life cycle, cold formed and dowelled joints are the most suitable options to be implemented in timber highrises; their final applicability will depend on considerations related to the load-bearing needs, the cost-effectiveness of manufacture and embodied energy of the overall structure of the project.

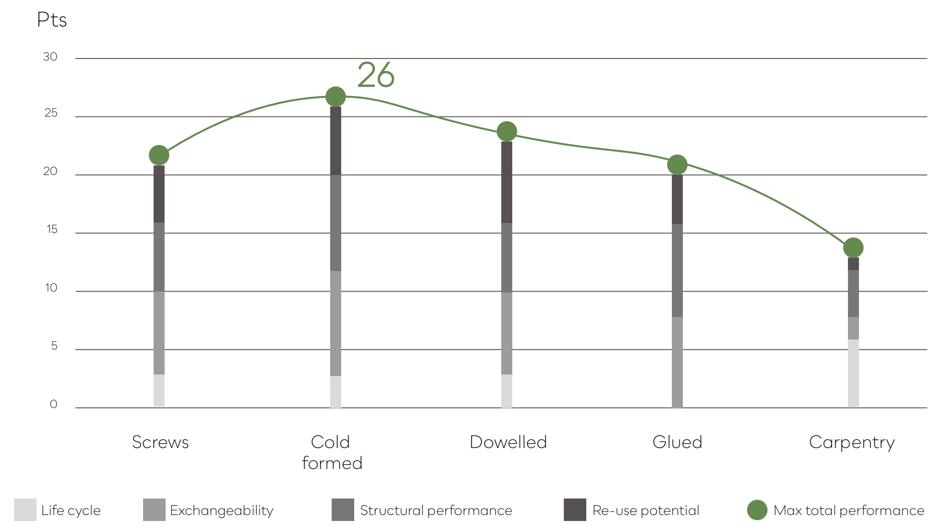


Fig 22: Joint assessment evaluation results

3.2. Material evaluation analysis:

The material selection plays an important role in the consolidation of finding the suitable material option that can fulfil the demanding requirements of joints for highrises. For that, a material analysis was developed to study and compare the properties and behaviours of potential options. To achieve this, the software Granta EduPack was used, where options of all materials universe, including metals, ceramics, polymers, and composites, were compared to understand their mechanical and physical properties as their manufacturing and environmental impact.

Appropriate mechanical properties of the material used in the connectors are fundamental to assure safety, serviceability and durability. Therefore, three principles were evaluated: **stiffness**, **strength** and **toughness**. Stiff to ensure the stability and rigidity of the overall structure. Helping to resist deflections and movement in response to dynamic accelerations. Strong enough to withstand the loads transmitted between members without failure and taught to absorb and dissipate energy without failing. In addition to this, other parameters were added to the analysis in order to have circular applicability of the options.

Durability was incorporated as a fundamental principle, with the aim of prolonging the lifespan of major structural components by resisting damage or deterioration caused by environmental or long-term degrading components. Additionally, the importance of material recyclability was emphasized, recognizing the significance of planning for the end-of-life scenario and the necessity of being able to recycle or reuse materials after their original purpose has been served. From 4000 possible materials options available in the database of the software, 20 potential materials fulfil the requirements, most of them Non-ferrous metals. Fig 23 shows mechanical properties comparison and results.

Stiffness, Strength and Toughness

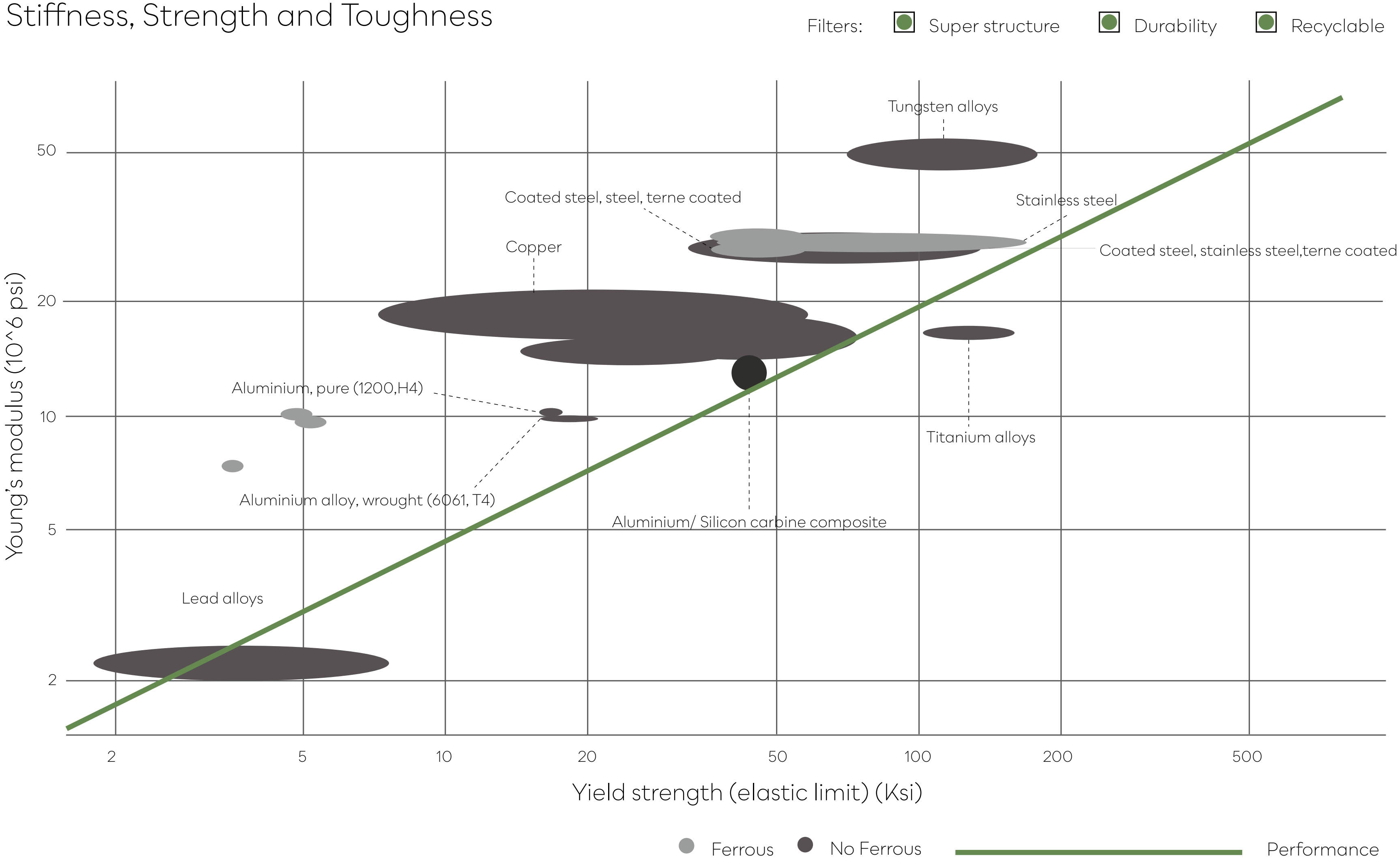


Fig 23: Mechanical properties.

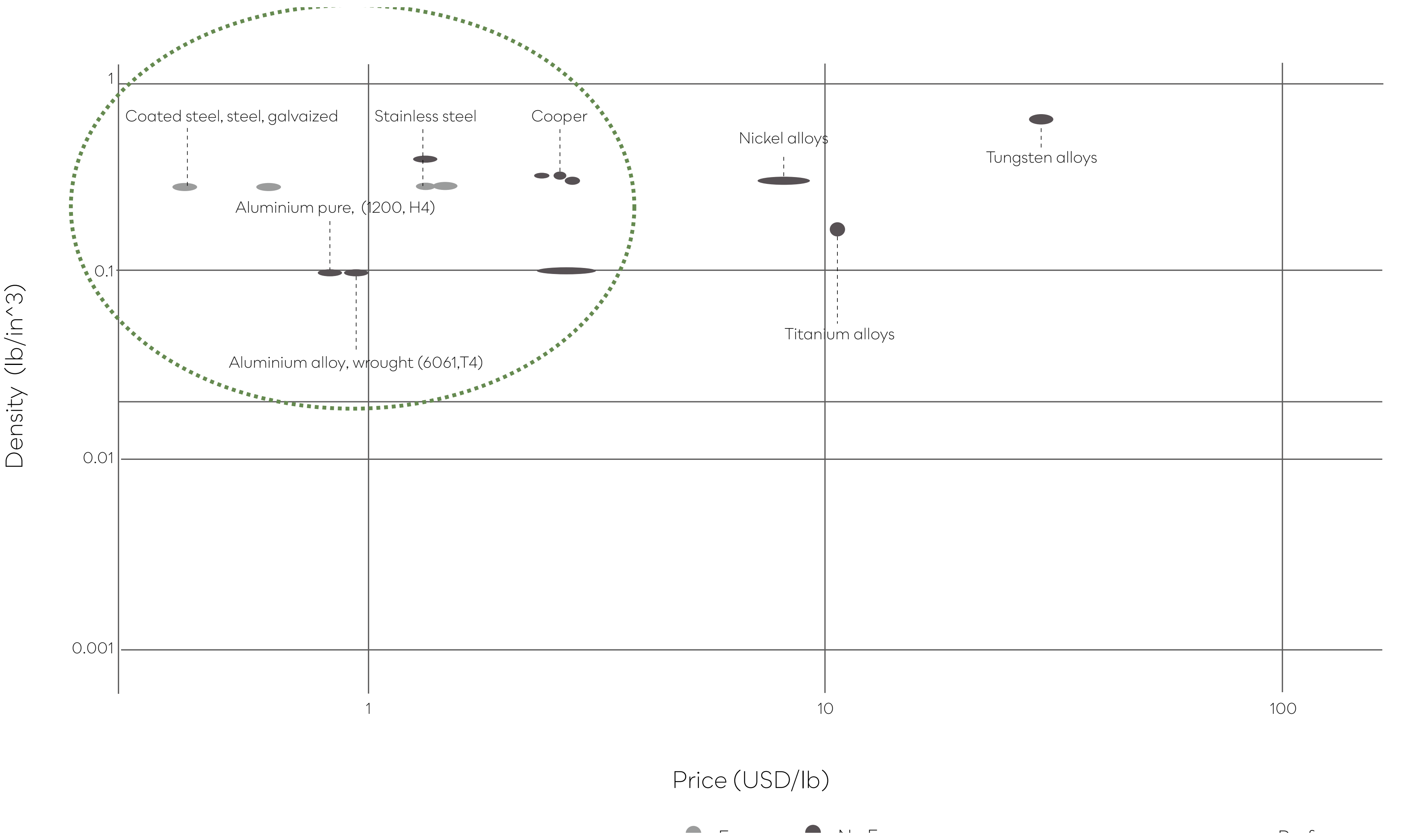


Fig 23: Cost effectiveness.

Once the mechanical properties of the materials have been analyzed, it is important to assess their feasibility and potential implementation. This involves considering the material's commercial value and accessibility. Additionally, it takes into account the EU's list of critical materials. These materials are scarce and may be concentrated in a limited number of countries, creating potential risks for supply chains; for that, it is crucial to reduce these risks by addressing them in the design stage. From the 20 possible options, the number dropped to 12. Fig 23 shows cost effectiveness comparison and results.

The final phase of the analysis involved an environmental impact assessment of a potential list of materials. The assessment considered the materials throughout their entire life cycle, from extraction, production, transportation, and use, to final disposal. To accurately measure the impact of the joint in different materials, a standard and commercial structural joint, the hidden joint AW-6060 from the company Rothoblaas, was used as a reference component. To see the complete information and technical specification of the joints can be seen in Appendix B: Joints design, B21 design base.

Other inputs that were considered in the measurement include the quantity of 2000 preliminary units, primary processes applicable to the list of materials, transportation of 20km and 55-tonne trucks (This refers to the distance from the manufacturer source to the customer. In this case, a distance of the south part of the Randstad, where the location of the project and many companies of metal appliances are located), and recyclability as end-of-life. The analysis revealed that the option with the highest impact on energy usage and CO_2 footprint was significantly concentrated in the embodied energy of the materials. Conversely, the manufacturing and transportation of the final product had a limited overall contribution to the impact. Despite the high embodied energy concentration, it was possible to identify the proportional EoI potential of all the materials, as they can be completely reusable or recyclable at the end of their life cycle. Detailed information of the environmental impact of each material can be seen in Appendix C: Material analysis. Fig 24 & 25 shows the environmental impact comparison and results.

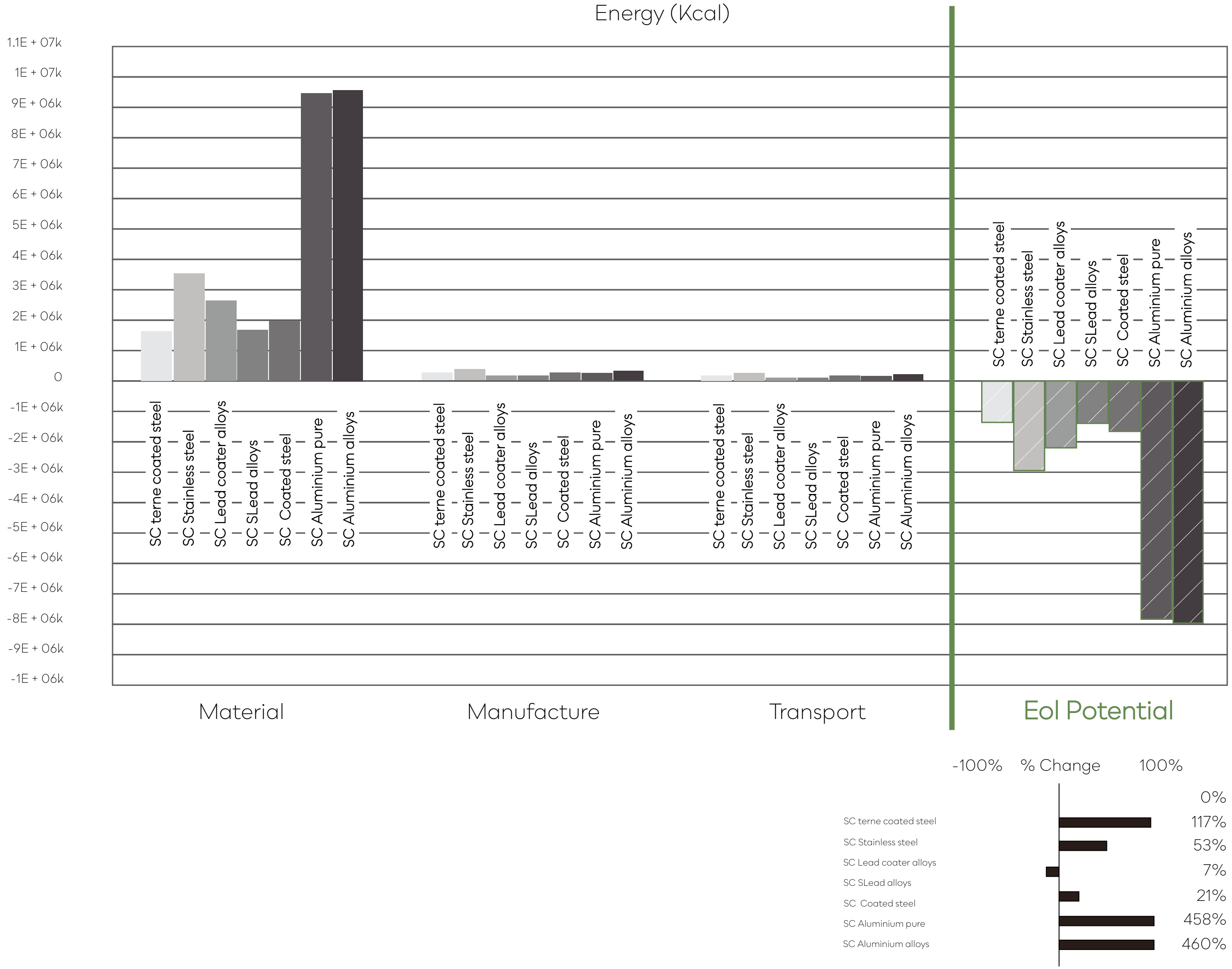


Fig 24: Environmental impact: Energy

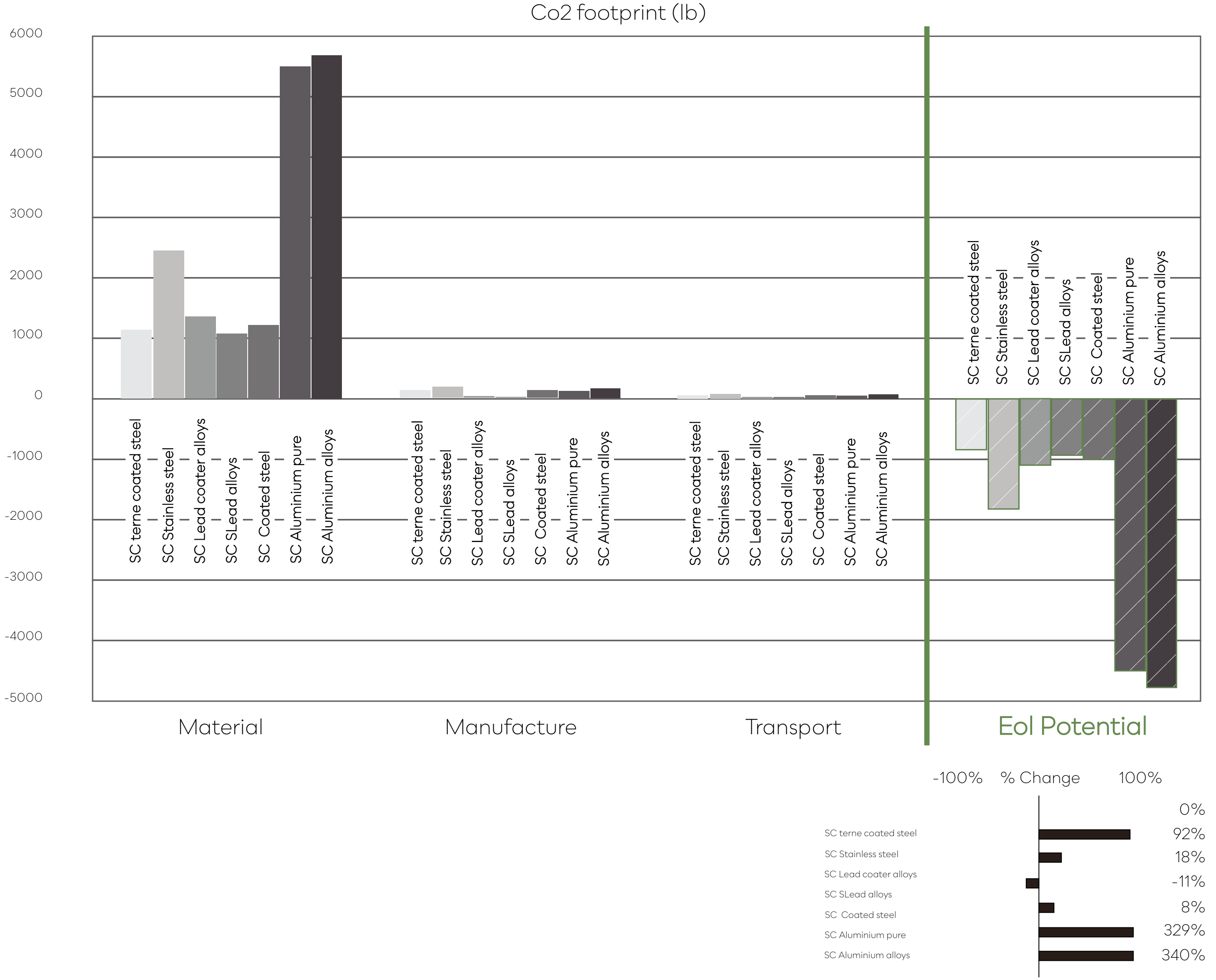
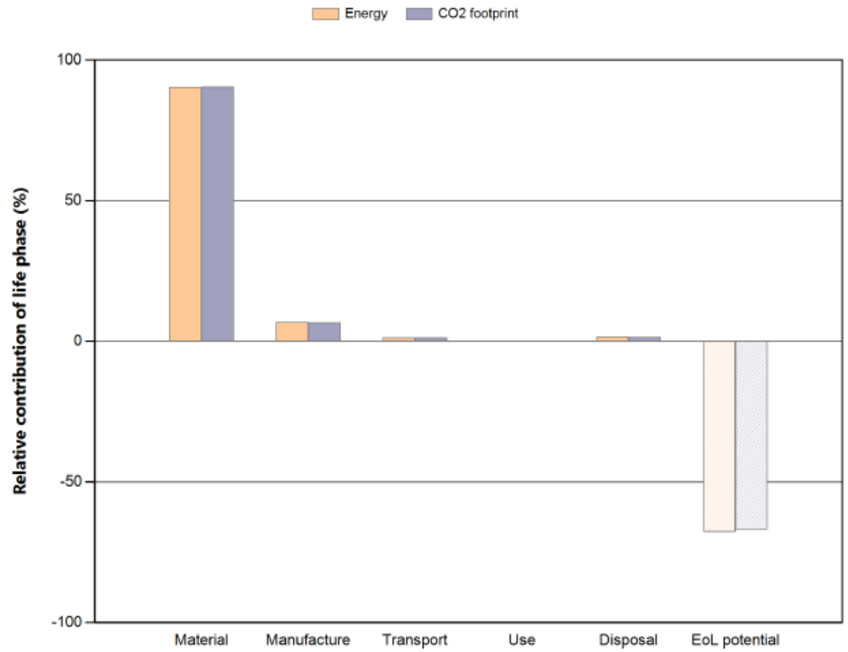


Fig 24: Environmental impact: CO_2 Footprint

Based on the analysis of the collected data, a final comparison was made to assess the mechanical properties of various materials against their Eol potential. The objective was to identify the material that could offer the best mechanical performance with the most negligible environmental impact. The findings revealed that the steel families, specifically the stainless steel grades 355-690, exhibited exceptional stiffness, strength, toughness, and durability, making them the most appropriate options for the structural performance required in manufacturing joints for timber high-rise structures.

Moreover, the data analysis also considered the embodied energy of the alloys, which is the total energy required for their production, transportation, and installation. The results showed that despite having a high embodied energy, stainless steel had a proportional Eol potential to its embodied energy, which meant that it could be completely reusable or recyclable at the end of its life cycle. Additionally, the embodied energy of the material extraction and processing for stainless steel was comparatively lower than that of other potential candidates.Therefore, the material analysis concluded that stainless steel was the optimal choice for the material to be used in the joints of timber high-rise structures due to its superior mechanical properties and ability to potentially meet circular economy principles.



Energy details CO2 footprint details

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	7.98e+03	90.4	601	90.6
Manufacture	592	6.7	44.5	6.7
Transport	118	1.3	8.47	1.3
Use	0	0.0	0	0.0
Disposal	140	1.6	9.78	1.5
Total (for first life)	**8.83e+03**	**100**	**664**	**100**
End of life potential	-5.99e+03		-444	

Fig 24.1: Stainless steel Environmental impact: CO_2 Footprint

4.0

Dynamic response timber highrise structures

Parametric model:

In the previous chapter, an assessment was conducted to determine the appropriate type of joints that the structure must follow. Additionally, a grid was established to serve as the foundation for the analysis of the structural mechanics of the timber highrise. This crucial step lays the groundwork for the upcoming stages of the project, ensuring that the structure is both stable and reliable. For this part of the investigation, a parametric model was developed using Grasshopper, a visual programming modelling software. This software allows the creation of designs that can be easily modified and updated by adjusting input parameters following a specific list of criteria and constraints. The main goal of implementing a parametric model is to analyse the dynamic response of highrise structures made of Timber.

The parametric modelling capabilities of Grasshopper allow data management, geometry manipulation, analysis and optimization, making the research efficient and reliable. The model's primary purpose is to analyze the structural behaviour of the structure; for that, the design is based on a tower of 36x36 m with a central core, a very common structural typology applicable to many potential design cases. The design will use Karamba, a structural analysis plugin of Grasshopper that will evaluate the structure's performance following applying design constraints, ensuring that the structure meets the ULS (ultimate limit state) and SLS (serviceability limit state) regulations.

4.1. Design parameters:

4.1.1. Structural system:

The structural design of high-rise structures tends to be governed by their dynamic behavior, which means that the stability system must be designed to provide not only sufficient resistance to the design loads, but also to provide sufficient global stiffness to ensure structural integrity and user comfort (Felicita M., 2021). This investigation focuses on studying the structural performance of two variations of the glulam frame with a central core. This typology uses the frame to distribute the vertical loads and the core as the stabilizer component against the horizontal loads. The scope of this investigation includes understanding its feasibility following ULS and SLS criteria and the environmental impact repercussions of a highrise with load-bearing and stabilizing structural components in timber.

Based on the structural grid on FIG 27 that generates intraoperatively of different scales, the structural plan follows an effective span between the frame columns of six meters inside a square layout of thirty-six meters with a square central core of twelve meters. Two options are compared: a glulam frame with a concrete core and a glulam frame with a CLT central core.

The comparison between the hybrid and timber-based systems aims to understand the feasibility and performance of a glulam frame and CLT core system and its potential applicability in the building industry as an alternative to the concrete core, which would decrease the embodied energy of the structure substantially and allow the consolidation of a modular and disassemblable timber highrise.

This parameter will answer the following question:
What strategies can be applied to replace the concrete core as a lateral stabilizer component?

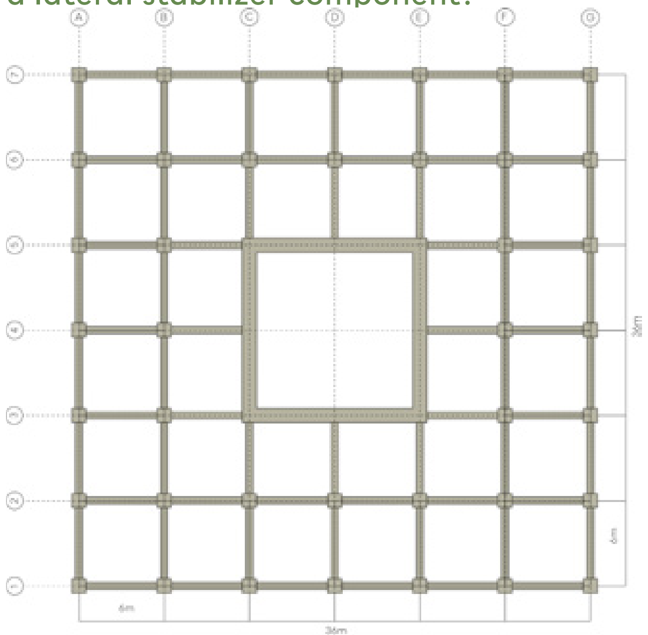


Fig 27:: Grid of the parametric study

4.1.2. Joints Stiffness:

In the design of structures that will be exposed to torsional forces or moments, it is essential to consider rotational stiffness. One effective joint configuration for timber structures is the slotted-in plate, but its stiffness is critical to ensure the safety and optimal performance of the entire structure.

The relationship between the rotational stiffness required at the joints and the global stiffness of the structure's frame and core is crucial to determine the amount of material needed in the joints. Evaluating different rotational stiffness levels can help understand their importance in structural performance and material requirements. For high-rise structures subjected to large dynamic loads, rotational stiffness values ranging from 50,000 KNm/rad to 300,000 KNm/rad are typically required to maintain structural integrity. This investigation will focus on three types: 100000, 200000 and 300000 KNm/rad. The data from Felicita M. (2021) was used to determine the stiffness specifications.

100000KN/rad=23.9kg 200000KN/rad=36kg 300000KN/rad=57kg

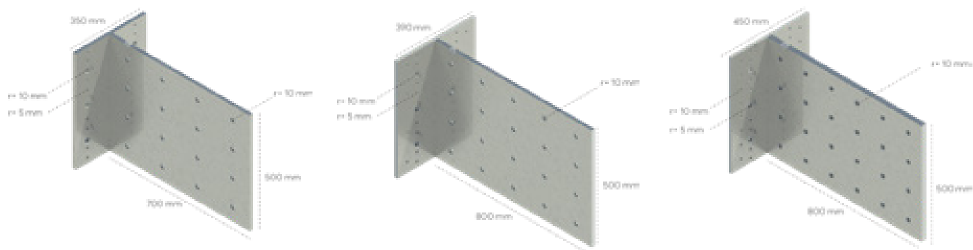


Image: Rotational stiffness steel plate Joints (own design)

This parameter will answer the following question:

To what extent is it possible to reduce the use of metal alloys in the joints of timber components?

4.1.3. Total structural height:

The height of a structure is a crucial parameter to consider when assessing its dynamic behaviour under horizontal loads.

Slenderness is also a crucial factor in the stability and integrity of high-rise structures. In this investigation, a standard storey height of 3m will be used across 34 storeys, resulting in a total structure height of 102m. This total height is ambitious but reasonable, especially when considering that the current record for the highest high-rise using only timber as load-bearing and stabilizing components, Mjøstårnet, is 85m. By analyzing the behaviour of a timber structure of this height and slenderness, the study aims to evaluate insights into the potential and limitations of timber as a building material for tall structures.

This parameter will answer the following question:

How do the wind loads affect the feasibility (cost, net floor area?) of a timber highrise?

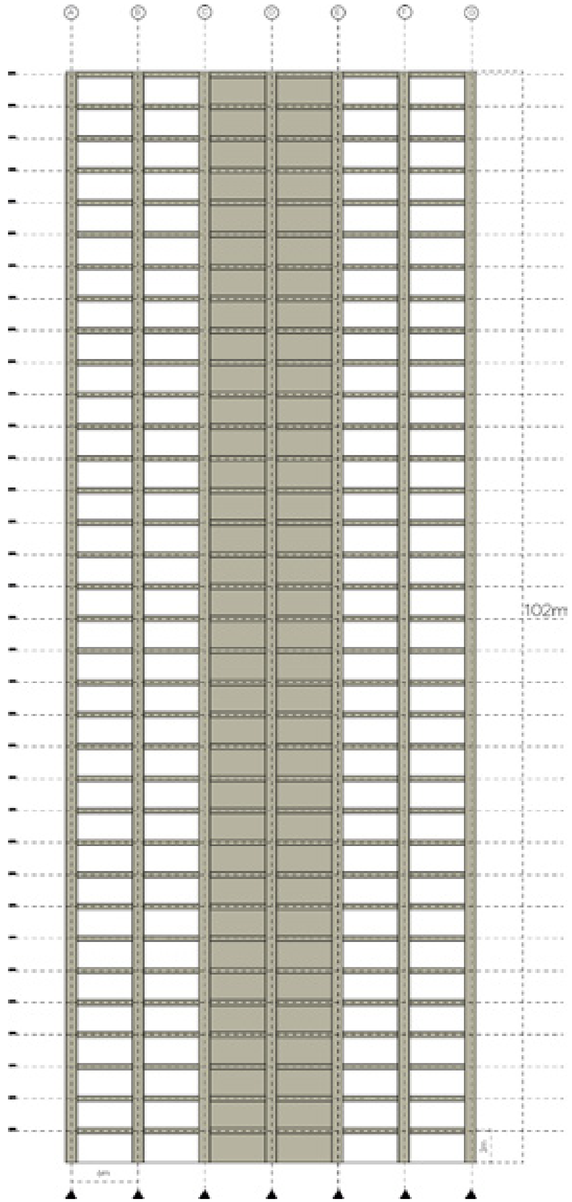


Fig 28: Structural height

4.1.4. Material configuration:

The configuration of materials is a critical aspect of setting up a parametric model. This study has considered three materials: **cross-laminated timber (CLT), glued-laminated timber (glulam), and reinforced concrete**. Glulam has been chosen for the frame, CLT for the core (which is being investigated as a potential alternative to concrete cores), and concrete for comparison and evaluation.

To identify the best glulam frame material, all available references in the European market have been evaluated. The following options have been considered: GL24h, GL24c, GL28h, GL28c, GL32h, GL32c, GL36h, GL36c, GL24h (ptg), GL24c (ptg), GL28h (ptg), GL28c (ptg), GL32h (ptg), GL32c (ptg), GL36h (ptg), and GL36c (ptg). (Karamba 3D) The material with the best combination of mechanical properties has been selected.

The mechanical properties of CLT vary depending on the manufacturer, and the most recent version of the Eurocode NEN-EN 1998-1 (EC8) does not provide a clear parameter for evaluation. For this study, the mechanical properties of CLT from KLH have been used as a reference. KLH is one of the oldest and most recognized manufacturers of timber products in Europe, with transnational quality and performance certifications.

The following mechanical properties have been used:

Young's modulus dir 1: 45 KN/cm^2, Young's modulus dir 2: 1200 KN/cm^2, In-plane shear modulus: 69 KN/cm^2, Transverse shear modulus parallel to the grain: 5 KN/cm^2, Specific weight: 5 KN/m^3, Tensile strength dir 1: 0.012 KN/cm^2, Tensile strength dir 2: 2.25 KN/cm^2, Compressive strength dir 1: -0.27 KN/cm^2, Compressive strength dir 2: -2.9 KN/cm^2, and Strength hypothesis: Rankine.

Finally, for the concrete core, the Shell counts cross-section component has been used. All available references in the European market have been analyzed to find the combination of materials with the best mechanical properties. The following options have been evaluated: C12/15, C16/20, C20/25, C25/30, C30/37, C35/45, C40/50, C45/55, C50/60, C55/67, C60/75, C70/85, C80/95, C90/105, and C100/115 (Karamba 3D).

4.2. Design constraints:

4.2.1. Accelerations:

According to Eurocode NEN-EN 1998-1 (EC8), to ensure structural integrity, the accelerations of a structure should not exceed 0.39 m/s^2.

4.2.2. Global deflection and interstory drift:

Global deflection and inter storey drift are essential serviceability limit state criteria used to verify the design of structures that are subjected to lateral loads such as wind (Felicita M., 2021). Global deflection is the measure of the overall dynamic response of a structure, while inter storey drift refers to the specific response of each two-story segment after the application of load stress.

Both criteria are crucial in ensuring that a structure remains functional, safe, and comfortable for its intended use. Global deflection and inter storey drift can be calculated with the following formulas:

$$\delta_{max} \leq \frac{h}{500}$$

$$\delta_{s,i} \leq \frac{h_s}{400}$$

Equation: Global deflection and Interstory drift according to NEN-EN 1991 & (Felicita M., 2021)

4.2.3. Loads:

4.2.3.1. Vertical loads:

Vertical loads are classified as **dead** and **live** loads. Dead loads refer to the self-weight of the structure and architectural components, and live loads are variable loads made by the occupants and their furniture. Eurocode NEN-EN 1991 (EC1) gives common values that can be used to calculate loading. The model will apply the self-weight of the structure analyzed, and an additional general value of 2.73 KN/m2, corresponding to flooring and walls weight, will be included, 1.75 KN/m² corresponding to a load of residential use and 0.56 KN/m² of a variable load of snow.

Additionally to this, a security factor must be included in order to count all the possible additional stresses that the structure must tolerate in its life span without putting at risk the structure integrity; for this investigation, a security factor of 1.2 will be applied. To ensure accuracy in the analysis, vertical forces are expressed in KN/m rather than KN/m² to avoid programming issues and reduce the potential impact on the analysis of structural components in Grasshopper for creating additional surfaces that will receive the loading and will be connected to the structural system.

This investigation focuses on analyzing the mechanical performance of load-bearing components such as beams, columns, and cores, with the exclusion of CLT slabs. Therefore, converting from KN/m2 to KN/m will enable the loads to be directly transferred to the beams and the columns. Given that the grid follows a 6x6m symmetry, the load distribution is equally distributed across the four beams that form the frame, with each component carrying a total vertical load of 17.4 KN/m.

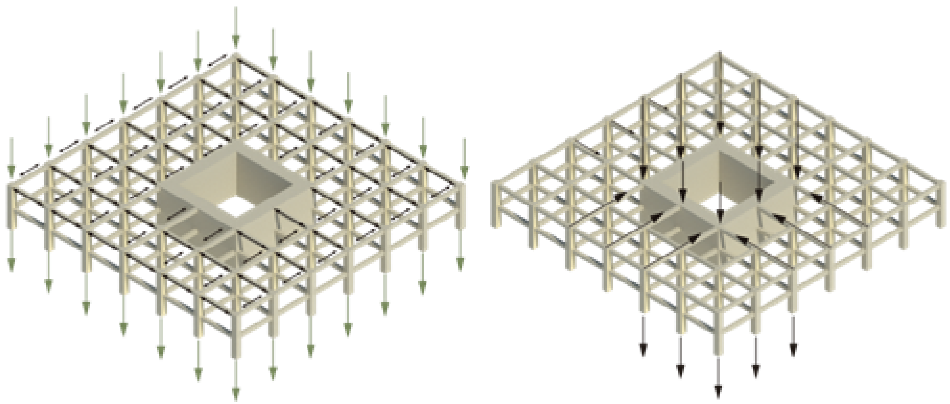


Fig 29: Vertical and horizontal load distribution.

4.2.3.2. Horizontal loads:

Horizontal loads, such as wind, exert pressure that increases with height. To calculate wind pressure, NEN-EN 1991 provides standards that are used in this investigation. The structure's total height is divided into three parts: h=b, h=2b, and h>2b. The first part, h=b, closest to the ground floor, is subjected to a lateral wind pressure of 0.86 KN/m². For the middle part, h=2b, a uniform pressure of 1.11KN/m2 is applied, although an exponential pressure increase is more accurate. The area with the highest wind pressure, h>2b, is subjected to a pressure of 1.27 KN/m².

To ensure accuracy in the analysis, horizontal forces are expressed in KN/m rather than KN/m2 to avoid programming issues and reduce the potential impact on the analysis of structural components in Grasshopper for creating an additional surface that will receive the loading and will be connected to the structural system.

The scope of this investigation focuses on analyzing the mechanical performance of load-bearing components such as beams, columns, and cores, with the exclusion of facades or other vertical surfaces that can affect the analysis evaluation of the components. Therefore, converting from KN/m2 to KN/m will transfer the loads directly to the beams and the columns. Given that the vertical grid follows an inter-story height of 6x3m, the load distribution is proportionally distributed across the two beams and two columns that form each plane.

The columns in h=b have a load of 1.935 KN/m, h=2b have a load of 2.4975 KN/m, and h>2b have a load of 2.8575 KN/m. The beams in h=b have a load of 1.29 KN/m, h=2b have a load of 1.665 KN/m, and h>2b have a load of 1.905 KN/m. In order to have a more accurate and realistic load case, the wind loads are applied in the "x" and the "y" direction, having a 3d analysis of the dynamic behaviour of the structure.

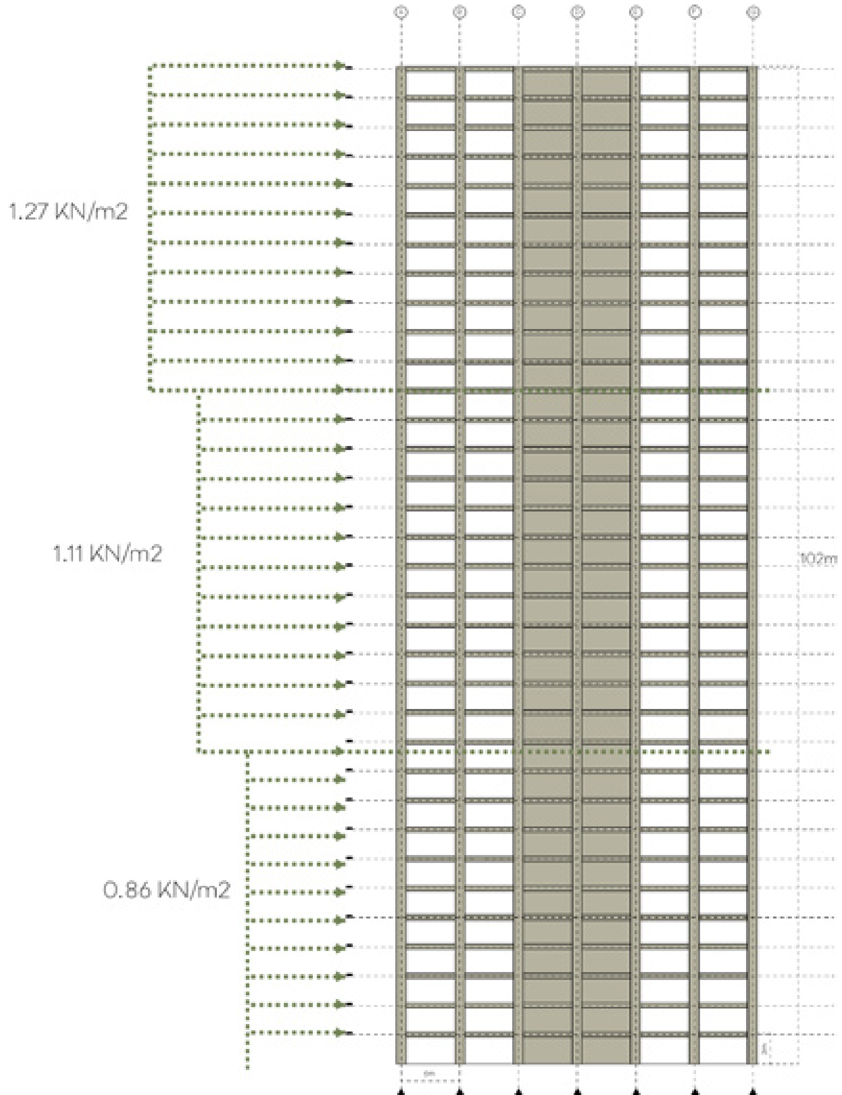


Fig 30: Wind pressure distribution over height, data according to NEN-EN 1991 and (Felicita M., 2021).

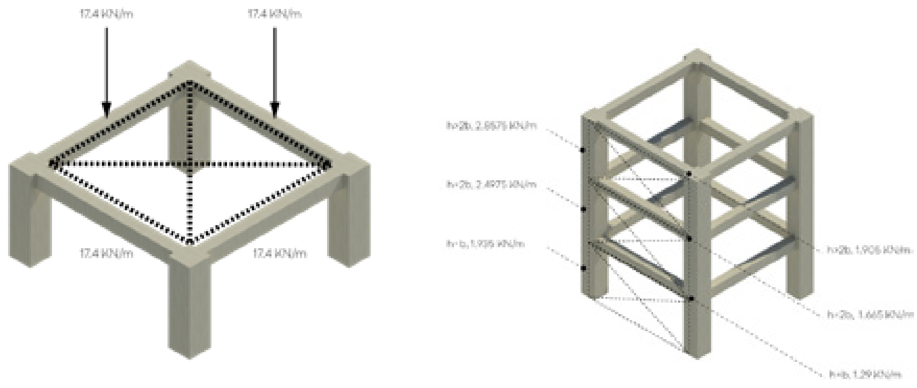


Fig 30.1:Horizontal and vertical loads distribution in KNm

4.2.4. Other considerations:

In addition to meeting all ultimate limit state and serviceability limit state requirements, architectural constraints are also considered. The continuity of the structural grid of 6m is an essential factor that must not be compromised. Smaller configurations could result in a complex and inflexible floor plan, potentially leading to future design obsolescence. Therefore, this investigation aims to achieve functional and flexible spaces through a modular and simplified assembly and disassembly process. Similarly, external stabilizing components like brazing will not be considered, as they would hinder the modularity and simplicity of the design.

4.2.5. Post processing:

A primary objective of this investigation is to create a modular set of structural components that can be integrated into a more significant structural system. To achieve this, the post-processing stage will aid in determining the optimal sizing of components that satisfy both ultimate limit state (ULS) and serviceability limit state (SLS) requirements. Maintaining the feasibility of design parameters is crucial in the post-processing stage, and this is achieved by applying constraints to the parametric model.

For example, the grid size is a crucial parameter that must remain unchanged during optimization. In the setup phase of the parametric study, preliminary sizing of cross sections was determined as the starting point of the analysis. The evolutionary algorithm will manipulate the cross-sections of the principal structural components, such as columns and beams. For the columns, the input range was set from 150cm to 150cm while maintaining 82% of the net floor area per storey. As for the beams, the effect of the vertical span was considered, and the input parameters were modified to a maximum width of 120cm and a height of 100cm to ensure structural integrity. The story height was also included in the optimization process to meet the new demand for beam cross-sections without affecting the structure's total height.

The selection of material references was a relevant criterion in the analysis and post-processing stages, as the technical specifications of available products can significantly impact the overall performance of the structure. Therefore, the commercial products specified in section 3.4.1.3. for Glulam and reinforced concrete were included. For CLT, we only considered one reference to ensure reliable and consistent data, thus avoiding the potential decrease in the material's actual performance.

The core plays a crucial role in global stiffness, being the component that will stabilize the structure against the horizontal loads made by the wind. As mentioned before, EWP has a low self-weight ratio compared to other materials; for that reason, the thickness of the core will play a fundamental role in the feasibility of this type of structure.

For that reason, from the design phase, the core can increment the thickness until it arrives at the cross-section needed to accomplish the structural constraints determined by the ULS and SLS. Similarly, joints play a crucial role in optimizing these types of structures. To achieve optimal performance levels, all joints in the model have been given three possible options for rotational stiffness: 100000, 200000, and 300000 KNm/rad. Choosing the appropriate rotational stiffness for each joint is vital to ensure the overall stability and performance of the structure.

To achieve the previously mentioned goals, this investigation will use an evolutionary algorithm (EA). This investigation will use the approach of shape optimization that, as Tedeschi, A., & Wirz, F.(2014) states: shape optimization attempts to reach an optimal solution concerning a set of parameters that define a fitness function. The optimization calculations can be performed with the component Galapagos. The decision to use this type of optimization is based on the methodology that evolutionary algorithms employ to select solutions.

Using the "natural selection principle," these algorithms can select the best factors and integrate them to find the optimal and ultimate option based on thousands of iterations. This approach is beneficial when dealing with complex models with multiple constraints, as it enables the algorithm to efficiently navigate the solution space and identify the best possible outcome.

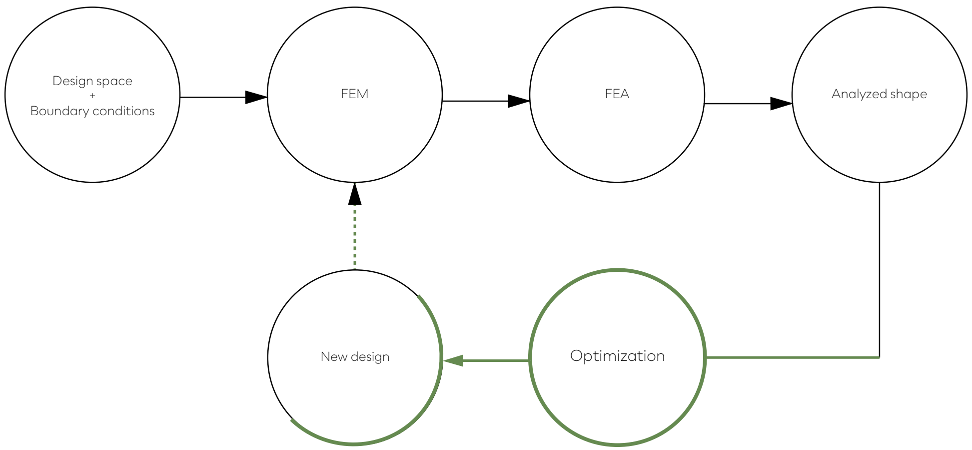


Fig 31: Optimization flowchart (Tedeschi, A., & Wirz, F.2014).

Even tho the optimization component Mopossum (Multi-Objective Particle Swarm Optimization) is used in this investigation due to the ability of this plug-in to use sectorization metrics to evaluate faster the best solutions. It is important to note that there is the need to establish precisely the optimization rules and limitations to allow Mopossum alone to provide completely reliable data because the many constraints applied to the model can conflict with each other when attempting to achieve design goals. For example, minimizing material usage is positive for environmental and cost reasons, but it can be negative for meeting ultimate limit state (ULS) and serviceability limit state (SLS) requirements. To address this issue, a Python script was incorporated into the optimization process to ensure that none of the setups or constraints were prioritized at the expense of others. In FIG 31.1 shows the parametric and optimization flowchart used in this investigation. Similarly, In Appendix A can, be seen complete Grasshopper and Python scripts.

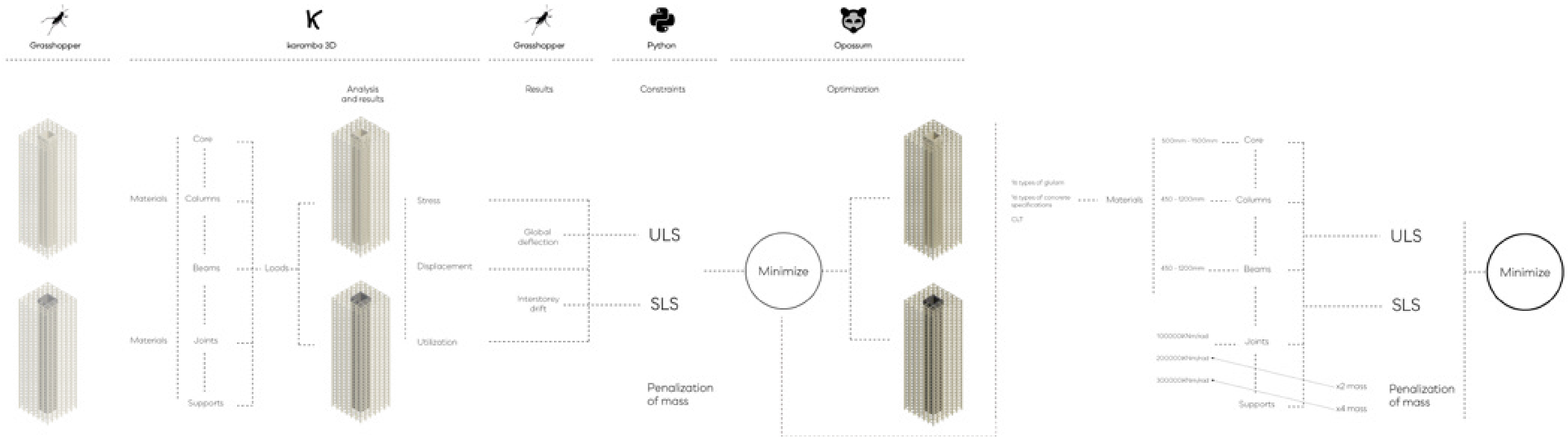


Fig 31.1: Optimization flowchart research.

4.3. Results and discussion:

In the previous chapter, was discussed the creation of a parametric model designed to evaluate the dynamic response of a high-rise building with timber as its primary load-bearing and stabilizing system. The model was crafted to incorporate a glulam frame capable of dissipating vertical loads and a CLT core responsible for dissipating the accelerations caused by wind forces. A parallel model was also developed to evaluate the performance of twin models with a slight variation in the core material further to understand the structural performance of such systems. This second model replaced the CLT core with concrete to investigate the behaviour, potentialities, and challenges of such a design. By creating these two models, the investigation gathered the data to compare the reactions of both structures and assess the strengths and limitations of each system. This information is relevant in informing future building designs and construction practices.

The results and observations of the previous parametric study aims to give insight to answer the following questions:

1. What strategies can be applied to replace the concrete core as a lateral stabilizer component?

2. To what extent is it possible to reduce the use of metal alloys in the joints of timber components?

3. How do the wind loads affect the feasibility of a timber highrise?

4.3.1. Glulam frame and CLT core

The optimization process for the structure involves a glulam frame and CLT core system, which aims to identify the best possible solutions from thousands of potential options, enabling the use of timber as the primary load-bearing material for high-rises without requiring hybridization with other materials.

An evolutionary algorithm was used to analyze various combinations of inputs, including the core thickness, glulam types for columns and beams, and the lower and upper widths for the cross-section of columns and beams. Additionally, three potential rotational stiffness values for joints (100000, 200000, and 300000 KNm/rad) were evaluated dynamically to ensure that design constraints were met. The genome was configured to minimize material usage while adhering to rigorous constraints of modularity, serviceability, and limited state regulations. The optimization maintained a global deflection limit of 0.204, an inter-storey drift limit of 0.0075, and an acceleration limit of 0.39 m/s^2.

However, a Python script was included in the post-processing stage to avoid potential conflicts between constraints. This script helped to ensure that the optimization prioritized rotational stiffness values based on their mass, penalizing those with higher masses to reduce their potential for use.

As a result, the optimization compensated for global stiffness and stability through other model components, such as columns, beams, and core, which prioritized timber mass over steel mass.

The values used for the rotational stiffness of joints were 100000 KNm/rad: 23.9 kg, 200000 KNm/rad: 36 kg, and 300000 KNm/rad: 57 kg.

Finally, penalization was implemented, limiting the utilization of the structural components more than once to avoid potential double or even more times stresses than a real component can withstand. By implementing these measures, the optimization process ensured the best possible solution for the given constraints, resulting in an efficient, stable, and sustainable high-rise structure option configuration.

- Total Iterations evaluated (Set of potential solutions): 1035
- Best value: 650055

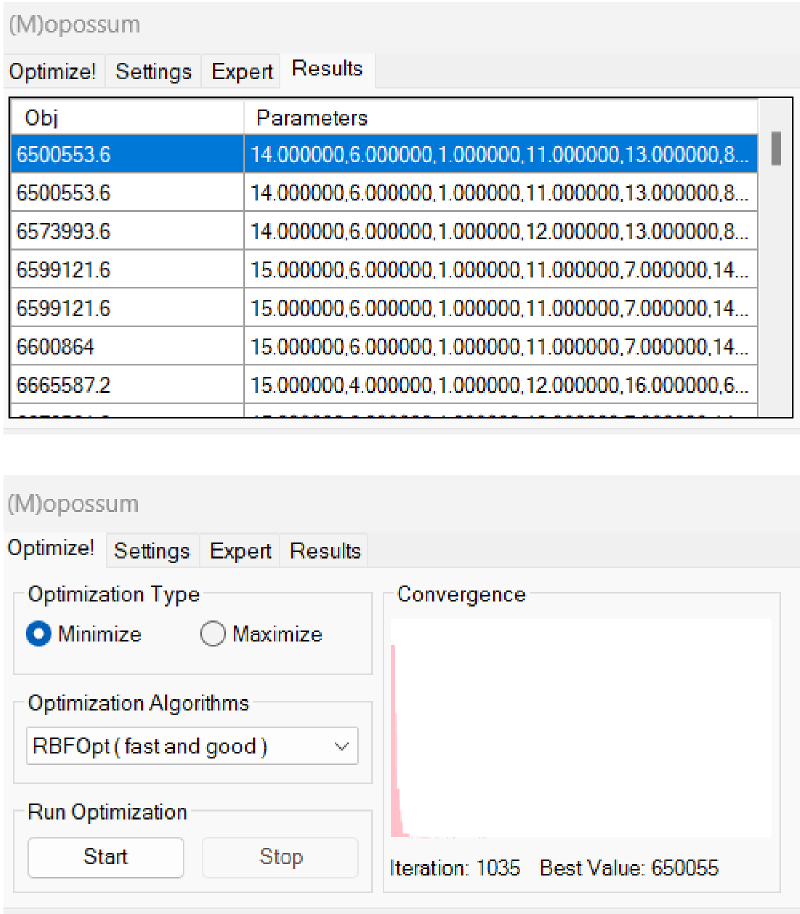


Fig 32: Optimization result: Iterations and best value.

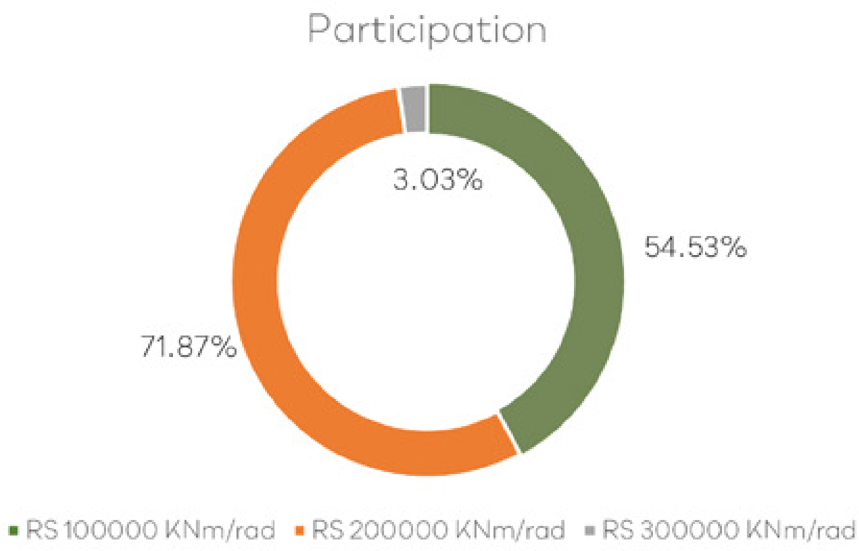


Fig 32.1: Optimization results: rotational stiffness participation.

For modularity and simplicity, the optimization was able to take only one option of the cross-section for columns and beams; in the case of rotational stiffness, the components were according to the demands selected in the specification previously explained. Components final sizing after optimization:

- Columns: 1300x800mm
- Core thickness: 1400mm
- Beams: 300x900mm
- Rotational stiffness:
  - 100000KNm/rad: 26 storeys
  - 200000KNm/rad: 1 storeys
  - 300000KNm/rad: 6 storeys

ULS and SLS results:

- Global deflection: 0.08983
- Inter-storey drift: 0.003918
- Utilization beams and columns: 0.929067
- Utilization core: 0.974764

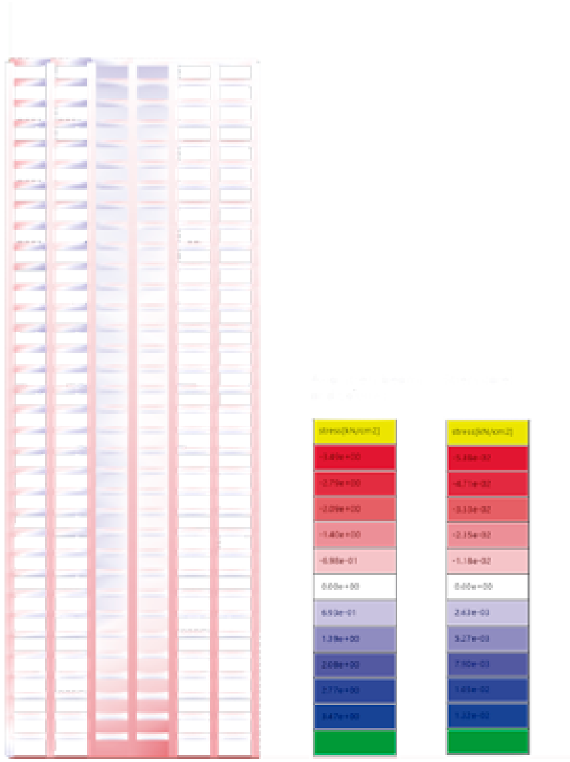


Fig 33: Axial stress beams and columns and stress core

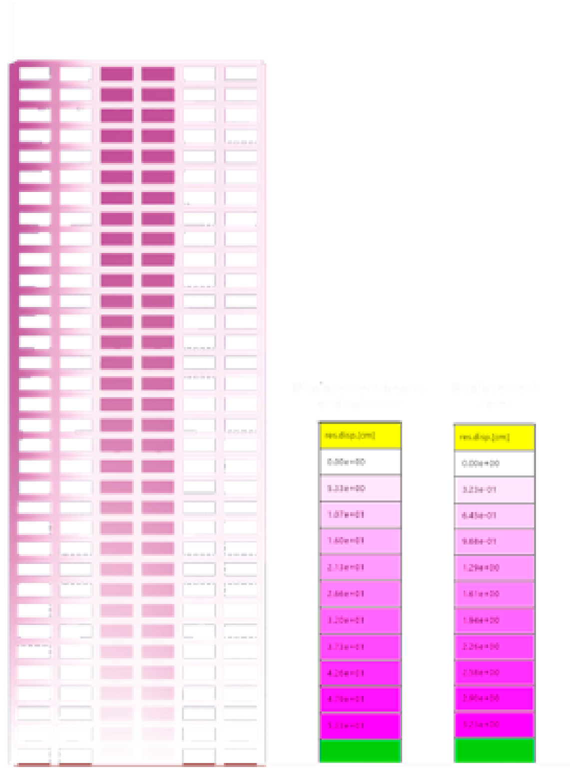


Fig 34: Displacements beams and columns and core

Discussion:

After 1035 iterations, the most optimal option for the structural design of a glulam frame and CLT core was selected, the option 650055. The analysis revealed that in order to meet the limit and serviceability limit state requirements according to Eurocode NEN-EN 1998-1 (EC8), the core plays a predominant role in the global stiffness of the structure, utilizing 94% of the maximum mass allowed in this investigation compared to only 46% for the columns and 36% for the beams.

The longer area of the columns was oriented perpendicular to the predominant wind pressure to resist the load. The thickness of the CLT core is inversely proportional to the rotational stiffness required by the joints. In this particular case, with a constant CLT core of 1400mm, the predominant rotational stiffness required is 100000KNm/rad, accounting for 78.8% of the total, while 3% is attributed to 200000KNm/rad and 18.2% to 300000KNm/rad. This significant reduction in the ecological footprint of the building is due to the reduced amount of steel required in the connection columns and beams. The mass of steel in the configuration of 100000KNm/rad is the lowest, with 23.9kg vs the 36 and 57kg from the 200000 and 300000KNm/rad, respectively. Additionally, the selection of glulam type GL32c, which has one of the highest weight-to-strength ratios in the European market, enabled a reduction in the cross-sections of beams and columns due to the material's mechanical properties.Other references with lower qualities would have increased the size of the cross-sections, exceeding the size constraints set in the parameters.

The stress distribution varies among the components. For columns, the highest concentration of compressive stresses is located on the lower floors due to the vertical loading of the structure and decreases exponentially in proportion to the height, from 3.49KNcm2 of compression to 1.39KNcm2 of tension at the highest point. The beams face constant perpendicular distributed vertical loads that remain as constant, resulting in compression on the top face and tension on the bottom.Additionally, stresses increase perpendicular to the cross-section as the height increases due to the wind pressure. The higher the location of the beam, the higher the stresses near the joints. The core behaves according to Bernoulli's beam theory, with the highest concentration of compression at the bottom of 5.88KNcm2 and tension of 2.63e-03 $KNcm^2$ at the highest part due to wind pressure.

The optimization resulted in a net floor area of 84%, which is highly efficient compared to the minimum of 75% required for a functional floor space. Due to design constraints of modularity, the core will always have a participation of 12% of the total, with its internal percentage varying according to the thickness of the shear walls. The columns had a participation of 4% of the total area.

4.3.2. Glulam frame and concrete core

This structural configuration uses materials with mechanical and manufacturing processes very different; for that reason and the circularity guidelines adopted in this investigation, the steel joints will connect the frame with the core, avoiding any permanent or pollutant hybridization. The Joint design configuration is based on two perpendicular steel plates; one will be slotted in the centroids beam using timber-steel penetration bolts, and the other will be attached to the core with screws anchored for concrete. The joint types can be found in chapter 5, design case.

The optimization process for the structure involves a glulam frame and concrete core system, which aims to create data that makes it possible to analyze and compare it with the proposal of glulam frame and CLT core. This optimization searches for solutions from thousands of potential options, enabling the use of timber as the primary load-bearing material for vertical loading in high-rises and reinforced concrete as lateral stabilizer. An evolutionary algorithm was used to analyze various combinations of inputs, including the core thickness, glulam types for columns and beams, and the lower and upper widths for the cross-section of columns and beams.

Additionally, three potential rotational stiffness values for joints (100000, 200000, and 300000 KNm/rad) were evaluated dynamically to ensure that design constraints were met. The genome was configured to minimize material usage while adhering to rigorous constraints of modularity, serviceability, and limited state regulations. The optimization maintained a global deflection limit of 0.204, an inter storey drift limit of 0.0075, and an acceleration limit of 0.39 m/s2.

However, a Python script was included in the post processing stage to avoid potential conflicts between constraints. This script helped to ensure that the optimization prioritized rotational stiffness values based on their mass, penalizing those with higher masses to reduce their potential for use. As a result, the optimization compensated for global stiffness and stability through other model components, such as columns, beams, and core, which prioritized timber mass over steel mass.The values used for the rotational stiffness of joints were 100000 KNm/rad: 23.9 kg, 200000 KNm/rad: 36 kg, and 300000 KNm/rad: 57 kg. By implementing these measures, the optimization process ensured the best possible solution for the given constraints, resulting in an efficient, stable, and sustainable high-rise structure option configuration.

- Total Iterations evaluated (Set of potential solutions): 1140
- Best value: 476945

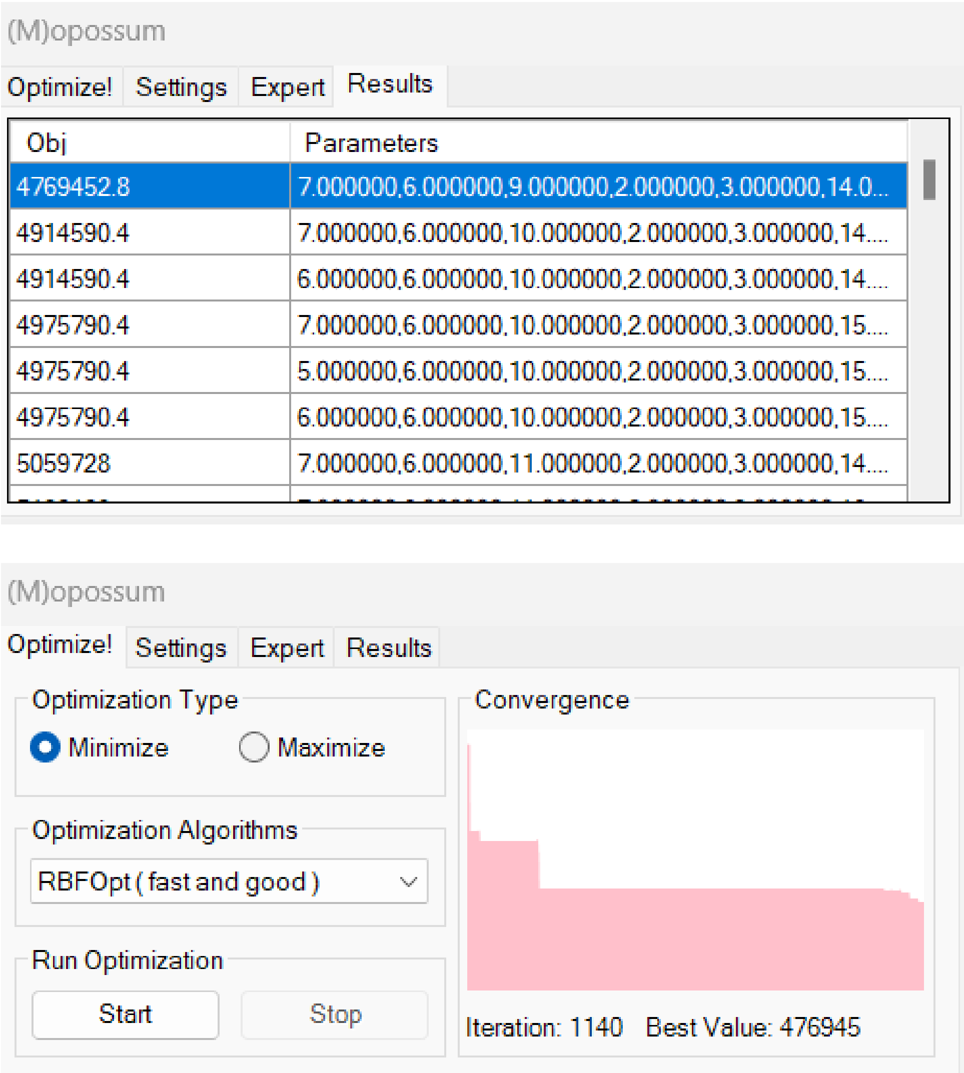


Fig 35: Optimization result: Iterations and best value.

For modularity and simplicity, the optimization was able to take only one option of the cross-section for columns and beams; in the case of rotational stiffness, the components were according to the demands selected in the specification previously explained. Components final sizing after optimization:

- Columns: 1400 x 300mm
- Core thickness: 700 mm
- Beams: 350x700mm
- Rotational stiffness:
    - 100000KNm/rad: 18 storeys
    - 200000KNm/rad: 14 storeys
    - 300000KNm/rad: 1 storeys

ULS and SLS results:

- Global deflection: 0.054933
- Inter-storey drift: 0.003056
- Utilization beams and columns: 0.921482
- Utilization core: 0.352703

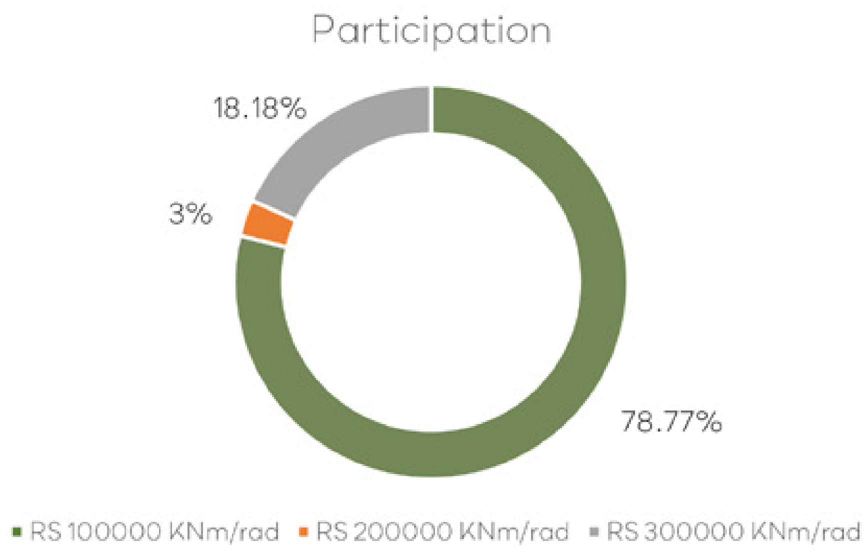


Fig 35.1: Optimization results: rotational stiffness participation.

Stress

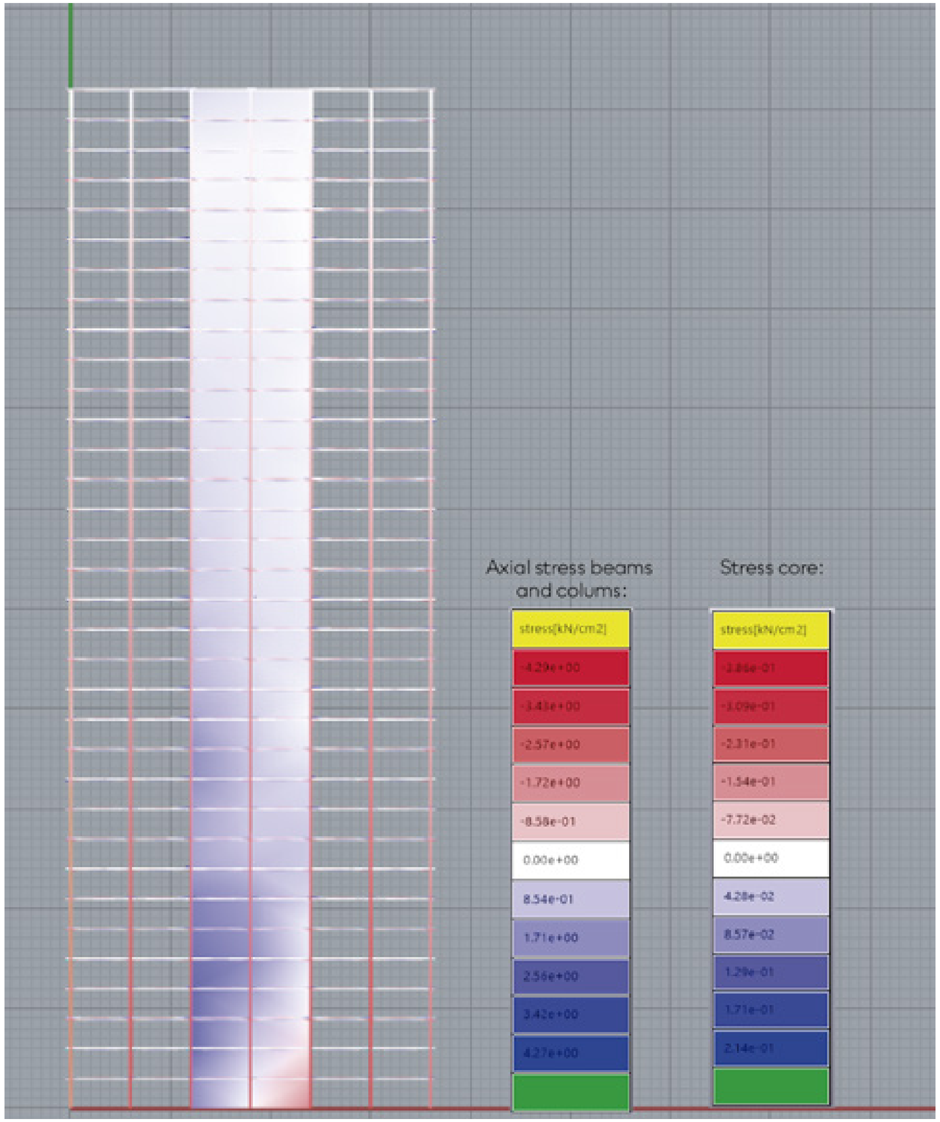


Fig 36: Axial stress beams and columns and stress core direction one.

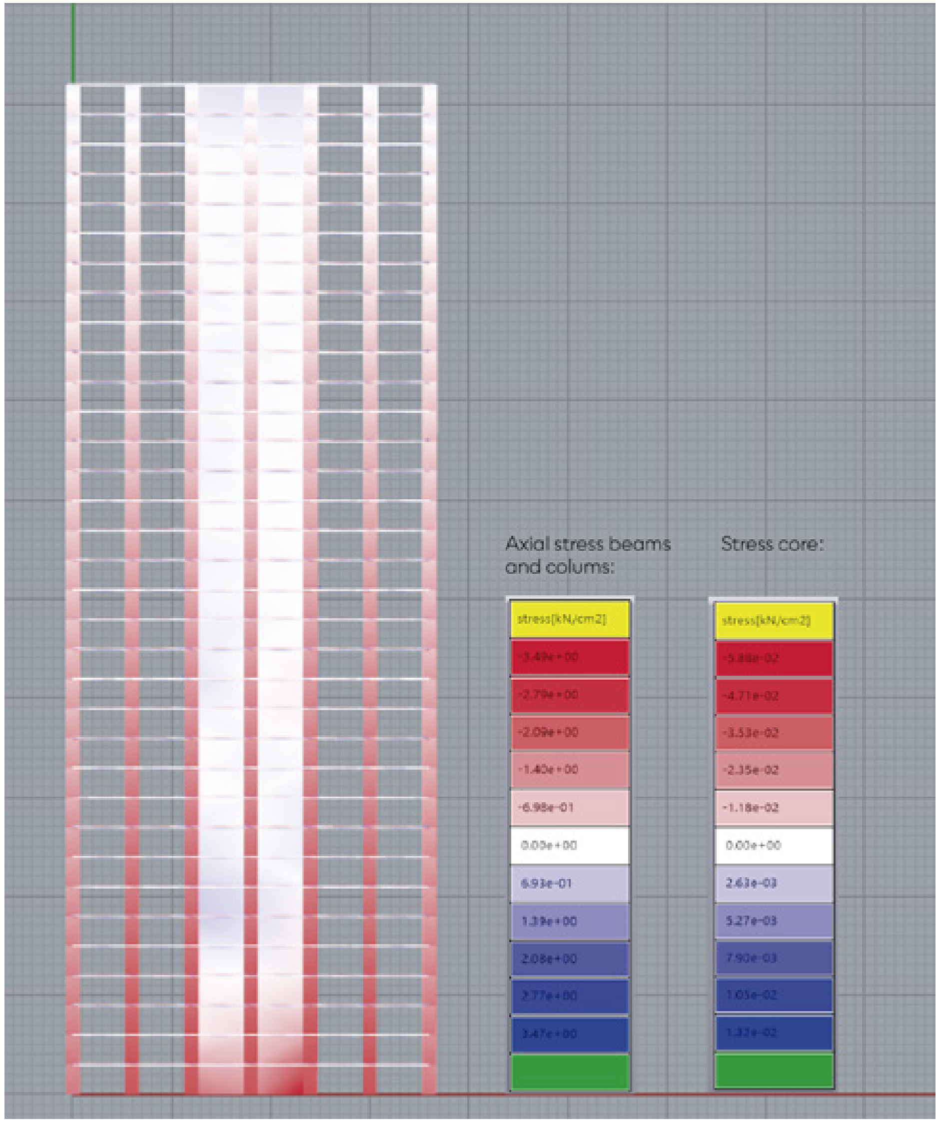


Fig 37: Axial stress beams and columns and stress core direction two

Displacement:

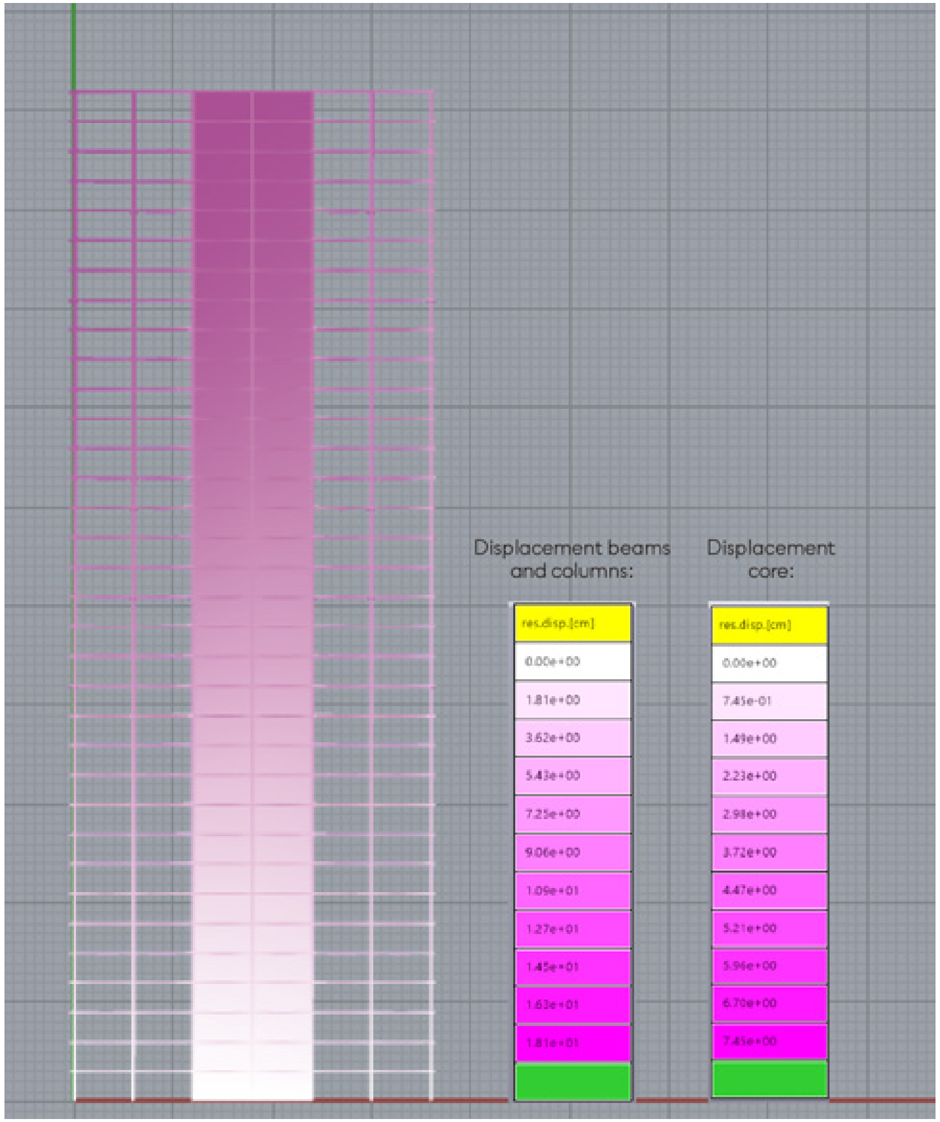


Fig 38: Displacements beams and columns and core direction one

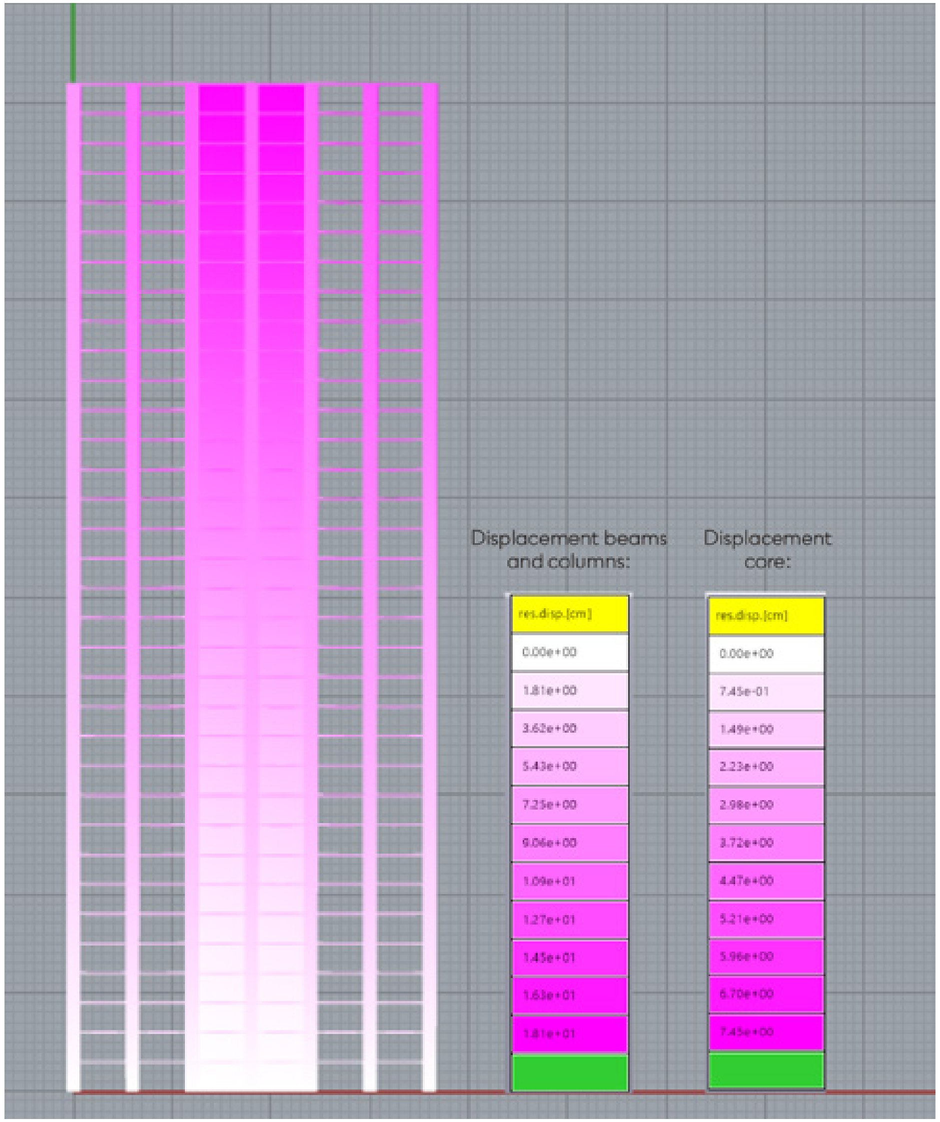


Fig 39: Displacements beams and columns and core direction two.

Discussion:

After conducting 1140 iterations, option 476945 was selected as the most optimal design for a glulam frame and concrete core structure. The analysis showed that the core played the most significant role in the global stiffness of the structure, as expected, but the columns also actively helped to dissipate wind pressure due to their cross-sectional shape of 1400x300mm facing the shorter width perpendicular to the predominant wind pressures.

The self-weight and toughness of the concrete core reduced the rotational stiffness requirement needed in timber joints. For this particular case, a core thickness of 700mm required a rotational stiffness of 100000KNm/rad in 55% of the joints, while 42% required 200000KNm/rad and only 3% required 300000KNm/rad. This indicates that the concrete core provides more global stiffness and requires less stiffness of joints related to height. But also shows that the evolutionary algorithm punished more the mass quantity in the concrete core than in the steel joints.

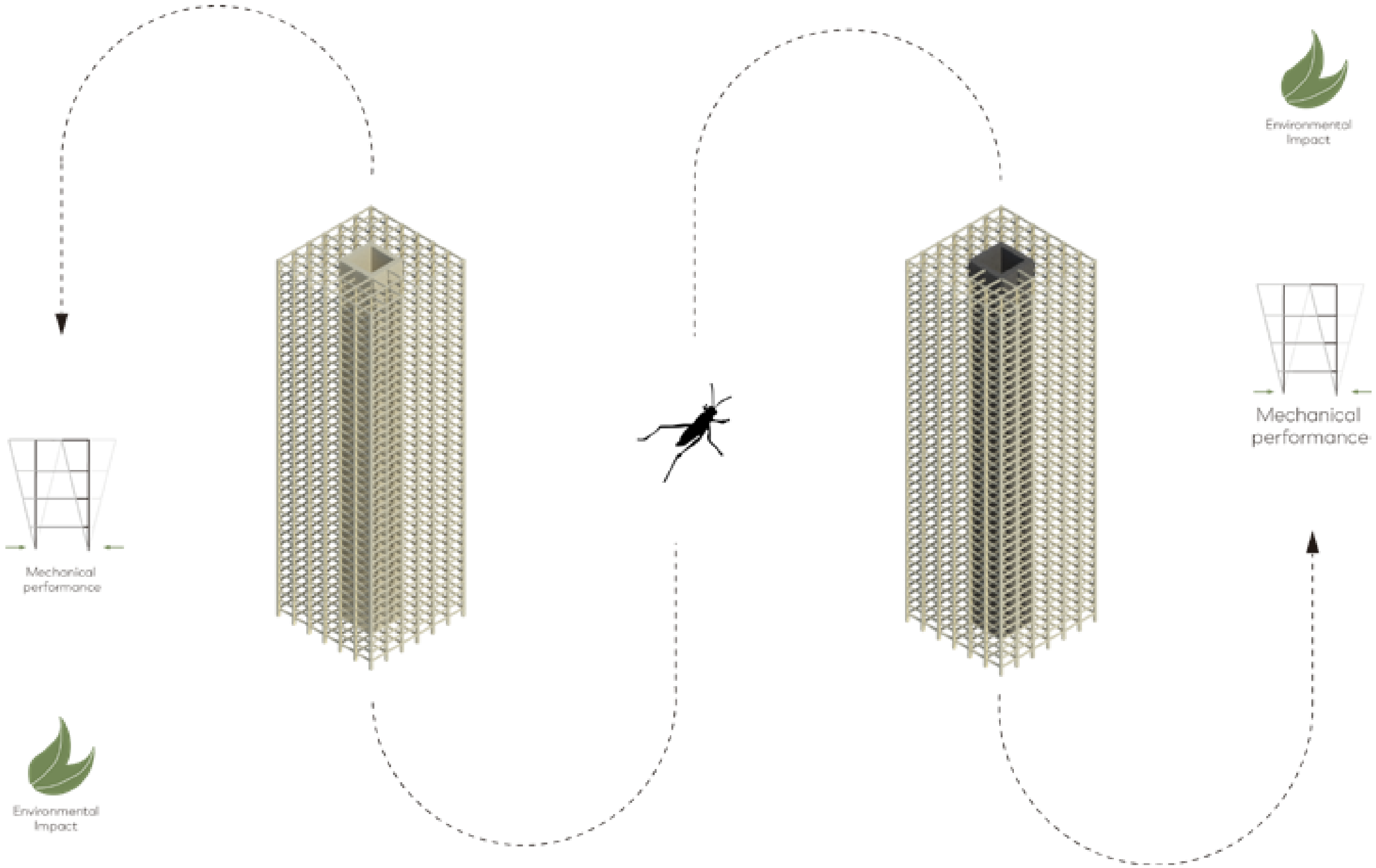
The use of glulam type GL32c was the option selected to meet the load requirements for a high-rise building. Despite this, the structural system had a mass reduction of 40% for the columns and 22% for the beams compared to the glulam frame and CLT core.

This resulted in a net floor area of 86%, which is higher than if only timber was used as the load-bearing material. Due to design constraints of modularity, the core will always have a participation of 12% of the total, with its internal percentage varying according to the thickness of the shear walls. The columns had a participation of 2% of the total area. The stress distribution was not as planned, due to the rectangular cross-section shape, which caused compressive stress to increase more than in more symmetrical cross-sections. However, the values were still within the range of ULS. The highest concentration of compressive stresses was located in the central part of the structure, with the corner columns being exposed more to tension. On the lower floors, the highest compression stress was 2.09KNcm2 at the base, decreasing exponentially in proportion to the height.

The beams faced constant perpendicular distributed vertical loads, resulting in compression on the top face and tension on the bottom. Additionally, stresses increased perpendicular to the cross-section as the height increased due to wind pressure. The higher the location of the beam, the higher the stresses near the joints. The highest concentration of compression was 5.88KNcm2 at the bottom, and tension was 2.63e-03 KNcm2 at the highest part due to wind pressure.

4.4. Environmental impact of the structural systems

- Glulam frame and CLT core
- Glulam frame and concrete core



- Building height: 102m, Beams total: 2448, Columns total: 1360, Cores: 1, Joints: 4752
- Building height: 102m, Beams total: 2448, Columns total: 1360, Cores: 1, Joints: 4752

In this subchapter, a preliminary analysis of the environmental impact of the two models is realized. The analysis aims to understand the environmental feasibility of building a structure with timber as the primary material of the load-bearing system.

In order to have an accurate and realistic analysis, this study will take the same parameter stipulated in chapter 4.1 and 4.2 as design constraints adding the results of the structural optimizations made in the subchapters 4.3.1 and 4.3.2.

Parametric model components for both cases:

- Building height: 102m
- Beams total: 2448
- Columns total: 1360
- Cores: 1
- Joints: 4752

For the configuration glulam frame and CLT core the following data will be analyzed:

- Columns: 4243.2m3
- Cores: 6054.72m3
- Beams: 3965.76m3

- Rotational stiffness:
    - 100000KNm/rad: 3744 units:11.79m3
    - 200000KNm/rad: 144 units
    - 300000KNm/rad:864 units

Results:

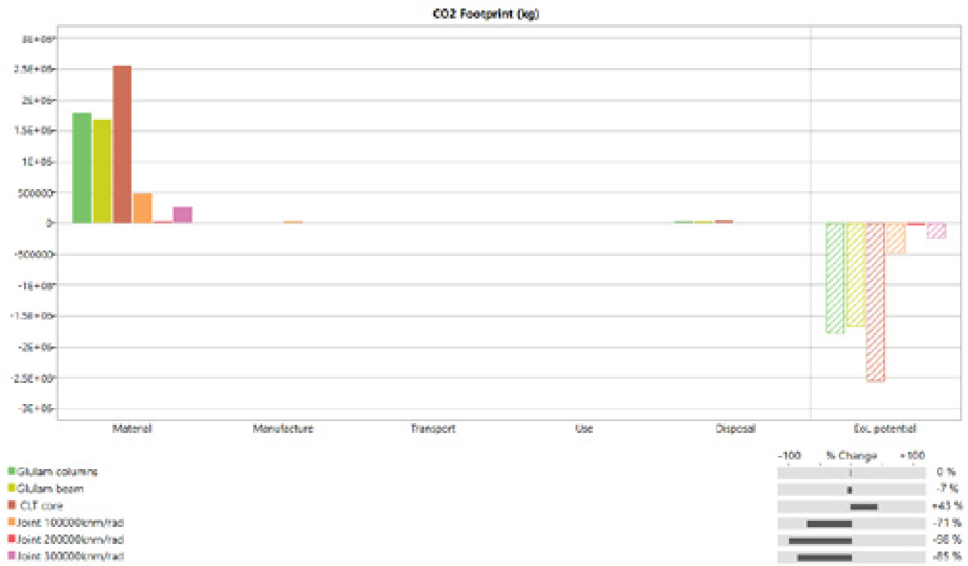


Fig 40 :Co_2 footprint Glulam frame and CLT core

For the configuration glulam frame and concrete core the following data will be analyzed:

- Columns: 1713.6m3
- Core: 3227.28m3
- Beams: 3598.56m3
- Rotational stiffness:
    - 100000KNm/rad: 2592 units
    - 200000KNm/rad: 2016 units
    - 300000KNm/rad: 144 units

Results:

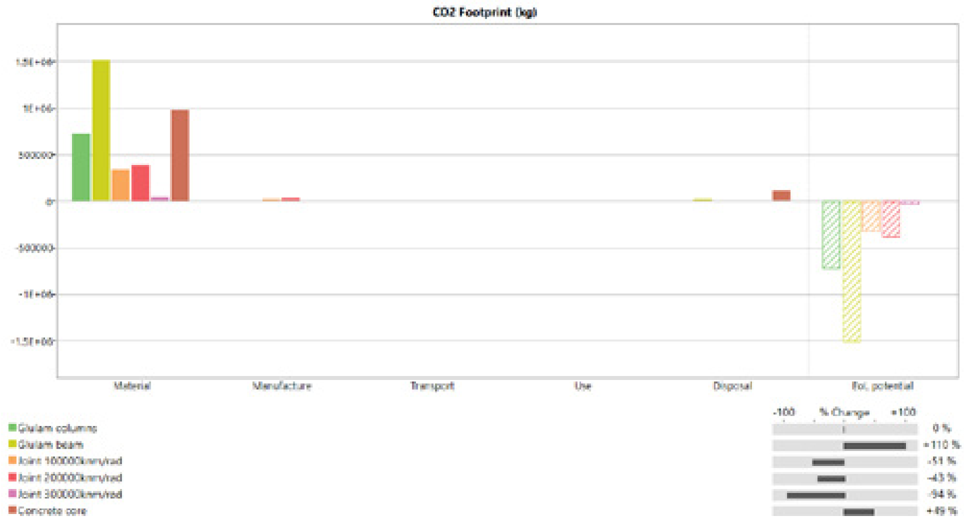


Fig 41 :Co_2 footprint Glulam frame and CLT core

Discussion:

The structural configuration: Glulam frame and CLT core was a challenging case study. The mechanical properties of these two materials are good, but their performance decreases due to the nature of the accelerations that high-rise structures must withstand.

In order to fulfil ULS and SLS considerations, the sizing of the cross sections was the most relevant factor; the low self-weight ratio of these two materials was one of the factors that considerably decreased their performance resisting wind accelerations, especially in the upper sections of the structure. This situation generated overpressure and maximum utilization of the core, arriving at 94% of the maximum allowable mass on this investigation and over the dimension of columns and beams above their loading needs to increase the self-weight.

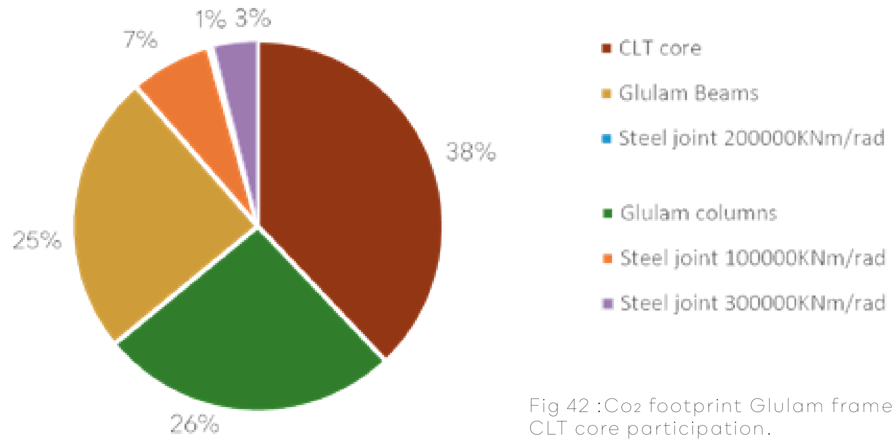


Fig 42 :Co_2 footprint Glulam frame and CLT core participation.

CLT core, an element that in the optimization required much mass to be structurally feasible as a stabilizer component, was the element that contributed more to the overall impact of the structure, followed by the columns and beams, respectively, for the oversizing required to create higher self-weight and contribute to the global stiffness of the structure.

On the other hand, the optimization helped to reduce the mass of steel required in the joints; a situation in the full spectrum of the analysis was a better outcome for the total environmental impact of the structure. The CLT core has a carbon footprint of 2,600,000 kilograms of CO2, which accounts for 38% of the total carbon footprint. The Glulam columns have a carbon footprint of 1,790,000 kilograms of CO2, which accounts for 26% of the total carbon footprint. The Glulam beams have a carbon footprint of 1,680,000 kilograms of CO2, which accounts for 25% of the total carbon footprint.

The steel joints also contribute to the carbon footprint, with the 100000KNm/rad joint having a carbon footprint of 487,000 kilograms of CO_2, which accounts for 7% of the total carbon footprint. The 200000KNm/rad joint has a carbon footprint of 28,400 kilograms of CO_2, which accounts for 1% of the total carbon footprint. Finally, the 300000KNm/rad joint has a carbon footprint of 268,000 kilograms of CO2, which accounts for 3% of the total carbon footprint. According to the data provided, the total carbon footprint of a construction project that includes CLT core, Glulam columns and beams, and various steel joints of different specifications is 6,853,400 kilograms of CO2. See Appendix C2: CO2 concentration material parametric study: Glulam frame and CLT core.

The structural configuration: Glulam frame and concrete core were more efficient regarding mechanical efficiency vs weight ratio. The concrete core, due to its high strength-to-weight ratio, the optimization only needed 50% of the total mass that a CLT core needed to achieve the same structural performance. It is important to remark that this mass reduction is relevant for the ecological impact because less material is needed. However, it did not affect or benefit the net floor area due to the increase of the core thickness was established to happen in a determined area only destinated to this function.

Similarly, the concrete by itself was able to resist better the accelerations made by the wind, which generated a considerable diminution of the cross sections of other elements, like the columns, that had a reduction of 40% of the total mass required. Even if it is important to remark that in this configuration, the participation of steel joints was superior, also because the reduction of the beams and columns cross sections needing more rotational stiffness.

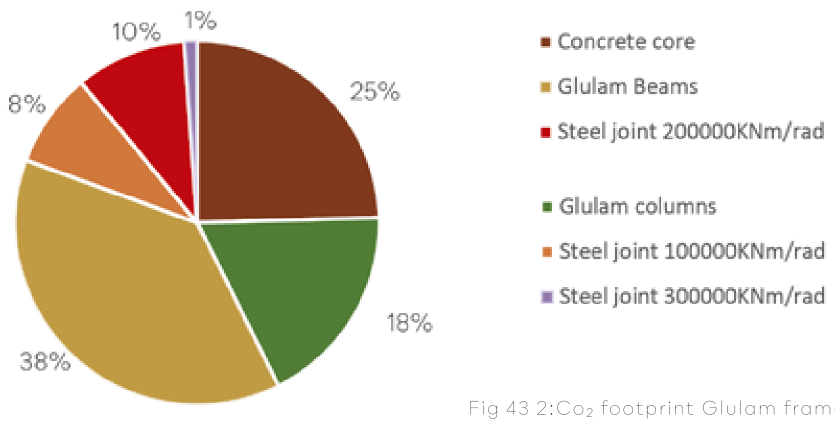


Fig 43 2:CO_2 footprint Glulam frame and concrete core participation.

The data presents that the concrete core, with a carbon footprint of 983,000 kg CO2, accounts for 25% of the total carbon footprint. The Glulam columns, with a carbon footprint of 724,000 kg CO2, contribute 18% to the overall carbon footprint. The Glulam beams, with a carbon footprint of 1,520,000 kg CO2, represent the largest contributor, accounting for 38% of the total carbon footprint. The steel joints also contribute significantly, with the 100000KNm/rad joint contributing 337,000 kg CO2, the 200000KNm/rad joint contributing 395,000 kg CO2, and the 300000KNm/rad joint contributing 44,600 kg CO2.

These three steel joints together account for 19% of the total carbon footprint. Overall, the carbon footprint of this configuration is 4,003,600 kg CO2, indicating that the materials and components used in the construction process have a significant environmental impact. See Appendix C3: CO_2 concentration material parametric study: Glulam frame and concrete core

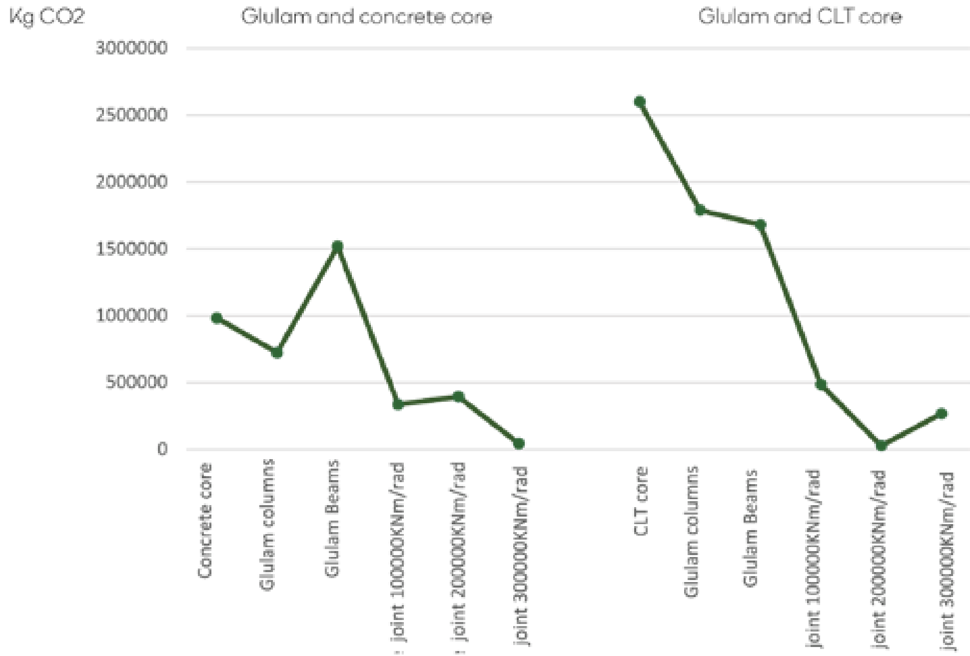


Fig 44: Total environmental impact Glulam frame and concrete core - Glulam frame and CLT core .

In conclusion, the study found that for the case of a 34 storey building, the Glulam frame and CLT core configuration were challenging due to the low self-weight ratio of the materials, which decreased their performance in resisting wind accelerations.

Oversizing of the components was required to increase self-weight and contribute to the global stiffness of the structure situation that increased very much ecological impact. The CLT core contributed the most to the overall carbon footprint, followed by the Glulam columns and beams. Steel joints also contributed significantly but less due to materials optimization, which prioritizes the sizing of biobased materials.

On the other hand, the Glulam frame and concrete core configuration were more efficient regarding mechanical efficiency vs weight ratio. The concrete core required only 50% of the total mass needed for a CLT core to achieve the same structural performance and could resist wind accelerations better, reducing 40% of the total mass required for columns. However, the participation of steel joints was also higher in this configuration.

Overall, both configurations had a significant environmental impact; the configuration of the Glulam frame and CLT core perform less in highrises, being until now, a better option is the use of concrete core or some hybridization; this option could have an enormous potential of reducing the footprint of timber as main load bearing structural system for highrises. Although it is important to note that the glulam and CLT core configuration offers higher end-of-life potential compared to concrete core options. This is because the design of the timber components and steel joints allows for disassembly and reconfiguration, resulting in a longer lifespan and increased durability.

This option is less vulnerable to ending up in a landfill or becoming obsolete due to its dependence on a concrete core that cannot be disassembled. Additionally, in the event that the structure reaches the end of its life cycle, the glulam components can be repurposed for other structures due to their modularity and simplicity. Alternatively, they can be used as biomass for energy generation in a controlled and certified facility. However, for more accurate joint optimization, a case study should also include the joints of CLT, which can significantly impact the structure's ecological footprint.

4.5. Conclusions:

What strategies can be applied to replace the concrete core as a lateral stabilizer component?

The parametric model highlighted the crucial role of the core in the global stiffness of highrise structures. Subchapter 4.3.1 demonstrated how a CLT core can replace a concrete core entirely, despite requiring considerable mass to meet the limit and serviceability parameters. In contrast, subchapter 4.3.2 revealed that a concrete core required only 50% of the mass required for a CLT core to achieve the necessary stiffness. FIG 45 shows that global deflection and inter-storey drift is inversely proportional to the core thickness. However, subchapter 4.4. indicated that the glulam and CLT core resulted in 2849800 KgCo2 more emissions than the configuration with a concrete core.

Two strategies can be considered to avoid the need for a concrete core. The first is to reduce the height of the highrise to a level where wind pressure does not require a CLT core thicker than 1000mm. Alternatively, adding more self-weight to the structure may be possible by implementing a composite material that can be used with CLT or glulam. FIG 46 shows how the self weight of the structural components determines the thickness of the core. This hybridization should have lower embodied energy than concrete and not create permanent connections that would hinder the potential for reuse, repurposing, or recyclability.

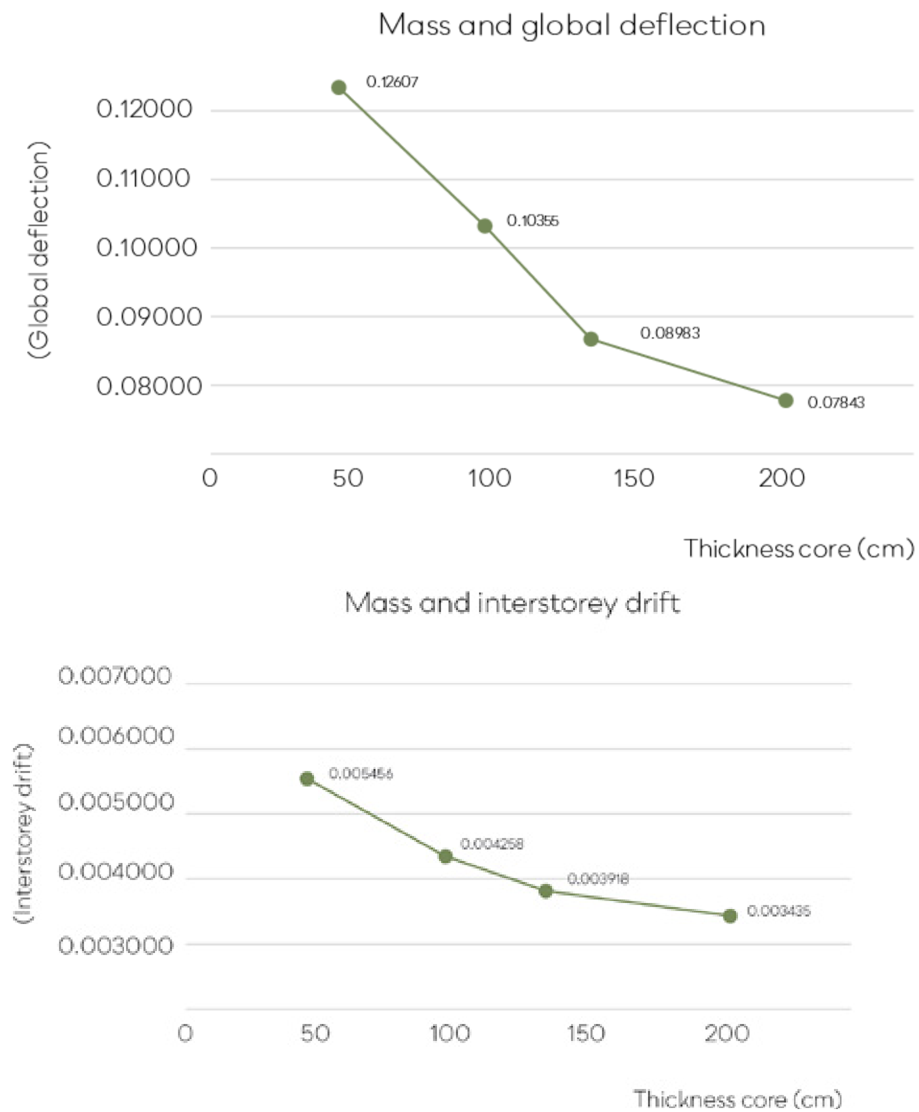
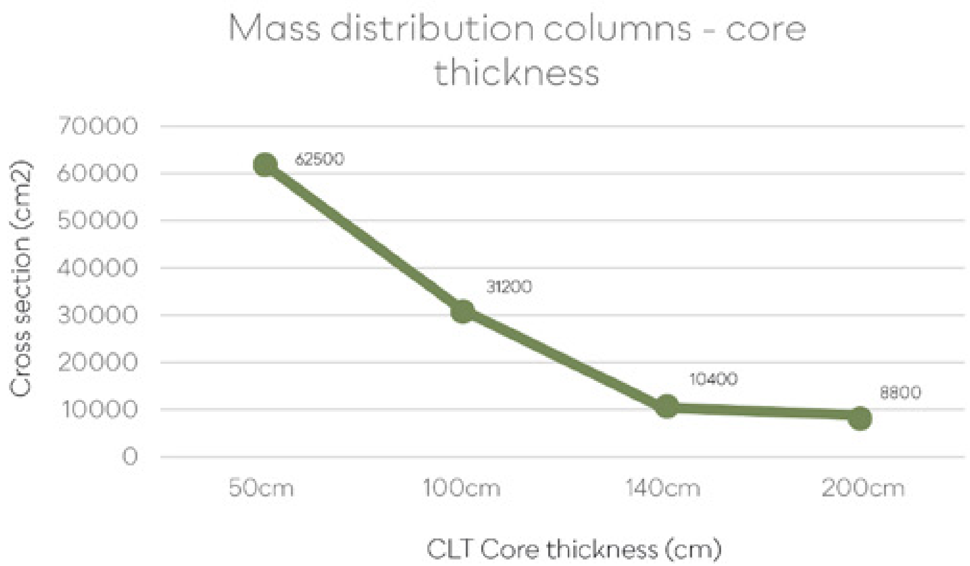


Fig 45: Global deflection and interstorey drift vs mass. CLT core and glulam frame configuration.



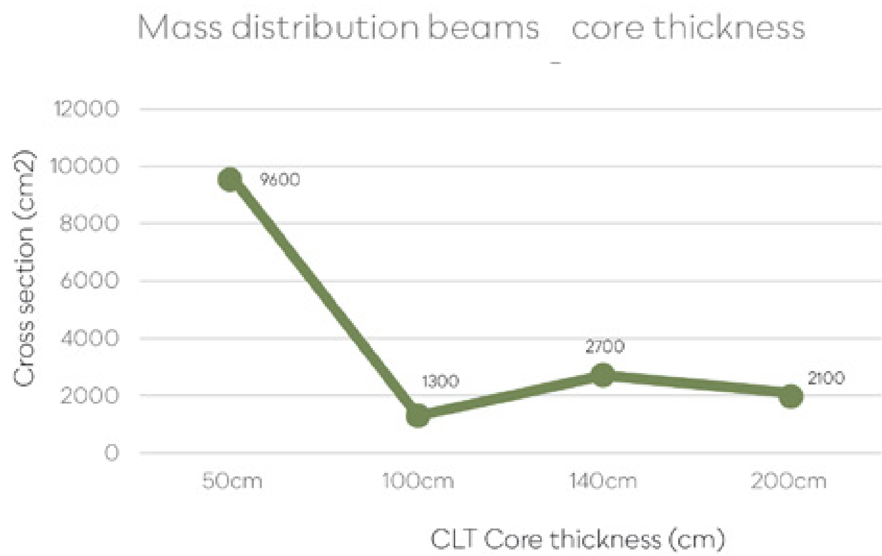


Fig 46: Mass distribution in columns and beams, CLT core and glulam frame configuration.

To what extent is it possible to reduce the use of metal alloys in the joints of timber components?

The feasibility of replacing steel with carpentry joints for high-rise structures was found to be deficient in mechanical behavior and economically and technically impractical, as explained in subchapter 3.1.1. Instead, optimizing the amount of material in metal joints was a more realistic and feasible solution.

The parametric model in subchapters 4.3.1. and 4.3.2. provided valuable insights into the structures' dynamic response and stress concentrations. The analysis revealed that the height and self-weight of the building were directly related to the demand for rotational stiffness in the joints. Higher rotational stiffness requires more material, resulting in higher embodied energy and cost. The global stiffness given by the core plays a direct role in the rotational stiffness requirements of the joints; FIG 47 shows this relation.

Structural optimization was a crucial tool for reducing the amount of steel in the connections. This was achieved by integrating several factors into the same optimization, including cross-sections of the frame and core and rotational stiffness values of 100000, 200000, and 300000 KNm/rad.

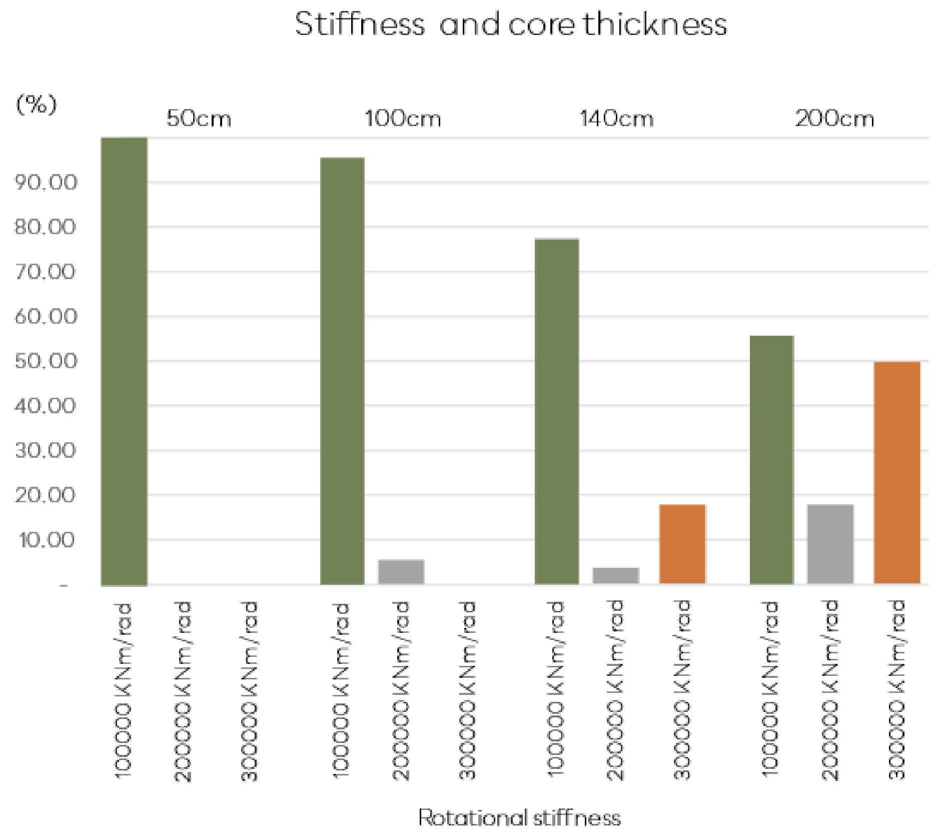


Fig 47: Rotational stiffness and core thickness, CLT core and glulam frame configuration.

The genome was set up to minimize the mass of all components, with a penalty of mass added to the rotational stiffness of 300000 KNm/rad, which multiplied its real mass, increasing the real value for optimization. This approach allowed the Opossum (Multi-Objective Particle Swarm Optimization) to prioritize the rotational stiffness of 100000 and 200000 KNm/rad while compensating for the self-weight of timber elements with higher mass. As a result, in the Glulam frame and CLT core configuration, the joint with a rotational stiffness of 200000 KNm/rad was used in 26 out of the 34 storeys, as it had the least mass. In the case of the Glulam frame and concrete core, the joint with a rotational stiffness of 300000 KNm/rad was needed only in the last storey. It is important to note that this was possible due to the compensation of the self-weight of the timber elements, and the optimization process ensured the best mechanical performance while reducing the amount of steel in the connections.

How do the wind loads affect the feasibility of a timber highrise?

The parametric model revealed that wind pressure is a crucial factor that significantly affects the feasibility of timber highrises in numerous ways, particularly in terms of structural mechanics. As outlined in subchapter 4.2.3.2. the height parameter is a crucial factor that affects the overall performance of the structure as it is directly correlated to the horizontal loads, such as wind pressure.

The pressure exerted by wind increases exponentially with height, which requires greater stiffness in the upper areas of the structure. This exponential pressure increase, in turn, demands a higher global stiffness that the structure must fulfill to meet the limit and serviceability state requirements. The structural analysis and optimization have been carried out to achieve the necessary global stiffness in subchapters 4.3.1. and 4.3.2. For glulam frames with two types of cores, two crucial factors have been applied to ensure accurate mass and high mechanical properties performance of materials.

However, it is important to note that wind pressure is not the only factor that should be considered when assessing the feasibility of timber highrises. Other analyses, such as the structure's environmental impact, must also be evaluated to ensure a well-rounded and sustainable design. While structural feasibility is undoubtedly an important factor to consider when evaluating the feasibility of a timber high-rise, it is not the only one. Other important analyses, such as an evaluation of the ecological impact of the structure, must also be considered. As was demonstrated in subchapter 4.4., the environmental impact of a structure can be significant, even when it is constructed using sustainable, biobased materials.

For example, the analysis showed that the glulam frame and CLT core produced a considerably higher amount of CO_2 concentration compared to a glulam frame with a concrete core. Therefore, it is essential to consider the mass efficiency of various structural configurations to identify the options with the least negative impact. A balanced and multi-feasible approach is necessary when evaluating the feasibility of a timber high-rise.

This means that the structural and environmental feasibility of different design options must be compared and evaluated to identify the most optimal solution.

The net floor area plays a critical role in the structural analysis of timber high-rise buildings, as demonstrated in subchapters 4.3.1 and 4.3.2. These subchapters shed light on how a high-rise structure requires a higher global stiffness to achieve accurate mass and mechanical performance of materials, which can lead to a significant reduction in the net floor area if no constraints are established. In the case of the glulam and CLT core, before the final optimization, the cross-section of the components did not have a size limit, resulting in column options with a width of over 1700mm, thereby affecting the architectural plan and considerably reducing the available floor area.

Therefore, it is essential to evaluate the total height of the building to analyze the structural system and the material more appropriate for each case. In the particular case of this investigation, the net floor area of the glulam and concrete core was only 2% better. However, it is important to note that this slight difference was mainly due to the optimization constraint of maintaining the net floor area above 80% by limiting the maximum sizing of the columns and beams. In situations without this constraint, the oversizing of the columns will be a factor that affects the floor plan.

The economical feasibility is out of the scope of this investigation.

Additional remarks:

This investigation into the ecological footprint of timber high-rises has found that reducing the number of joints in the structure can significantly reduce its impact. Connecting columns every 2 or 3 storeys instead of every single storey reduces the number of joints needed, leading to more sustainable and efficient construction.

One of the assumptions made in this investigation is that the structure's core behaves according to Bernoulli's beam theory. This simplification allowed for optimizing joints between different CLT components as a single element.

5.0

Design case

5.1. Circular economy and sustainable structure design:

This chapter will help to answer the following question:

How can modular timber systems lead to highrise buildings that are technically feasible and adaptable to future use scenarios?

According to Brand (1995) and his theory of building layers, the structure has the longest lifespan among the components of a system. In the context of the circular economy, the design of the structure in this project incorporates various factors that promote sustainability and efficient use of resources.

One key factor involves minimizing resource consumption and waste generation. This is achieved by designing structural components to be durable, modular, and easily repairable. Reducing the amount of materials used in manufacturing and consumption minimizes waste generation, thereby reducing the environmental impact. Sustainable production practices are also integral to the design. without the use of harmful chemicals. Considering the entire lifecycle of products, from sourcing raw materials to their eventual disposal, ensures minimal environmental impact throughout. Efficient and responsible resource utilization is another crucial principle. The design of structural components and processes focuses on maximizing resource efficiency while minimizing waste generation. This approach helps decrease the overall demand for raw materials, contributing to a more sustainable production and consumption model. Promoting the extension of product and component lifespans through repair, refurbishment, or repurposing is encouraged. Emphasizing product reuse reduces the need for new items, resulting in resource conservation and waste reduction. Recycling plays a vital role in circular structural design. Waste materials are processed and transformed into new products or raw materials. For instance, timber can be reprocessed or used as biomass. Recycling contributes to resource conservation, reduces landfill waste, and decreases energy and environmental impact during production. By integrating these interconnected factors, the circular structural design enables a more sustainable and resource-efficient approach. Prioritizing waste reduction, sustainable production, resource efficiency, product reuse, and recycling contributes to developing a circular and sustainable economy.

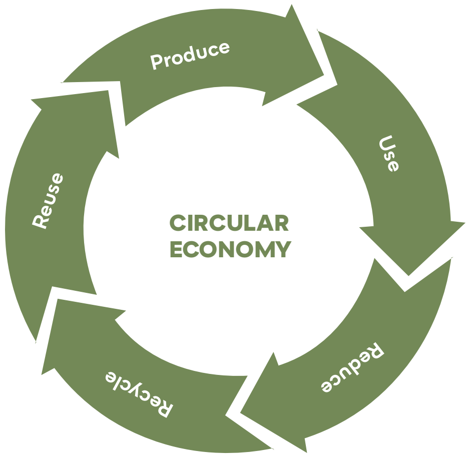


Fig 26: Circular economy scheme https://www.researchgate.net/figure/Presenting-the-6Rs-of-circular-economy_fig1_357870104

5.2. Design for modularity and simplicity:

The design process for the modular multipurpose structure began with establishing guidelines that would enable the creation of a cohesive building, so a grid was implemented to facilitate connectivity and complementarity between the various components of the system. The grid was based on a standard unit of 0.6m and multiples, allowing for the standardization of all building components. This range of values provides functional alignment between small and macro scales. It allows for an exponential proportionality between the architectural components (such as partition walls and facade panels) and the structural components (such as columns and beams), resulting in a complete modular system.

The structural optimization made on previous chapter's demonstrated the practicality of maintaining a single grid of 6x6m while using a limited variety of component types. Utilizing a singular cross-section for columns and beams significantly reduces the complexity of the assembly process. This approach also facilitates the replacement of spare parts and enables the potential reuse of system components in future projects. The standardized commercial cross-section and length sizing further enhance the feasibility of incorporating these components into other endeavours. Overall, this optimized design simplifies construction and enhances the system's versatility and potential for resource efficiency.

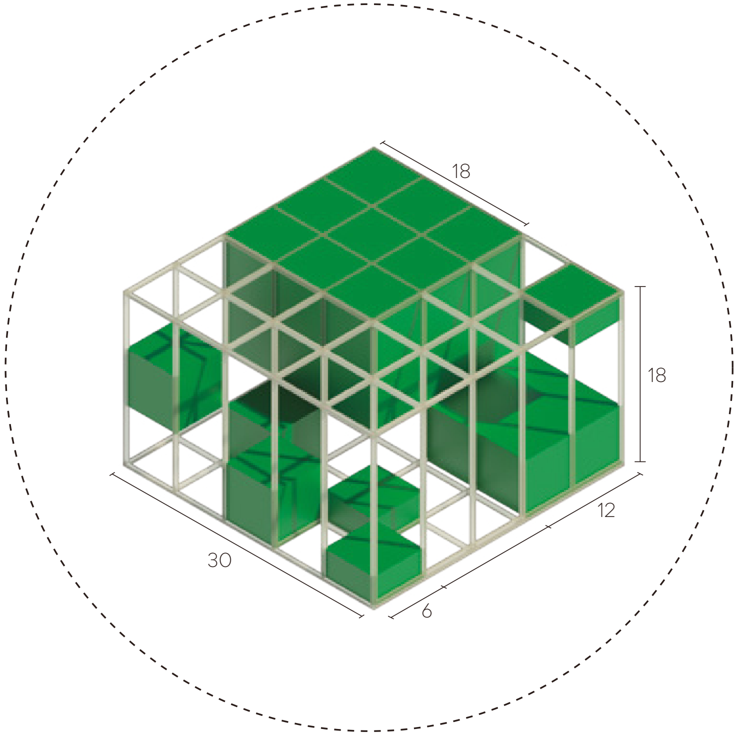


Fig 26.1: Interoperability of different architectonic scales

5.3. Design for (dis)assembly criteria:

After modularity, design for disassembly is one of the most important key factors to consider from the early stages of a project to avoid the obsolescence of any building. Crowther (2005) set a list of criteria to consider, and that was readapted to this project to have an applicable disassemble design also following the Brand (1995) concept of a building environment conformed by different layers with different timespans due to user requirements, durability factors or the dynamism and changing panorama of the users.

The demountability criteria is conformed by five groups that integrate all the physical components and stages of a project: materials, connections, manipulation, design and management. These groups have a specific list of principles that defines each group's scope and goal. The principles are classified as Highly relevant, relevant, or not relevant in terms of recyclability, remanufacture, reuse and relocation potential in 3 different scales: material, component, and building, see FIG 14.1 and 14.2.

	Legend: ● Highly relevant ● Relevant ● Not so relevant	Material	Component		Building
	Principles	Recycling	Remanufacturate	Re-use	Relocation
Materials	Recycled - recyclable	Highly relevant	Highly relevant	Not so relevant	Not so relevant
	Reduce quantity of options used	Highly relevant	Highly relevant	Not so relevant	Not so relevant
	Avoid toxic and hazardous materials	Highly relevant	Highly relevant	Not so relevant	Not so relevant
	Avoid secondary finishes	Highly relevant	Highly relevant	Not so relevant	Not so relevant
	Lightweight	Highly relevant	Highly relevant	Highly relevant	Highly relevant
Connections	Minimize number of components	Highly relevant	Highly relevant	Not so relevant	Not so relevant
	(Dis)assembly tolerances	Not so relevant	Not so relevant	Highly relevant	Highly relevant
	Minimize number of connectors	Not so relevant	Relevant	Highly relevant	Highly relevant
	Minimize types of connectors	Not so relevant	Relevant	Highly relevant	Highly relevant
	Resistance to repeated use	Not so relevant	Highly relevant	Highly relevant	Highly relevant
	Avoid chemical connectors	Not so relevant	Not so relevant	Highly relevant	Highly relevant
	Accessibility to connection points	Relevant	Relevant	Highly relevant	Highly relevant

Fig 14.1: Demountability criteria: modification made from (Crowther 2005) & (Mariller N., 2020)

Manipulation	Design to use common tools ans equipment	● (light grey)	● (dark)	● (green)	● (green)
	Handling size	● (light grey)	● (dark)	● (green)	● (green)
	Provide ans locate means of handling	● (light grey)	● (light grey)	● (green)	● (green)
	Parallel disassembly	● (dark)	● (dark)	● (green)	● (dark)
Design	Open system	● (light grey)	● (light grey)	● (green)	● (green)
	Modular	● (light grey)	● (light grey)	● (green)	● (green)
	Independent system from other system of the building	● (light grey)	● (light grey)	● (green)	● (dark)
	Stantad grid	● (light grey)	● (light grey)	● (light grey)	● (green)
	Prefabrication and mass production	● (light grey)	● (light grey)	● (green)	● (green)
Management	Points of disassembly	● (light grey)	● (dark)	● (green)	● (green)
	Spare parts	● (light grey)	● (light grey)	● (light grey)	● (green)
	Open and updated information of components and materials	● (light grey)	● (light grey)	● (dark)	● (green)
	Identification of material types	● (green)	● (green)	● (light grey)	● (light grey)
	Minimize the numbr of different types of components	● (light grey)	● (dark)	● (green)	● (green)
	Provide identification of component type	● (light grey)	● (dark)	● (green)	● (dark)

Fig 14.2: Demountability criteria: modification made from (Crowther 2005) & (Mariller N., 2020)

The remarks and prioritization conclusion of the criteria for this particular study case were:

- Materials:

The selection criteria are focused on selecting options with the highest potential to be recyclable/reuse ultimately so that the hybridization of the components with hazardous materials would not happen. Similarly, material efficiency is a priority; for that reason, the optimization of the use is a predominant constant.

For this project, this means that using a biobased material such as timber as the main load-bearing component is optimized to have the most efficient structure configuration possible in terms of material use. Implementing any permanent connection will not happen, allowing the exchangeability and potential reuse of the components in other projects or in a controlled and sustainable transition of the component into biomass to recover part of the embodied energy.

- Connections:

A reduced number of connectors, components, and types not only reduce the environmental and monetary cost of the project but also facilitate the process of dis(a) assembly. Similarly, the connection must be accessible and durable. This will create a less complex system that will facilitate and make the project more feasible.

This project implements Joints made of stainless steel, a material discussed in the material analysis subchapter, with high mechanical and durable performance qualities. This criterion makes the joints able to tolerate not only the load stresses but also the possibility of being disassembled multiple times, a relevant characteristic in the life span of a product. Additionally, implementing commercial screws and bolts in the slotted-in plate system allows them to be compatible with traditional steel structures. Such compatibility makes them components appropriate to use in other structures.

- Manipulation:

Sizing of components proportional to human scale and the compatibility of commercial equipment are principles of high relevance. The sizing of the components it's a factor that must be considered. Today the sizing of components is limited by external factors different from the manufacture, transportation, and consequent access to the construction site are the relevant limitation factors.

The project implements a multiscale interoperativity of structural and architectural components. This allows the assembly of components on at small and big scale. Depending on the demands and restrictions of the construction site. The individual size of the components can be manipulated by 2-3 construction workers, making easier the manipulation on-site and developing a “column by column system“. On the other hand, if its more practical to preassembly elements out of site and transport them as preassembled modules, this is also a practical possibility. the only factor to consider is the transportation limitations.

- Design:

The design and implementation of a structural grid are vital for enabling interoperability among all system components. This entails adopting an open system concept that embraces modular and standardized parts, ensuring independence from other systems and facilitating prefabrication.

The project uses as one of the main constraints a structural grid of 6x6m and multiples; this generates interoperability of different scales and optimal architectural flexibility that makes the building optimal to adapt to future scenarios.

- Management:

The management plays a crucial role in the project where identifying and minimizing the number and types of components will provide faster and more efficient identification of the elements that will facilitate the disassembly process.

The implementation of structural optimization in this project, following a grid and a minimum amount of types of components as constraints, facilitates considerable the management of the (dis) assembly and change of spare parts. Utilizing a single reference of column and beam and only three options of stiffness joints facilitate considerable piece management.

5.4. Structural kits:

The most predominant timber highrises built until today are similar to many other types of conventional structures. The lack of modularity and the implementation of permanent pollutant connections make it very complicated to implement an end-of-life panorama. For this situation, an opportunity to develop a modular set of pieces for highrises could be one of the solutions to achieve the ambitious goals of the circularity of the timber highrise industry. The group of components conform to the structural kit, a package of previously analyzed components that fulfill all the ULS and SLS considerations but also the circular principles of modularity and design for disassembly.

The construction kits were created to build the modular high-rise: a structural kit. These kits are versatile and functional for small and large-scale uses and are designed to be interoperable with each other. This interoperability provides a wide range of architectural options and allows for a highly adaptable system that can be applied to various uses and requirements. The result is a flexible and versatile building that can be tailored to meet the variety of needs of its users.

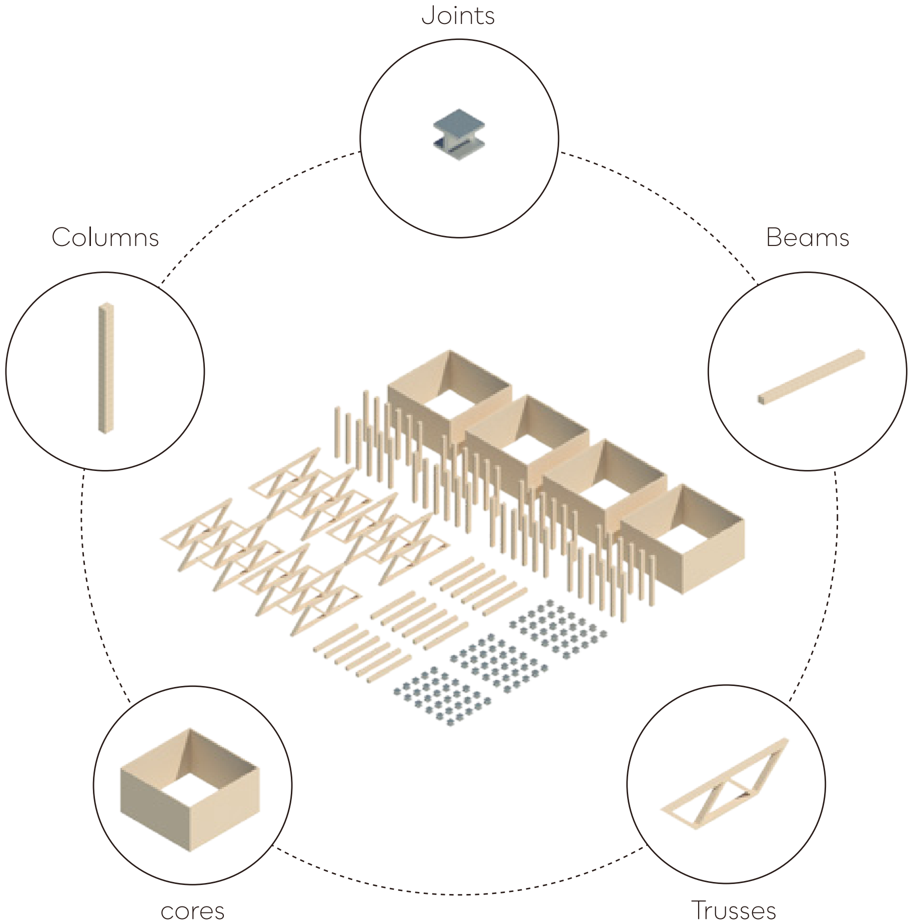


Fig 45 :Constituent parts of the structural kit.

The structural kit is a versatile package of building components designed to meet a range of scale requirements. It includes prefabricated columns, beams, trusses, and cores made of Glulam and CLT, with options for S (6x6x3m), M (6x6x6m), L (18x6x12m), and XL (30x6x18m) configurations. The components are connected using steel joints with various rotational stiffness specifications to meet specific project requirements.

The manufacturing and assembly methodology of the structural kit emphasizes compatibility between components and joints while avoiding any permanent connections between them. This means the components are prefabricated in a specialized EWPs manufacturing facility, pre drilled and milled for easy assembly. Similarly, the steel joints are also prefabricated with all the screws and bolts necessary for quick and efficient on-site assembly. Overall, this approach allows for a faster, more efficient, and sustainable construction process while maintaining the highest structural integrity and safety levels.

The scales are a standard combination of the components, which is an example of the multiple scales and configurations this set of pieces can achieve. The following measurements of the different scales are given considering the vectorial length of the components; the element's cross sections vary depending on its mechanical requirements. S scale is a module of 4 columns of 3m height connected by four beams of 6m. M scale is a module of 4 columns of 6m height connected by four beams of 6m. These two groups of components create glulam frames that can be pre-assembled before installation or assembled in pieces, depending on the needs and limitations of the construction place. L scale is a module of 4 columns of 12m height connected by two beams of 6m and two trusses of 18m. An XL scale is a module of 4 columns of 16m in height connected by two beams of 6m and two trusses of 30. The cores are conformed by prefabricated panels that conform to the box. Fig 46 Shows a representation of the multi scale modularity.

Fig 46 :Multi scale modularity.

5.4.1. Beams

The development of structural components was guided by simplicity and modularity. To enable easy configuration of beams, the establishment of the structural grid and component homogenization as parameters in the parametric tool. The beams were designed to be manufactured from the most optimal material reference, glulam GL32c, based on the requirements determined in the analysis conducted in the previous chapter. The potential sizing of the beams ranges from 450mm to 1200mm for the upper and lower width and a cross-section height of 450mm to 1200mm.

Similarly, the total length will vary depending on the mechanical requirements and will be within the range of 4500mm to 5550mm. The beam design is symmetrical and uses standardized joints to simplify the assembly process. Pinned connectors are used to connect the beams to the columns at the extreme points of the element. The beams are pre-cut and drilled precisely to match the type of joints, which reduces onsite work and ensures high assembly precision. Furthermore, the non-permanent connection allows for exchangeability, disassembly, and potential recyclability.

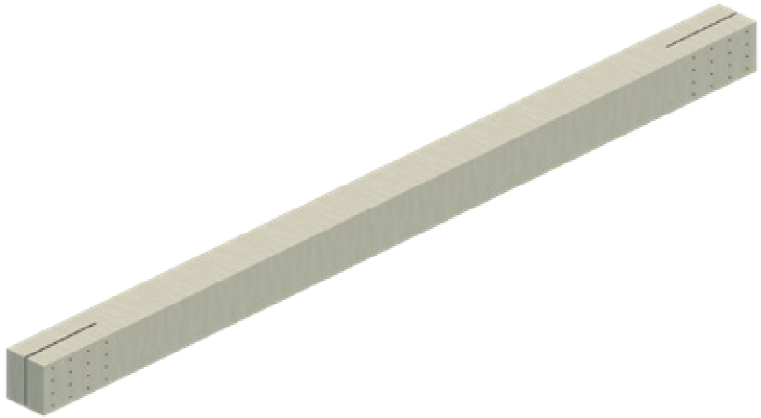


Fig 47: Standard beam length.

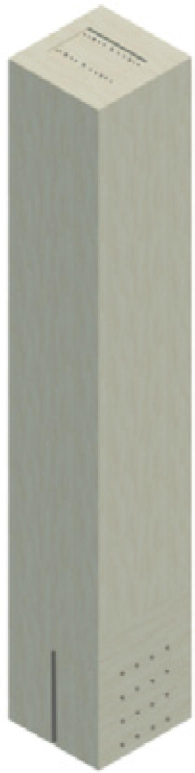
Fig 48: Beam connection detail.

5.4.2. Columns

As in the beams, The development of columns was guided by the concepts of simplicity and modularity. To enable easy configuration of these components, the establishment of the structural grid and component homogenization were parameters in the parametric tool.

The beams were designed to be manufactured from the most optimal material reference, glulam GL32c, based on the requirements determined in the analysis conducted in the previous chapter. The potential sizing of the beams ranges from 450mm to 1200mm for the upper and lower width and a cross-section height of 450mm to 1200mm. Similarly, the total length will vary depending on the mechanical requirements and will be within the range of 4500mm to 5550mm.

The column design uses standardized joints to simplify the assembly process. Pinned connectors are used to connect the columns to the beams at the extreme points of the element. The columns are pre-cut and drilled precisely to match the type of joints, which reduces onsite work and ensures high assembly precision. Furthermore, the non-permanent connection allows for exchangeability, disassembly, and potential recyclability.



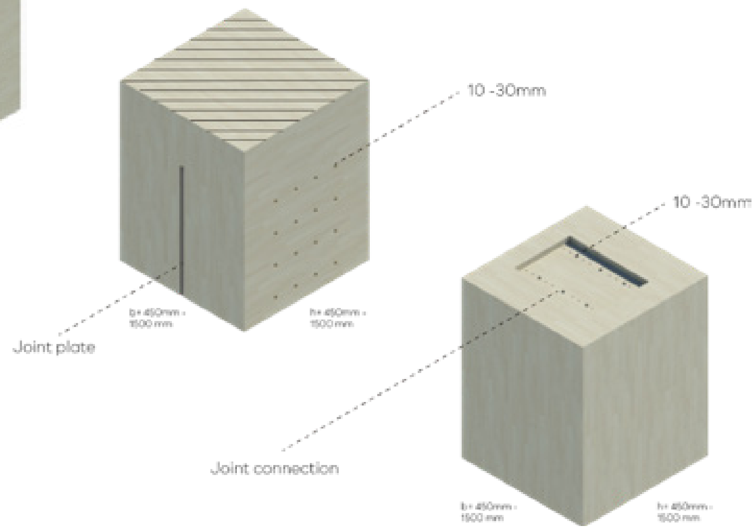


Fig 49: Standard column length.

Fig 50: Column to column connection details: bottom connection (left) and top connection (right).

5.4.3. Core

The core is a crucial element that determines the structure's overall stiffness and height potential. The mechanical properties and thickness of the core significantly influence the structure's performance, serviceability level, and even the sizing of cross-sections of other components. Therefore, determining the thickness of the core is an important factor to consider during the assembly phase, especially for taller buildings.

The core's size is considerably larger than the other components of the structural system, and for modular construction, the shear walls conform to a module of 9x6m. This configuration allows for eight shear walls, with two per face, that can cover the height of three storeys. Additionally, this configuration allows for maximum sizes that are transportable by commercial trucks, which facilitates logistics for distribution and assembly. Moreover, working with large components is also better for the dynamic response of the structure, as it reduces the number of connections and increases the structural integrity.

5.4.4. Joints

The parametric model highlights the crucial role of rotational stiffness in determining the structural behaviour of high-rise buildings under dynamic loads. To maintain structural integrity, rotational stiffness values typically range from 50,000 KNm/rad to 300,000 KNm/rad, depending on the required stiffness. For example, joints with rotational stiffness of 50,000 KNm/rad are suitable for components located in the high-rise where h=b, while 100,000 and 200,000 KNm/rad are required for h=2b and h>2b, respectively, and 300,000 KNm/rad to h>2b. It is important to highlight these values based on having a central core as a stabilizing component against horizontal loads. The stiffness requirements may vary depending on the structural system employed.

In order to achieve optimal mechanical performance, the kits joints will be made of slotted-in plates crafted from stainless steel grades s355-690, as specified in the material analysis section. Unlike many joint designs that utilize two slotted-in plates, this kit's design features a single plate at the centroid of the beam. This approach minimizes the number of cuts made perpendicular to the cross-section of the timber, preventing the division of the cross-section into three thinner components.

Each joint consists of two plates that are welded perpendicular to one another, with precise axial alignment and rotational resistance. To maintain the modularity and disassembly of the design, the timber component and joint will not be permanently joined. During assembly, the joint will be pre-installed into the column using high-strength bolts, followed by installing the beam on-site. For trusses, the joints will pre-assemble the top and bottom chords and install them with the webs on-site.

This preliminary design was created in consideration of rotational stiffness requirements and sizing design constraints.The preliminary Joints design part of the structural kit of this investigation is based on the sizing calculations made by Felicita M. (2021).To see the complete information and complete data can be seen in Appendix B: Joints design, B2:B22 design base.

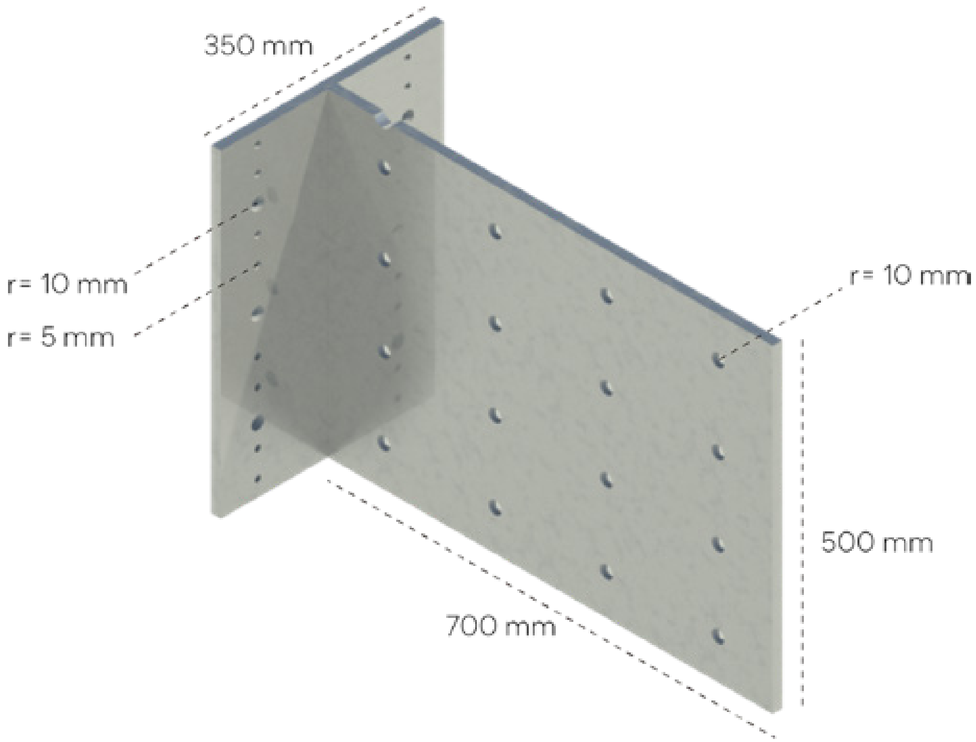


Fig 51:Joint Column - Column and Column - Beam 100000 KN m/rad rotational stiffness

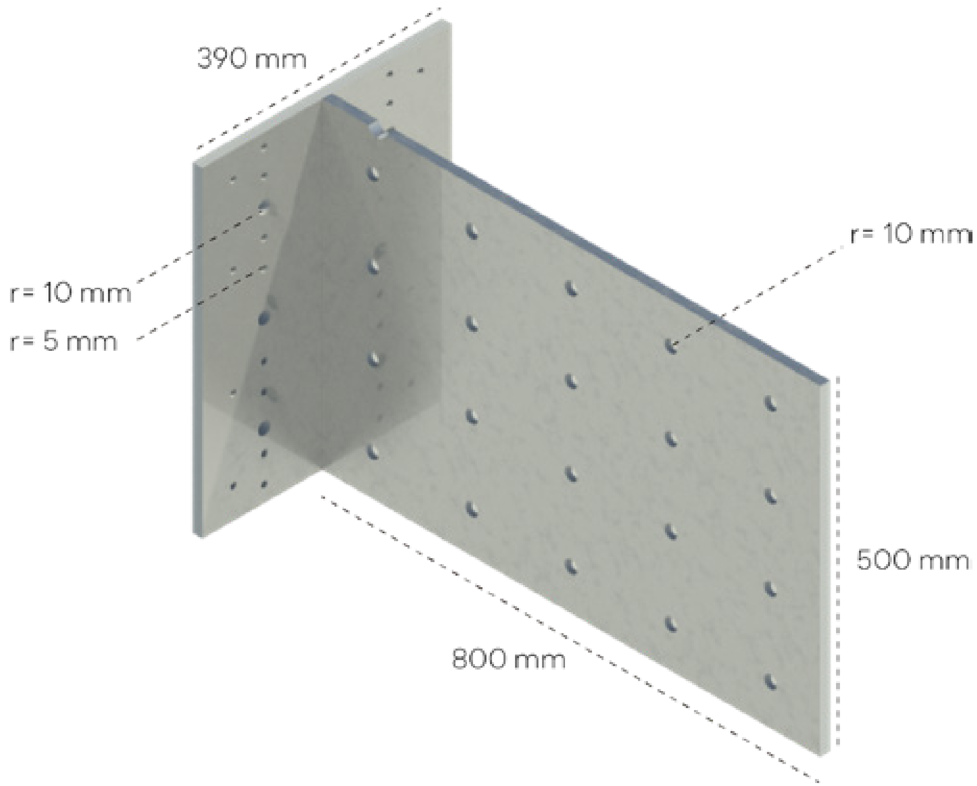


Fig 52: Joint Column - Column and Column - Beam 200000 KN m/rad rotational stiffness

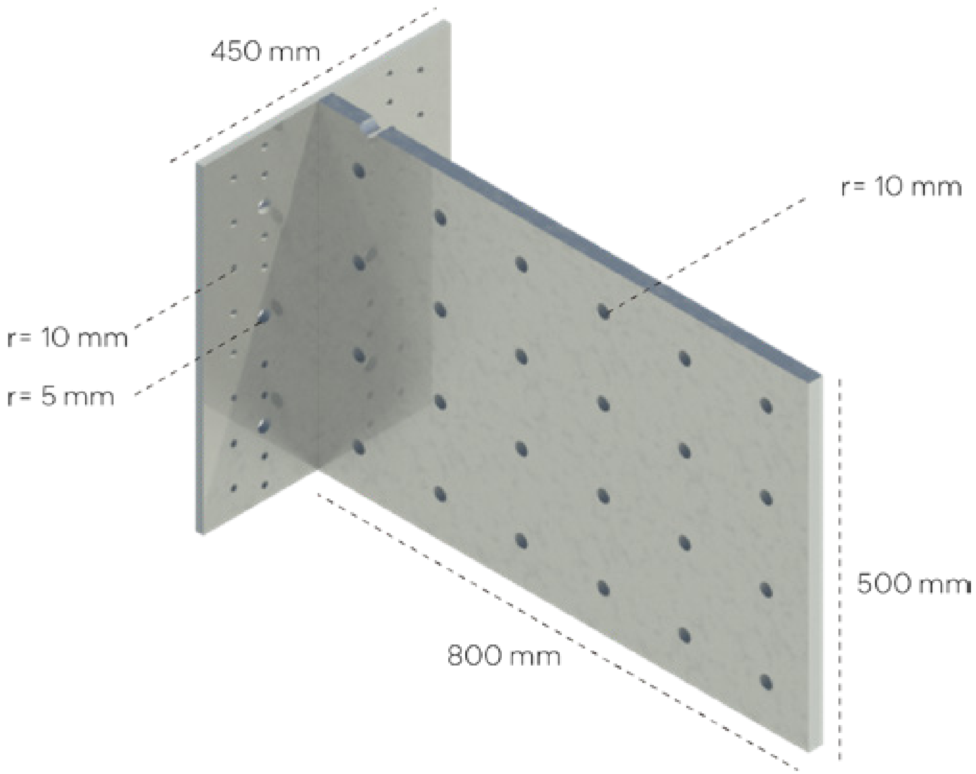


Fig 53: Joint Column - Column and Column - Beam 300000 KN m/rad rotational stiffness.

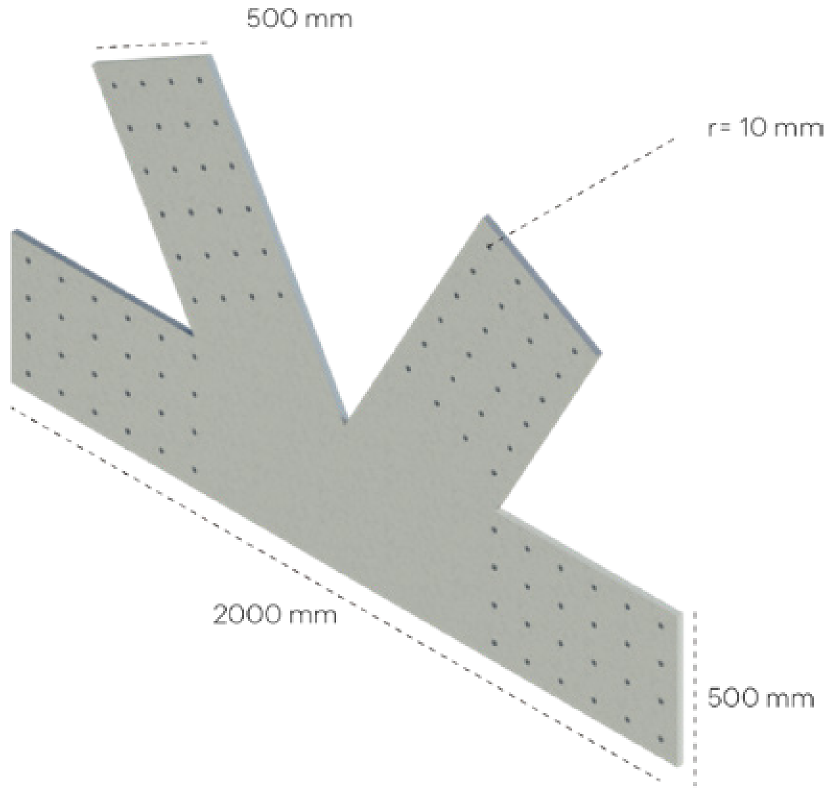


Fig 54: Joint truss Chords - webs

5.4.5.Truss:

The truss is the only component of the structural kit that was not evaluated in the parametric model, due to the fact that the use of trusses in timber and additionally in the context of highrises is highly uncommon, and the goal of the analysis was to understand the dynamic behavior of a frame with central core. Designing a circular component with both modularity and sustainability in mind presented a significant challenge. The challenge arose from the fact that a truss, due to its geometric configuration and load distribution requirements, comprises multiple components that are inherently dissimilar. The chords and webs within each section must be of identical scale to achieve a modular truss.

The scope of the modularity needed to be defined, whether it should be at the macro scale or at the structural component scale. If the modularity is at the macro scale, the webs and chords need to have cross-sectional constraints to align with other components in the system, such as columns or beams. This level of modularity would require the webs and chords to have 90° ending faces, avoiding diagonal cuts in the timber, thus allowing the beams or columns to be reused in other scenarios.However, to achieve this, the truss nodes would need to be the components connecting the different parts of the truss, making necessary a cold formed joint which would concentrate all the stresses in the metallic joint, requiring additional material with a high embodied energy to make it stiff enough to resist high loads.

Alternatively, achieving modularity at the structural component scale would eliminate the possibility of reusing truss components as columns or beams but still maintain the possibility of reusing the truss or part of it as the same component in future projects. This approach results in timber elements that can only be used to construct the truss. However, their geometrical configuration facilitates load distribution. It reduces stresses in the joints, reducing the required material and simplifying the joint design as it requires only a slotted-in steel plate. For this reason, this approach was selected as the preferred option. Fig 55 Shows the macro and components scale modularity possibilities.

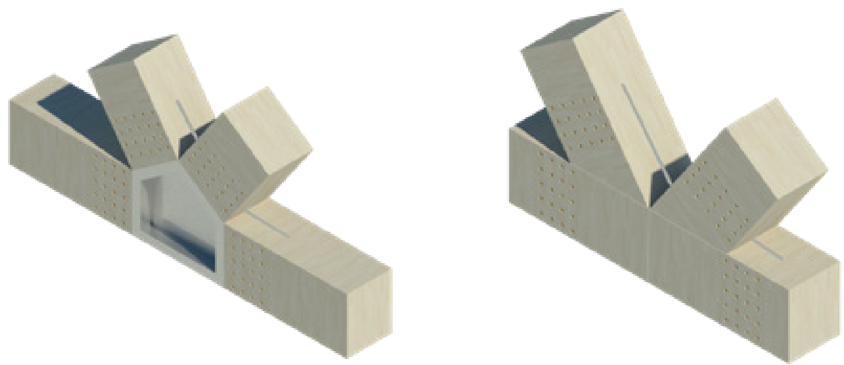


Fig 55: Truss macro and component scale modularity possibilities.

6.0

The timber highrise

6.1 Location

Fig 10: Merwe-Vierhavens panoramic view 1970´s (Rotmans J., Weel van der S., 2005)

The Merwe-Vierhavens area comprises about 200 hectares; The site is located between the borders of Schiedam and Rotterdam-West. This part of the port of Rotterdam was completed in 1930, aiming to receive large ocean-going vessels, positioning Rotterdam as one of the most important commercial ports for the Netherlands and countries of central Europe. The port was heavily damaged in WW II and was quickly rebuilt and expanded in the following years. Rapid industrialization, water and soil pollution, and the drastic reduction of labour caused urban decay between the 1970s-80s. Today, most of the land is used mainly for Storage and transhipment and is owned by the port authority and the municipality (Rotmans J., Weel van der S., 2005).

By 2030 Rotterdam wants to be the pioneer in being a "living laboratory" of implementation on the big scale of the economic transition from a linear to a circular economy (Rotterdam circular 2020). In 2017, the municipality and the port authority entered a unique collaboration to create M4H, an ambitious urban renewal project in Niew-Mathenesse. The initiative wants to transform a deteriorated industrial area into an innovative living and working environment, optimally equipped for the innovative manufacturing industry and with a mix of working, living, culture, catering, sports and education (Ruimtelijk Raamwerk M4H., 2020).

Fig 11: Spatial framework Merwe-Vierhavens (Ruimtelijk Raamwerk M4H., 2020).

Urbanistic goals of the master plan:

- Create an urban residential environment on and around the Maerwepieren.
- Develop the area as a testing ground and showcase for the circular future of the city and port.
- Realize and open innovation environment with diverse mix use of companies, education, and sustainable manufacture.

The master plan is divided into five districts to create a mixed environment that generates an active and dynamic neighbourhood.

M4H Rotterdam, according to the project's spatial framework, is an area where experimentation with new products or processes is possible. New technologies are conceived, tested, and applied. These new technologies are based on digitization, robotization, additive manufacturing, and the application of new, renewable energy and materials. This goal makes the district a testing ground and showcases the new economy. For that reason, the timber highrise will be developed in the sector categorized as: "urban communities-Merwehaven" the sector of the master plan with the highest mix-use requirements in a dynamic and circular urban context.

6.2. Design brief:

Following the circular goals of the M4H master plan and the Gemeente Rotterdam the circular highrise will have the following design brief:

Project Description:

The Circular Highrise is a sustainable and adaptable building designed with the principles of design for disassembly, adaptability, modularity, and durability. The building is designed to address the challenge of construction waste generated by infrastructure obsolescence, set a standard for high-rise design that is environmentally and socially responsible, and create a symbiotic relationship between the building and its environment.

Use:

Mix use: Cultural (Black box, library, art gallery), housing (flexible configuration), public space at different levels

Height:

Max height 105m.

Design Concept:

The Circular Highrise is a modular and completely demountable building, allowing it to be prefabricated, relocated, expanded, or reconfigured to meet the changing needs of occupants or the city. The building prioritizes sustainability, versatility, and longevity of its structural system. The components are easily removable and recyclable, considerably reducing waste generation. The building uses modular components, simplifying the disassembly process and allowing for easy repair and maintenance over time. The structure allows the building to increase its floor area vertically as additional square meters are required. The interior spaces of the building are flexible and adaptable, allowing for changes to the building's layout and function over time.

Goals and Objectives:

1. To address the challenge of construction waste generated by infrastructure obsolescence.

2. To set a standard for high-rise design that is environmentally and socially responsible.

3. To create a symbiotic relationship between the building and its environment, following the renovation plan and goals of the spatial framework of M4H.

Materials:

The building is constructed with prefabricated engineered wood

6.3. Design strategy:

Timber is a highly efficient material for low-rise construction, offering numerous advantages that make it more competitive than traditional construction materials. However, when it comes to high-rise buildings, the implementation of timber poses challenges due to its insufficient self-weight and strength, which are essential for load-bearing materials in tall structures. In contrast, concrete and steel have unquestionable advantages over timber in high-rise constructions.

In Chapter 4, the structural analysis was conducted to compare two variations of a 102m tower with a 36m square base. The structural systems examined included a modular frame of 6x6m and a central core made of Glulam-CLT core and Glulam-concrete core. The analysis revealed that the traditional slender high-rise design used in both configurations put the biobased option at a disadvantage due to its inferior mechanical properties compared to traditional construction materials.

Considering a slenderness ratio of 3:1, the structural analysis tested the structural configurations limit state based solely on their mechanical properties. This factor directly impacts the dynamic response of a high-rise structure, regardless of the material used for the core. Implementing a slender high-rise design using solely timber as the load-bearing system disregards the limitations of the material's mechanical properties. In the case of a 102m timber tower, the cross-sections of the components become technically impractical and result in high environmental and financial costs. However, by reevaluating the concept of timber high-rise buildings and opting for more suitable typologies, the challenges posed by horizontal accelerations can be addressed, leading to a feasible and more efficient use of the material. For the purposes of this investigation, a slenderness ratio of 1:1 was chosen for the study case, meaning that the height of the building is equal to its width or depth. This results in a cubic shape, creating a compact and stiff structure. Buildings with a slenderness ratio of 1:1 are geometrically the most stable and least prone to issues such as excessive lateral deflection or buckling.

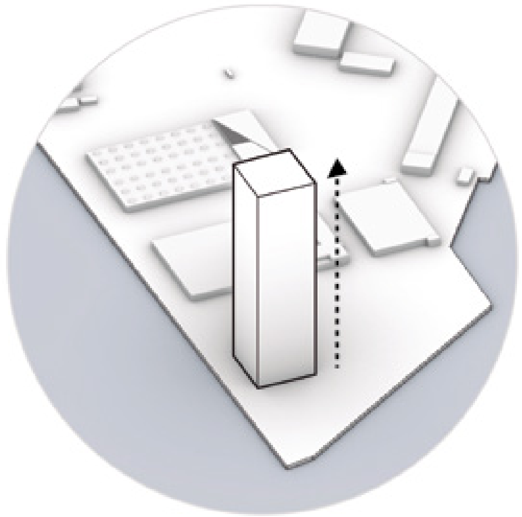
Slenderness superior to 1:1 behaves as Bernoulli's beam theory; for that reason, The transition from a vertically rectangular shape to a cubic configuration amplifies the support area, resulting in higher global stability and reduced dependence on core stiffness. The cubic shape creates a stiffer system. This was evident in the analysis of chapter 4. where the deflection of the system under a given horizontal load was directly proportional to its length. Adopting a slenderness ratio of 1:1 makes the system more rigid and experiences smaller deflections than other typologies.

Taking into consideration the change slenderness ratio for a better material and structural performance and the ambitious architectural program, the building is conceptualized as a combination of high and low rise, considering a cube as the natural equilibrium between the horizontal and the vertical. The circular high-rise is designed with the concept of a city within a city, serving as both a residential and cultural landmark that is integral to the urban renovation plan and economic transition of the city.

Located on the waterfront in the Gelileopark area, the high-rise is a crucial element in the transformation of the surrounding blocks into a vibrant urban neighborhood, offering a self-contained and multi-functional building. The vertical city concept aims for a compact and efficient urban environment that maximizes the use of available space. The project's particular location potentializes the idea of creating a new cultural hub for Rotterdam and an experimentation showcase of circularity in the building environment through implementing modular timber construction to a complex architectural program.

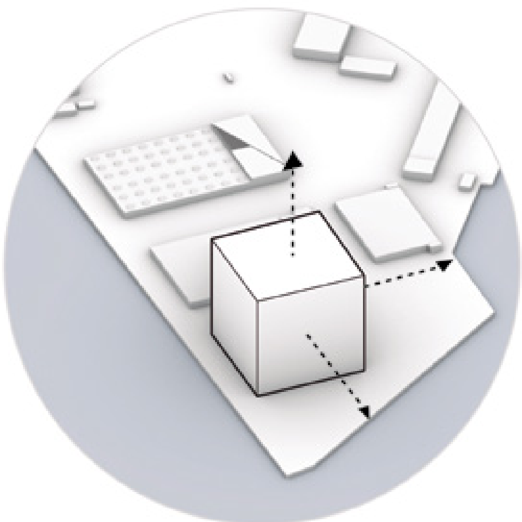
The DNA of the project came from the idea of mixing two different spatial configurations, one the vertical densification of the highrises and the horizontal and dynamic relation of a city in the ground floor. For that reason, the traditional slenderness and verticality of a rectangular volumetry of conventional highrises was not applicable technically and spatially. The understanding of the circulation as a variable that shapes the city and the architectural volume was clear, were the verticality of the densification and the horizontality of an active city should be implemented.

1. Vertical typology



2. Horizontal typology

3. Vertical & Horizontal



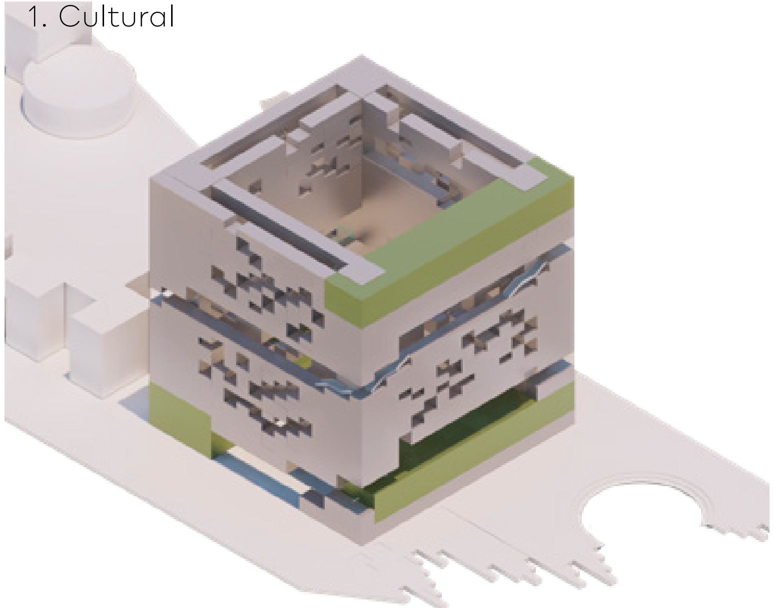
4. Spiral circulation

Fig 57: Volumetric Massing

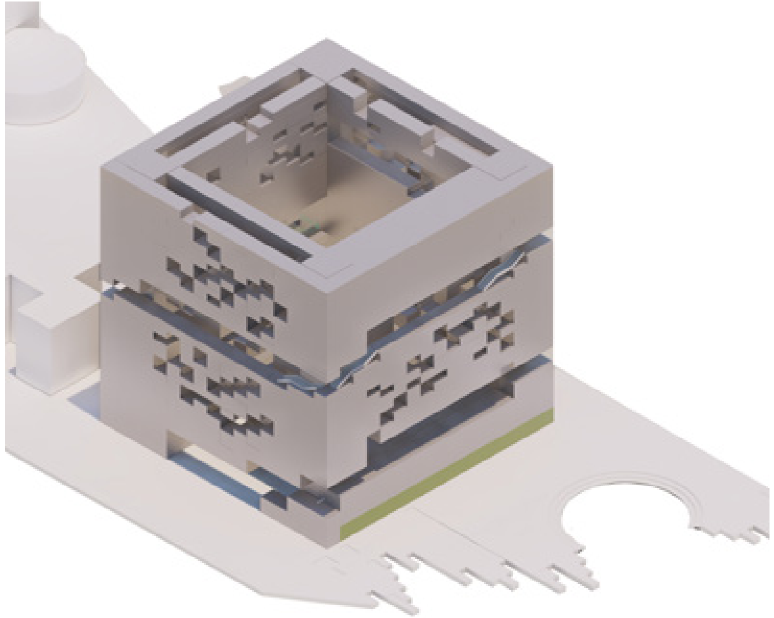
The cube starts a process of modification where its central interior part is extracted to create a courtyard. This central patio will serve as the epicenter of the volume, establishing a connection between the building and its surroundings. The solidity of the faces of the volume began to deconstruct through an open peripheric and spiral circulation that runs from the bottom to the top, allowing a multilevel connection and space generation. One of the project's goals is to generate a dynamic project avoiding challenges of traditional high rises like social isolation and inaccessibility to public space. For that reason, the cultural uses are located in the vertical extremes of the building, with an important component of housing and open circulation in between.

The theater and art gallery are located on the ground floor, creating with the courtyard a gathering space in the middle of the building with a direct metropolitan connection with flows that come from the west, allowing a multidirectional relation of the volume with the city and the surrounding public space network. The spiral peripheral circulation connects the ground floor to the top of the building, generating a walkable and multilevel public space until the public library is located on the building's top floor, providing different views of the city and the harbour.

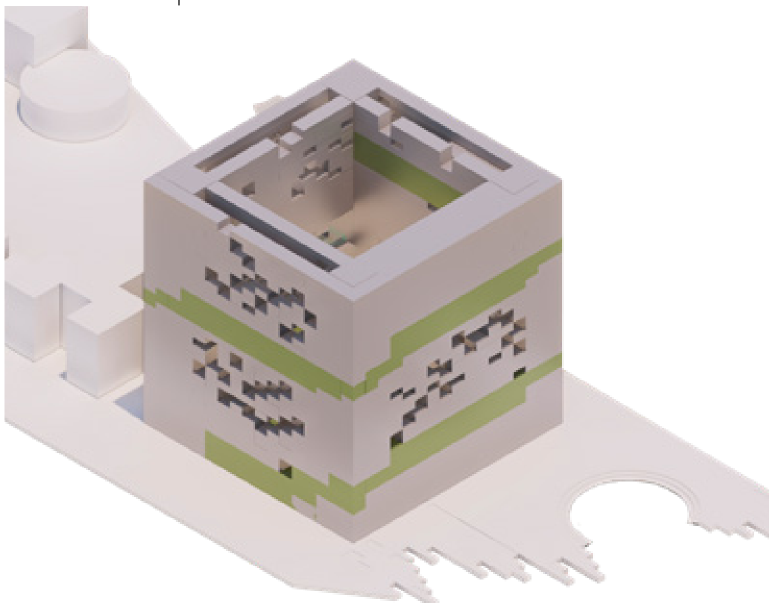
1. Cultural



2. Retail



3. Public space



4. Housing

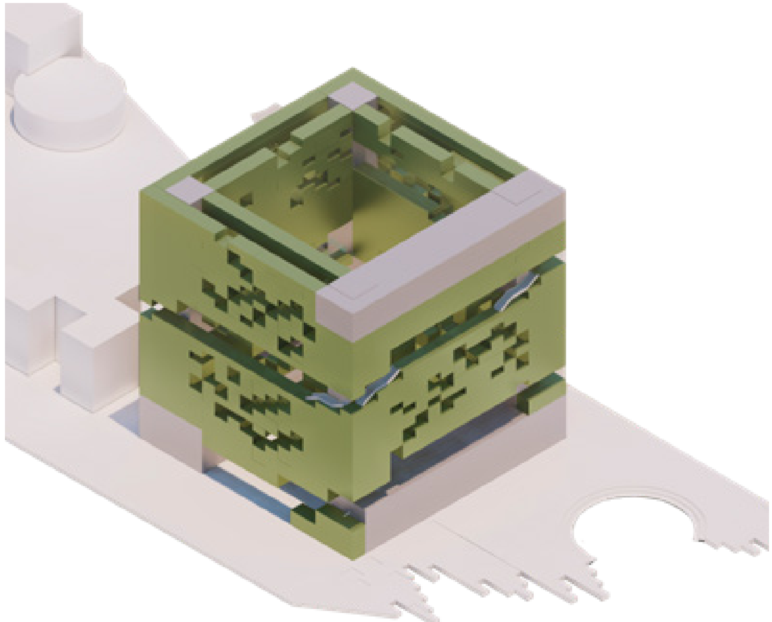


Fig: Azonometric view

6.4. Structural design strategy:

The integration of various scales within the same structure presents the primary challenge of this project. Spaces such as the theatre, art gallery, and public areas necessitate significantly larger spans than residential sections. Consequently, a multiscale configuration must be implemented to address this demand. To achieve this, the building's structure has been divided into three distinct groups: small, medium, and large spans. These different spatial requirements emphasise the priority of ensuring compatibility among multiscale components. This compatibility is crucial for effectively integrating functions with diverse spatial needs. As outlined in chapters 4 and 6.3, the parametric model highlights the significance of height, slenderness, and core variables. These factors play a decisive role in the structure's stability and serviceability. Thus, it becomes essential to consider these challenging factors as potential strengths for this particular project.

The architectural program's complexity makes it impractical to implement the typology of a conventional and slender high-rise due to the different space requirements. To address this challenge, the change in slenderness ratio from 1:3 to 1:1 resulted in a more geometrically stable and feasible shape structurally and architecturally. The cube's total volume is reduced to have a usable area along the volume's perimeter. At the same time, the central region remains hollow to ensure adequate natural light and ventilation levels, creating a square ring shape. The massing configuration forms a central patio with four perpendicular faces surrounding it, which are interrelated in a multilevel way by four cores positioned at the central areas of the corners of the square-shaped ring.

The results from the parametric model presented in Chapter 4 demonstrate the significant stress levels a single core configuration must endure. However, implementing a cubic shape with four cores makes stress dissipation much more manageable. This is attributed to the multi-level stability configuration inherent in the geometry, which enables different parts of the structure to collaborate and facilitate distributed dissipation of wind-induced accelerations. As a result, this promotes enhanced efficiency and stability in the overall structure while simultaneously alleviating the stresses imposed on a single core. Figure 59 illustrates the structural configuration of the building, showcasing the implementation of the cubic shape with four cores.

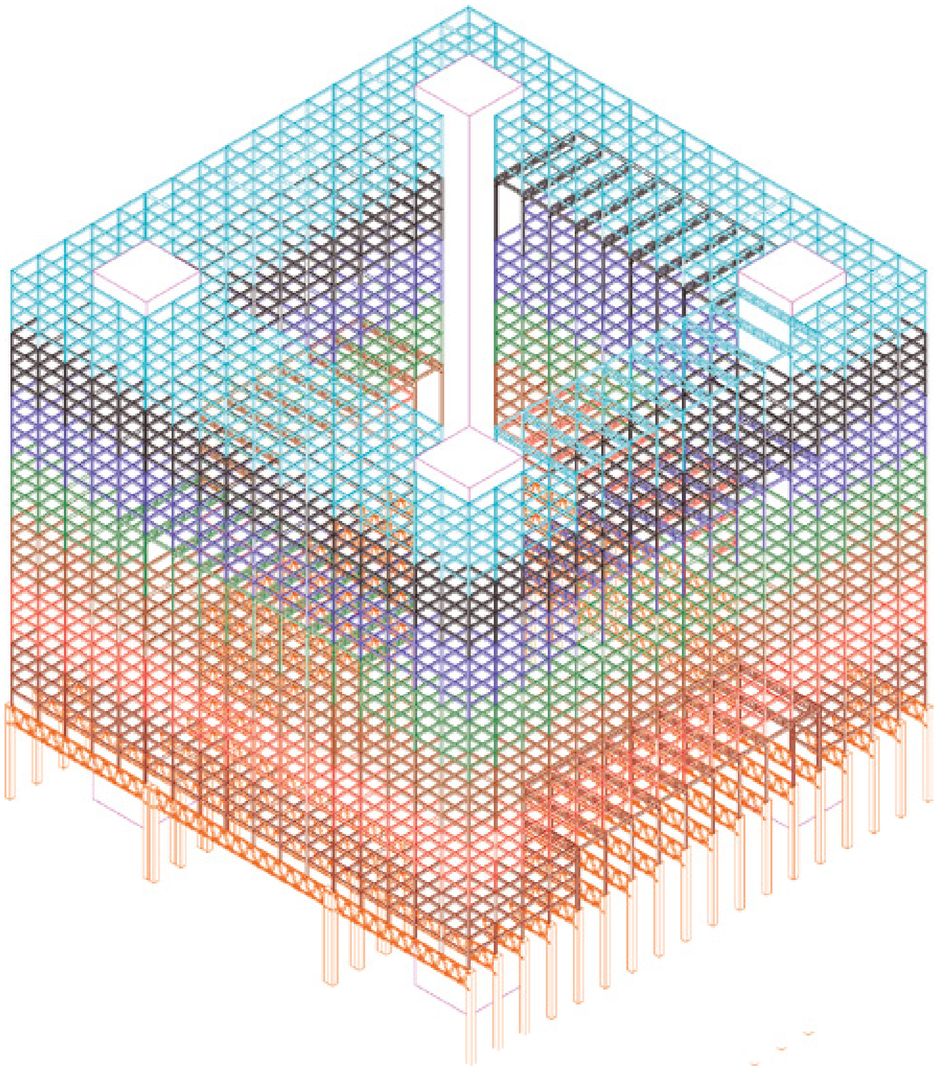


Fig 59 :Structural configuration

The cluster map's colours represent different sections of the building's structure. Starting from the bottom, the orange section represents the theatre area, which features the largest truss system. Designing this space presented a challenge as it required an effective horizontal span of 30 meters, divided into one 18-meter span and two 6-meter spans, to create a functional interior. The main challenge was meeting the load-bearing requirements for this component, which amounted to 348 kN/m, corresponding to each linear load from the stories above. To address this, the design employed a proportional approach while adhering to the constraints of the structural grid. The rectangular area was divided into narrow and wide spans, utilizing the 6-meter distance between axes for the longer section of the rectangle, while the shorter section accommodated the required 30-meter span (see FIG 60). Due to the high load-bearing requirements, timber was not a viable material option. Instead, high-strength steel was chosen for the Pratt truss system to effectively distribute vertical loads to the supports located at the perimeter of the floor area, resulting in a completely open floor plan underneath. Additionally, to ensure global stability and prevent buckling, two beams with a 1-meter cross-section were employed to stabilize the columns at the top and middle points in the direction of the 6-meter spans between the truss axes. The trusses are interconnected by nodes every 6 meters until they reach the cores, creating a high level of stiffness within the overall structural configuration. This integration of trusses and cores significantly contributes to achieving global stiffness throughout the entire large-span structure.

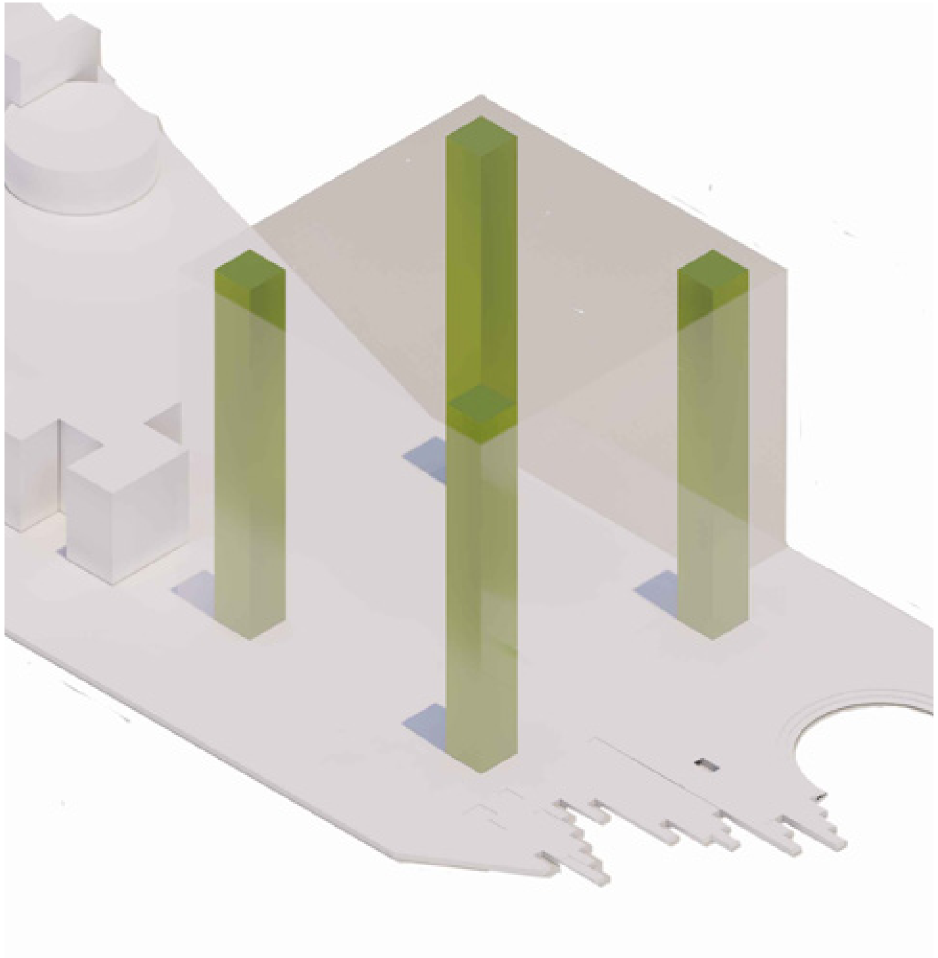


Fig: cores

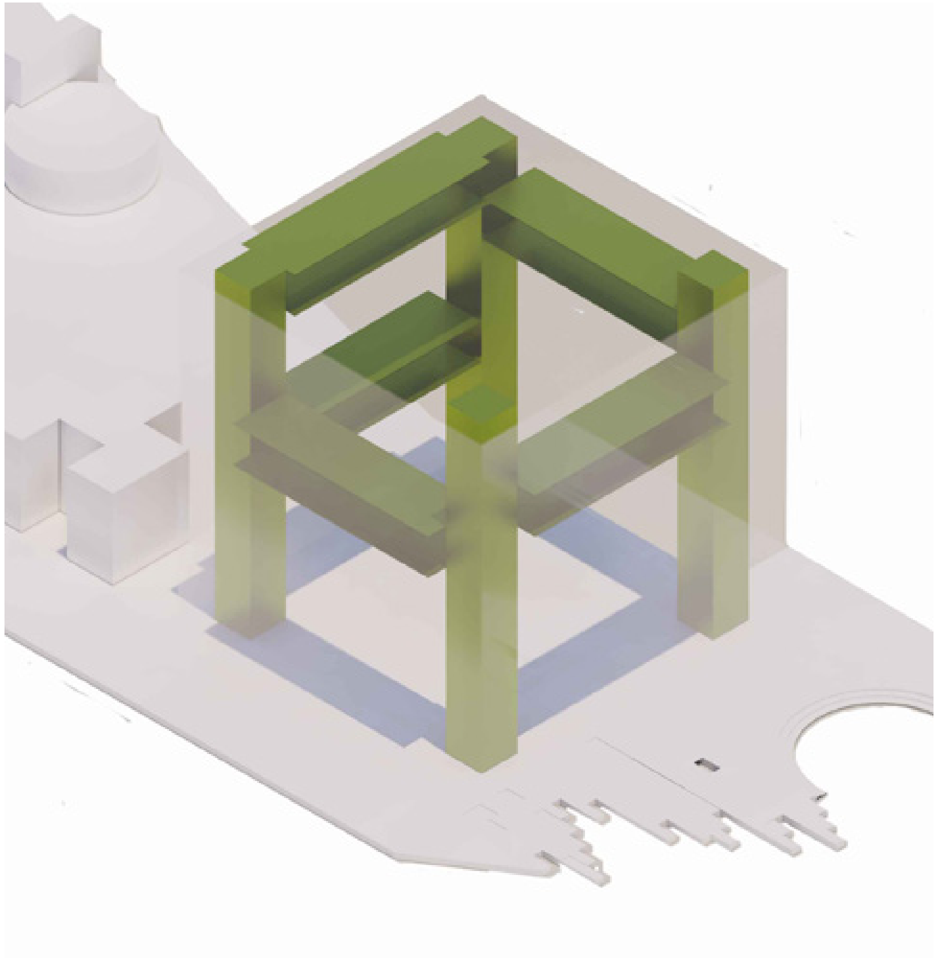
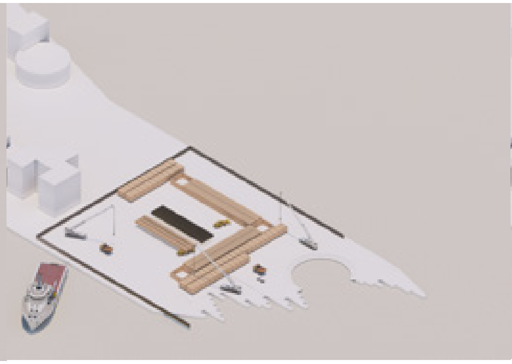
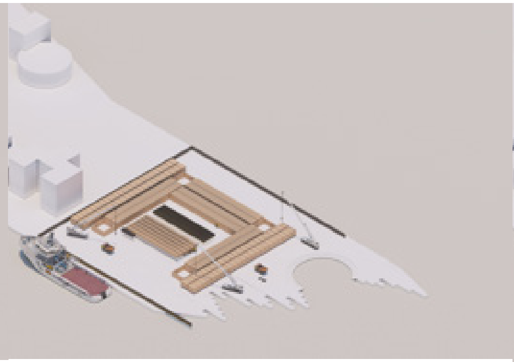
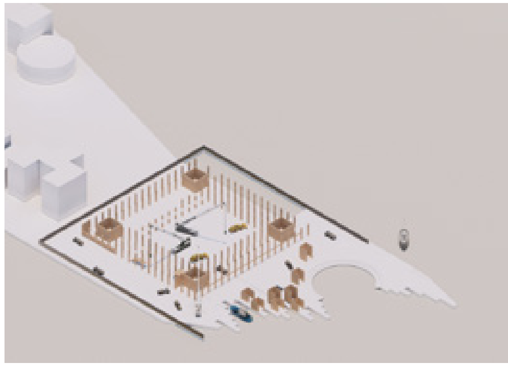
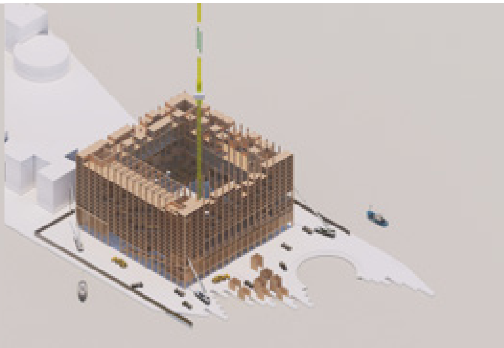


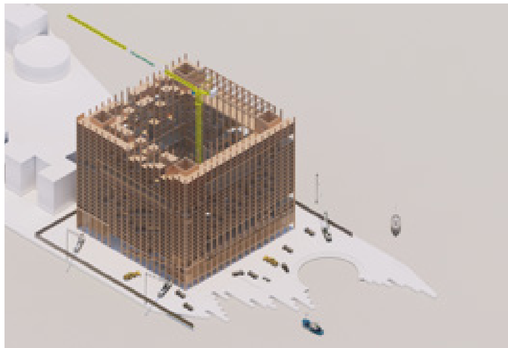
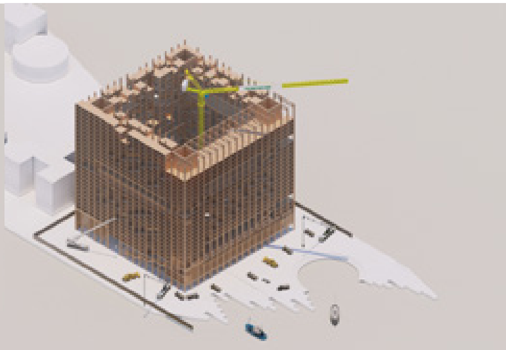
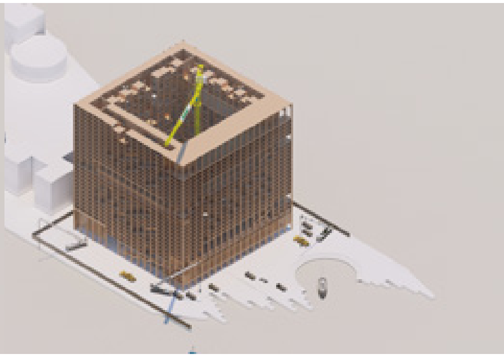
Fig: Selft weight flooring/platforms





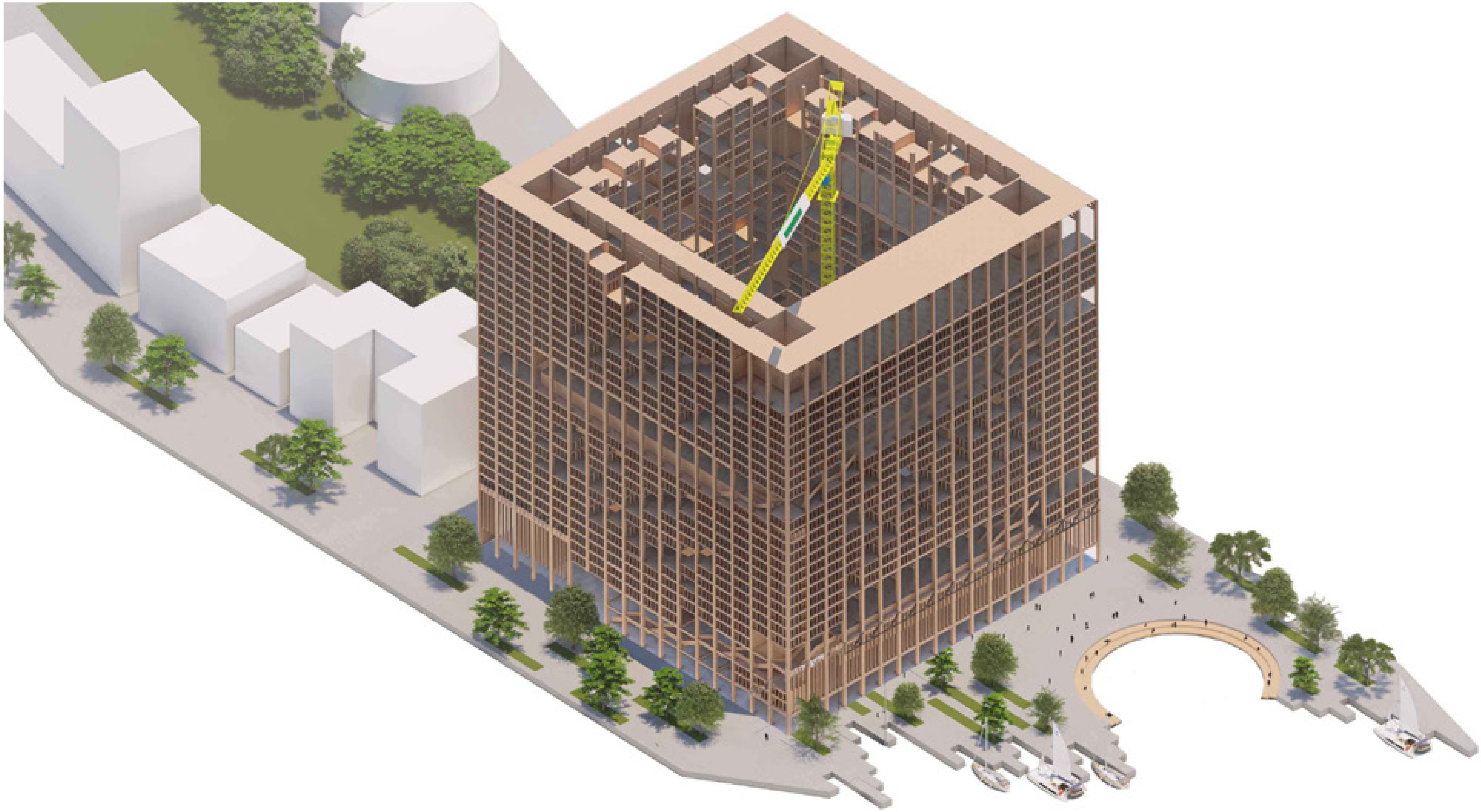



Fig: Macrostructure

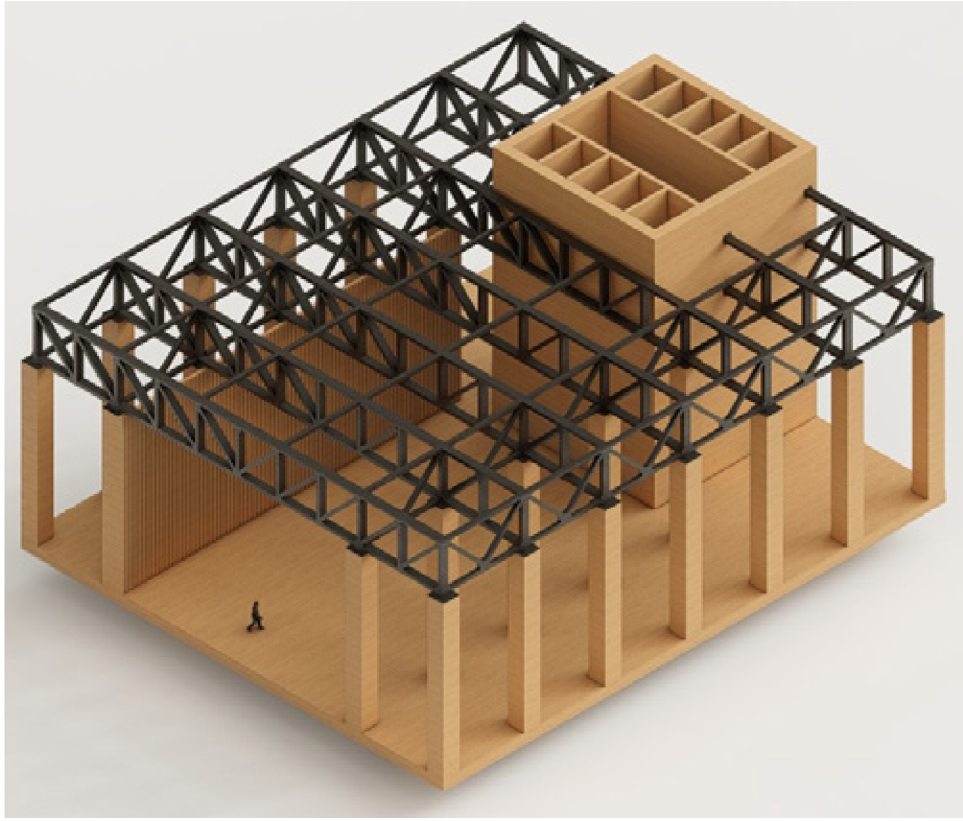


Fig 60 :Structural configuration Theater (orange section).

Following the colour code depicted in FIG 59, as we move upwards from the bottom, clusters with smaller and medium spans are represented by varying shades from brown to light blue. These colour variations reflect the different structural configurations resulting from changing spatial requirements driven by the architectural program. The medium-span spaces are designated for the multilevel public area and the library on top of the building. To achieve functional spaces within the medium-scale configurations, an 18m span is necessary. For this purpose, a Warren truss system is employed, a truss type suitable for medium-span lenghts and highly compatible with the multiscale layout between the small and medium scales. The 18m span is achieved by creating three series of "V" shapes using the webs of the truss, each covering a 6m span. This aligns precisely with the small-scale glulam frames. Each truss cord facilitates an equidistant and uniform distribution of loads along the entire 18m truss length. This configuration ensures structural integrity and stability within the medium-span area while accommodating the multiscale compatibility required in the overall design.

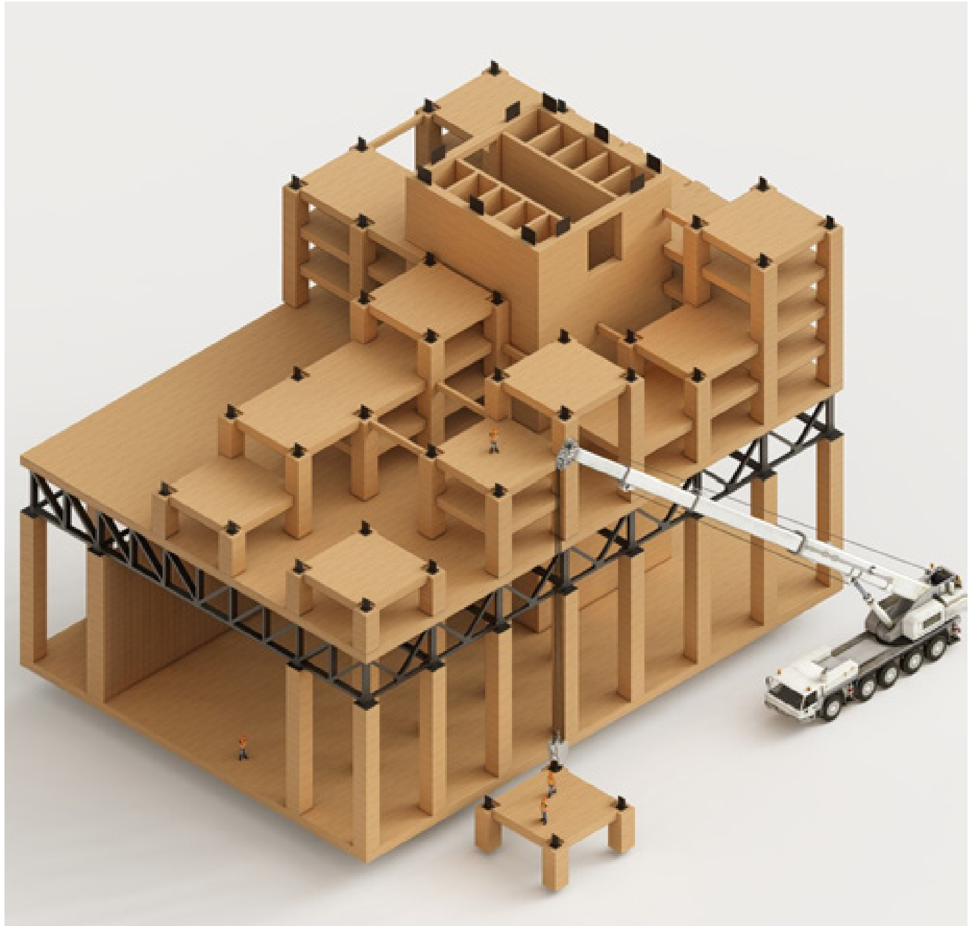


Fig 61 : Correlation of different scales in one cluster, frame and truss

The cubic shape of the building is formed by a sequence of layers of clusters that create two different structural systems with different dynamic reactions to the wind. The four cores in the corners function as a core and frame typology, while the long facades between the corners behave as a frame system. Sections 4.3.1.and 4.3.2. of the parametric model demonstrate the importance of the core in the stability system of the building, as well as its significance for global stiffness. Moreover, the model provided insights into how a structure without a horizontal stabilizer system responds to horizontal accelerations. The glulam frames between the four cores are exposed to strong accelerations, requiring high-strength components and joints to maintain ultimate service limits. Since these frames lack a core the subchapter 6.5. will evaluate the dynamic response of this configuration.

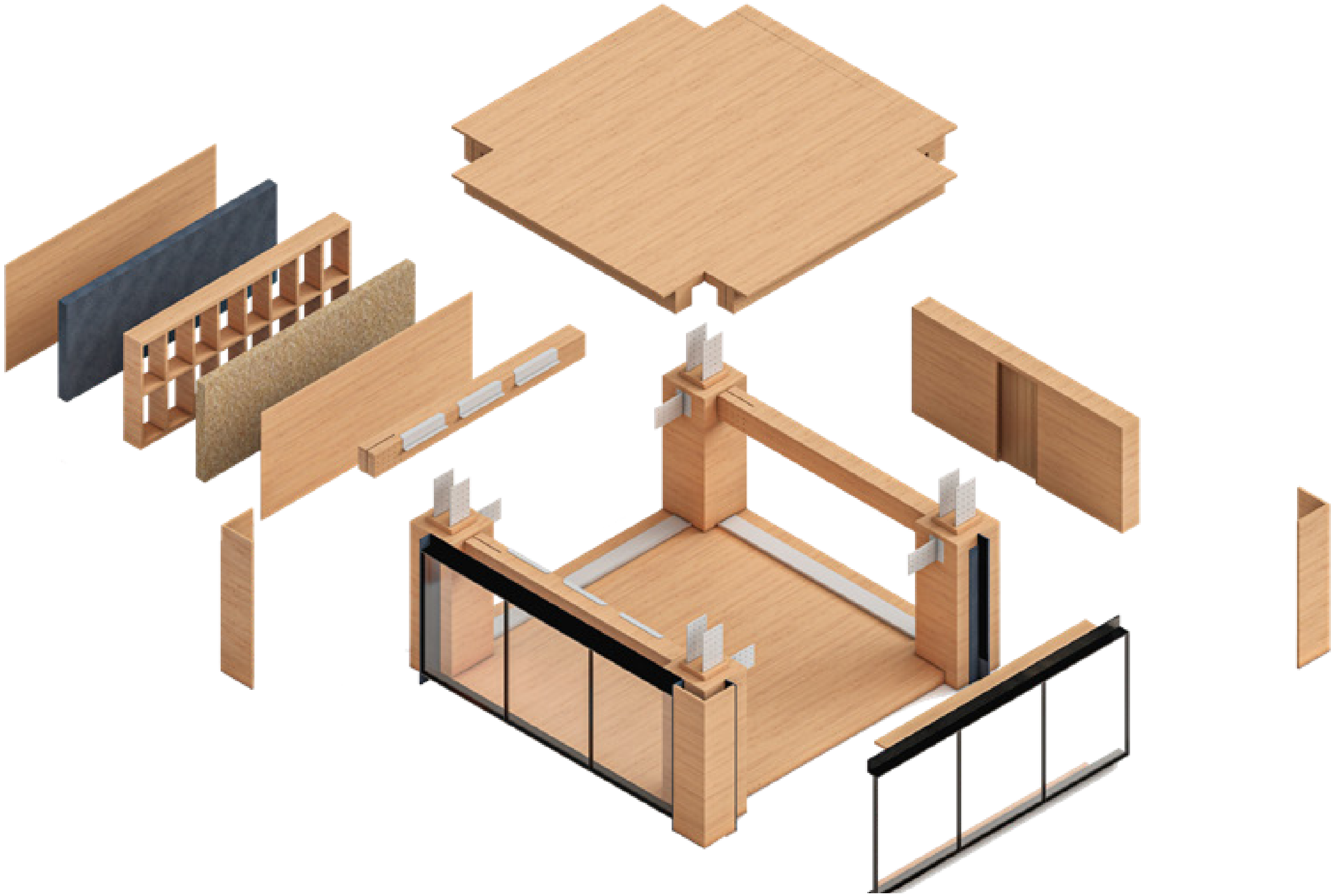


Fig: Construction process module

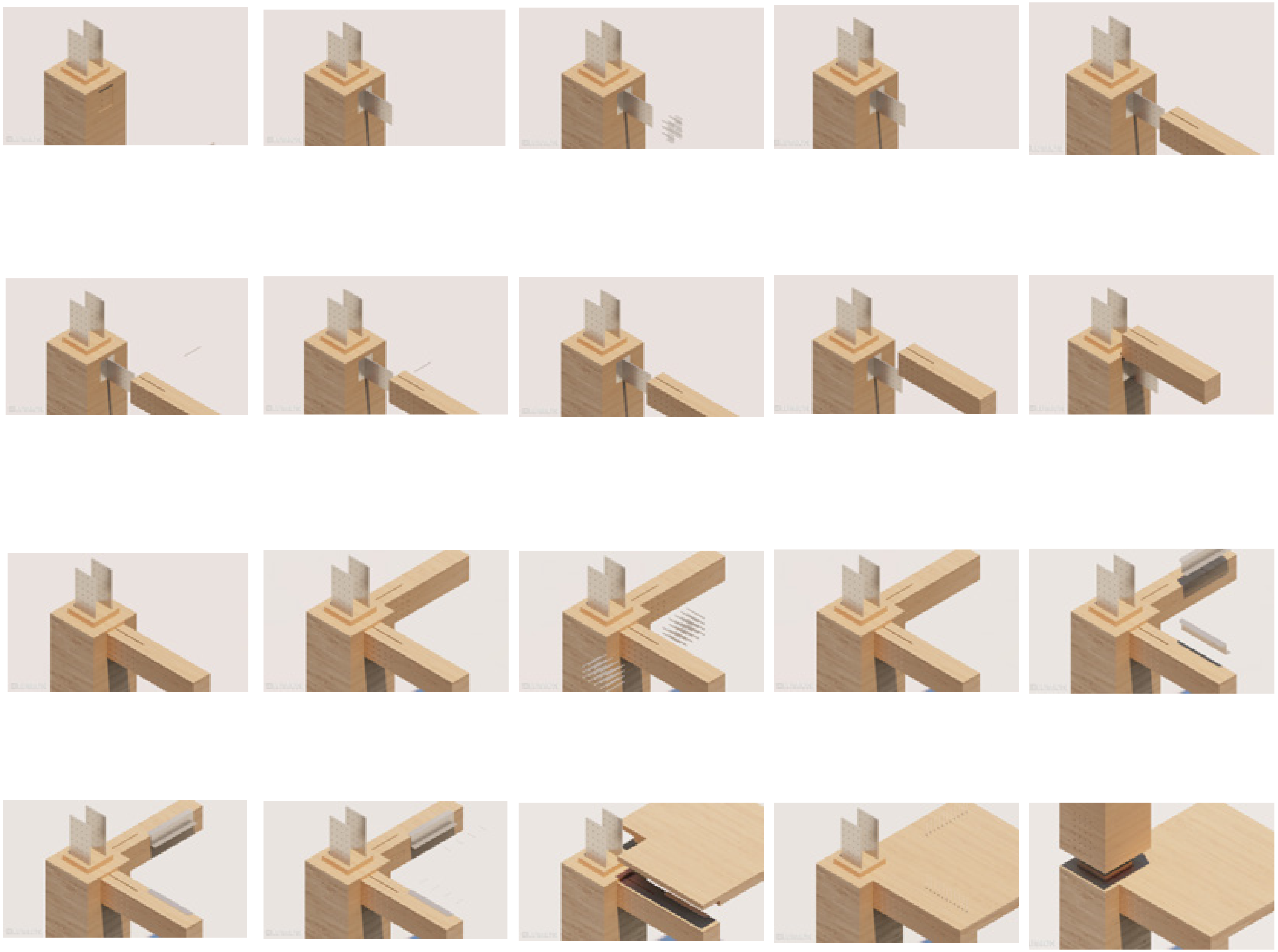


Fig: Construction process module

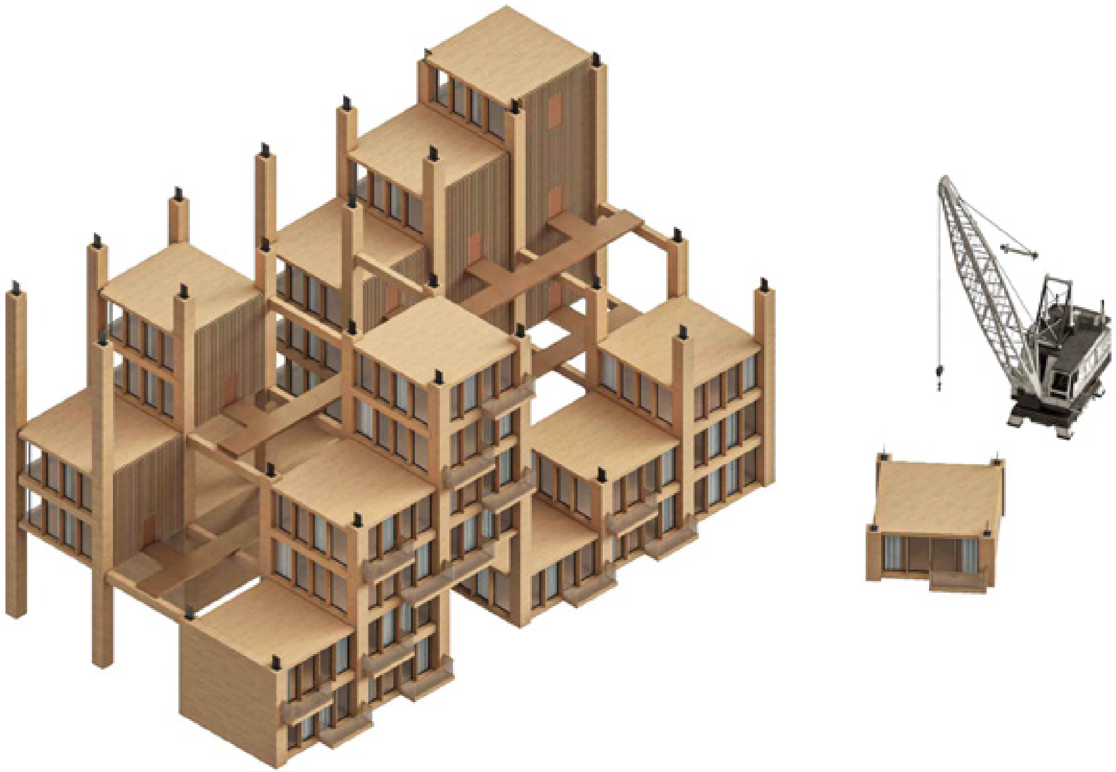


Fig: Construction process module

6.5. Dynamic response structure:

Since the volumetry of the building changed, an additional study regarding its dynamic response was made to analyse and see the behaviour of the structure with the implementation of a square ring shape configuration with four cores. The optimization process for the structure involves a glulam frame and CLT core system, which aims to create data that makes it possible to analyze and compare it with the parametric models of the single tower typology. This optimization searches for solutions from thousands of potential options, enabling the use of timber as the primary load-bearing material for vertical loading in high-rises and CLT as lateral stabilizer. An evolutionary algorithm was used to analyze various combinations of inputs, including the core thickness, glulam types for columns and beams, and the lower and upper widths for the cross-section of columns and beams.

Additionally, three potential rotational stiffness values for joints (100000, 200000, and 300000 KNm/rad) were evaluated dynamically to ensure that design constraints were met. The genome was configured to minimize material usage while adhering to rigorous constraints of modularity, serviceability, and limited state regulations. The optimization maintained a global deflection limit of 0.204, an inter storey drift limit of 0.0075, and an acceleration limit of 0.39 m/s2.

However, a Python script was included in the post processing stage to avoid potential conflicts between constraints. This script helped to ensure that the optimization prioritized rotational stiffness values based on their mass, penalizing those with higher masses to reduce their potential for use. As a result, the optimization compensated for global stiffness and stability through other model components, such as columns, beams, and core, which prioritized timber mass over steel mass. The values used for the rotational stiffness of joints were 100000 KNm/rad: 23.9 kg, 200000 KNm/rad: 36 kg, and 300000 KNm/rad: 57 kg. By implementing these measures, the optimization process ensured the best possible solution for the given constraints, resulting in an efficient, stable, and sustainable high-rise structure option configuration.

- Total Iterations evaluated (Set of potential solutions): 340 for the time os optimization was not possible a higher number
- Best value: 247472

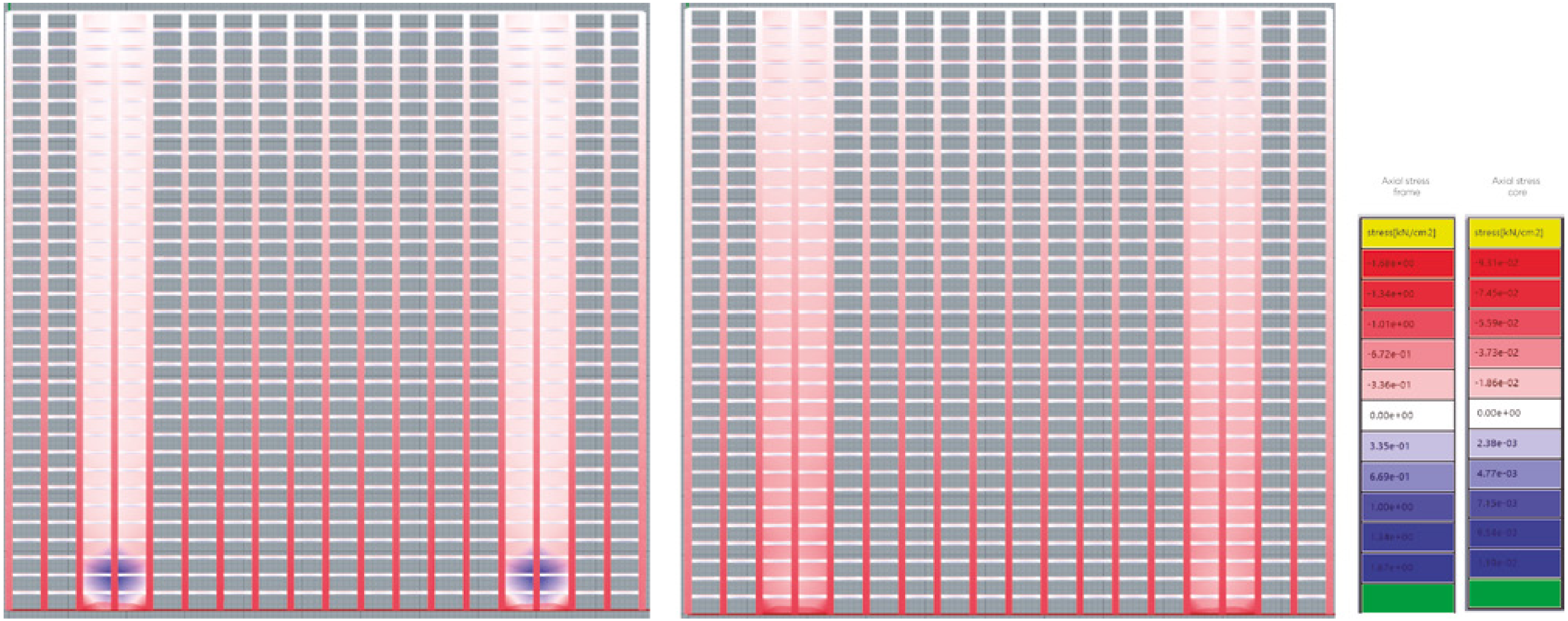


Fig 62 : Axial stresses

For modularity and simplicity, the optimization was able to take only one option of the cross-section for columns and beams; in the case of rotational stiffness, the components were according to the demands selected in the specification previously explained. Components final sizing after optimization:

- Columns: 1400 x 300mm
- Core thickness: 700 mm
- Beams: 350x700mm
- Rotational stiffness:
-
    - 100000KNm/rad: 4 storeys
    - 200000KNm/rad: 23 storeys
    - 300000KNm/rad: 6 storeys

ULS and SLS results:

- Global deflection: 0.145234
- Inter-storey drift: 0.006845
- Utilization beams and columns: 0.921482
- Utilization cores: 0.869

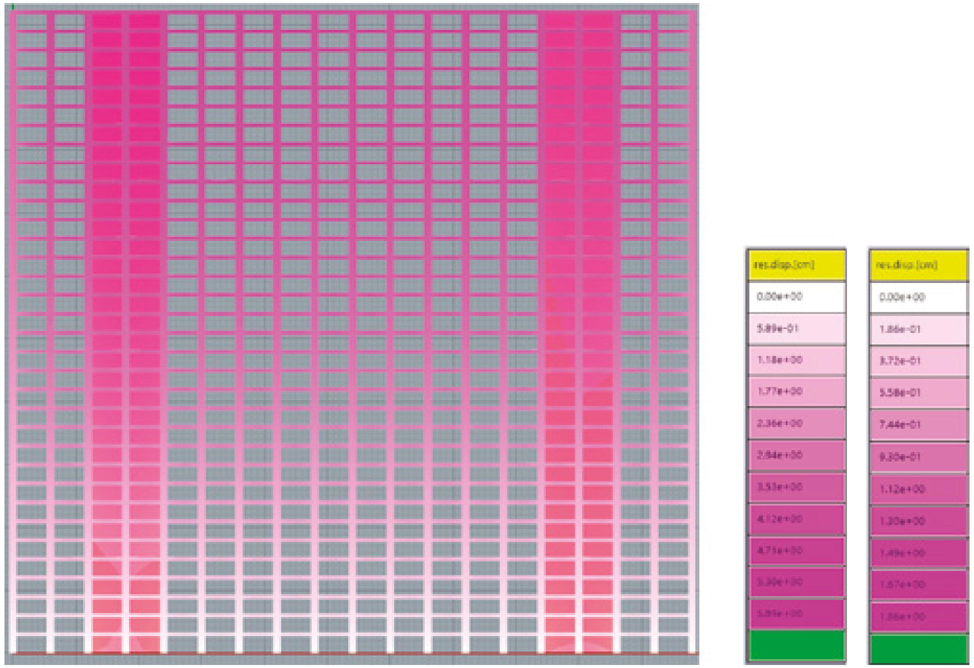


Fig 63 : Displacements.

Conclusion and discusion:

After conducting 340 iterations, option 247472 was selected as the most optimal design for a glulam frame and concrete core structure. The analysis revealed that, in order to meet the limit and serviceability limit state requirements according to Eurocode NEN-EN 1998-1 (EC8), the cores play a predominant role in the global stiffness of the structure, experiencing the highest concentration of stresses.

To resist the load, the longer area of the columns was oriented perpendicular to the predominant wind pressure. The thickness of the cross-laminated timber (CLT) core is inversely proportional to the rotational stiffness required by the joints. In this particular case, the CLT cores achieved a thickness of 80cm, with the predominant rotational stiffness required being 100,000 kNm/rad, accounting for 13% of the total. Additionally, 68.6% is attributed to 200,000 kNm/rad, and 18.4% to 300,000 kNm/rad. The higher mass concentration of steel is due to the use of the two heavier configuration of rotational stiffness, which has a weight of 36kg and 57kg for 200,000 and 300,000 kNm/rad, respectively. This led to the selection of glulam type GL32c, which has one of the highest weight-to-strength ratios in the European market.

The stress distribution varies among the components. For columns, the highest concentration of compressive stresses is located on the lower floors due to the vertical loading of the structure, gradually decreasing exponentially in proportion to the height, from 1.68 kN/cm of compression to 1.39 kN/cm of tension at the highest point. The beams experience constant perpendicular distributed vertical loads, resulting in compression on the top face and tension on the bottom face. Additionally, stresses increase perpendicularly to the cross-section as the height increases due to the wind pressure. The higher the location of the beam, the higher the stresses near the joints. The two cores facing the predominant winds experience tension in the bottom close to 1.34 kN/cm, while the cores located on the opposite side of the predominant winds act more in compression, stabilizing the structure.

The analysis revealed that the geometrical shape significantly benefited the areas near the core. As a result, the required thickness of the core decreased from 1.4m to 0.8m when compared to the analysis conducted in Chapter 4. This reduction in thickness is reasonable and brings about a more efficient design. However, the glulam frame located between the cores presented a challenge. This area lacks any vertical stabilizer component and relies solely on the rotational stiffness of the joints to maintain the required ULS and SLS considerations. To address this, it is recommended to consider the area between the cores as a critical zone and incorporate a hybrid system of slabs. This will increase the self-weight of this area and consequently reduce the stresses on the joints, allowing for a smaller cross-section of the components and an overall best structural performance.

7.0

Conclusions

7.1. Conclusions:

Modularity in the circular highrise:

How can modular timber systems lead to highrise buildings that are technically feasible and adaptable to future use scenarios?

The building is designed to showcase both modularity and timeless adaptability. These two concepts are interrelated and work together to create an efficient and enduring system. The modularity of structural systems should be incorporated into the design phase and continued throughout construction.The lack of multidisciplinary coordination that understands the dynamic nature of cities, users, and building layers has led to the obsolescence and demolition of many constructions.

The structure of a building has the longest lifespan but is often wasted or minimized. Modular design and disassembly of structural systems is key to creating a building environment that can adapt to current and future scenarios. The dynamic requirements of today's world require us to rethink how we approach static systems and adapt them to meet changing needs. The structural kit is a versatile and functional system of building components designed to meet a wide range of scale requirements. The prefabricated Glulam and CLT columns, beams, trusses, and cores are designed to be interoperable with each other, providing the building industry with a wide range of architectural options. The steel joints used to connect the components are prefabricated to meet specific project requirements, and the components are pre-drilled and milled for easy assembly on-site. This approach enables faster, more efficient, and sustainable construction processes while maintaining the highest structural integrity and safety standards. With a range of configurations available, the structural kit is a flexible and adaptable system that can be tailored to meet the variety of needs of its users today and in 100 years.

The implementation of the five factors of the circular economy use, reduce, recycle, reuse, and produce - was crucial in establishing sustainable and efficient management principles for the infrastructure project discussed in this study.

The initial stage focused on production, highlighting the significance of the origin and manufacture of construction components. The ecological analysis in subchapter 4.4 emphasized the importance of considering the entire life cycle of raw materials, from their use to disposal. Regarding timber, it is important to emphasize that certified sources, such as the Forest Stewardship Council International or EU-certified wood agencies, should be utilized to ensure a sustainable origin.

Maximizing the use factor was achieved through two main factors. First, the multiscale modularity of the structure enabled a simplified and minimal amount of components, facilitating easy replacement and repair and thereby extending the structure's lifespan. Second, high-quality materials like stainless steel grades 355-390 and Glulam reference GL36C were implemented to ensure durability and reliability.

Reduction was accomplished through the efficient use of resources, employing various strategies outlined in this investigation. The structural optimization discussed in Chapter 4 and subchapters 6.5 highlighted the importance of designing based on performance to reduce material usage. The analysis results demonstrated that critical components, such as steel connections, could be optimized to decrease mass without compromising ULS and SLS requirements. Additionally, the modular design of structural components facilitated precise material use, enhancing material efficiency and simplifying post-life management.

Considering the life cycle perspective was a crucial aspect of this investigation. As mentioned in Chapter 1, the obsolescence of structures poses significant challenges in the built environment. Therefore, the concept of design for disassembly was implemented in Chapter 5, allowing all structure components to be dismantled and reused in other constructions. The high-quality raw materials and commercial modularity of the components made this process simple and feasible. However, it is important to consider the long-term durability of timber components and recommend implementing their reuse in less demanding load-bearing conditions than their current use.

Finally, to complete the loop, the recycling stage is addressed. Timber in its current form is not directly recyclable due to the glue used in creating Engineered Wood Products (EWP). Although EWP captures CO2 in the material, the process of creating it makes sustainable recycling unfeasible. Therefore, after use and reuse, the best option for this material is to utilize it as biomass. Many facilities in Europe produce biomass sustainably, effectively reducing the emission of pollutants during combustion and recovering some of the energy expended during manufacturing.

Related to the dynamic response of timber highrise strcutures, This investigation discusses the feasibility of timber high-rise structures and the various factors that must be considered when evaluating them. The parametric model presented in subchapters 4.3.1. and 4.3.2. highlighted the crucial role of the core in the global stiffness of high-rise structures. Subchapter 4.3.1. demonstrated how a CLT core could replace a concrete core entirely, despite requiring considerable mass to meet the limit and serviceability parameters.

In contrast, subchapter 4.3.2. revealed that a concrete core required only 50% of the mass required for a CLT core to achieve the necessary stiffness. However, subchapter 4.4. indicated that the glulam and CLT core resulted in significantly more emissions than the configuration with a concrete core.

The investigation explores two strategies that can be considered to avoid the need for a concrete core. The first is to reduce the height of the high-rise to a level where wind pressure does not require a CLT core thicker than 1000mm. Alternatively, adding more self-weight to the structure may be possible by implementing a composite material that can be used with CLT or glulam.

The feasibility of replacing steel with carpentry joints for high-rise structures was found to be deficient in mechanical behaviour and economically and technically impractical. Instead, optimizing the amount of material in metal joints was a more realistic and feasible solution. The parametric model provided valuable insights into the structures' dynamic response and stress concentrations. The analysis revealed that the height and self-weight of the building were directly related to the demand for rotational stiffness in the joints. Structural optimization was a crucial tool for reducing the amount of steel in the connections.

Wind pressure was the crucial factor that significantly affected the feasibility of timber high-rises in numerous ways, particularly in structural mechanics. The height parameter is a crucial factor that affects the overall performance of the structure. The structural analysis and optimization were carried out to achieve the necessary global stiffness, considering the exponential increase and demandings of horizontal accelerations.The massing study conducted in Chapter 5 proved to be a significant factor to consider. It analyzed the performance of a 1:1 slenderness ratio with a four-core implementation. The study revealed that the volumetric shape enabled the use of CLT (Cross-Laminated Timber) cores with a thickness of less than 1m. However, it also resulted in increased stress in the middle sections of the structure frame, necessitating higher rotational stiffness requirements. To address this, it became necessary to implement a composite or hybrid slab system to increase the self-weight of these areas.

The structural and environmental repercussions are factors that should be considered when evaluating the feasibility of a timber high-rise. The environmental impact of structure configurations must also be evaluated to ensure a well-rounded and sustainable design. amount of CO_2 concentration. A balanced and multi-feasible approach is necessary when evaluating the feasibility of a timber high-rise, considering the structural and environmental feasibility of different design options.

Finally, the net floor area plays a critical role in the structural analysis of timber high-rise buildings. These buildings require a higher global stiffness to achieve accurate mass and mechanical performance of materials, which can significantly reduce the net floor area if no constraints are established.

7.2. Reflection:

Timber is a remarkable material that has gained increasing importance in the construction industry. Its qualities as a natural carbon storage make it attractive for environmental reasons. Additionally, the constant innovation in Engineered Wood Products (EWP) industry has made them more efficient and competitive, positioning them as alternatives to traditional construction materials. However, it is crucial to put timber into context and address its limitations, particularly when considering its applicability in high-rise structures.

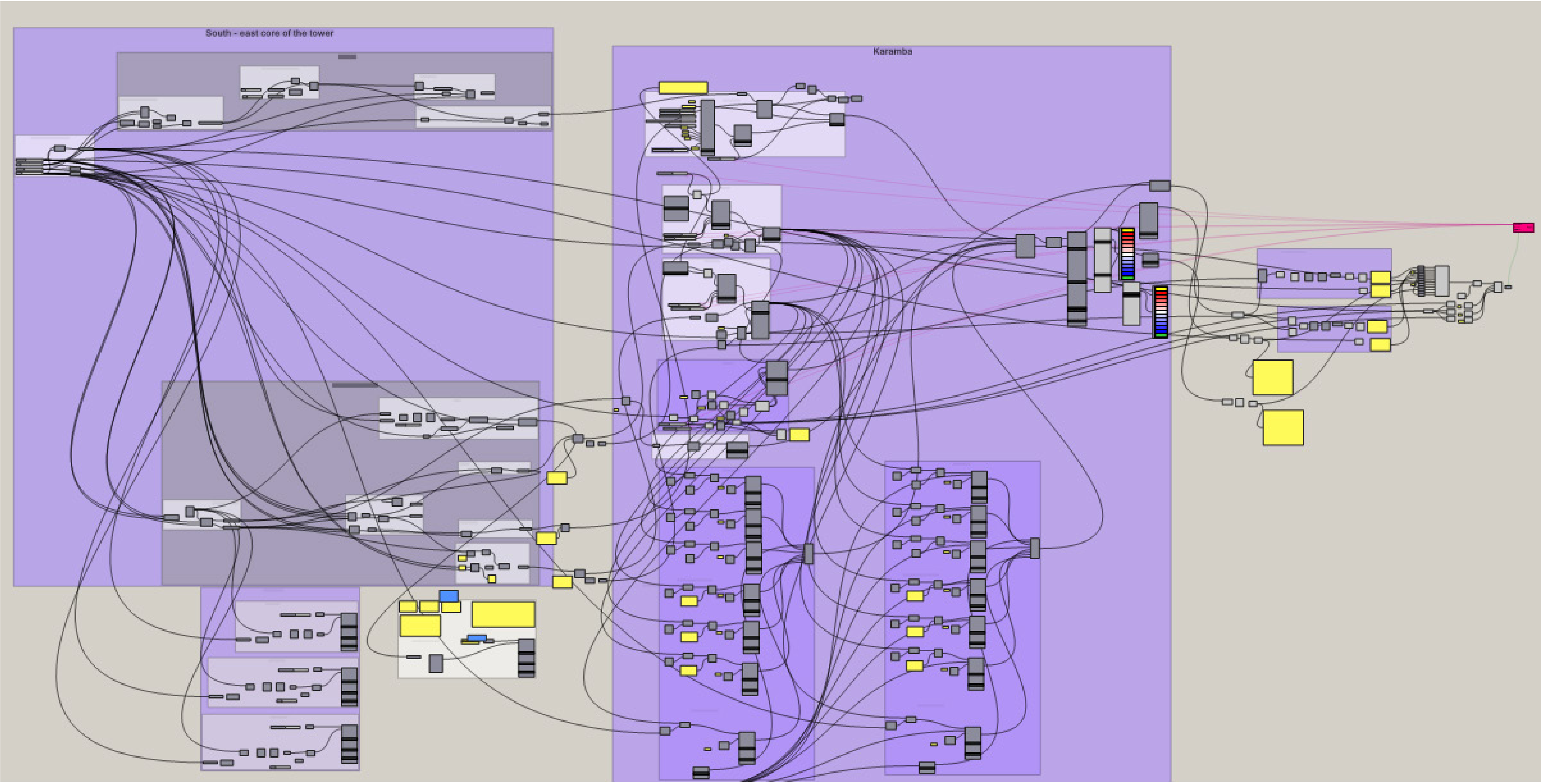
The requirements of high-rises demand structures with mechanical properties capable of withstanding high multidirectional loads and stresses. Timber, a lightweight and weaker material compared to concrete and steel, puts it at a clear disadvantage in meeting the stringent standards of structural performance. The parametric studies conducted in Chapters 4 and 6 highlighted the complexity of implementing timber as the primary load-bearing material. Achieving the Ultimate Limit State (ULS) and Serviceability Limit State (SLS) requirements necessitated larger mass and constant oversizing of cross sections of different structural components, compromising its sustainable advantage due to the increased material consumption.

Timber can meet ULS and SLS requirements in the context of high-rises of approximately 100 meters or less. However, achieving acceptable levels of performance efficiency requires evaluating the shape, slenderness, and reduction of the net floor area. In such cases, a hybridization approach, combining timber with other materials like steel, can generate better structural performance and efficiency. If it's not permanently mixed with chemicals or concrete, the steel's recyclability and the timber's non-polluting nature make this hybridization strategy optimal for high-rise structures. It is essential to recognize that using timber as a sustainability goal should not be unthinkingly assumed as automatically sustainable. A sustainable structural design needs to conduct parallel life cycle analyses to assess the real impact of design decisions. Applying the circular economy concepts of: produce, use, reduce, reuse, and recycle, along with its associated principles, will generate a sustainable structural design. The primordial positive impact of timber in structural design lies primarily in low-rise structures and high-rises that utilize the non-permanent hybridization of components.

6.0

Appendix

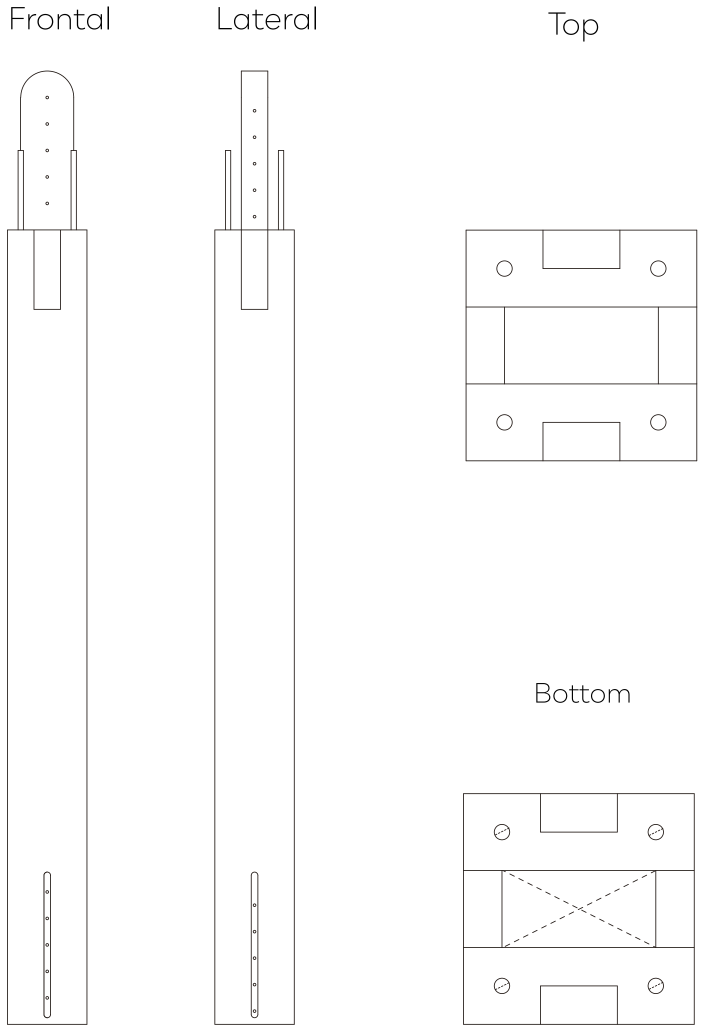
Appendix A: Grasshopper Script

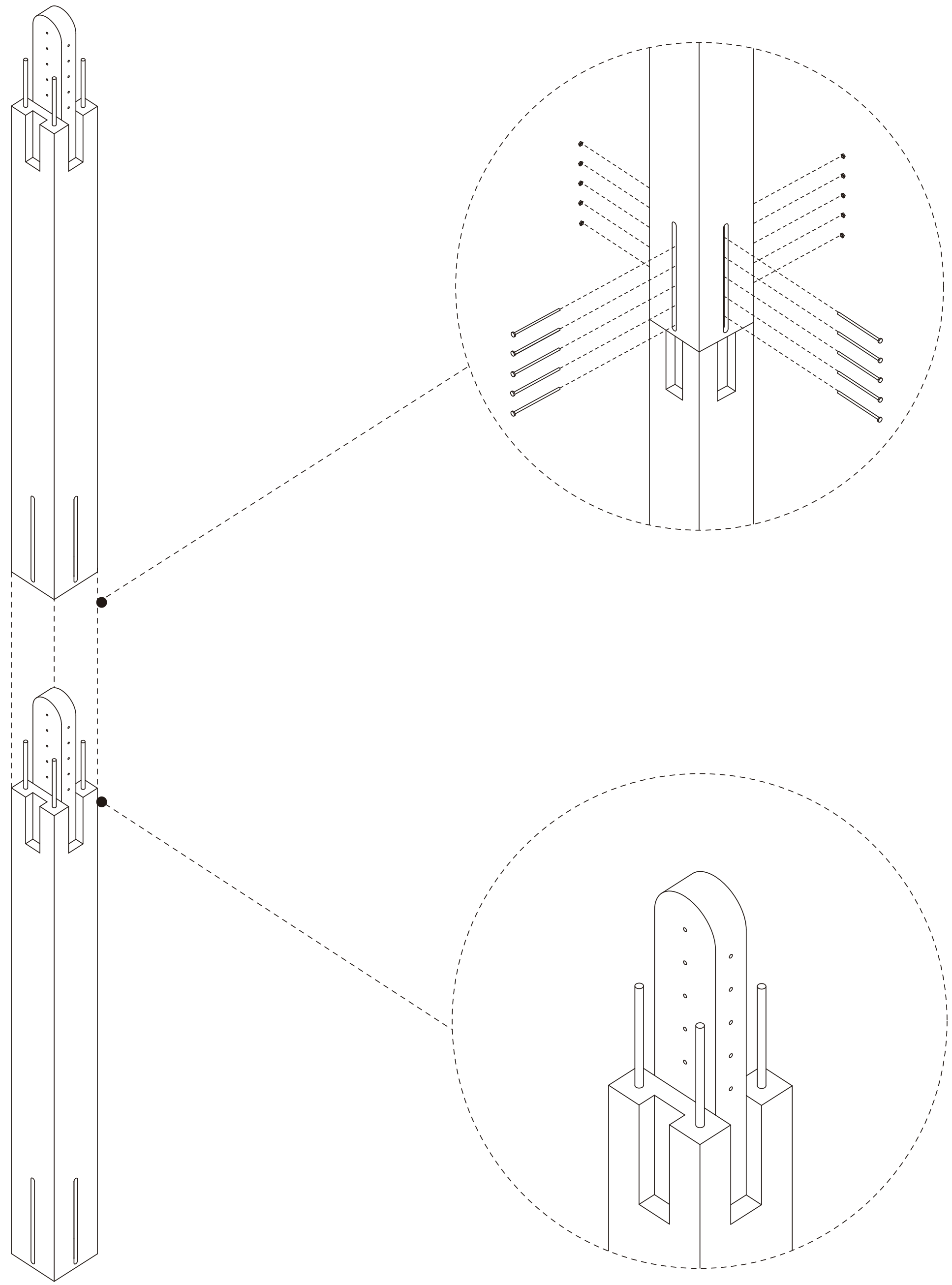


Appendix C: Material analysis

C1 Environmental impact materials:

Column to column

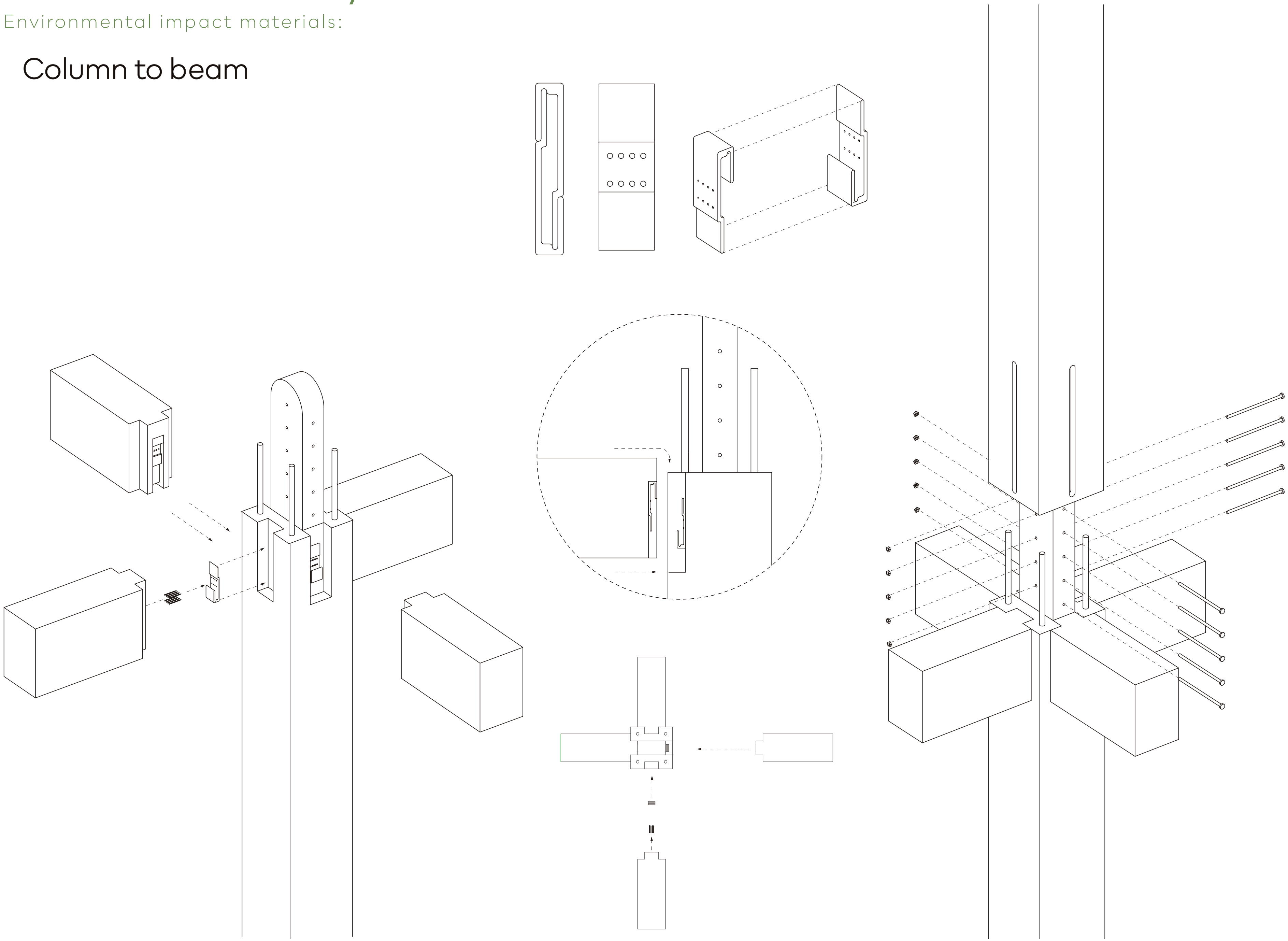




Appendix C: Material analysis

C1 Environmental impact materials:

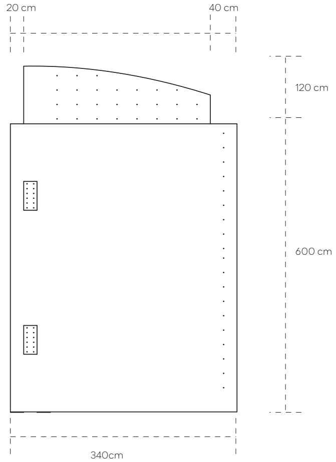
Column to beam

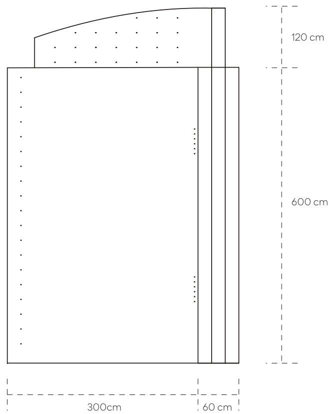


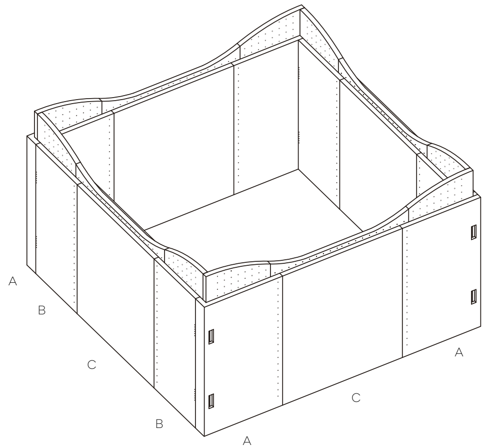
Appendix C: Material analysis

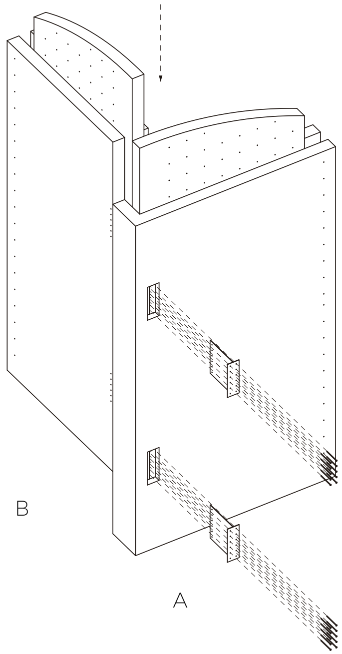
C1 Environmental impact materials:

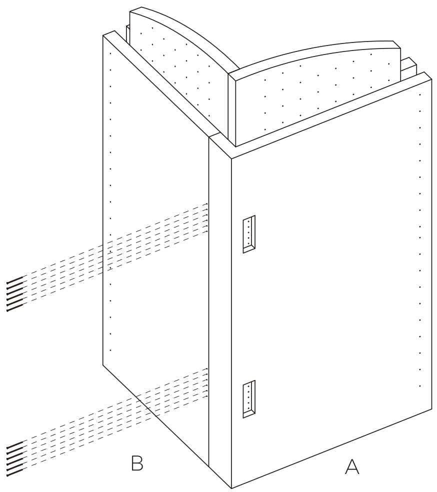
Core to core connection

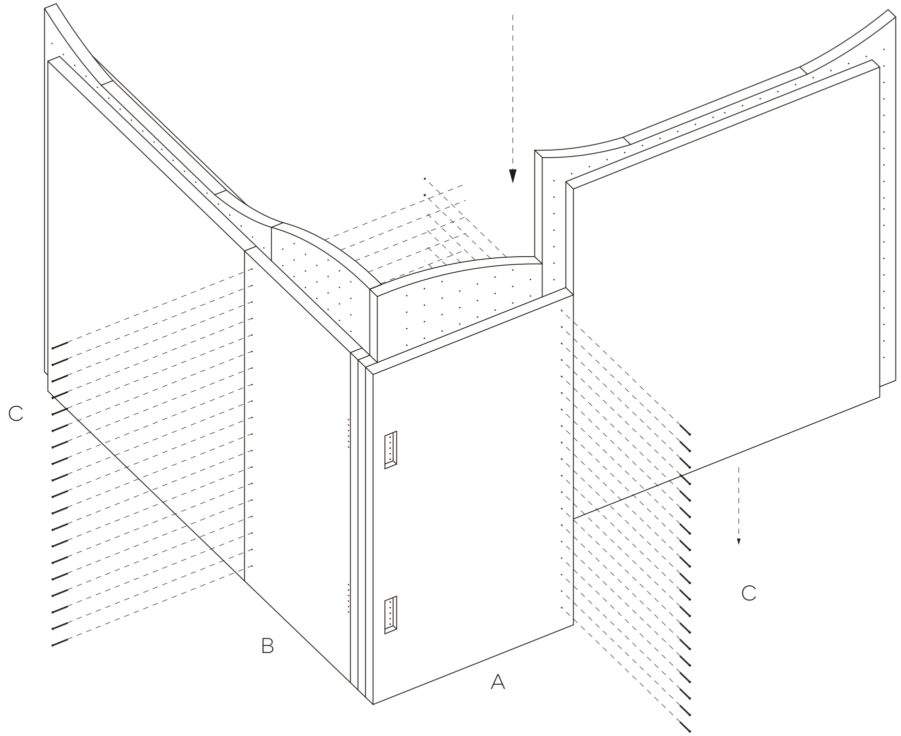






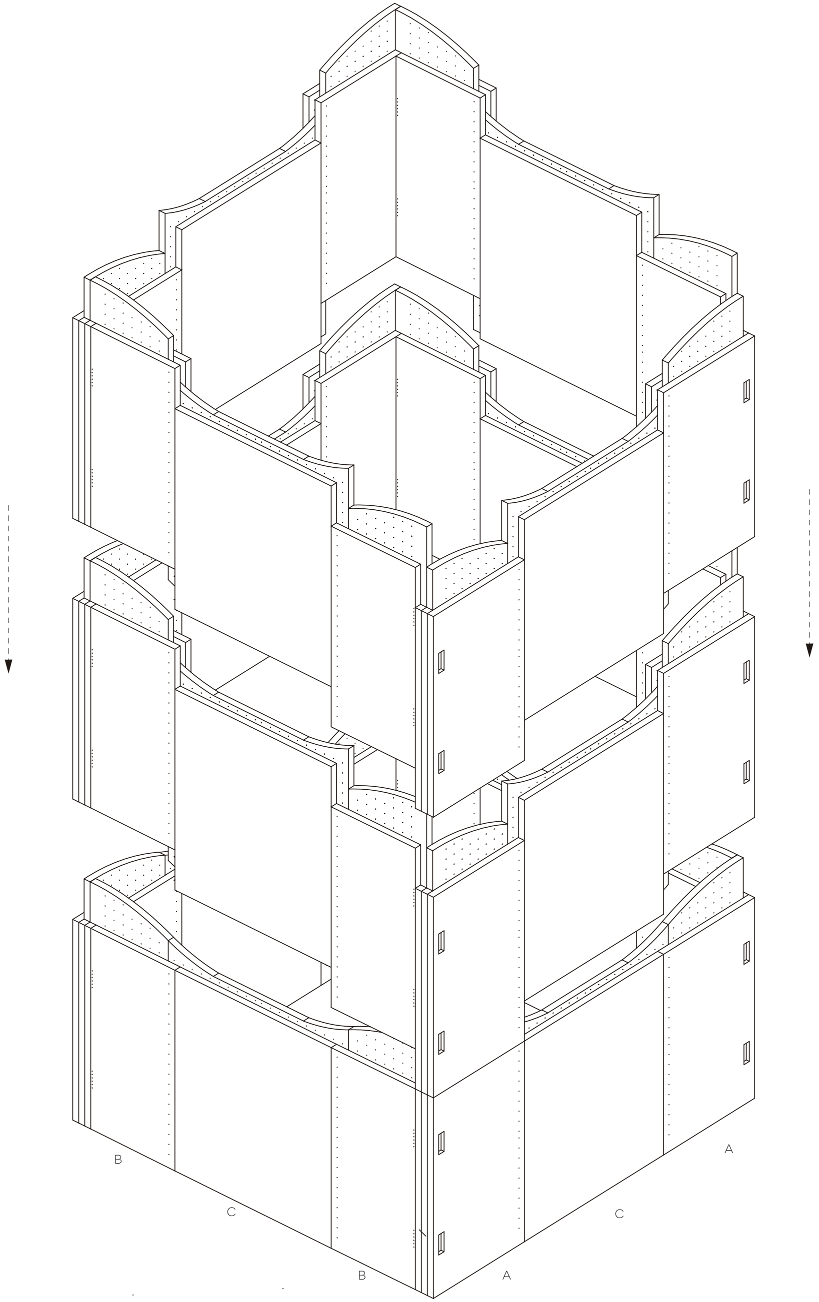


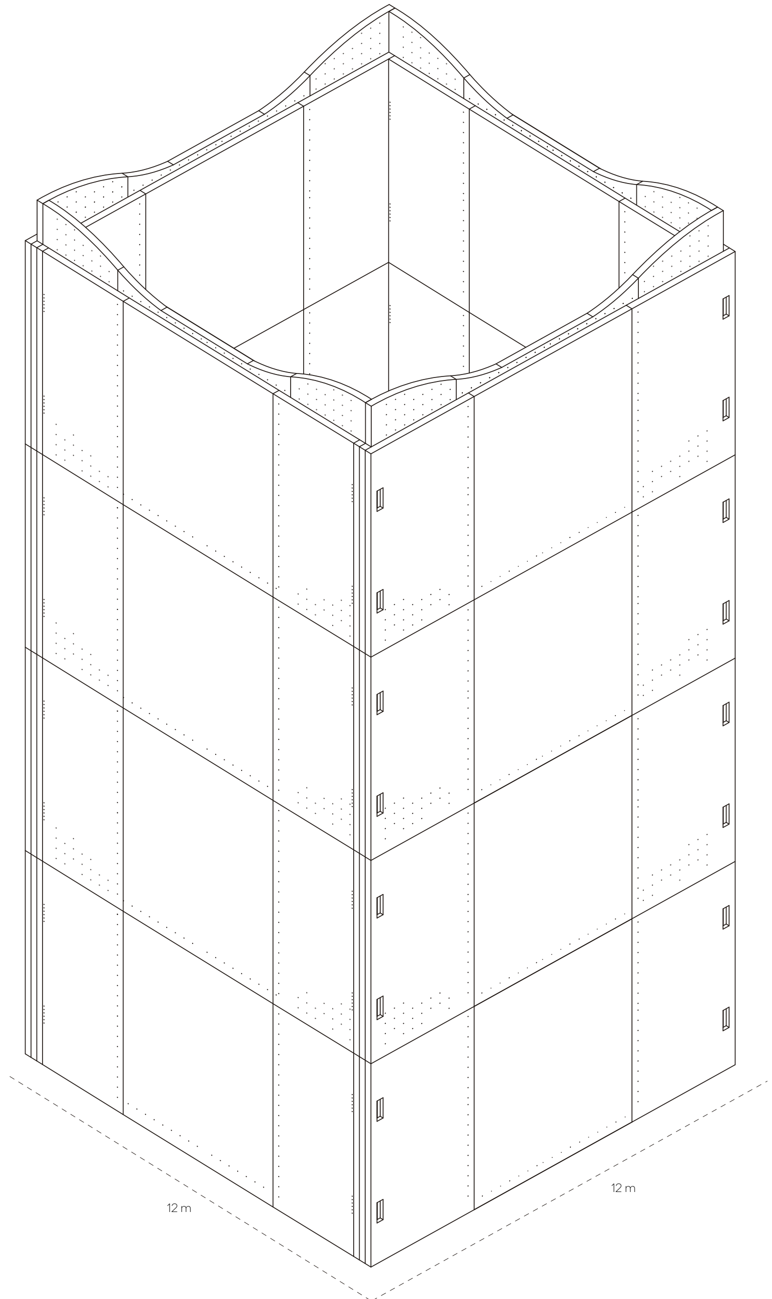




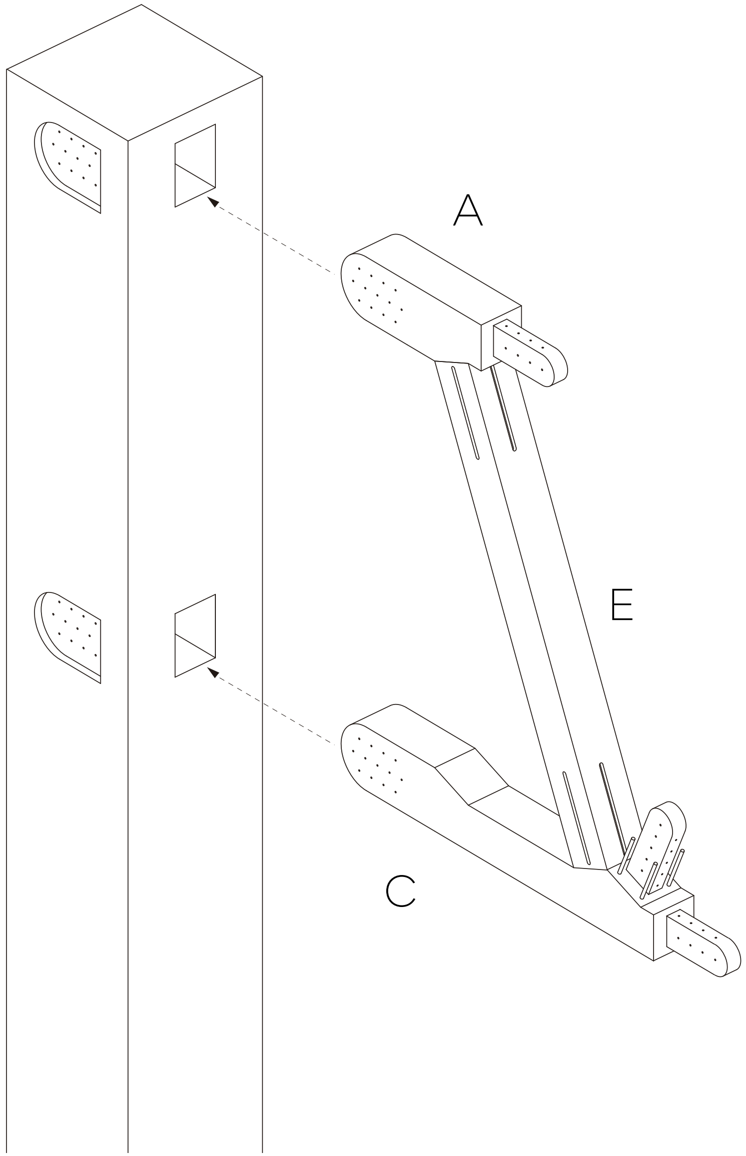
Appendix C: Material analysis

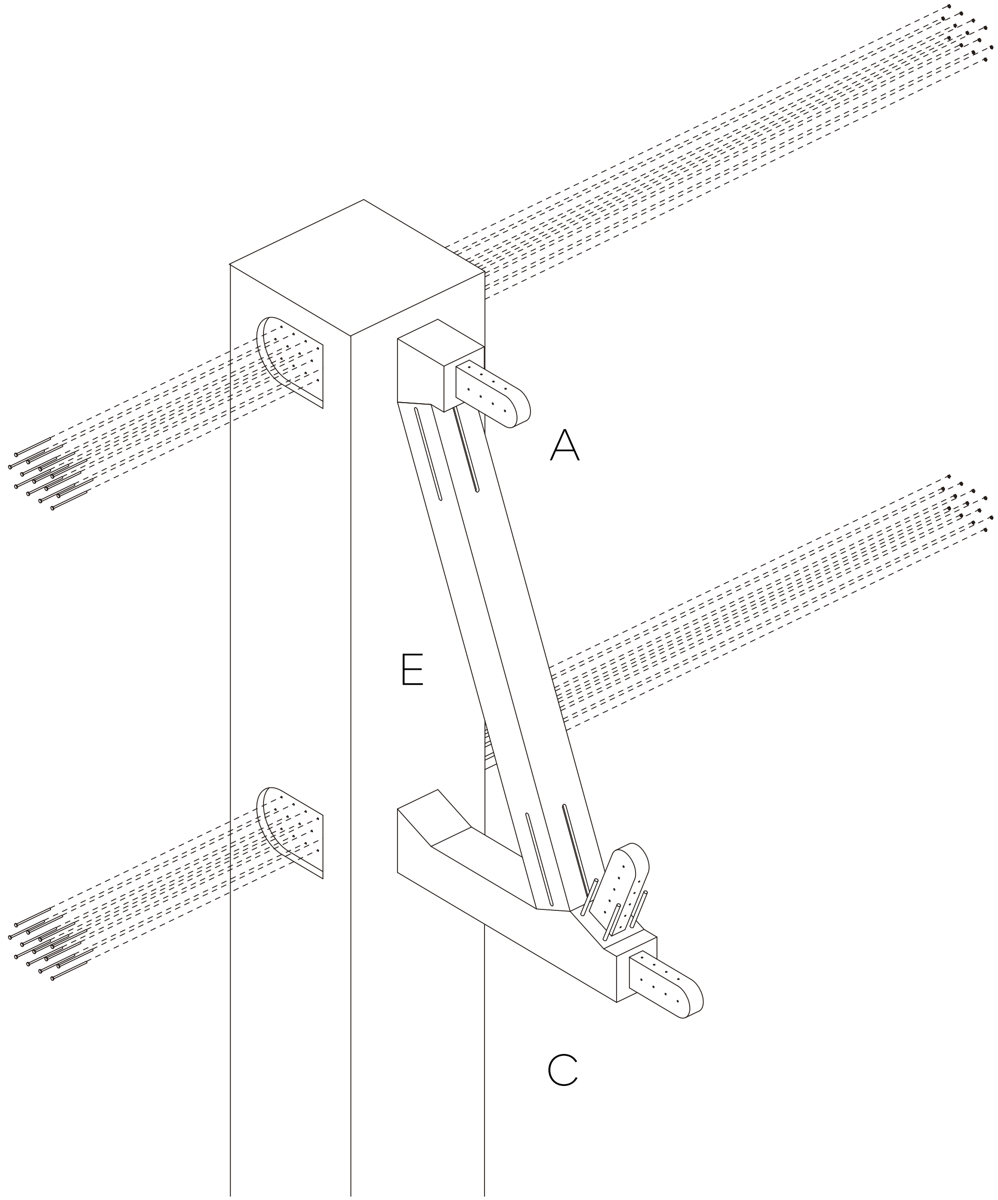
C1 Environmental impact materials:





Truss - column

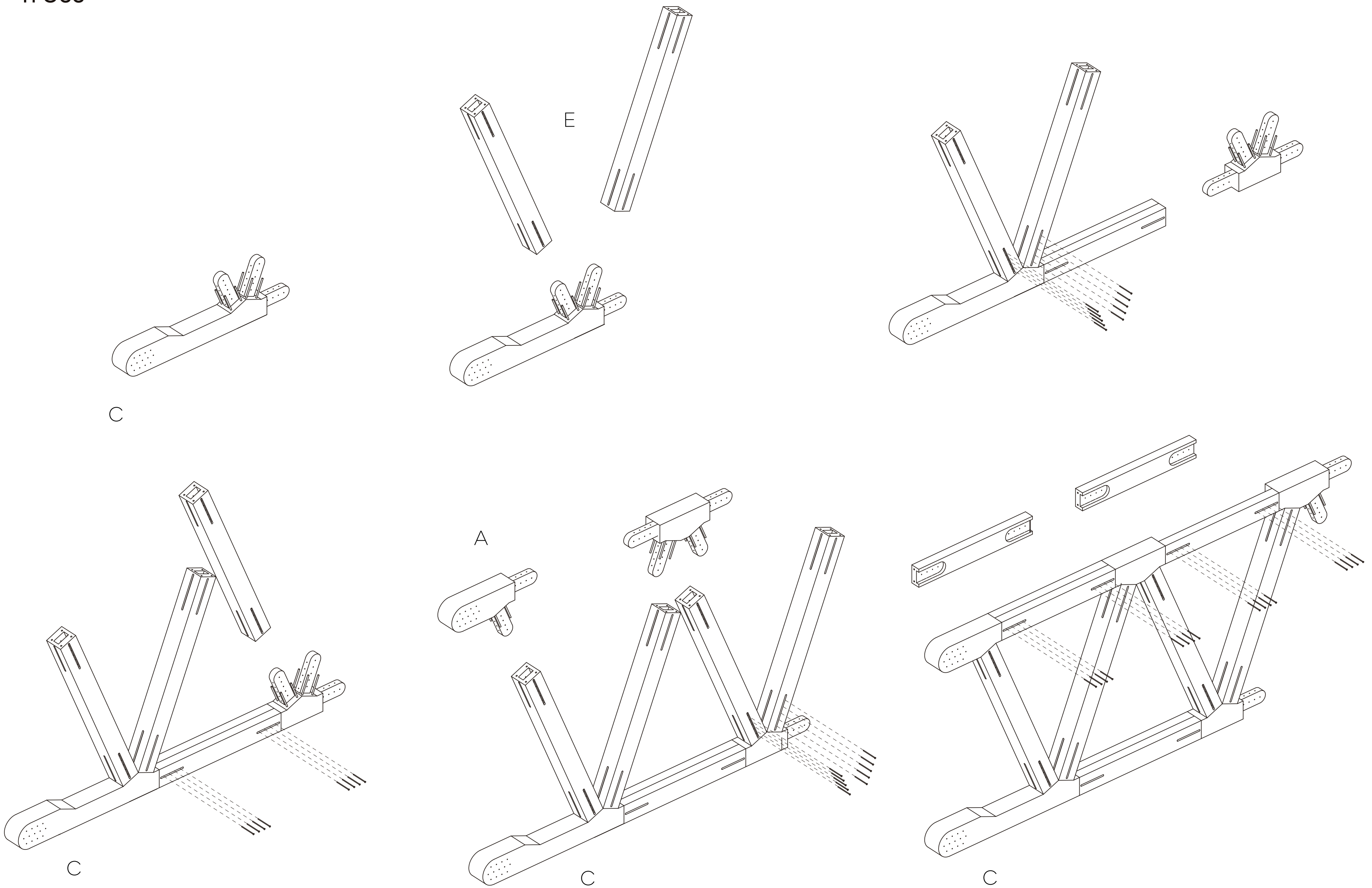




Appendix C: Material analysis

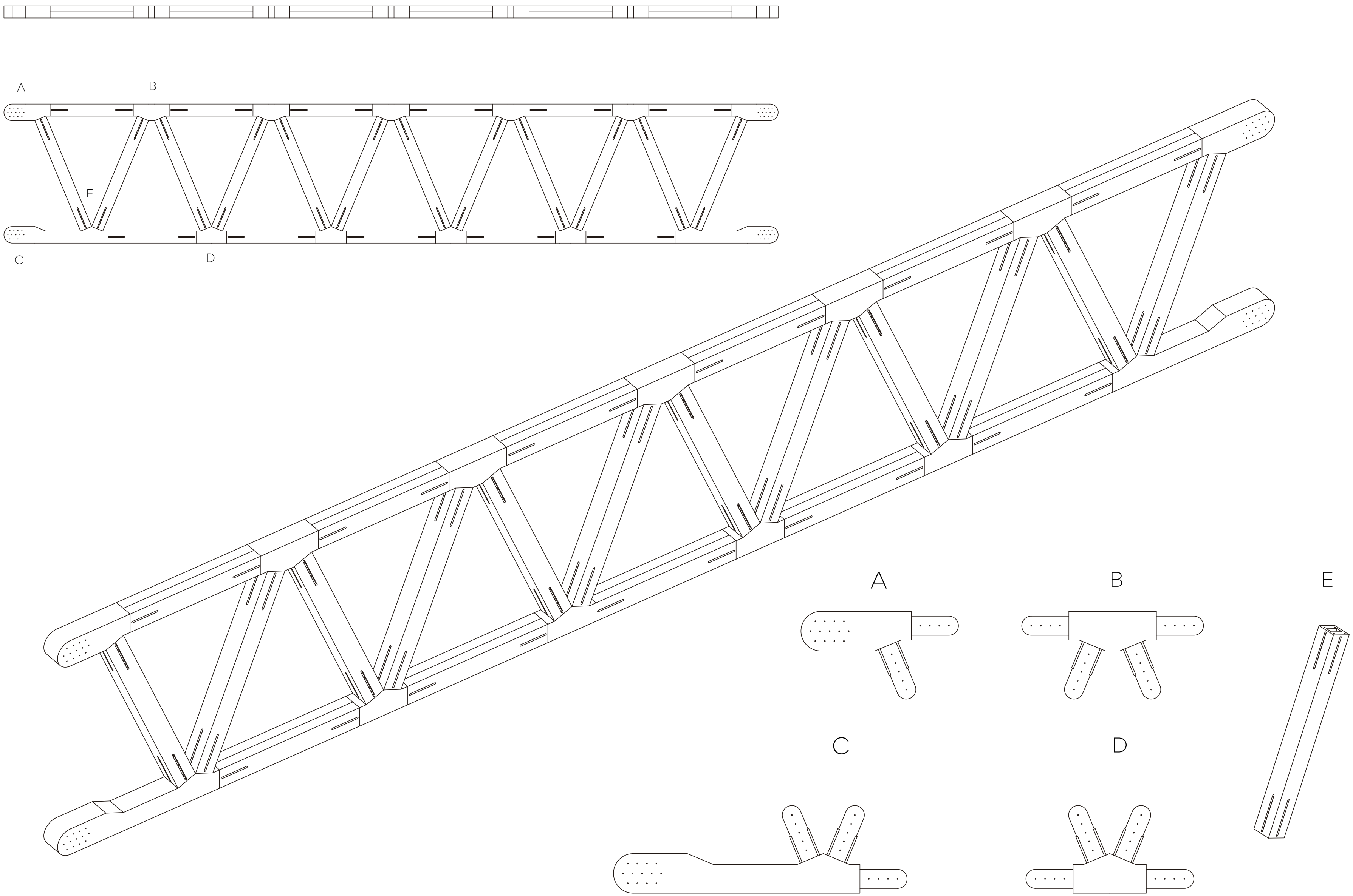
C1 Environmental impact materials:

Truss



Appendix B: Joint Design

B1 Carpentry Joints preliminary design



Appendix B: Joint Design

B2 - Base Design:

This subchapter of the appendix B, shows the literature and products in the market used as reference for the design of the joints applicable for the investigation.

B21:
Rothoblaas, a timber beam company, utilized a hidden support system as a reference point for their assembly methodology. The system involves connecting a metallic joint to a surface, wall, or beam and then interlocking the beam with the plate using a guide bolt. The joint's high-strength bolts, featuring deep and medium perforation, ensure uniform stress distribution across the metal plates. This approach makes the methodology used joint an

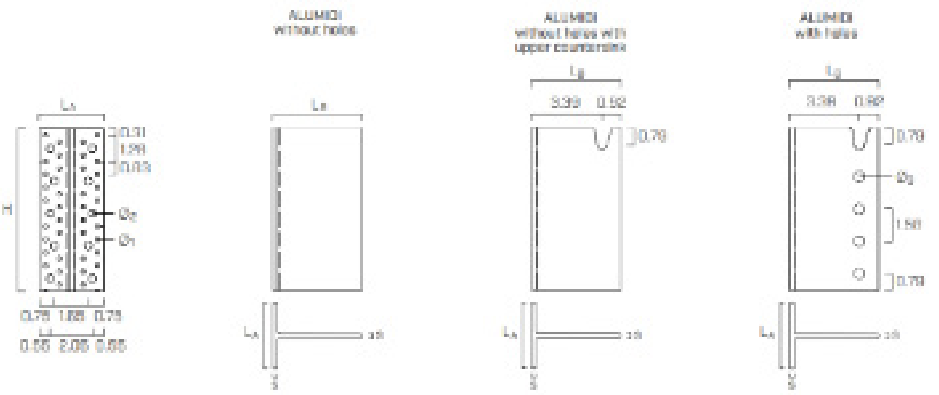


Fig B21: Alumidi: concealed support with and without holes Rothoblaas).

B21:
The steel plates designed by Felicita M. (2021) are an important base for the joint design of the construction kit, being very valuable in the sizing of the plates and its rotational stiffness data.

B22A

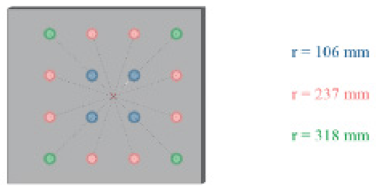


Fig B22A: RS: 100000 KN m/rad (Felicita M., 2021).

B22B

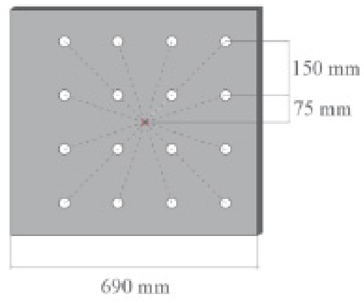


Fig B22B: RS: 100000 KN m/rad (Felicita M., 2021)

B22C

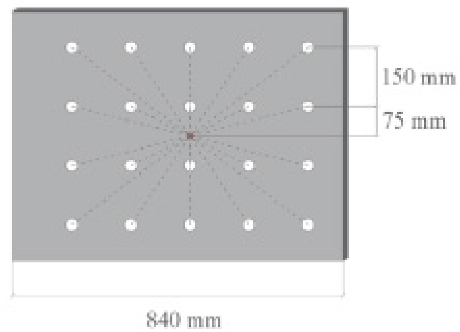


Fig B22C: RS: 200000 KN m/rad (Felicita M., 2021).

B22D

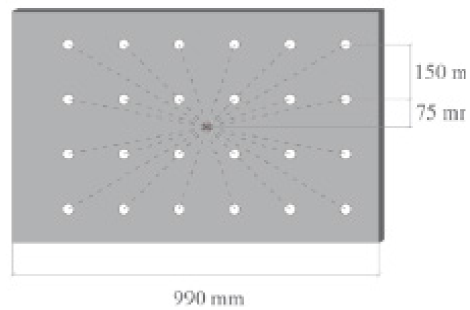


Fig B22D: RS: 300000 KN m/rad (Felicita M., 2021).

Appendix C: Material analysis

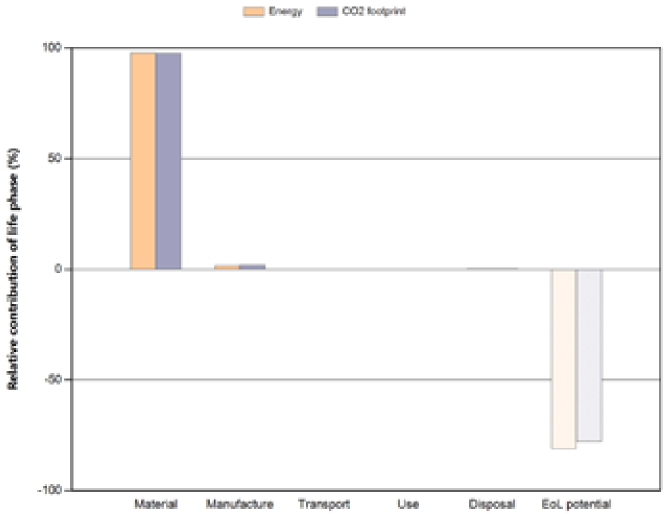
C1 Environmental impact materials:

C1A: Aluminum alloys

Eco Audit Report

Product name	SC Aluminium allows
Country of use	Netherlands
Product life (years)	100

Summary:



Energy details   CO2 footprint details

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	3.99e+04	97.8	2.64e+03	97.6
Manufacture	693	1.7	51.8	1.9
Transport	54.3	0.1	3.91	0.1
Use	0	0.0	0	0.0
Disposal	140	0.3	9.78	0.4
Total (for first life)	**4.08e+04**	**100**	**2.71e+03**	**100**
End of life potential	-3.31e+04		-2.11e+03	

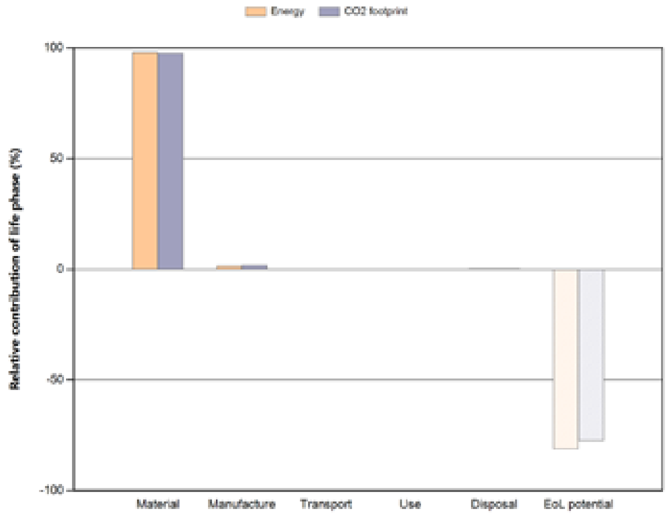
SC Aluminium allows.prd   NOTE: Differences of less than 20% are not usually significant.
See notes on precision and data sources.   Page 1 / 5   Sunday, April 30, 2023

C1B: Aluminum pure

Eco Audit Report

Product name	SC Aluminium pure
Country of use	Netherlands
Product life (years)	100

Summary:



Energy details   CO2 footprint details

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	3.98e+04	98.0	2.58e+03	97.7
Manufacture	623	1.5	46.7	1.8
Transport	54.3	0.1	3.91	0.1
Use	0	0.0	0	0.0
Disposal	140	0.3	9.78	0.4
Total (for first life)	**4.06e+04**	**100**	**2.64e+03**	**100**
End of life potential	-3.3e+04		-2.05e+03	

SC Aluminium pure.prd   NOTE: Differences of less than 20% are not usually significant.
See notes on precision and data sources.   Page 1 / 5   Sunday, April 30, 2023

Appendix C: Material analysis

C1 Environmental impact materials:

C1C: Coated steel

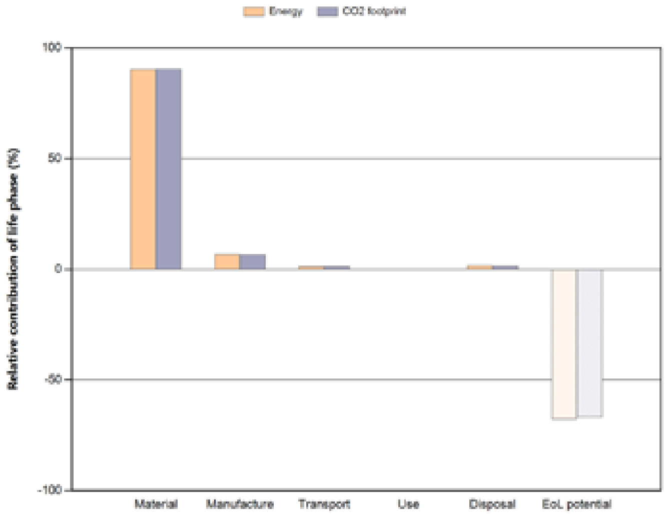
Ansys

GRANTA EDUPACK

Eco Audit Report

Product name	SC coated steel
Country of use	Netherlands
Product life (years)	100

Summary:



Energy details CO2 footprint details

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	7.98e+03	90.4	601	90.6
Manufacture	592	6.7	44.5	6.7
Transport	118	1.3	8.47	1.3
Use	0	0.0	0	0.0
Disposal	140	1.6	9.78	1.5
Total (for first life)	**8.83e+03**	**100**	**664**	**100**
End of life potential	-5.99e+03		-444	

SC coated steel.prd NOTE: Differences of less than 20% are not usually significant. See notes on precision and data sources. Page 1 / 5 Sunday, April 30, 2023

C1D: Lead alloys

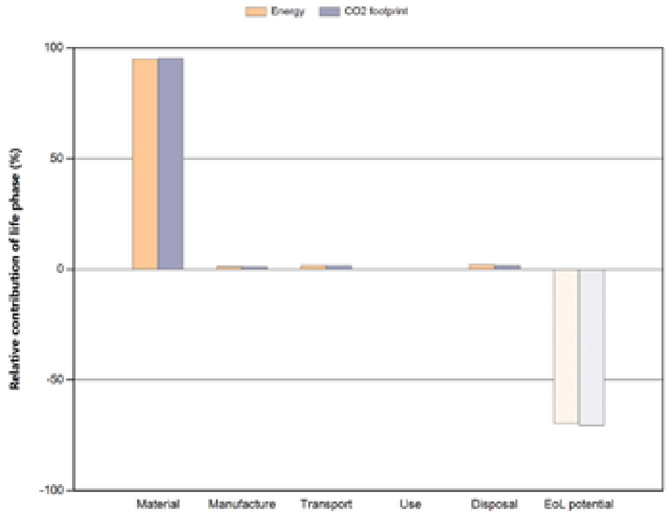
Ansys

GRANTA EDUPACK

Eco Audit Report

Product name	SC Lead alloys
Country of use	Netherlands
Product life (years)	100

Summary:



Energy details CO2 footprint details

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	6.45e+03	94.9	521	95.5
Manufacture	87.5	1.3	6.56	1.2
Transport	118	1.7	8.47	1.6
Use	0	0.0	0	0.0
Disposal	140	2.1	9.78	1.8
Total (for first life)	**6.79e+03**	**100**	**546**	**100**
End of life potential	-4.74e+03		-387	

SC Lead alloys.prd NOTE: Differences of less than 20% are not usually significant. See notes on precision and data sources. Page 1 / 5 Sunday, April 30, 2023

Appendix C: Material analysis

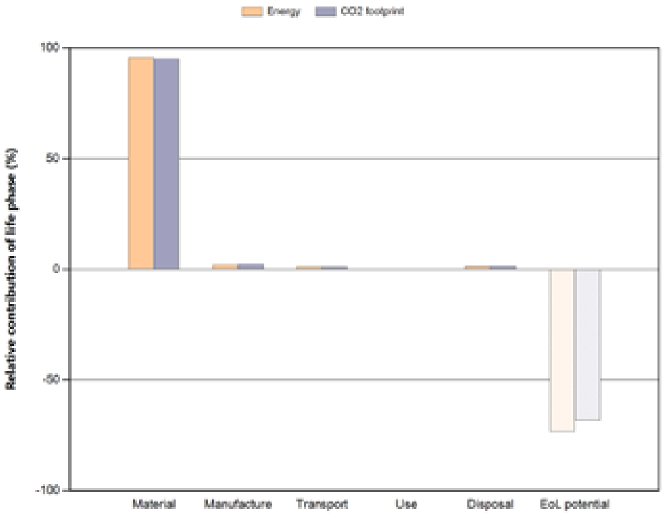
C1 Environmental impact materials:

C1E: Lead coated copper

Eco Audit Report

Product name	SC Lead coater copper
Country of use	Netherlands
Product life (years)	100

Summary:



Energy details CO2 footprint details

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	1.06e+04	95.7	692	95.2
Manufacture	222	2.0	16.7	2.3
Transport	118	1.1	8.47	1.2
Use	0	0.0	0	0.0
Disposal	140	1.3	9.78	1.3
Total (for first life)	**1.11e+04**	**100**	**727**	**100**
End of life potential	-8.15e+03		-496	

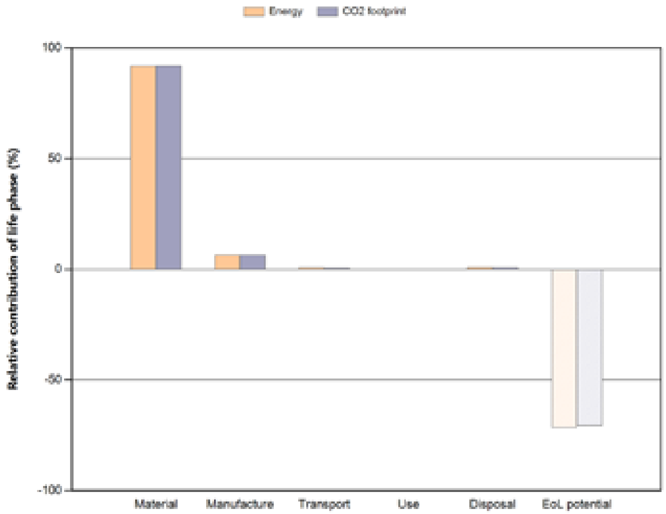
SC Lead coater copper.prd NOTE: Differences of less than 20% are not usually significant. See notes on precision and data sources. Page 1 / 5 Sunday, April 30, 2023

C1F: Stainless steel

Eco Audit Report

Product name	SC Stainless steel
Country of use	Netherlands
Product life (years)	100

Summary:



Energy details CO2 footprint details

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	1.45e+04	91.9	1.09e+03	91.9
Manufacture	1.03e+03	6.5	76.9	6.5
Transport	118	0.7	8.47	0.7
Use	0	0.0	0	0.0
Disposal	140	0.9	9.78	0.8
Total (for first life)	**1.58e+04**	**100**	**1.18e+03**	**100**
End of life potential	-1.13e+04		-836	

SC Stainless steel.prd NOTE: Differences of less than 20% are not usually significant. See notes on precision and data sources. Page 1 / 5 Sunday, April 30, 2023

Appendix C: Material analysis

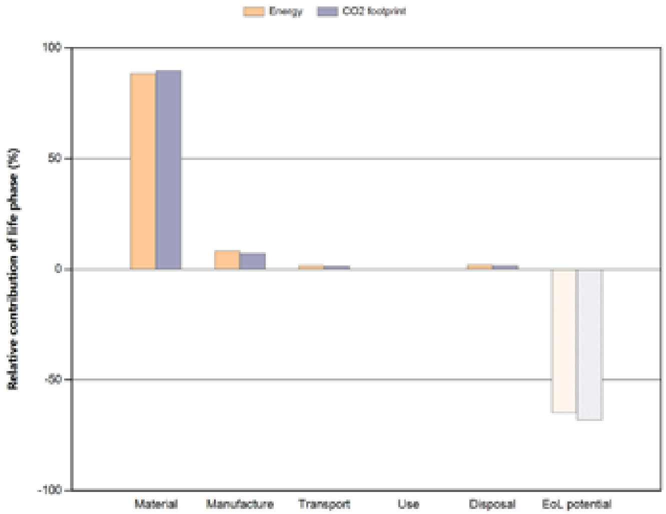
C1 Environmental impact materials:

C1G: Terne coated steel

Eco Audit Report

Product name	SC terne coated steel
Country of use	Netherlands
Product life (years)	100

Summary:



Energy details CO2 footprint details

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	6.43e+03	88.4	553	89.8
Manufacture	590	8.1	44.3	7.2
Transport	118	1.6	8.47	1.4
Use	0	0.0	0	0.0
Disposal	140	1.9	9.78	1.6
Total (for first life)	**7.28e+03**	**100**	**616**	**100**
End of life potential	-4.73e+03		-420	

SC terne coated steel.prd NOTE: Differences of less than 20% are not usually significant. Page 1 / 5
See notes on precision and data sources. Sunday, April 30, 2023

Appendix C: Material analysis

C2: CO2 concentration material parametric study: Glulam frame and CLT core

CLT core:

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	6.11e+07	98.9	2.56e+06	98.2
Manufacture	0	0.0	0	0.0
Transport	5.69e+04	0.1	4.1e+03	0.2
Use	0	0.0	0	0.0
Disposal	6.05e+05	1.0	4.24e+04	1.6
Total (for first life)	**6.17e+07**	**100**	**2.61e+06**	**100**
End of life potential	-6.11e+07		-2.56e+06	

CLT core.prd NOTE: Differences of less than 20% are not usually significant. Page 1 / 3

Glulam column:

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	4.28e+07	98.9	1.79e+06	98.2
Manufacture	0	0.0	0	0.0
Transport	3.99e+04	0.1	2.87e+03	0.2
Use	0	0.0	0	0.0
Disposal	4.24e+05	1.0	2.97e+04	1.6
Total (for first life)	**4.33e+07**	**100**	**1.83e+06**	**100**
End of life potential	-4.28e+07		-1.79e+06	

Glulam column.prd NOTE: Differences of less than 20% are not usually significant. Page 1 / 3

Glulam beam:

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	4e+07	98.9	1.68e+06	98.2
Manufacture	0	0.0	0	0.0
Transport	3.73e+04	0.1	2.68e+03	0.2
Use	0	0.0	0	0.0
Disposal	3.97e+05	1.0	2.78e+04	1.6
Total (for first life)	**4.04e+07**	**100**	**1.71e+06**	**100**
End of life potential	-4e+07		-1.68e+06	

Glulam beam.prd NOTE: Differences of less than 20% are not usually significant. Page 1 / 3

Appendix C: Material analysis

C2: CO2 concentration material parametric study: Glulam frame and CLT core

Joint 100000KNm/rad

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	6.49e+06	93.1	4.87e+05	93.1
Manufacture	4.6e+05	6.6	3.45e+04	6.6
Transport	1.68e+03	0.0	121	0.0
Use	0	0.0	0	0.0
Disposal	1.79e+04	0.3	1.25e+03	0.2
Total (for first life)	**6.97e+06**	**100**	**5.23e+05**	**100**
End of life potential	-6.49e+06		-4.87e+05	

Joint 100000knm.prd NOTE: Differences of less than 20% are not usually significant. Page 1 / 3

Joint 200000KNm/rad

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	3.76e+05	93.1	2.82e+04	93.1
Manufacture	2.67e+04	6.6	2e+03	6.6
Transport	97.5	0.0	7.02	0.0
Use	0	0.0	0	0.0
Disposal	1.04e+03	0.3	72.6	0.2
Total (for first life)	**4.04e+05**	**100**	**3.03e+04**	**100**
End of life potential	-3.76e+05		-2.82e+04	

Joint 200000knm.prd NOTE: Differences of less than 20% are not usually significant. Page 1 / 3

Joint 300000KNm/rad

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	3.57e+06	99.7	2.68e+05	99.7
Manufacture	0	0.0	0	0.0
Transport	926	0.0	66.7	0.0
Use	0	0.0	0	0.0
Disposal	9.85e+03	0.3	689	0.3
Total (for first life)	**3.58e+06**	**100**	**2.69e+05**	**100**
End of life potential	-3.57e+06		-2.68e+05	

Joint 300000knm.prd NOTE: Differences of less than 20% are not usually significant. Page 1 / 3

Appendix C: Material analysis

C3: CO2 concentration material parametric study: Glulam frame and concrete core

Concrete core:

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	6.6e+06	80.4	9.83e+05	89.7
Manufacture	0	0.0	0	0.0
Transport	0	0.0	0	0.0
Use	0	0.0	0	0.0
Disposal	1.61e+06	19.6	1.13e+05	10.3
Total (for first life)	**8.21e+06**	**100**	**1.1e+06**	**100**
End of life potential	0		0	

concrete core.prd NOTE: Differences of less than 20% are not usually significant. Page 1 / 3

Glulam column:

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	1.73e+07	98.9	7.24e+05	98.2
Manufacture	0	0.0	0	0.0
Transport	1.61e+04	0.1	1.16e+03	0.2
Use	0	0.0	0	0.0
Disposal	1.71e+05	1.0	1.2e+04	1.6
Total (for first life)	**1.75e+07**	**100**	**7.38e+05**	**100**
End of life potential	-1.73e+07		-7.24e+05	

Glulam column.prd NOTE: Differences of less than 20% are not usually significant. Page 1 / 3

Glulam beam:

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	3.63e+07	98.9	1.52e+06	98.2
Manufacture	0	0.0	0	0.0
Transport	3.38e+04	0.1	2.44e+03	0.2
Use	0	0.0	0	0.0
Disposal	3.6e+05	1.0	2.52e+04	1.6
Total (for first life)	**3.67e+07**	**100**	**1.55e+06**	**100**
End of life potential	-3.63e+07		-1.52e+06	

Glulam beam.prd NOTE: Differences of less than 20% are not usually significant. Page 1 / 3

Appendix C: Material analysis

C3: CO_2 concentration material parametric study: Glulam frame and concrete core

Joint 100000KNm/rad

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	4.5e+06	93.1	3.37e+05	93.1
Manufacture	3.19e+05	6.6	2.39e+04	6.6
Transport	1.16e+03	0.0	83.9	0.0
Use	0	0.0	0	0.0
Disposal	1.24e+04	0.3	867	0.2
Total (for first life)	**4.83e+06**	**100**	**3.62e+05**	**100**
End of life potential	-4.5e+06		-3.37e+05	

Joint 100000knm.prd NOTE: Differences of less than 20% are not usually significant. Page 1 / 3

Joint 200000KNm/rad

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	5.27e+06	93.1	3.95e+05	93.1
Manufacture	3.73e+05	6.6	2.8e+04	6.6
Transport	1.36e+03	0.0	98.2	0.0
Use	0	0.0	0	0.0
Disposal	1.45e+04	0.3	1.02e+03	0.2
Total (for first life)	**5.66e+06**	**100**	**4.24e+05**	**100**
End of life potential	-5.27e+06		-3.95e+05	

Joint 200000knm.prd NOTE: Differences of less than 20% are not usually significant. Page 1 / 3

Joint 300000KNm/rad

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	5.96e+05	99.7	4.46e+04	99.7
Manufacture	0	0.0	0	0.0
Transport	154	0.0	11.1	0.0
Use	0	0.0	0	0.0
Disposal	1.64e+03	0.3	115	0.3
Total (for first life)	**5.97e+05**	**100**	**4.48e+04**	**100**
End of life potential	-5.96e+05		-4.46e+04	

Joint 300000knm.prd NOTE: Differences of less than 20% are not usually significant. Page 1 / 3

Appendix D: Environmental analysis

5.0

References

Akande, A., Cabral, P., Gomes, P., & Casteleyn, S. (2019). The Lisbon ranking for smart sustainable cities in Europe. Sustainable Cities and Society, 44(October 2018), 475–487. https://doi.org/10.1016/j.scs.2018.10.009

Invidiata, A., Lavagna, M., & Ghisi, E. (2018). Selecting design strategies using multi-criteria decision making to improve the sustainability of buildings. Building and Environment, 139, 58–68. https://doi.org/10.1016/j.buildenv.2018.04.041

Castro-Lacouture, D., Sefair, J. A., Flórez, L., & Medaglia, A. L. (2009). Optimization model for the selection of materials using a LEED-based green building rating system in Colombia. Building and Environment, 44⑥, 1162–1170. https://doi.org/10.1016/j. buildenv.2008.08.009.

Franzoni, E. (2011). Materials selection for green buildings: Which tools for engineers and architects? Procedia Engineering, 21, 883–890. https://doi.org/10.1016/j.proeng. 2011.11.2090

Pulselli, R. M., Simoncini, E., Pulselli, F. M., & Bastianoni, S. (2007). Emergy analysis of building manufacturing, maintenance and use: Em-building indices to evaluate housing sustainability. Energy and Buildings, 39⑤, 620–628. https://doi.org/10. 1016/j.enbuild.2006.10.004.

Roser, M., Ritchie, H., Ortiz-Ospina, E., & Rodés-Guirao, L. (2013, May 9). World population growth. Our World in Data. Retrieved November 22, 2022, from https://ourworldindata.org/world-population-growth

Felicita M., (2021, March 21) Timber High-Rise Buildings Parametric study of the influence of preliminary design parameters on the wind-induced dynamic response of timber high-rise buildings. – Delft university of Technology

Construction and demolition waste. (n.d.). Environment. from https://environment.ec.europa.eu/topics/waste-and-recycling/construction-and-demolition-waste_en - European comission

M van Vliet.(2018) Disassembling the steps towards building circularity redeveloping the building disassembly assessment method in the building circularity indicator.

J, B (2015). Sustainable housing and building materials for low-income households. Journal of Architectural Engineering Technology, 05(01), 1–9. https://doi.org/10.4172/ 2168-9717.1000158.

Darby, H., Elmualim, A. A. and Kelly, F. (2013) A case study to investigate the life cycle carbon emissions and carbon storage capacity of a cross laminated timber, multi-storey residential building. In: Sustainable Building Conference, SB13, 23-25 April 2013, Munich, Germany. .

Sara Cultural Centre, Skellefteå - A new home for culture. (2022, April 26). White Arkitekter. https://whitearkitekter.com/project/sara-cultural-centre/

What Is Design for Disassembly? - News - Cradle to Cradle Products Innovation Institute. (2017, October 10). https://www.c2ccertified.org/news/article/what-is-design-for-disassembly

He M, Sun X, Li Z. Bending and compressive properties of cross-laminated-timber (CLT) panels made from Canadian hemlock. Constr Build Mater (2018) https://doi.org/10.1016/j.conbuildmat.2018.07.072.

EMF, 2019. Completing the picture: How the circular economy tackles climate change., Ellen MacArthur Foundation. Visited: 20/09/22. https://ellenmacarthurfoundation. org/completing-the-picture.

Hertwich, E.G., Ali, S., Ciacci, L., Fishman, T., Heeren, N., Masanet, E., Asghari, F.N., Olivetti, E., Pauliuk, S., Tu, Q., Wolfram, P., 2019. Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics—a review. Environ. Res. Lett. 14 ④, 043004.

Climate Mitigation from Circular and Sharing Economy in the Buildings Sector. (2020). Resources, Conservation and Recycling, 158, 104817. https://doi.

org/10.1016/j.resconrec.2020.104817

EMF and MCK, 2014. Towards the Circular Economy: accelerating the scale-up across global supply chains. http://www3.weforum.org/docs/WEF_ENV_TowardsCircularEconomy_Report_2014.pdf/.

Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E.J., 2017. The Circular Economy e a new sustainability paradigm? J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2016.12.048.

Bilal, M., Khan, K. I. A., Thaheem, M. J., & Nasir, A. R. (2020). Current state and barriers to the circular economy in the building sector: Towards a mitigation framework. Journal of Cleaner Production, 276, 123250. https://doi.org/10.1016/j.jclepro.2020.123250

Machado, N., & Morioka, S. N. (2021). Contributions of modularity to the circular economy: A systematic review of literature. Journal of Building Engineering, 44, 103322. https://doi.org/10.1016/j.jobe.2021.103322

Adams K., Osmani M, Thorpe T.,and Thornback J., (2016) Circular economy in construction: current awareness, challenges and enablers. https://www.icevirtuallibrary.com/doi/epdf/10.1680/jwarm.16.00011

Wood Design & Building (2018) Dowel Laminated Timber http://www.wooddesignandbuilding.com/dowel-laminated-timber

Design of timber structures: Structural aspects of timber construction (2nd ed., Vol. 1). (2016). Swedish Forest Industries Federation. https://www.svenskttra.se/siteassets/5-publikationer/pdfer/design-of-timber-structures-1-2016.pdf

Philion, E., Chorlton, B., Gales, J., & Kotsovinos, P. (2022). Structural Fire Modeling Strategies for Exposed Mass Timber Compartments and Experimental Gaps for Model Validation. Journal of Performance of Constructed Facilities, 36⑥. https://doi.org/10.1061/(asce)cf.1943-5509.0001761

A. Law, L. Bisby (2020), The rise and rise of fire resistance, The rise and rise of fire resistance | Elsevier Enhanced Reader

Gernay, T. (2021). "Fire resistance and burnout resistance of timber columns." Fire Saf. J. 122 (Apr): 103350. https://doi.org/10.1016/j .firesaf.2021.103350.

Pastori A S., Mazzucchelli E S., Wallhagen B M., (2022) Hybrid timber-based structures: A state of the art review https://www.sciencedirect.com/science/article/pii/S0950061822031610

Sandhaas, C., Munch-Andersen, J., Dietsch, P. (eds.), Design of Connections in Timber Structures: A state-of-the-art report by COST Action FP1402 / WG3, Shaker Verlag Aachen, 2018.

Versteeg C J., (2022) A computational study of the application of efficient dual structural systems for achieving desirable comfort levels in timber high-rise structures.

Pastori S., Mazzucchelli S E., Wallhagen M., (2022) Hybrid timber-based structures:A state of the art review www.elsevier.com/locate/conbuildmat

E. Augeard, L. Michel, E. Ferrier, (2018)Experimental and analytical study of the mechanical behavior of heterogeneous glulam–concrete beams and panels assembled by a specifc treatment of wood, Constr. Build. Mater. 191 812–825, https://doi.org/10.1016/j.conbuildmat.2018.10.038.

S. Benkai, L. Weiqing, Y. Huifeng, (2021), Experimental investigation on the long-term behaviour of prefabricated timber-concrete composite beams with steel plate connections, Construction and Building Materials, Volume 266, Part A https://doi.org/10.1016/j.conbuildmat.2020.120892.

L.F.C. Jorge, S.M.R. Lopes, H.M.P. Cruz, (2011) Interlayer influence on timber-LWAC composite structures with screw connections, J. Struct. Eng. ASCE 137 ⑤ 618–624.

McLain, R., Steimle, D. (2019) Accommodating Shrinkage in Multi-Story WoodFrame Structures. WoodWorks

Ayanleye, S., Udele, K., Nasir, V., Zhang, X., & Militz, H. (2022). Durability and protection of mass timber structures: A review. Journal of Building Engineering, 46, 103731. https://doi.org/10.1016/j.jobe.2021.103731.

B.F. Tjeerdsma, M. Boonstra, A. Pizzi, P. Tekely, H. Militz, (1998) Characterisation of thermally modifed wood: molecular reasons for wood performance improvement, Holz-Roh-Werkst.

B. Esteves, H. Pereira, Wood modification by heat treatment: a review. https://www.researchgate.net/publication/279900105_Wood_modification_by_heat_treatment_A_review

P. Morris., (2015) Optimizing the Design of Mass Timber in Exterior Applications, FP Innovations,. https://www.researchgate.net/publication/327590248_DURABILITY_OF_MASS_TIMBER_STRUCTURES_A_REVIEW_OF_THE_BIOLOGICAL_RISKS

C Geurts., (1997) Wind-induced pressure fluctuations of on building facades.

G van Oosterhout (1996) Wind-induced dynamic behaviour of tall buildings. file:///C:/Users/USER/Downloads/ceg_oosterhout_19960923.PDF

American Society of Civil Engineers, & Engineers, A. S. C. (2010). Minimum Design Loads for Buildings and Other Structures: ASCE Standard 7-10. American Society of Civil Engineers.

Vayas, I., Ermopoulos, J., & Ioannidis, G. (2018). Design of Steel Structures to Eurocodes (Springer Tracts in Civil Engineering) (1st ed. 2019). Springer.

Domański, T., & Kmiecik, K. (2019). Load-bearing capacity of the steel-to-timber connections in fire temperature. MATEC Web of Conferences, 262, 09005. https://doi.org/10.1051/matecconf/201926209005

Sandberg, L. B., Bulleit, W. M., & Reid, E. H. (2000). Strength and Stiffness of Oak Pegs in Traditional Timber-Frame Joints. Journal of Structural Engineering-Asce, 126⑥, 717–723. https://doi.org/10.1061/(asce)0733-9445(2000)126:6(717

Crocetti, Roberto. (2016). Timber Structures for Large-Span Structures. 10.11159/icsenm16.124.

Branco, J., Dietsch, P., & Tannert, T. (2022). Reinforcement of Timber Elements in Existing Structures: State-of-the-Art Report of the RILEM TC 245-RTE (RILEM State-of-the-Art Reports, 33) (1st ed. 2021). Springer.

Lathuillière D, Bléron L, Descamps T, Bocquet J-F (2015) Reinforcement of dowel type connections. Constr Build Mater 97:48–54. https://doi.org/10.1016/j.conbuildmat.2015.05.088

Fonseca, E. M. M., Leite, P. A. S., Silva, L. D. S., Silva, V. S. B., & Lopes, H. M. (2022). Parametric Study of Three Types of Timber Connections with Metal Fasteners Using Eurocode 5. Applied Sciences, 12③, 1701. https://doi.org/10.3390/app12031701

Feldt P., & Thelin A., (2018) Glued-in Rods in Timber Structures Finite Element Analyses of Adhesive Failure

N.M.P. Bocken, E.A. Olivetti, J.M. Cullen, J. Potting, R. Lifset, Taking the circularity to the next level: a special issue on the circular economy, J. Ind. Ecol. (2017) 1–7, https://doi.org/10.1111/jiec.12606.

F. Sariatli, Linear economy versus circular Economy : a comparative and analyzer study for optimization of economy for sustainability, Visegrad J. Bioecon. Sustain. Dev. 6 (2017) 31–34, https://doi.org/10.1515/vjbsd-2017-0005

Machado, N., & Morioka, S. N. (2021). Contributions of modularity to the circular economy: A systematic review of literature. Journal of Building Engineering, 44, 103322. https://doi.org/10.1016/j.jobe.2021.103322

C.Y. Baldwin, K.B. Clark, Managing in an age of modularity, Harv, Bus. Rev. 75 (1997) 84–93.

P. Gu, M. Hashemian, S. Sosale, E. Rivin, An integrated modular design methodology for life-cycle engineering, CIRP Ann 46 (1997) 71–74, https://doi.org/10.1016/S0007-8506(07)60778-1.

J. Pandremenos, J. Paralikas, K. Salonitis, G. Chryssolouris, Modularity concepts for the automotive industry : a critical review, CIRP J. Manuf. Sci. Technol. 1 (2009) 148–152, https://doi.org/10.1016/j.cirpj.2008.09.012.

R. Minunno, T. O'Grady, G.M. Morrison, R.L. Gruner, Exploring environmental benefits of reuse and recycle practices: a circular economy case study of a modular building, Resour. Conserv. Recycl. 160 (2020) 104855, https://doi.org/10.1016/j.resconrec.2020.104855

[110] H. Yuan, Barriers and countermeasures for managing construction and demolition waste: a case of Shenzhen in China, J. Clean. Prod. 157 (2017) 84–93, https://doi. org/10.1016/j.jclepro.2017.04.137.

Chini, A., & Schultmann, F. (2001). Design for deconstruction and material reuse. Proceedings of the CIB Task Group 39 - Deconstruction Annual Meeting, Karlsruhe 2002. CIB Publication 272.

e engineering to building design & constructio: Vol. ISBN-10: 90-9020341-9. Cedris M&CC.

Ruimtelijk Raamwerk M4H. (2020, December 15). M4H Rotterdam. https://m4hrotterdam.nl/ruimtelijk-raamwerk-m4h/

Rotterdam Circular -. (2020, May 18). https://rotterdamcirculair.nl/en/about-rotterdam-circular/

Rotmans J., Weel van der S., (2005) MERWE-FOUR-PORTS: From desert to gold mine

Mariller N., (2020) Design of a multi-use, demountable, timber arena: A research in re-usable timber structures.

J.L. Miotto, A.A. Dias, Evaluation of perforated steel plates as connection inglulam–concrete composite structures, Constr. Build. Mater. 28 (2012) 216–223, https://doi.org/10.1016/j.conbuildmat.2011.08.045.

E. Ferrier, A. Agbossou, L. Michel, Mechanical behaviour of ultra-high-performance fbrous-concrete wood panels reinforced by FRP bars, Compos. PartB Eng. 60 (2014) 663–672, https://doi.org/10.1016/j.compositesb. 2014.01.014.

G. Youssef, L. Loulou, S. Chataigner, S. Car´e, A. Flety, R. Le Roy, Analysis of the behaviour of a bonded joint between laminated wood and ultra-high-performance fbre reinforced concrete using push-out test, Constr. Build. Mater. 53 (2014) 381–391, https://doi.org/10.1016/j.conbuildmat.2013. 10.074.

Tedeschi, A., & Wirz, F. (2014). AAD_algorithms-aided design : parametric strategies using Grasshopper.

The construction kits were created to build the modular high-rise: a structural kit. These kits are versatile and functional for small and large-scale uses and are designed to be interoperable with each other. This interoperability provides a wide range of architectural options and allows for a highly adaptable system that can be applied to various uses and requirements. The result is a flexible and versatile building that can be tailored to meet the variety of needs of its users.

The structural kit is a versatile package of building components designed to meet a range of scale requirements. It includes prefabricated columns, beams, trusses, and cores made of Glulam and CLT, with options for S (6x6x3m), M (6x6x6m), L (18x6x12m), and XL (30x6x18m) configurations. The components are connected using steel joints with various rotational stiffness specifications to meet specific project requirements.

The manufacturing and assembly methodology of the structural kit emphasizes compatibility between components and joints while avoiding any permanent connections between them. This means the components are prefabricated in a specialized EWPs manufacturing facility, pre drilled and milled for easy assembly.

Similarly, the steel joints are also prefabricated with all the screws and bolts necessary for quick and efficient on-site assembly. Overall, this approach allows for a faster, more efficient, and sustainable construction process while maintaining the highest structural integrity and safety levels.

The scales are a standard combination of the components, which is an example of the multiple scales and configurations this set of pieces can achieve. The following measurements of the different scales are given considering the vectorial length of the components; the element's cross sections vary depending on its mechanical requirements. S scale is a module of 4 columns of 3m height connected by four beams of 6m. M scale is a module of 4 columns of 6m height connected by four beams of 6m.

These two groups of components create glulam frames that can be pre-assembled before installation or assembled in pieces, depending on the needs and limitations of the construction place. L scale is a module of 4 columns of 12m height connected by two beams of 6m and two trusses of 18m. An XL scale is a module of 4 columns of 16m in height connected by two beams of 6m and two trusses of 30.

The cores are conformed by prefabricated panels that conform to the box. Fig 46 Shows a representation of the multi scale modularity.