ECOLE
POLYTECHNIQUE
DE BRUXELLES

DOCUMENT TO BE INCLUDED IN THE MASTER THESIS

CONSULTATION OF THE MASTER THESIS

I, the undersigned

NAME Deroisy

FIRST NAME Julie

MASTER PROGRAM Architectural engineering

MASTER THESIS TITLE Carbon emissions of CLT buildings: the case study of Sara Cultural Centre

AUTHORIZE*

~~**REFUSE***~~

(IN CASE OF REFUSAL, THIS DOCUMENT MUST BE COUNTERSIGNED BY THE MASTER THESIS SUPERVISOR)

(Delete as appropriate)*

Consultation of this master thesis by users of the libraries of the Université libre de Bruxelles.

If consultation is authorised, the undersigned hereby grants the Université libre de Bruxelles a free and non-exclusive licence, for the duration of the legal term of protection of the work, to reproduce and communicate to the public the above-mentioned work, on graphic or electronic media, in order to enable users of the libraries of the ULB and other institutions to consult it within the framework of inter-library loan.

Brussels, 18/08/2024

Signature of the student

Julie Deroisy

Signature of the supervisor
(only if consultation is refused)

Carbon emissions of CLT buildings

The case study of Sara Cultural Centre

Deroisy Julie

2023-2024

Architectural Engineering at Polytechnical School of Brussels

Promoter: Ahmed Khan

Acknowledgement

First of all, I would like to express my deepest gratitude to my supervisor, Prof. Ahmed Khan, for his invaluable guidance and support throughout the duration of this master thesis. His expertise, especially in the academic aspects of the work, has been instrumental in shaping the direction and quality of this research. His encouragement and constructive feedback have been a source of inspiration, and his commitment to excellence has set a standard I will strive to uphold in my future endeavors.

I would also like to extend my sincere thanks to my friends and family whose insights and advice have greatly contributed to the development of this thesis. Their willingness to share their knowledge and provide feedback at various stages of my research has been incredibly helpful. Moreover, their patience and understanding during this demanding period have been a great source of strength.

Additionally, I am grateful to my colleagues and fellow students at ULB and VUB for their camaraderie and support. The collaborative atmosphere and intellectual exchanges have enriched my academic experience.

Thank you all for your contributions to the successful completion of this thesis.

Abstract

This thesis critically examines the carbon emissions of Cross-Laminated Timber (CLT) buildings, positioning them as a viable sustainable alternative to conventional construction materials like concrete and steel. The primary objective is to assess the carbon footprint of CLT buildings, particularly through the case study of the Sara Cultural Centre, designed by White Arkitekter. The research employs a comprehensive Life Cycle Assessment (LCA) methodology to evaluate the carbon budget of the Sara Cultural Centre, which is claimed to be carbon-negative over its 50-year lifespan.

The findings indicate that the use of CLT significantly reduces the overall carbon footprint of the building compared to traditional materials. The LCA results reveal that the carbon sequestration potential of CLT, combined with low energy consumption, contributes to a net reduction in carbon emissions. However, the study also identifies key barriers to the widespread adoption of CLT, including market acceptance, regulatory challenges, and the entrenched reliance on traditional materials due to historical fire safety concerns.

In conclusion, while the Sara Cultural Centre exemplifies the potential of CLT to reduce buildings carbon footprint, the research underscores the need for supportive building codes and increased investment in CLT production. The thesis advocates for a model shift in construction practices, promoting CLT as a standard material to enhance sustainability in the built environment and mitigate climate change impacts.

Key words: Cross-Laminated Timber (CLT), carbon footprint, Sara Cultural Centre, Life Cycle Assessment (LCA), carbon sequestration, sustainable building materials.

Table of contents

Glossary

CLT: Cross-Laminated Timber

CO2eq: CO2 equivalent. This term is used to quantify the impact of different greenhouse gases on global warming. This is achieved by expressing the emissions in terms of the amount of carbon dioxide (CO_2) that would have the same effect over a specific time period.

EOL: End-Of-Life

EPD: Environmental Products Declaration

EWP: Engineering Wood Products

FU: Functional Unit

GHG: Greenhouse Gas

LCA: Life Cycle Assessment

mPt: milli-Point. Dimensionless unit used in TOTEM taking into account multiple indicators for assessing the environmental footprint of a product or building.

OSB: Oriented Strand Boards

PEB: Performance Energy Building

PV: Photovoltaic Panels

UFA: Usable Floor Area

GLT: Glued Laminated Timber

TOTEM: Tool to Optimise the Total Environmental impact of Materials. The LCA software used in this paper

1. Introduction

Today, the building and construction sector is responsible for almost 40% of global energy-related CO2 emissions (United Nations Environment Programme 2022). This makes it one of the most polluting sectors, but it also means that it is the sector in which any progress can potentially have a huge impact. More specifically, it is estimated that the materials used in building construction (i.e. concrete, steel, aluminium, glass, bricks and wood) are responsible for around 9% of global energy-related CO2 emissions (United Nations Environment Programme 2022). This is counted as "embodied carbon in buildings" which must be addressed immediately to avoid compromising the carbon reductions achieved through energy efficiency. A whole-life cycle approach to construction is essential to maximise sustainability (United Nations Environment Programme 2022).

Cement, which is the main component of concrete, accounts for around 8% of CO2 global emissions (Lehne and Preston 2018). This can be explained by the proportion of concrete used in the construction sector compared to other materials. According to the Figure 1 shown below, in 2017, the global use of concrete in the construction sector represented more than 7 billion tonnes, compared with less than half a billion tonnes for wood.

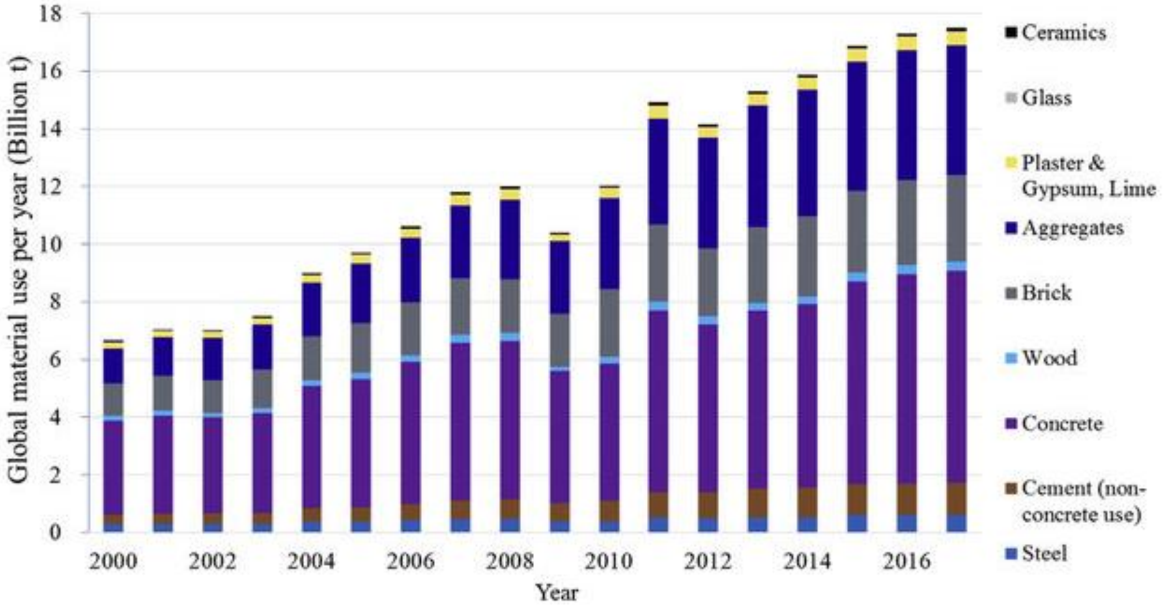


Figure 1: Global building material use by materials

However, these figures must take into account the fact that concrete is heavier (~2300-2500 kg/m³) (CEN 2004) than wood (~400-800 kg/m³) (Green and Taggart 2020) per unit of m³. But this does not detract from the fact that these latest figures show concrete's contribution to overall carbon emissions. In addition, it explains Europe's determination to reduce the concrete production in order to achieve carbon neutrality by 2050. With this objective in mind, there is growing interest in Europe and around the world in engineered wood products such as Cross Laminated Timber (CLT).

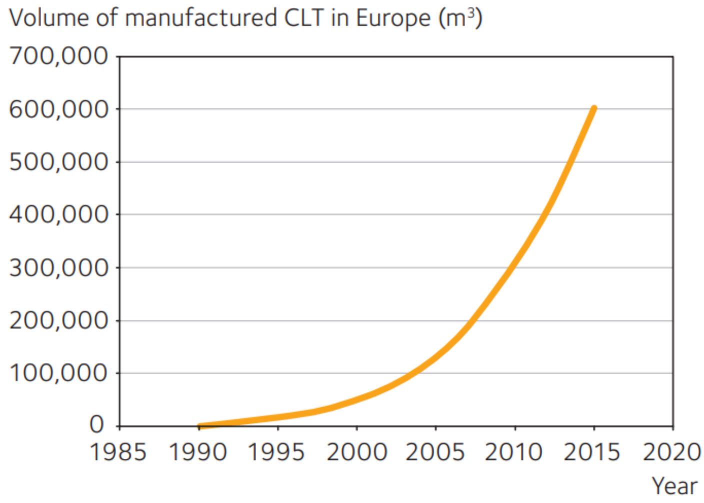


Figure 2: Development of CLT in Europe

Figure 3 and 4 present a comparison of the carbon emissions of the most commonly used building materials in the construction industry. Figure 3 indicates that aluminium is the most polluting material, with 24,732 kgCO2e/m³, followed by steel with 11,388 kgCO2e/m³. In the same graph, concrete reaches 2,185 kgCO2e/m³, but only between approximately 150 kgCO2e/m³ and 400 kgCO2e/m³ in Figure 4 due to differing strength class of concrete. The values from these references are very far apart and show that data on carbon emissions must be taken with caution and compared with several sources. From another reference, researchers obtained carbon emissions of concrete ranging from 317 kgCO2e/m³ to 362 kgCO2e/m³ (Arenas and Shafique 2024) which is more similar to values from Figure 4. For aluminium and stainless steel, they obtained 25,832 kgCO2e/m³ and 8778 kgCO2e/m³ respectively (Arenas and Shafique 2024).

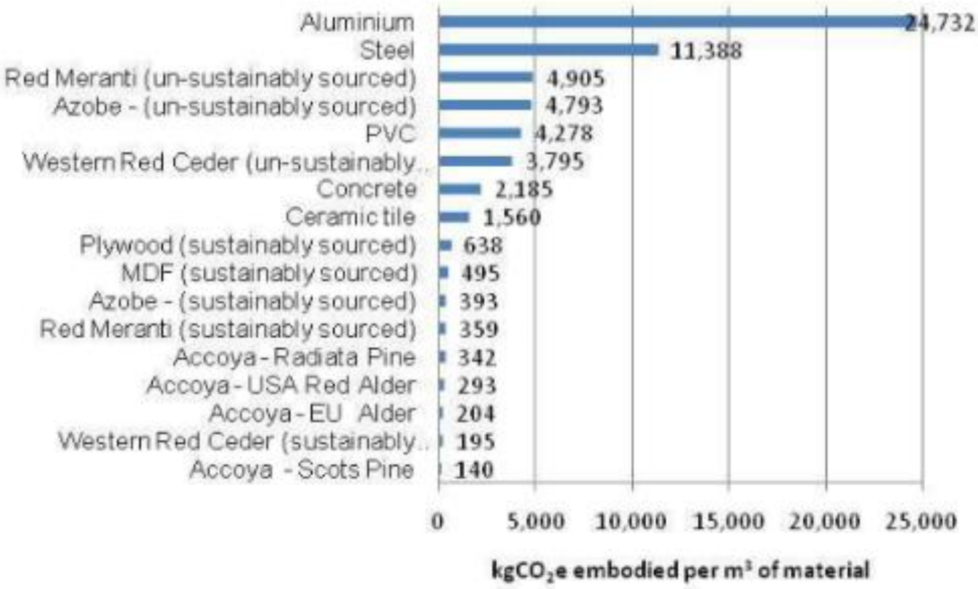


Figure 3: the greenhouse gas emissions of several building materials per cubic meter based on a cradle to gate scenario (Lugt, et al. 2014)

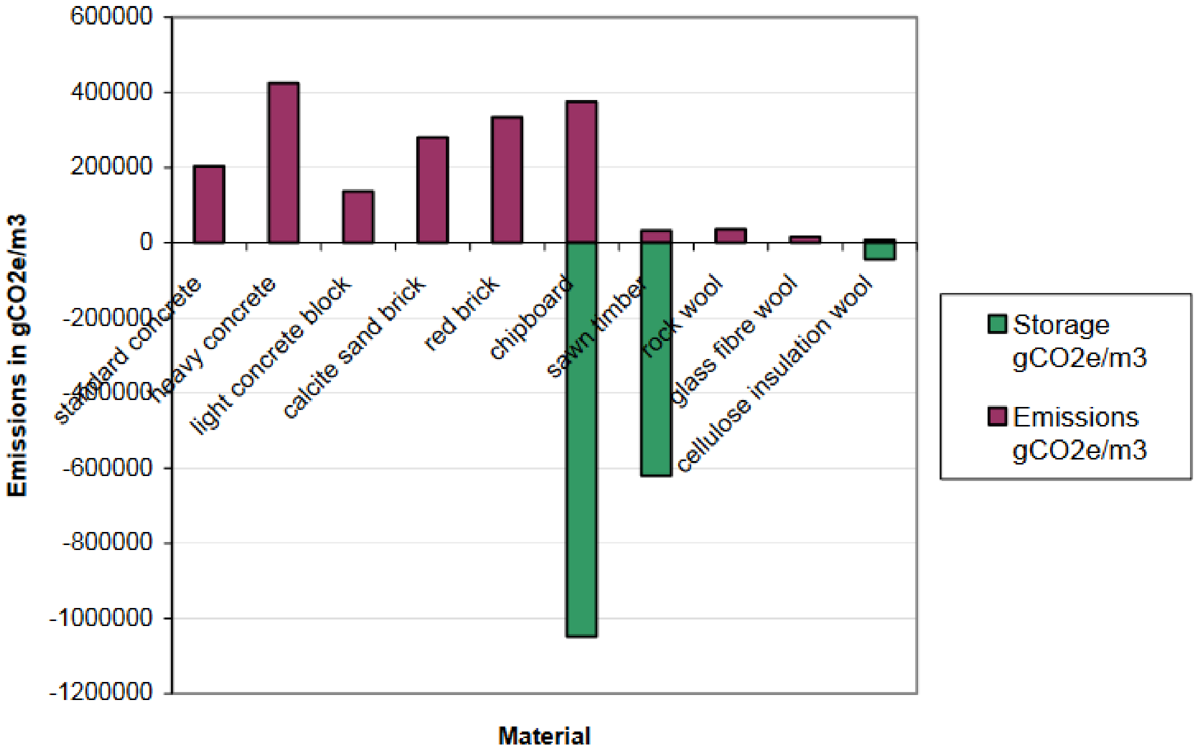


Figure 4: Emissions from building materials in gCO2e per m³ of material (Reid, et al. 2004)

Engineered Wood Products (EWP) in Figure 3 have a wide range of carbon emissions, depending on the type of wood and the method of construction. The EWP can emit as little as 140 kgCO2e/m³ in case of Scot pines, and as much as 4,905 kgCO2e/m³ in the case of unsustainably produced red meranti. For the case of wood in Figure 4, it can be observed that chipboard almost rejects 400 kgCO2e/m³ and sawn timber 50 kgCO2e/m³. This reference offers supplementary data regarding the carbon storage capacity of wood. Chipboard can absorb more than 1000 kgCO2e/m³ and 600 kgCO2e/m³ for sawn timber. This significantly reduces the carbon footprint of wood, resulting in a negative value, thereby making it negative in carbon. The latter values for aluminium, steel and wood are comparable to those in Figure 3, which shows that they can be reliable although those for concrete were clearly overestimated. For the material of brick, carbon emissions of 300-350 kgCO2e/m³ were observed (Reid, et al. 2004). This shows that using wood can be a very interesting way of limiting the energy consumption of a building, but that attention must be paid to the type of wood used and the method of construction (Lugt, et al. 2014).

This proves that wood is an attractive raw material from a sustainability point of view. Additionally, 1m³ of wood can in fact stores 1,000 kg of carbon dioxide approximately (Green and Taggart 2020). Moreover, CLT has a high strength in relation to the self-weight of the material which makes it an interesting structural material (Swedish wood 2022).

This led to the gain of interest and popularity for tall wood buildings as sustainable construction practices and advancements in engineered timber materials, like CLT (see Figure 2), continue to evolve (Green and Taggart 2020). The Sara Cultural Centre is one of the world's tallest buildings constructed using CLT. The architects and other stakeholders in the project claim that the building is carbon-negative meaning that more carbon is stored in the building than is released over its entire lifespan.

1.1. Research goals

The primary objective of this research is to critically examine the extent to which the architects of the Sara Cultural Centre can credibly claim that the building is carbon negative. This involves an in-depth analysis of the materials and methods used in the construction, with a specific focus on CLT and its environmental impact. The study aims to contextualize this claim within the broader framework of sustainable architecture and carbon accounting practices. To achieve this overarching goal, the research is structured around several key sub-questions:

1) **What are the key factors preventing CLT from becoming the standard construction material, despite its recognized environmental benefits?**

This sub-question aims to explore the historical development and adoption of CLT as a construction material. Understanding the evolution of CLT usage is crucial in assessing its current role in sustainable building practices. The research will trace the material's origins, the leader countries in its production, and the growing popularity in modern construction. By doing so, it will provide a context for evaluating the significance of CLT in the Sara Cultural Centre’s carbon-negative claim. At the same time, it will analyse factors other than sustainability in order to understand which aspects of CLT may complicate its use in the field of construction.

2) **What are the factors that enable a building to achieve a carbon-negative status?**

The thesis illustrates the mechanisms through which a building can achieve this status. By answering this question, it will explore the concept of biogenic carbon and carbon sequestration thanks to bio-based materials such as CLT. As the focus will be on CLT, one section will also include the importance of sustainable forest management in the production cycle for this type of material.

3) **What are the different approaches of Life Cycle Assessment (LCA) to estimate the carbon footprint of buildings and how can they be analysed using a software?**

Life Cycle Assessment (LCA) is a method for evaluating the environmental impact of buildings. This sub-question will explore the various approaches within LCA, including cradle-to-grave and cradle-to-gate assessments. By reviewing these different approaches, the research will identify the most relevant and accurate methods for assessing the environmental footprint of the Sara Cultural Centre, particularly in relation to its carbon emissions.

This question also addresses the practical aspect of carbon accounting through LCA software tools. Therefore, it focuses on the functionalities of LCA software, such as assumptions on carbon emissions, the incorporation of various construction materials and the simulation of different life cycle stages. Thanks to this, this work can offer a framework enabling anyone to determine the carbon impact of a building. By applying this tool to the Sara Cultural Centre, the research aims to quantify the building's carbon footprint, thereby evaluating the architect's claim that the building is carbon negative.

1.2. Methodology

The overall approach of this master thesis is both quantitative and qualitative. On the one hand, a large part of the paper is based on an analysis of the existing literature in order to obtain the framework needed to analyse the case study of the Sara Cultural Centre designed by White Arkitekter. On the other hand, a Belgian LCA software called Totem is used to obtain results and quantify its carbon footprint in comparison with other architectural projects. The resulting calculations yielded a specific quantity of tons of CO2e.

The case study sample focuses on a single project, which also explains why this document is not exclusively quantitative. It does not provide a general overview of the carbon footprint of all CLT buildings. This case study was chosen because it has received a lot of media coverage thanks to the architect’s claim that the building is carbon negative.

Both primary and secondary sources were employed. Indeed, to provide sufficient information regarding the composition of the building and its energy consumption, it was necessary to gather precise data from the architects, White. In addition, a meeting was arranged with one of the main architects, Robert Schmitz, to discuss the project. This provided an opportunity to hear the architects' thoughts and decisions when designing the project. This was combined with documents from media and architecture magazine such as *dezeen* about the studio.

1.3. Structure of the thesis

The thesis is organized into key sections that explore the topic of CLT buildings and their carbon emissions. The introduction first outlines the research goals, methodology, and the overall structure of the thesis. It aims at highlighting CLT significance regarding the reduction of carbon emission and the promotion of sustainable construction.

Then, a comprehensive overview of CLT building characteristics is given, focusing especially on the evolution of CLT and tall wood buildings, on the inherent properties of the material, on the leading countries in CLT usage and on the various challenges and opportunities.

Following the state of the art of CLT and tall wood buildings, the paper focuses on the topic of carbon emissions associated with CLT buildings, comparing them to traditional construction methods and discussing their environmental impact. The issues of sustainability and LCA of CLT buildings, with concepts such as biogenic carbon, sustainable forest management, and the methodology of the Totem LCA tool will be explored. This section outlines a framework for assessing the carbon footprint of buildings utilizing an LCA software.

The third part tackled the case study of the Sara Cultural Centre, including a description of the building, an analysis of its carbon budget, and a discussion of its various components and their contributions to the overall carbon footprint.

Finally, the thesis concludes by comparing the carbon budget published by White with the analysis carried out using the LCA software. All this was made possible by an in-depth understanding of the current literature on the subject. Annexes containing the plans, the data implemented in the software and the transcript of the interview with Robert Schmitz are provided at the very end of this document.

2. Cross-Laminated Timber Buildings: a state of the art

2.1. Evolution of CLT and tall wood buildings

Historically, the use of wood in the structure of buildings was limited to lightweight framework systems with linear solid-wood elements of limited span. But in 1666, the Great Fire of London destroyed more than 80% of the city. This led the city to introduce a law requiring buildings to be constructed of stone or brick. Then in 1871, the Great fire of Chicago destroyed over 17,500 buildings of the city centre. This event was favoured by unusually strong winds and a very dry summer, combined with the fact that the facades of the buildings were made of wood in a very dense urban environment. Similarly to London, safety regulations were put in place following this event. (Green and Taggart 2020)

At the beginning of the twentieth century, steel and concrete became the basic construction materials, thanks to their accessibility, cost-effectiveness and durability over time. Wood was largely replaced by reinforced concrete (Jeleč, Varevac and Rajčić 2018).

In the 1960s, there was a revival of interest in wood with the introduction of a new wood-based product called "Engineered Wood Product" (EWP) initially developed in Austria and Germany, which included different timber structural composites improving wood materials by the application of modern gluing technologies. The objective of the development of engineered wood products was to enhance the strength of timber elements and to reduce the variability of their behaviour (Green and Taggart 2020). These also offered to designers a greater flexibility in dealing with the design situations (Frank 2001) and participated to the development of modern production technologies and improved methods for protecting wood against fire (Wieruszewski and Mazela 2017).

One of the most well-known wood engineered product is glued laminated timber (GLT or glulam) which consisted of using laminates of wood glued together rather than a whole piece of solid timber, improving its structural capacity and allowed the construction of more complex wooden structures with much greater spans (Jeleč, Varevac and Rajčić 2018). One of the first products in plate form in the EWP were laminated veneer lumber (LVL), which consists of gluing together thin boards of wood in the same direction. This is mostly used as secondary elements in the cladding and protection of structures, as their properties were not strong enough to be used in the main structure of buildings (Frank 2001). Following on from the development of EWP, a new composite product called CLT was patented in the mid-1990s (Jeleč, Varevac and Rajčić 2018).

In 2004, the Eurocodes "Design of Timber Structures" defined good practice for timber construction. However, it was then up to regional and national authorities to legalise EWP structures and bring them into line with European directives. (Green and Taggart 2020)

Nevertheless, building regulations in European countries still imposed limitations on the height and surface area of timber buildings and required the construction of tall buildings to be exclusively with non-combustible materials such as concrete, masonry or steel. These regulations were not immediately relaxed in all countries following the publication of the Eurocode for timber, as there is still a certain perception of timber due to the catastrophic fire events mentioned above. However, extensive research has demonstrated that massive timber components do not readily ignite. It is indeed the case that they burn, but they do so at a slow and very predictable rate (Green and Taggart 2020). One of the main rules detailed in the Eurocodes concerning the fire design of buildings is that the structure must retain its load-bearing capacity for at least two hours (Östman, et al. 2018).

2.2. Leader countries in CLT

The countries that have led the production and utilisation of CLT are Austria and Germany. This is because, as previously stated, they were the first countries to develop this innovative EWP. However, other countries have also emerged as leaders in the field, including Switzerland, Sweden, Norway, the United Kingdom, New Zealand and Australia.

Furthermore, in Nordic countries such as Sweden, forests are a pervasive feature of the landscape, with 70% of the land covered by forest. Additionally, the construction of wooden houses is a deeply entrenched tradition. This is evidenced by the fact that Sweden is one of the few European countries to construct a significant proportion of its housing stock from wood, in comparison with the rest of the continent. Nowadays, up to 20% of new multi-storey edifices in Sweden are constructed using wood. (Giacometti and Salonen 2023).

On the contrary, Belgium only built less than 7% of its new construction with wood. This phenomenon remains an enigma for researchers. Despite the European Union's promotion of wood as a key material in the fight against global warming through initiatives such as the European Green Deal and the target of carbon neutrality by 2050, and even the President of the European Commission, Ursula von der Leyen, emphasising the potential of the construction sector to become a carbon sink through the use of organic materials such as wood, the use of wood in the Belgian construction sector remains limited. The reasons for this may be linked to the sanitary crisis caused by the 2019 Coronavirus pandemic, the increase in the price of wood and building materials, as well as supply chain issues affecting the availability of wood, which have had a negative impact on the timber construction sector in Belgium (Hout Info Bois 2022). Belgium's forest cover is only 23% of the total land area (Belgique, Société Royale Forestière de 2024), which necessitates the importation of wood from other European countries (Hout Info Bois 2022).

2.3. Description of CLT

CLT is a wood composite material made up of wood laminae stacked one on top of the other, with the orientation of the fibres alternating perpendicularly from one layer to the next.

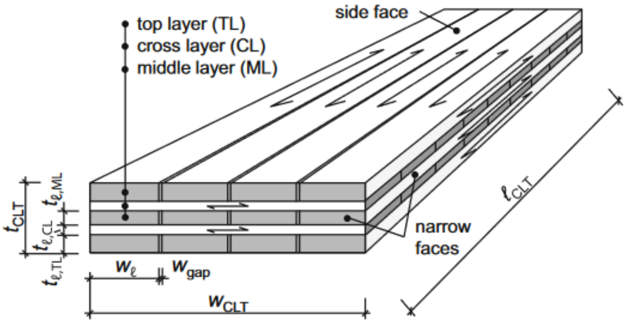


Figure 5: Technical drawing of a CLT element (Brandner, et al. 2016)

Figure 6: Picture of a CLT element

CLT is always made up of an odd number of layers so that the wood fibres of the lamina in the bottom layer and the top layer are in the direction of the span. Usually, CLT are made of 3, 5, 7 or even 11 layers of laminae in the case of bridge decks (Jeleč, Varevac and Rajčić 2018). In Figure 7 is detailed the composition of wood at different scale.

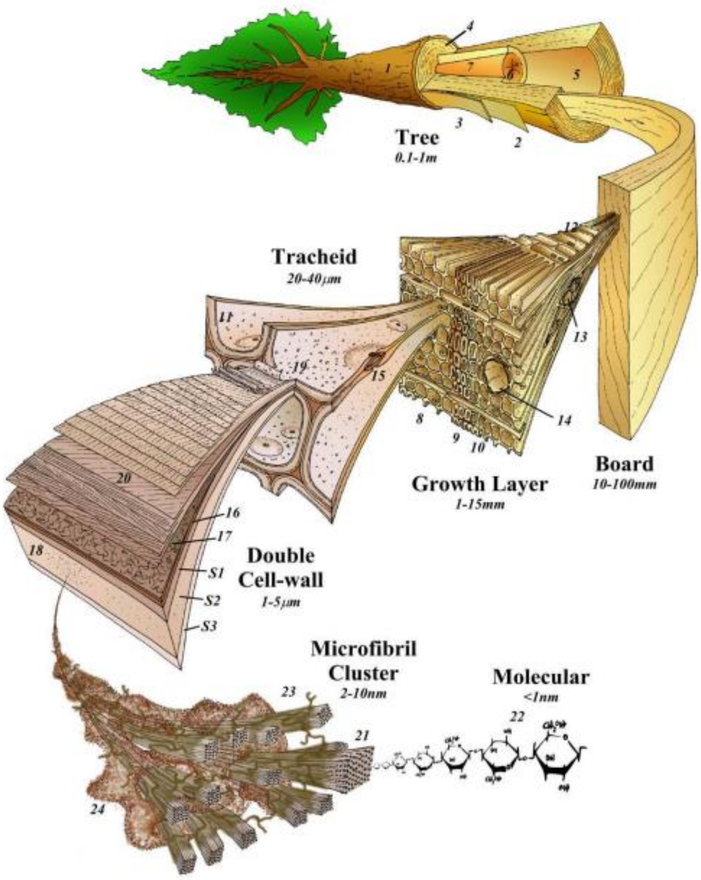


Figure 7: Schematic softwood structure at different scale. (Harrington 2002)

At a microscopic scale, wood can be described by a straw model, a porous box composed of fibres aligned in the same direction (Figure 8). At the nanoscopic scale each fibre is made up of chains of cellulose and hemicellulose held together by a matrix, a kind of natural glue, lignin. (Harrington 2002)

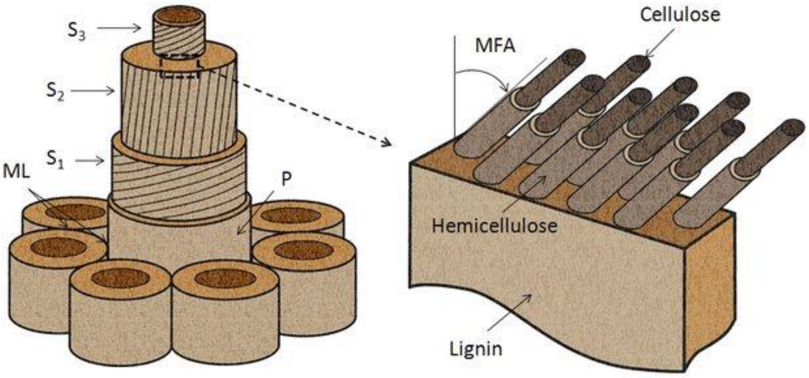


Figure 8:
Left: Three-dimensional model of the different cell-wall of wood fibre at microscopic scale.
Right: Three-dimensional structure of the secondary cell wall of a wood fibre at nanoscopic scale.
(Ricardo Gherardi Hein 2011)

Wood is an orthotropic material, which means that it has three perpendicular principal directions with different properties. This is because it is mainly the fibres that carry the applied loads (Ricardo Gherardi Hein 2011). The wood fibres follow the longitudinal direction of the tree stem, as shown in Figure 9. An analogy to easily understand how the anisotropic behaviour of wood works is to compare it to the human fingers Figure 10). The strength of wood in reaction to stresses applied in the direction of the fibres will be greatest, while the one in the case of stresses applied perpendicular to the fibres will be lowest, especially in tension.

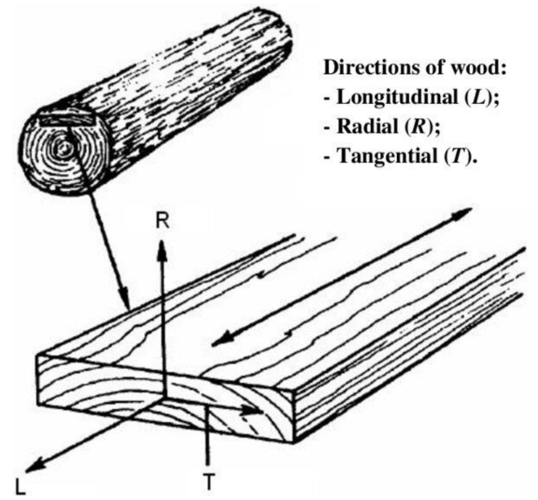


Figure 9: Direction of wood fibres

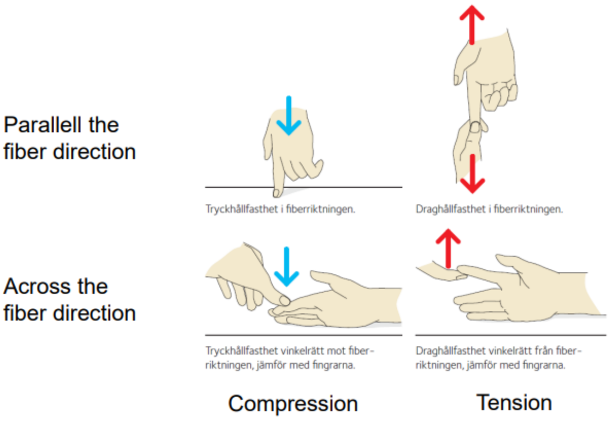


Figure 10: Analogy of human fingers to represent mechanics of wood fibres

2.4. CLT manufacturing technology

The cycle of production of CLT can be easily described by the diagram in Figure 11. The wood lumbers are first cut into boards, also known as lamellae or laminates. The thickness of these boards can vary from 20 to 60 mm. The boards then need to dry to evacuate the water and achieve a moisture content of between 8 and 15%. This step is very important because the timber strength falls as the moisture content rises.

Later, they are classified and selected on the basis of their resistance in accordance with standard EN 14081-1. The cross-section of CLT generally contains boards of the highest strength class in the direction of the main load, i.e. in the direction of the span, to exploit the timber's strength to the greatest possible extent. In order to create longer boards and achieve the required span, the individual lamellae are finger-jointed, which involves joining and gluing two lamellae together lengthways using a saw-tooth cut.

This step is necessary; however, it is crucial to acknowledge that such a connection may potentially lead to a decline in the mechanical properties of the material (Jeleč, Varevac and Rajčić 2018). The amount of material loss due to defect removal and finger-joint process is estimated to be around 15% (Brandt, et al. 2019). This estimation can vary between 10-30% according to different factors such as the precision of initial cutting, the quality of raw materials, and the specific production methods used. Once the glue has hardened, the boards must be smoothed to remove the excess glue and to ensure that they are straight. The CLT panels are made by assembling the lamellae into large sheets and glued together under the necessary constant pressure.

Finally, the panels undergo a final refinement process, which involves sawing the edges, milling channels for installations, drilling holes and preparing joints and fixings. The visible surfaces of each panel are polished, and the components are visually inspected and labelled before being packaged and loaded for transport to a building site or warehouse. (Swedish wood 2022)

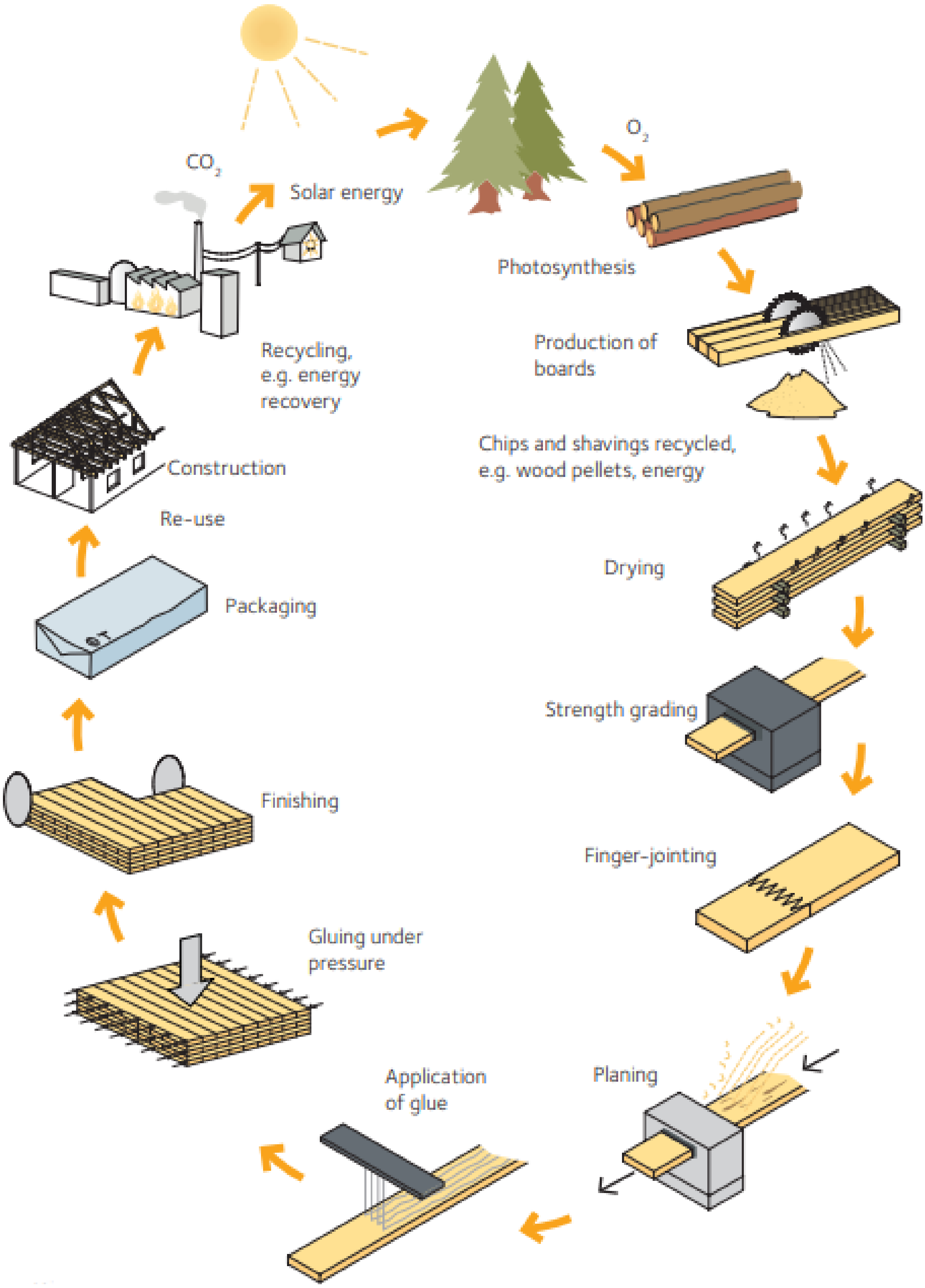


Figure 11: Schematic diagram of the CLT production process (Swedish wood 2022).

2.5. Material properties

In this section, the main properties and advantages of CLT will be explored, although this is not an exhaustive list of its benefits.

a. Load-bearing capacity

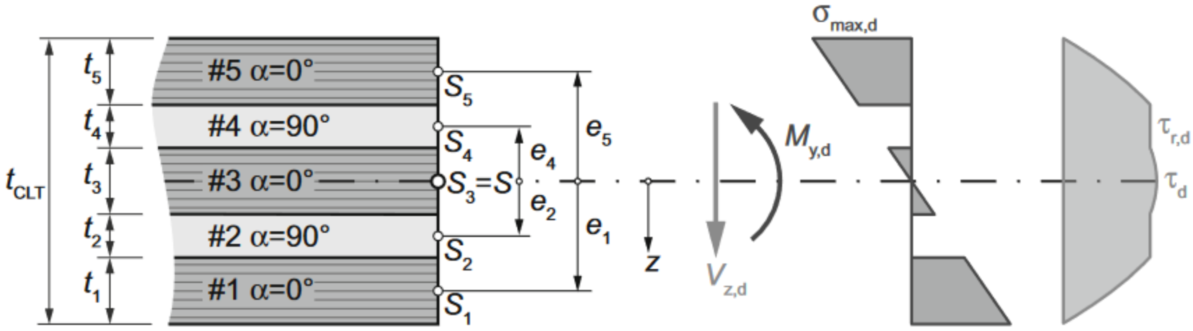


Figure 12: Cross section of a five-layer CLT element loaded out-of-plane: normal and shear stress distributions assuming E90 = 0 (Brandner, et al. 2016).

First of all, CLT is an isotropic material, exhibiting a variation in strength according to the angle between the stress and the direction of the fibres. CLT presents good strength capacities, but these vary depending on whether the force is applied parallel to the direction of the fibre or perpendicular to it. Its compressive strength capacity can vary from 16 to 24 [MPa] (Swedish wood 2022) along the grain but only from 2 to 2.7 [MPa] (Swedish wood 2022) perpendicular to the grain. In comparison, typical compression strength of concrete is of 20 to 40 [MPa] (CEN 2004) which is slightly higher than that of CLT. However, high-strength concrete can achieve compressive strengths exceeding 100 MPa (CEN 2004).

While not as strong in tension as in compression, CLT still offers significant tensile strength. The tensile strength can vary but typically falls within 7 to 19 [MPa] (Swedish wood 2022) along the grain but remains at only 0.4 [MPa] (Swedish wood 2022) perpendicular to the grain. This weakness in tension perpendicular to the direction of the grain is typically something that must be considered in CLT structural systems. In terms of bending strength, CLT can range from 14 to 30 [MPa] (Swedish wood 2022). The elastic modulus (Young's modulus) of CLT varies between 7,000 to 12,000 [MPa] (Swedish wood 2022) in the main fibre direction.

CLT can bear loads in both in-plane and out-of-plane directions. This versatility allows it to be used effectively in various structural applications, including walls, floors, and roofs. CLT panels have been engineered to resist lateral loads, which is crucial for the stability of tall buildings, especially in areas prone to earthquakes or high winds. (Quesada, Smith and Berger 2018)

Furthermore, CLT can bear loads in both in-plane and out-of-plane directions. This versatility allows it to be used effectively in various structural applications, including walls, floors, and roofs. CLT panels have been engineered to resist lateral loads, which is crucial for the stability of tall buildings, especially in areas prone to earthquakes or high winds. (Quesada, Smith and Berger 2018)

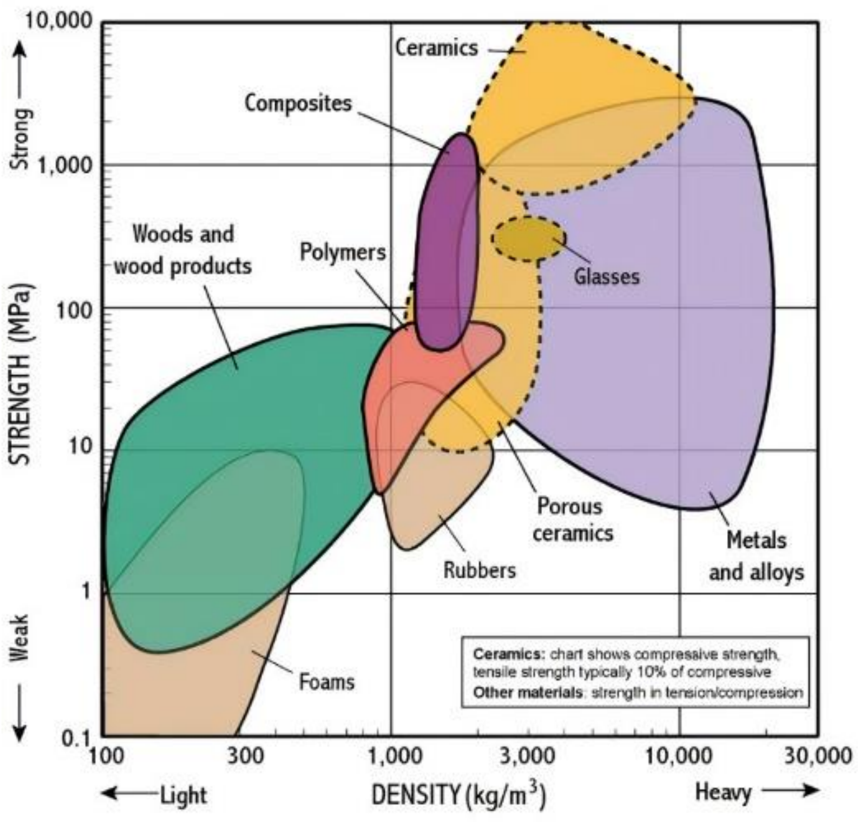


Figure 13: Strength to density ratio.

Finally, the self-weight of CLT remains low reducing then the dead-load of the structure. This related to its high strength means that CLT can support substantial loads while being relatively lightweight compared to other construction materials, such as concrete or steel. This property allows for efficient structural designs that do not require excessive material use.

b. Prefabrication and ease of installation

Figure 14: Brock Commons Project in Vancouver

The design of CLT allows for a high degree of prefabrication, enabling efficient construction processes compared to traditional construction methods. Wall assemblies can be constructed with clear separation in layers for construction, insulation, installation, and cladding, facilitating easier on-site assembly and modifications (Brandner, et al. 2016). This can lead to faster construction times and lower labour costs, as fewer resources are needed for lifting and moving heavy materials (Swedish wood 2022).

c. Thermal performance

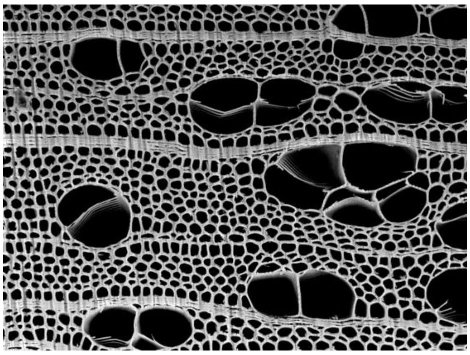


Figure 15: Microstructure of birch

CLT has good thermal insulation properties and can contribute to energy efficiency in buildings. This is due to the natural thermal performance of wood (Quesada, Smith and Berger 2018). Wood is composed of a network of hollow cells and cell walls. These cells are filled with air, which is a poor conductor of heat. The air pockets trap heat, reducing the transfer of heat through the material.

d. Design flexibility

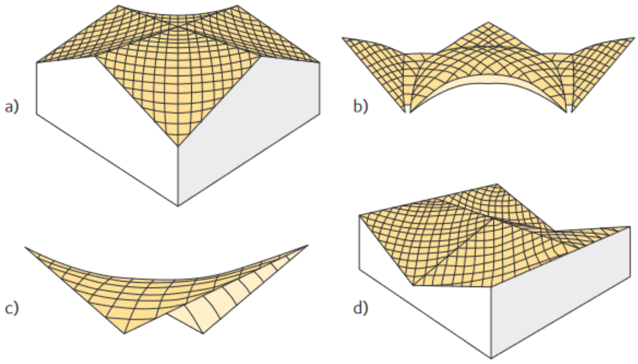


Figure 16: Examples of shell structures (Swedish wood 2022)

The engineered nature of CLT allows for design flexibility, enabling architects to create innovative and aesthetically pleasing structures. This flexibility encompasses the integration of large openings and cantilevers. In practical terms, no lintel is needed to hold the void created by an opening such as a window or door, as the CLT supports itself. Moreover, depending on the manufacturing procedure, bent and folded components can be produced to a certain extent.

e. Sustainability

In addition to other properties, perhaps one of the most important and the reason for its growing popularity, CLT is a durable material (Green and Taggart 2020). CLT is made from wood, a renewable and sustainable resource, making it an environmentally friendly building material (Swedish wood 2022). In addition, the production process for this material is very energy efficient. However, this point will be explored in greater detail in the following sections.

2.6. Challenges and outlook

Similarly as for the properties, some challenges and outlook of the use of CLT are presented. This gives an overview of why this material is so interesting and is gradually gaining in popularity, as well as explaining the reasons that may prevent its use.

a. Connections

Due to the high stiffness and resistance of CLT panels, the majority of its performance depends on the connections (Brandner, et al. 2016). According to a study compiling the testimonies of several experts and workers in the field, the most important research needs are the structural performance of CLT and its connections (Espinoza, et al. 2015). In CLT systems, connections are typically made using screws, nails, metal brackets, and bolts to join panels and other structural elements. These connections ensure structural integrity and load transfer between the panels. However, there is yet no suitable connection system for CLT, such as a line instead of point connectors. New connection technologies and systems are being developed to improve the performance and efficiency of CLT connections. For example, research is ongoing to explore the use of advanced materials and techniques, such as prefabricated connection systems, to streamline construction processes and improve the overall performance of CLT structures. (Swedish wood 2022).

b. Moisture sensitivity

CLT is susceptible to moisture, which can lead to swelling, warping, and degradation over time. The CLT base material is generally preserved at a moisture content of u = 12 ± 2% (Brandner, et al. 2016). The strength falls as the moisture content rises. The structure needs to be protected over the intended lifetime of the building. Therefore, proper sealing and protection during transportation, storage, and construction are essential to prevent moisture-related issues.

c. Fire resistance

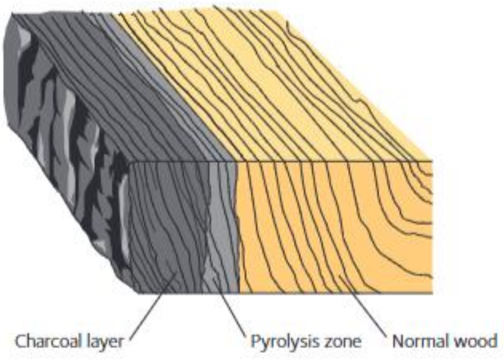


Figure 17: Fire penetration (Swedish wood 2022)

As seen in a previous section, the main weakness of timber structures in the past was the timber resistance to fire. But EWPs, including CLT, have managed to minimise this defect. In fact, the outer layers char when exposed to fire, which protects the inner layers and maintains structural integrity for a considerable period. The charring rate is predictable and slow, allowing for safe evacuation and firefighting efforts. Obviously, it is still a combustible material. Enhanced fire protection measures, such as fire-resistant coatings and sprinklers, are often required. (Falk, Dietsch and Schmid 2016)

d. Cost

The CLT manufacturing process requires high levels of investment, ranging from 10 to 15 million euros for a 50,000 m³/year CLT production line (Quesada, Smith and Berger 2018). This can be a significant barrier for new entrants into the market. Additionally, several countries are struggling to obtain consistent supplies of high-quality raw materials, as CLT manufacturing requires specific sizes, quality, and species of wood. This can complicate logistics and increase costs.

e. Market acceptance

The acceptance of CLT as a safe and high-performance construction material is still rejected by many groups, particularly in Europe. This indicates a broader issue of market and code acceptance that affects its commercialization. Different building regulations across countries can create barriers to the acceptance and expansion of CLT systems. Many architects and engineers lack experience with CLT, which can further complicate its integration into projects.

In addition, there is a lack of knowledge among architects, civil engineers, and builders regarding the advantages and disadvantages of wood products, including CLT. This knowledge gap can limit the adoption of CLT in construction (Quesada, Smith and Berger 2018).

A challenge noted by one company is the certification process for the acceptance of CLT systems in the construction industry. Nowadays, there is no common standard; instead, all companies must comply with general quality guidelines set forth in European Union agreements (Quesada, Smith and Berger 2018).

f. CLT composites

Forming new alliances with other materials, notably reinforced concrete, glass and steel, could be another avenue for CLT research and development. These composite materials can attempt to combine the main strengths of each material to produce the most effective element possible (Wålinder 2022). This may also provide solutions to structural problems relating to floor stability (Swedish wood 2022).

Figure 18: Timber-concrete hybrid floor. (Wålinder 2022)

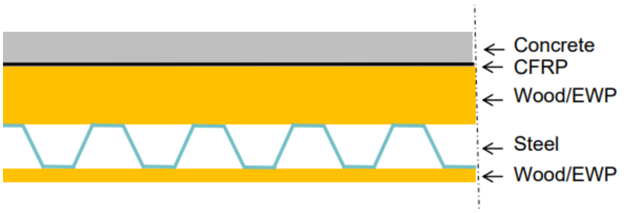


Figure 19: Example design of high-performance timber-based hybrid structures. Composite slab composed of concrete, carbon fibre-reinforced plastic (CFRP), EWP and steel. (Wålinder 2022)

2.7. Carbon emissions of CLT buildings

One of the main reasons for the recent surge in popularity of CLT and timber structures in general is the reduced carbon footprint of these construction techniques in comparison to traditional construction methods.

Figure 20 illustrates the comparative greenhouse gas emissions of the production phase for six distinct four-storey building designs. The result of this study shows that the cast-in-place concrete frame building, including the foundation slab, floor structure and load-bearing walls, emitted significantly more greenhouse gas than other construction techniques. While the differences between the emissions of the 5 constructions using wood for the structure remain relatively small. The graph provides a clear illustration of the significant influence that concrete plays in the context of these emissions during the phase of building production.

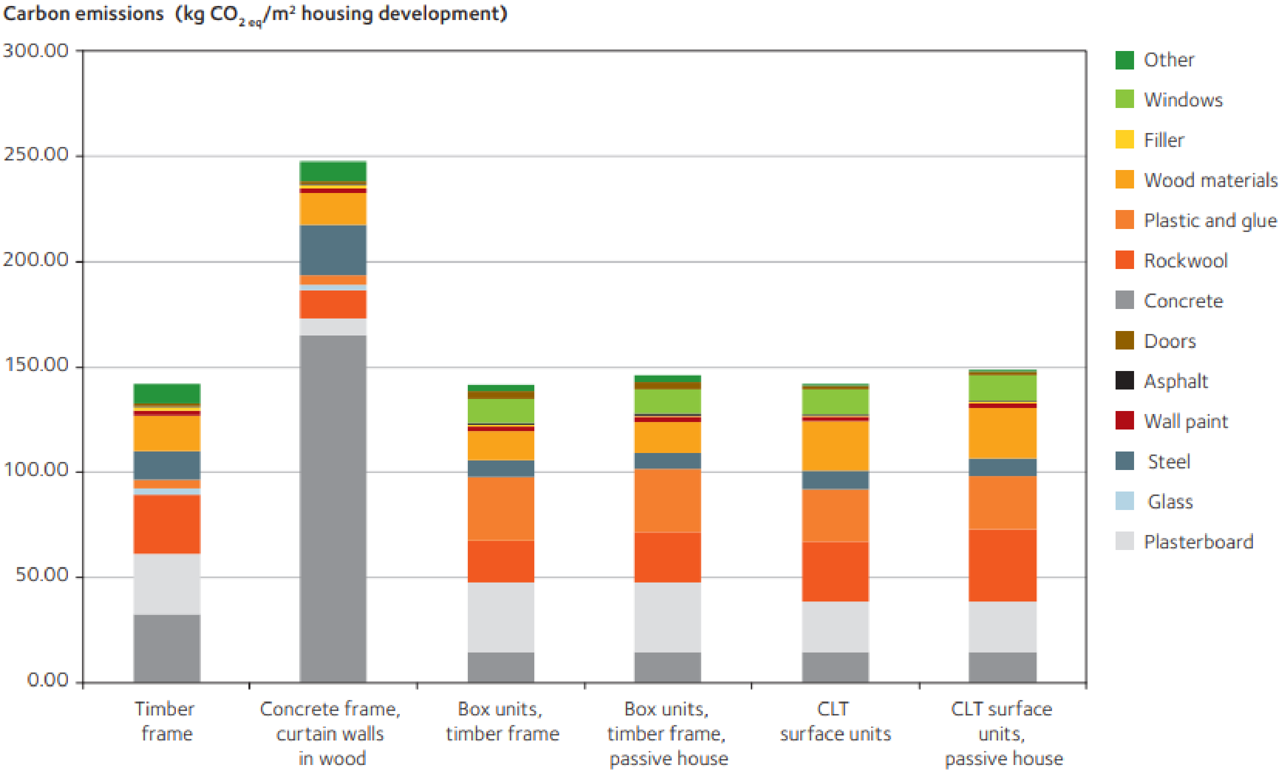


Figure 20: Greenhouse gas emissions (carbon dioxide equivalents, CO2 eq) from the production phase for six different designs of a four-storey building. Standard means a building insulated to Boverket's Building Regulations (BBR) 2012 and passive house means a building insulated according to the passive house standard issued by the Forum for Energy-efficient Buildings (FEBY) (Swedish wood 2022)

Another study demonstrated that the use of CLT resulted in a notable reduction in the embodied energy of the building, with a 40% decrease observed (Younis and Dodoo 2022). The CLT construction exhibits lower impacts with respect to global warming potential, terrestrial ecotoxicity, land use, and ozone layer depletion (Younis and Dodoo 2022).

3. Sustainability and Life Cycle Assessment of CLT buildings

3.1. Life Cycle Assessment (LCA)

The most accurate method for assessing the carbon footprint of a building is through the utilisation of an LCA. LCA can be calculated using a multitude of different methodologies. But as a general rule, LCA involves taking into account the life stages of a product or building and summing up their environmental impacts to obtain the total impact. This allows for the comparison of different products or buildings and helps to determine which life stages need improvements.

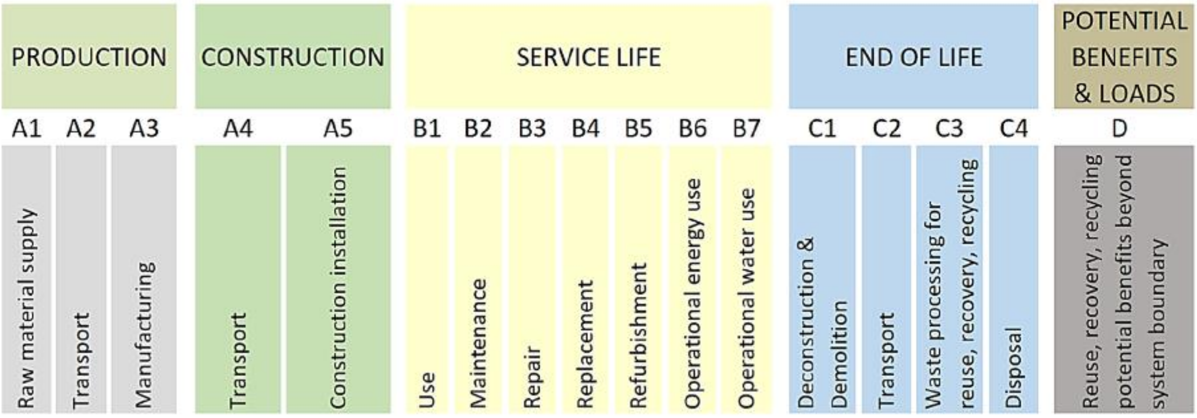


Figure 21: Life cycle stages and modules of a building as per EN 15978 (Younis and Dodoo 2022)

Figure 21 provides a detailed overview of the stages of a building's life cycle that should be considered in a LCA in accordance with the Eurocodes. This methodology, which is called cradle-to-grave, encompasses the entire life cycle of a building, from the initial harvesting of raw materials, also known as cradle, to the building End-Of-Life (EOL), called grave. An alternative approach frequently employed in LCA is the cradle-to-gate methodology. The cradle-to-gate boundary system is a methodology that exclusively considers the production phase of the building to the point of departure or 'gate' of the manufacturing facility. In the context of a building, the gate would correspond to the completion of the construction phase, immediately preceding the beginning of the operational phase. This methodology ends the calculation at A5 primarily due to the difficulty in forecasting the future of a building. (Younis and Dodoo 2022)

Cradle-to-gate and cradle to grave including biogenic and external benefits are the most realistic approaches to assess the greenhouse gas (GHG) emissions of a building over its life cycle. Although the overarching analysis employing the cradle-to-grave methodology offers the global "picture" of the GHG emissions fluctuating in a building project. In any case, studies have shown that timber-based buildings emit fewer GHG than buildings constructed using more conventional materials such as concrete (Petrović, Eriksson and Zhang 2023). Some studies have indicated a need for the development of a unified methodology, or "best practice," to ensure the reliability of carbon footprint predictions for CLT buildings (Younis and Dodoo 2022) (Too, et al. 2020).

3.2. Biogenic Carbon

An important aspect to understand about carbon emissions from timber buildings is that wood absorbs carbon as it grows. Over its lifespan, a tree utilizes the sunlight it receives to absorb carbon dioxide and transform the carbon it contains into cellulose, the principal constituent of wood. It is estimated that a cubic meter of wood can store in total around 1,000 kg of carbon. (Green and Taggart 2020)

The carbon stored or sequestered by organic matter is referred to as biogenic carbon. Consequently, trees, plants and soil are all considered to be biogenic feedstocks. Furthermore, the EWP can also be regarded as a biogenic carbon source (Younis and Dodoo 2022).

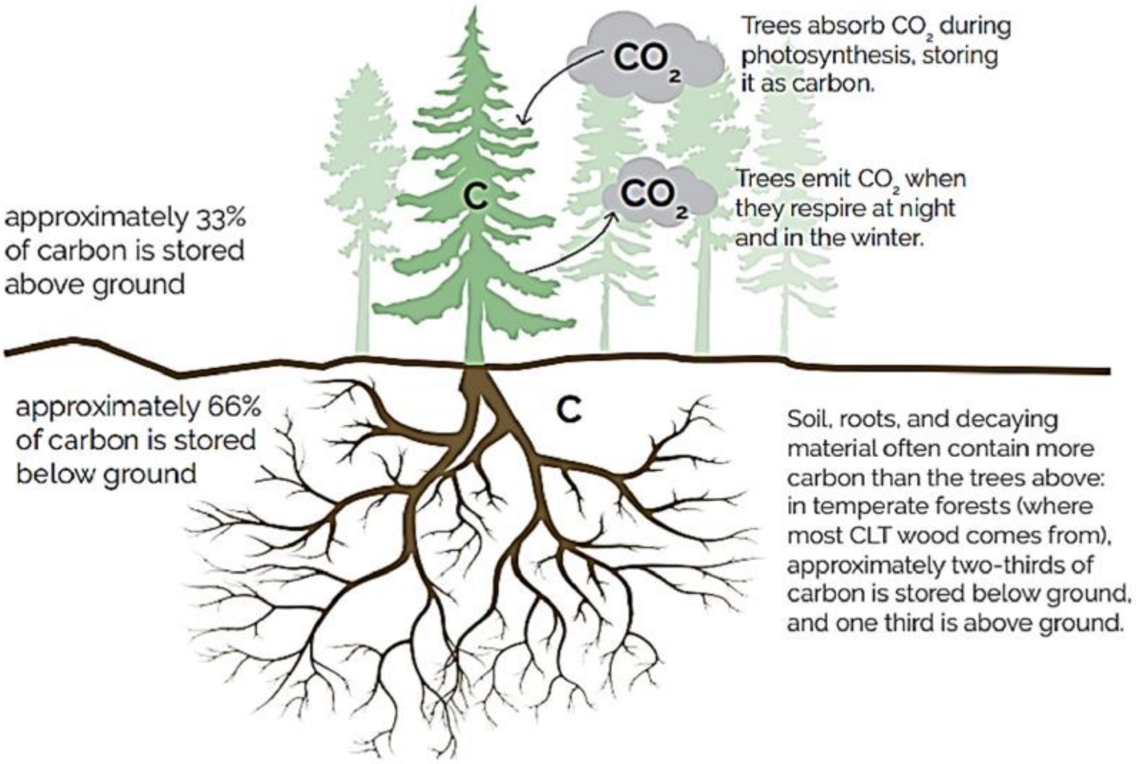


Figure 22: The concept of biogenic carbon (Kwok, et al. 2019)

However, as the tree begins to decompose, some of the carbon that it has stored is released into the atmosphere as carbon dioxide (Green and Taggart 2020). The remainder is trapped in the soil, or in the creatures that use the wood for food or as a shelter. Nevertheless, it is complex to evaluate the contribution of decomposing wood to the global carbon cycle. (Cassela 2021)

It is though crucial to differentiate between biogenic carbon and non-biogenic carbon. Non-biogenic carbon has not been absorbed by living matters. This identifies the carbon stored in fossil fuels in the form of oil, coal or gas resulting from millions of years of extreme atmospheric pressures.

In the case of a tree that has been felled for use in construction, the carbon that was stored in the tree is retained until the end of its useful life. At this point, the tree is either burnt or returned to nature to decompose (as shown in Figure 23), thus releasing a part of the stored carbon back into the environment. The global contribution of insects to the decomposition of dead wood and the subsequent release of carbon remains poorly understood and still require more studies to evaluate precisely the amount of CO_2 and CH_4 emitted every year during the decomposition of the wood. Although, several studies have demonstrated that only a small proportion of wood is degraded, thereby releasing greenhouse gases. This is because wood is composed of a complex lignin matrix, which glues together hemicellulose and cellulose. A more detailed analysis of the deterioration of hardwood and softwood lumber in landfill sites demonstrated that the degradation of carbon was minimal, with values ranging from 0 to 9% after 1.5-2.5 years (Head, et al. 2021). In contrast, the degradation of carbon in EWP materials, including OSB, has been observed to reach a range of 5 to 23% (Head, et al. 2021). However, these values should be treated with caution, as they can vary considerably from one study to another.

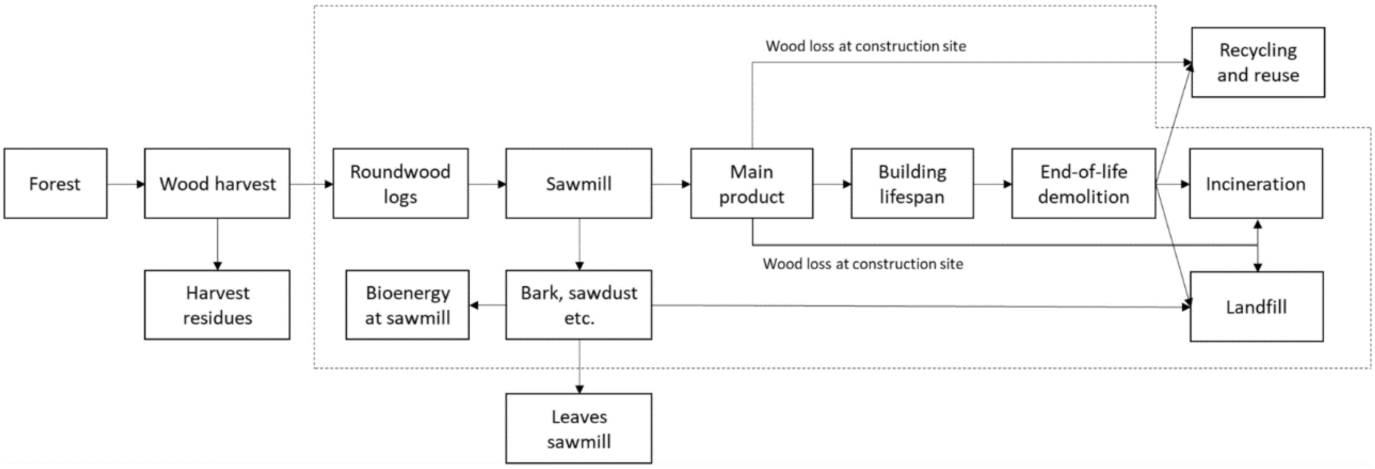


Figure 23: Life cycle process of engineered wood products (Head, et al. 2021)

In addition, the recycling of wood results in a reduction in the amount of material destined for landfill, which in turn leads to a decrease in the emission of methane (CH_4) and carbon dioxide (CO_2) (Head, et al. 2021). This illustrates the importance of recycling in the construction materials cycle.

Figure 24 presents the findings of a study that seeks to represent the impact of the life stages of a building, with a comparison of the same six buildings as in Figure 14. It can be seen that the concrete building emits approximately twice the greenhouse gases during the production phase as the CLT ones. In the succeeding stages, the impact of the two structures is approximately equivalent. However, when the advantages over the system limits, including biogenic carbon, are taken into account, the CLT building stores approximately twice as much as the concrete structure. In fact, it is estimated that $1m^3$ of CLT can absorb as much as 985 CO2eq (Puettmann, Sinha and Ganguly 2018). This value is a bit less than the value for raw wood material.

However, concrete also absorbs carbon in its own way, known as the carbonation phase, as shown in module B1 on the graph below (CEN 2004).

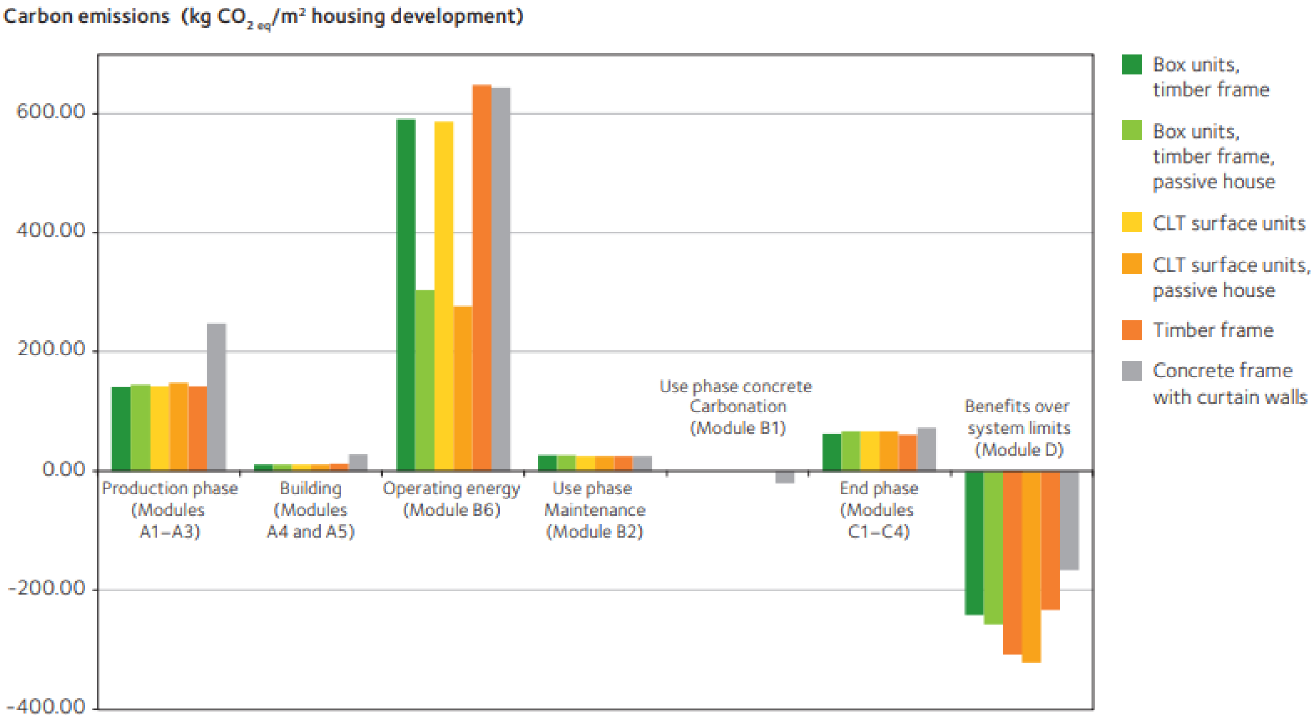


Figure 24: Greenhouse gas emissions (carbon dioxide equivalents, CO2 eq) from the building's life cycle for six different designs of a four-storey building. The two end columns represent alternative scenarios regarding end use of the wood material. (Swedish wood 2022)

From this graph, it is possible to extract the carbon footprint from the CLT passive house. A quantity of about 150 kgCO2eq/m² is approximated for the production phase, almost 300 kgCO2eq/m² for the operation use, the sum of A4, A5, B2 and C1-C4 results in approximately 50 kgCO2eq/m². And finally, the benefits over the system limit almost 220 kgCO2eq/m². All this results in a final sum of:

$$150 + 300 + 50 \; - \; 220 \; = \; 280 \; [\mathrm{kgCO2eq/m^2}]$$

As a conclusion, it can be stated that wood, and more specifically CLT, is a sustainable material and that it absorbs more CO_2 than it releases. Indeed, a minor quantity of carbon is released at the end of the product's life cycle but this is emitted at a later stage, shifting the CO_2 and CH_4 emissions over time thus rebalancing the carbon cycle which is currently being accelerated by greenhouse gas emissions from human activities (Head, et al. 2021).

3.3. Sustainable Forest Management

The use and harvesting of wood can obviously contribute to deforestation. Every tree felled is one less tree available to absorb CO_2. Many organizations and companies are now embarking on massive reforestation projects, but the management of these reforestations needs to be well thought out. The planting of as many trees as possible, or at least more trees than have been felled for an architectural project, represents an ultra-simplistic solution to the problem of carbon emissions in climate change. Nevertheless, this approach is not a solution unless it is considered in the context of the overall scheme of the complexity of the natural system (Holl and Brancalion 2020). More specifically, a study carried out in 2020 proved that trees planted on heather moorland store less carbon dioxide than the moor itself. Moorlands are precious ecosystems that can store significant quantities of carbon (Friggens, et al. 2020). This example shows that the global obsession of planting trees can lead to negative consequences. Ecosystems such as grasslands and savannahs can be seriously disrupted by the plantation of a new tree. (Holl and Brancalion 2020). Therefore, to achieve the desired results of increasing the carbon stock in trees, tree planting must be integrated as part of a multi-faceted approach to complex environmental problems.

A good way to ensure that a tree is planted in a suitable location is to give preference to areas that were recently forested, so as not to destroy an already well-established ecosystem (Friggens, et al. 2020). Sustainable forest management involves long-term monitoring to ensure that the trees are developing properly and planting local and diverse species to conserve the biodiversity (Green and Taggart 2020). These are all good practices that allow the forest to grow in good conditions.

3.4. Presentation of TOTEM

Totem is the LCA tool used in this paper. It means **T**ool to **O**ptimise the **T**otal **E**nvironmental impact of **M**aterials. The creation of this instrument represents the conclusion of five years of research and development. It was developed through a joint effort between Belgian universities and engineering offices and was supported by the Belgian, French, Dutch and Danish governments. The approach to creating this tool was based on 3 pillars: stimulating creativity while meeting the demands of environmental issues; enabling the environmental footprint of a construction element or architectural project to be assessed transparently and objectively; and promoting innovation in eco-design. providing rationalized and simple calculation tools. The idea was to create a simple, streamlined tool that could be easily used by stakeholders in the Belgian construction industry (architects, engineers, contractors, developers). It was designed using databases from the Belgian construction sector. The project partners are OVAM (a Flemish waste management and soil clean-up company), Brussels Environment and the public service of Wallonia (Totem 2024).

It works by first creating the different elements that will compose the building. These elements which can be a wall, a window or a floor, are made of raw materials like concrete, CLT panels, gypsum, etc. The raw materials can be found in the library of Totem, they are based on Environmental Product Declarations (EPDs). EPDs are documents that communicate transparently the environmental impact of a product. The list of material present in the Totem library is limited, it is sometimes impossible to find the exact element that was used in the building. In addition, it is not possible to create a material from scratch, although it is possible to suggest elements to Totem, for example a column section size. However, this can take a little time, as approval must be awaited and EPDs have to be supplied for the element so that it can be integrated into the software. Therefore, when it is impossible to find the exact material, the element that most closely resembles the one used in the building should be preferred.

Some elements are simply columns or solar panels. But others need to be designed by combining several materials. For example, when defining a floor, each layer of the floor's composition must be detailed, i.e. concrete slab, insulation, flooring, etc. Each element must be integrated in order from top to bottom. It is even possible to create composite layers. These can be used, for example, to represent the case of floors made up of beams with insulation attached between them.

Once all the elements that form the building have been created, the next step of the procedure is to detail its composition i.e. the square meters of floors, the length of each column, the amount of solar panel etc.

Data about the energy consumption and generation, as well as heat demand also need to be input in the software. Totem offers two options for the description of energy use. Either the simplified approach based on an equivalent number of days, or an approach based on Energy Performance of Building (EPB) output. The description of both method is more deeply described in the next section.

Since Totem is a Belgian software, in the energy section, it is based on the Belgian mix of energy production. Consequently, the impact of energy consumption must be carefully considered, as the energy mix depends on the location of the architectural project under study.

In the end, from the EPDs of each material, their composition, and the energy use of the building, Totem gives an environmental score to the project in mPt/m²UFA (milli-point divided by square meters of unit). This score is indicated on a graph compared to an indicative reference in the form of a scale (as shown in Figure 25). This scale was developed based on the environmental rating of a set of reference buildings. The mPt is a dimensionless unit that takes into account multiple indicators. These indicators are climate change, ozone depletion, acidification, eutrophication, photochemical ozone formation, depletion of abiotic resources, water use, particulate matter emissions, ionizing radiation human health, eco-toxicity, human toxicity and land use related impact. (Totem 2023)

Figure 25: Graph showing the environmental score from Totem

Obviously, they do not all have the same units of impact value, for example climate change has the unit CO2 equivalent while acidification is in mol of H+ equivalent. Consequently, each indicator was assigned an "aggregation factor" based on a combination of normalization factor and weighting factor of PEF proposed by the JRC (Joint Research Centre which is the European Commission’s science and knowledge service) (Sala, Cerutti and Pant 2018).

The aggregation factors are calculated by multiplying the inverse of each normalisation factor with its corresponding weighting factor and 1000 for the conversion from Pt to mPt (e.g. the aggregation factor of the indicator climate change is 0.02601 ((1 ÷ 8.10E+03) × 0.2106 × 1000) (Totem 2023). The normalisation factors are expressed as impact per capita per year (based on a global value in reference year 2010) were proposed by the European Platform on Life Cycle Assessment (Totem 2023).

The weighting allows for the evaluation of impact categories with the greatest relevance, stages of the life cycle, processes and consumption of resources or emissions. This ensures that the cursor is focused on the aspects with the most significant impact on the environmental footprint. This method of calculation is obviously not essentially based on natural science but involves a choice of value that depends on policy, culture and other preferences.

In conclusion, this tool allows to obtain a final score that is easily calculated and can be determined on any building to compare buildings with each other. If the intention is to focus exclusively on a single indicator, it is possible to view the details of the result and obtain the characteristic values of each indicator. In this paper, the focus is on the values of climate change in CO2 equivalent, which was selected for comparison with the carbon budget published by White.

3.5. Framework to assess the carbon footprint of a building

To conclude the last chapters, a framework for assessing a building's carbon footprint can be developed. A sort of recipe to follow to analyse a building using this tool.

This framework was established following my analysis of the Sara Cultural Building and is therefore a framework created with the notions and needs of someone from outside a project that has already been built. This framework proposal is therefore heavily based on plan reading and assumptions extracted from them. Obviously, if the assessment is carried out by an architect or engineer working on the building being analysed, and who therefore has much more precise information, this framework can be greatly simplified. In contrast, if the analysis is to be carried out on a building project that has published very few details and sections, the analysis is likely to be complicated and too approximate to be relevant.

1) Collection of plans

All the plans, sections, details and façades that have been published or that it is possible to obtain for the building under study will be necessary for its analysis. A 3D model can also contribute enormously to understanding the functioning and composition of the building. Some well-known buildings have 3D models published on the internet.

These need to be read to scale. If the plans or details do not have a scale, it is impossible to determine their dimensions and therefore impossible to estimate their environmental impact. These plans can be printed in the page size of the pdf so that they can be measured manually. Or they can be imported into 2D software such as AutoCAD so that they can be scaled and measured directly from the 2D software.

2) Subscribing to the Totem tool

Totem requires no download. It is a free website on which to register. The URL of the website can be found in the references (Totem 2024).

3) Creation of the project in Totem

The project must be created in the tool. It is possible to create several projects at the same time to compare different buildings. First, there is some basic information to enter, such as the name of the building and its address, the year of the completion, the usable floor area [m²], the heated volume [m³], and the number of storeys [-].

4) Input of the elements

All the elements of the project must be selected and add to the project library. This means that each type of each column, beam, floor, windows, walls, roof and even technical elements such as heat pump or solar panel must be detailed and named.

For the columns and beams, it only requires finding the exact dimensions or at least the most similar to the project. To determine those types, one technique may be to try to find the one with the cross-section closest to that of the project. Doing so will ensure the closest possible approximation to the final volume of wood used. If a very large number of different types of columns and beams are used because the project is very big, it may be possible to reduce the work by creating groups of the most similar ones and defining the average dimensions of each group. This is a way of approximating the situation as closely as possible, without having to count and measure each of the project's columns/beams.

The floors must have each of its layers described, trying to obtain the thickness of each of them as accurately as possible according to the information from the details. Many of the materials in the Totem database can have adaptable thicknesses. It is therefore possible to adapt these to the dimensions of the analysed project.

For the selection of materials such as insulation or glass, it is also important to pay attention to the U-value which will have an impact on the final energy use of the building in the case of the simplified approach (with equivalent degree days).

5) Describe the composition

Once the individual elements of the project have been defined, it is then necessary to specify the quantities that have been utilised throughout the project. If an inventory of the project components is available, this stage is very easy. If not, the task can be more laborious.

For columns and beams, the quantity of these must be entered in a quantity multiplied by a length. The quantity can be determined from the plans and the length from the sections. If the beam/column element is not exactly the same as in reality, and the choice has been made for the element with the closest cross-section, a factor can be considered to correct this detail. This factor is equal to the cross-section of the actual column divided by the cross-section of the column selected in Totem:

$$f = \frac{Cross - section\ of\ actual\ colomn/beam}{Cross - section\ of\ colomn/beam\ from\ Totem} = \frac{A_{real}}{A_{Totem}} [-]$$

This factor is dimensionless and will multiply the quantity. This will allow to meet the most exact volume of material used in the end.

For floors, the composition must be given as a quantity multiplied by a surface area [m²]. Their dimensions can be measured from the plans. The section can help to determine what type of floor is being used where. In the case of timber structures, it is very common to use concrete for the foundations as well as for the ground floors and basements.

For the windows and walls, they are also defined as a quantity multiply by a surface area [m²]. This time, the facades will be used to measure their surface area and quantity.

For technical elements such as solar panels or ventilation systems, they are counted by number dimensionless [-]. Unfortunately, Totem does not have yet photovoltaic panels.

6) Input the energy use of the building

First, the type of ventilation system must be chosen between a) natural ventilation or mechanical ventilation but without heat recovery or b) mechanical ventilation with heat recovery. Next, the airtightness has to be selected between the default EPB value (~12m³/h.m²), the low energy standard (~6m³/h.m²) and the passive standard (~1m³/h.m²). Finally, the type of heat production must be decided between a condensing gas boiler, a condensing oil boiler, and an air-to-water heat pump.

Then, precise information about the energy consumption of the building is required. As in the first case, it is necessary to specify the type of energy used for heating, cooling and ventilation but also their final amount in MJ/y (megajoule per year). This is only possible if the building was completed a few years ago and a consumption measurement has been carried out.

7) Environmental score and result of climate change

When all the other steps are done, it is possible to display the environmental score of the building. As explained in the previous section, this score considers not only climate change (carbon emissions), but also other impact values such as acidification or eutrophication. Only the climate change will be used for this framework. It is displayed in the detailed results, in the section "impact per indicator". This gives an impact value in kilogramme of CO2 equivalent per square meters of useful floor area [kg CO2 eq/m²UFA].

This value must be multiplied by the useful floor area to obtain the total carbon impact of the building.

8) Balancing with the biogenic carbon

The final score given by Totem does not take into account the biogenic carbon stored by the wood. If the project analysed contains wood, to take this aspect into account the quantity of carbon stored in the wood must be subtracted from the total carbon impact of the building obtained in the previous step. To do this, the volume of wood needs to be calculated. This can be done using the inventory established in step 5. Note that the quantity of wood harvested is not the quantity of wood used. Only the quantity of wood used can be considered as stored carbon, as the sawdust and any leftovers will certainly be burnt and therefore release the carbon that was stored there. As an approximation, 1m³ of wood stores 1000kg of carbon (1 ton). Thus, to obtain the quantity of biogenic carbon, simply multiply the volume of wood by 1000, this will give a quantity in kilograms [kg].

4. The case study of Sara Cultural Centre

Figure 26: Birdview of the Sara Kulturhus Centre in Skellefteå. Photo by Åke Eson Lindman

4.1. Description of the Sara Cultural Centre

The Sara Cultural Centre is situated in Skellefteå, a small town just outside the artic circle in northern Sweden. The project began in 2018 and was completed in 2021. The architectural firm White was responsible for its design, and it was commissioned by the Skellefteå Municipality. The building is 27,867 square meters, reaches 75 meters high and is composed of 20 floors (Ravenscroft 2021).

The Sara Cultural Centre is divided into 2 different parts: a cultural centre and a hotel. The first part contains several lowered volumes comprising theatre stages, a gallery, a library, a museum, several conference and meeting rooms, restaurants and a large congress hall with a capacity of 1,500 people. The second part is the hotel located in the tower comprises 205 hotel rooms from level 5 to 17, a spa and a bar on the 2 highest floors (Ravenscroft 2021).

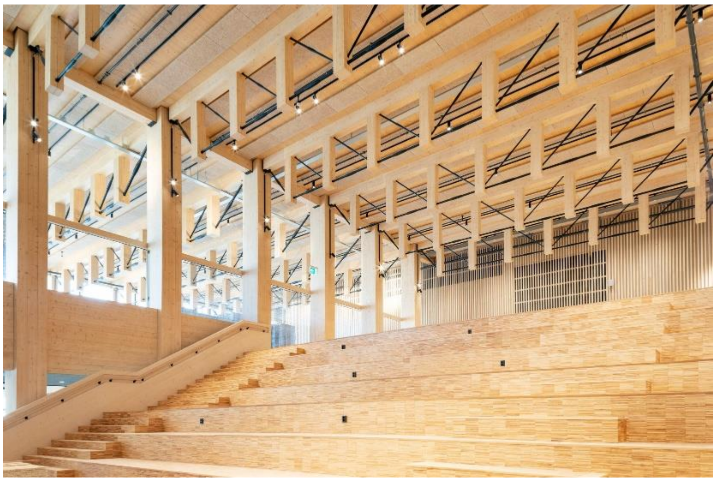


Figure 27: Cultural stairs. Photo by Åke Eson Lindman

Figure 28: Room of the hotel. Photo by Oliver Wainwright

The construction of the high-rise hotel is based on a modular approach, whereby the prefabricated 3D modules are assembled from CLT panels. The modules are stacked between two elevator cores, which are themselves constructed from CLT. According to Therese Kreisel, Skellefteå's planning architect, 12,200 m³ of wood was harvested for the construction of the Sara Cultural Centre (Sara Kulturhus n.d.).

Figure 29: CLT structure of the building

In contrast, the low-rise cultural centre is constructed using columns and beams of glulam, as well as cores and shear walls in CLT. Additionally, steel structural elements were employed in the construction of the necessary spans for theatres and expansive, open foyer spaces (Ravenscroft 2021). The utilisation of alternative materials has enabled the construction of the building to be completed in a shorter period of time, while simultaneously reducing the carbon footprint of the structure (Fundació Mies van der Rohe 2024). This tower is wrapped in glass, creating a double-skin façade.

Figure 30: View on the glazed tower of Sara Cultural centre. Photos by Åke Eson Lindman

4.1. Carbon budget of the Sara Cultural Centre

According to the architects, "Over 50 years, Sara Cultural Centre is a carbon-negative building. And the building is designed to have a lifespan of at least 100 years".

How is that possible? They calculated that the total emissions during the life of the building would be around 5,631 tons of CO2eq, but thanks to the carbon captured in the wood and the production of renewable energy by the photovoltaic panel, they accounted that 10,190 tons of CO2eq was balancing in the building. In the end, a small calculation allows to guess the final building carbon footprint: 5,631-10,190 = -4,559 tons of CO2eq which is the reason why they claim that Sara Cultural Centre is carbon negative. More specifically, it was calculated that 3,550 tonnes of CO2eq were emitted due to the materials (42% by concrete, 23% by glass, 16% by wood, 12% by steel, 4% by insulation, 2% by sheet metal and 1% by gypsum). (White 2021)

520 tonnes of CO2e were released during the construction process and 25 tonnes of CO2e from transport. In a normal project, transport would account for a much larger proportion of the carbon footprint, but in this case the 12,200 cubic metres of wood were collected from within a 60 km radius of the site and the number of truck deliveries was reduced by 90% (Wainwright 2021). It is estimated that 1,540 tonnes of CO2e will be emitted over the 50-year life of the building. Again, this was achieved thanks to a heat pump owned by Skellefteå kraft installed in the building and covering 90% of the heating demand (White 2021).

The energy mix from the Sara Cultural Centre is very different from that of Belgium, since the town of Skelleftea is 100% powered by renewable energy, according to White. Therefore, the analysis of the energy use made by Totem must be considered carefully because Belgium is not 100% powered by renewable energy.

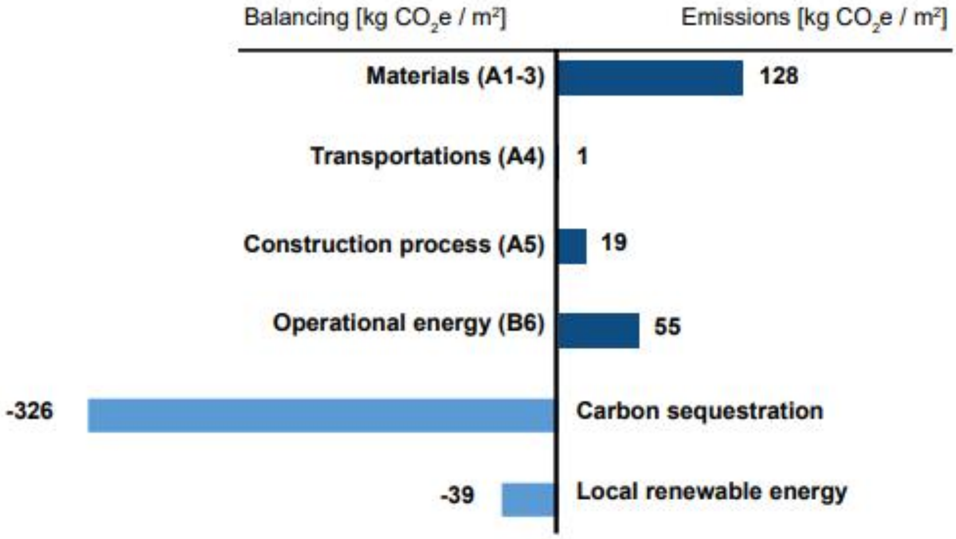


Figure 31: Carbon emissions per life cycle stages (White 2021)

The calculated climate impact from materials, transportation, construction process and operation are cancelled out by carbon sequestration and renewable energy production. Around -9,095 tonnes of CO2eq is sequestrated in the wood composing the building while -1,095 tonnes of CO2eq because the electricity of the building is 100% powered by renewable energy generated mostly by 374 modules of photovoltaic panels equivalent to 1,200 square meters which are installed on the rooftop of the building. This system is owned by Skellefteå Kraft and communicates with nearby buildings, and for that matter, the entire energy system in Skellefteå. Excess energy in the property is sent on to other parts of the city or stored in batteries. The rest of the energy is supplied from renewable source because Skellefteå runs on 100% renewable energy from hydroelectricity and wind power and recycles 120,000 tonnes of electronic waste a year (Wainwright 2021).

In Figure 32, the pie graph shows the impact of the foundations (41%) made of concrete on the total carbon emissions of the project. Surprisingly, even if the majority of the materials used for the structure and the furniture is wood, it is still the concrete that generates most of the carbon emissions. Concrete was only used for the foundation, the basement slab et some small low part of the facade as a junction with the ground. Some steel was also used in the truss beams of the main stages and the cultural stairs. A significant amount of glass composes the building for the windows as well as the wrapping around the tower.

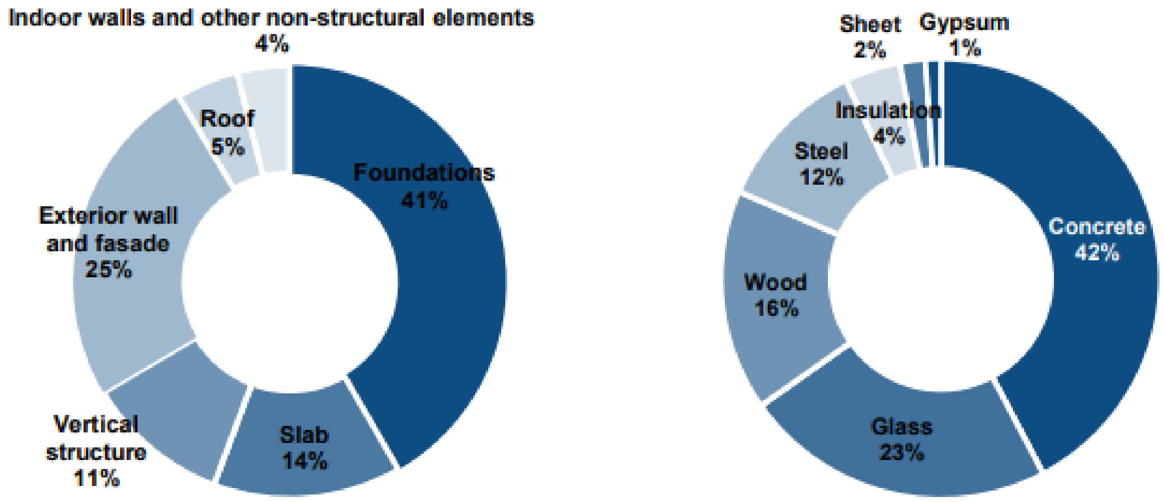


Figure 32:
Left carbon emissions per building part.
Right: Carbon emissions per material.
(White 2021)

4.2. Life Cycle Assessment of Sara Cultural Centre with TOTEM

Now that the context has been defined and enough information about the Sara Cultural Centre has been gathered, time has come to use TOTEM to create the building's LCA. To do this, an inventory of the building's components and details of its energy consumption must be drawn up. These two steps are necessary to display the results in TOTEM. This section provides some answers to the main question of this work, that of critically examining White's assertion that the Sara Cultural Centre building is carbon negative.

a. Inventory of building elements

In this section, the elements need to be defined in terms of quantity, length or surface area, depending on the functional unit of each element. By analysing the plans, sections and details presented in DETAIL magazine (White Arkitekter 2021) and provided on website of White, it was possible to identify components of elements employed in the construction of the building. Those plans from which the information was taken can be found in the annexes. They were supplied in A4 format at a scale of 1:750 for the plans and sections and 1:20 for the details. It would have been preferable to have an inventory drawn up and supplied by the architects or builders themselves to get the exact data, but it was not possible to obtain them.

Floors

In the following table, the three floor types are detailed. The first one is the one used for the basement floor. It is composed of concrete and is not insulated. The second one is the same as the first one but with a layer of insulation. The third is made of CLT for its structure. It was used for all the other floors in the cultural centre, as well as for the floors in the hotel rooms.

The uninsulated concrete floor has been assigned to the basement and ground floor knowing that the so-called "ground floor" in this paper is semi-buried. The insulated concrete floor was assigned to the 1st floor which can be seen as a ground floor on one side of the building. Finally, the CLT floors were assigned to the hotel's upper floors. The surface of each floor is displayed in the Table 1 below.

Table 1: Inventory of floor elements defined in Totem

Name of element defined in Totem	Lifetime [years]	U-value [W/m²K]	Description	Location	Surface Area [m²]
Uninsulated concrete floor	>= 60	1.81	C4: Chipboard (22mm) C3: Gypsum plater board (12.5mm) C2: Proofing sheet PE (0.2mm) C1: Cast in situ reinforced concrete (300mm)	Basement floor of the cultural centre	3,760
				Ground floor of the cultural centre	5,800

Name of element defined in Totem	Lifetime [years]	U-value [W/m²K]	Description	Location	Surface Area [m²]
Insulated concrete floor	>= 60	1.18	C7: Parquet hardwood (22mm) C6: Chipboard (22mm) C5: Gypsum plaster board (12.5mm) C4: PE foam board (20mm) C3: PE foam board (20mm) C2: Proofing sheet PE (0.2mm) C1: Cast in situ reinforced concrete (300mm)	First floor of the cultural centre	5,800
CLT floor	>= 60	0.19	C8: Carpet tiles Polyamide (500x500x5.8mm) C7: Fibre cement board (22mm) C6: Gypsum plaster board (2x12.5mm) C5: PE foam board (20mm) C4: PE foam board (20mm) C3: CLT panel (140mm) C2: EPS board (100mm) C1: CLT panel (100mm)	Second floor of cultural centre	2,560
				Third floor of cultural centre	4,520
				Storey floors of the hotel rooms	10,240

External walls

Similarly, as for the floors, there are three types of walls. The floors and external walls are the most interesting elements of the building in this analysis, since 2 types were used in both elements. One using CLT and the other with concrete. This will enable the software to compare the impact of the choice of materials on its carbon footprint.

Two types of external walls and an inner one. The first external wall is composed of timber and vertical wood element. This was used for most of the facades but above the ground to preserve the wood from humidity. The second one is made of terrazzo which is a common composite material using cement as a binder, it looks like concrete. It combines chips of marble, granite, quartz, glass, shell or other suitable materials with cement or an epoxy. This wall was used for the parts of the walls connected to the ground. Finally, the inside wall is mainly made of CLT, which is used as the load-bearing part of the structure. It was only used in the division of the hotel rooms. Almost every facade had some terrazzo and timber eternal walls, and their surface areas were measured using the facades plans. They are displayed in the table below.

Table 2: Inventory of wall elements defined in Totem

Name	Lifetime [years]	U-value [W/m²K]	Description	Location	Surface area [m²]
Timber external wall	>= 60 years	0.21	C6: Thermally modified wood planks (22mm) C5: Softwood battens (36x27mm - c.t.c. 275mm) C4: Softwood battens (47x22mm – c.t.c 400mm) C3: Proofing sheet PE (0.2mm) C2: Composed layer: a. 10% softwood beams (260mm) for between insulation b. 90% EPS board 260mm C1: CLT panel (120mm)	East facade	1,631
				North facade	872
				South facade	489
				West facade	1,470
Terrazzo external wall	>= 60 years	0.33	C4: Terrazzo cast floor (150mm) C3: Isomo EPS board (100mm) C2: Proofing sheet PP-PE (0.22m) C1: Cast in situ reinforced concrete	East facade	217
				North facade	202
				South facade	/
				West facade	143
Timber inside wall	>= 60 years	0.2	C3: CLT panel (120mm) C2: EPS board (120mm) C1: CLT panel (120m)	Inside walls partition between hotel room	3,473

Windows

There are two types of windows. The triple-glazed windows used throughout the cultural centre, and the glazed facade balustrade, which is the layer of glass that wraps around the hotel tower. Triple-glazed windows are a crucial element in building insulation. The Table 3 below shows a U-value of 0.88 W/m²K for the triple glazing, compared with no less than 5.48 W/m²K for the balustrade facade. This demonstrates the enormous difference in insulation between single and triple glazing in terms of its contribution to thermal insulation. The single glass in the hotel tower is only used as a balustrade and is not expected to make a significant contribution to the thermal insulation of the building.

The functional unit of the windows is the surface area, and their description and quantity are displayed in the table below.

Table 3: Inventory of window elements defined in Totem

Name	Lifetime [years]	U-value [W/m²K]	Description	Location	Surface area [m²]
Triple glass window	30	0.88	C1: composed layer: a. Aluminium profile (Uf 1.6 W/m²K) b. Triple glazing panel (36mm – Ug = 0.5 W/m²K)	East façade of cultural centre	665
				North façade of cultural centre	357
				South façade of cultural centre	594
				West façade of cultural centre	981
Glazed facade balustrade	30	5.48	C1: composed layer a. Steel powder coated profiles (Uf = 2.6 W/m²K) b. Single glazing panel (6mm - Ug = 5.8 W/m²K) c. Single glazing panel (6mm - Ug = 5.8 W/m²K) d. Single glazing panel (6mm - Ug = 5.8 W/m²K)	East façade of hotel tower	2,075
				North façade of hotel tower	825
				South façade of hotel tower	2,075
				West façade of hotel tower	825

Roof

A flat roof was used throughout the roof with the same composition. Its structure is made of a layer of CLT. No plans for the roof could be found on the internet. However, the surface area of the roof is simply the same as that of the ground floor. This is displayed in the table below.

Table 4: Description of roof element chosen in Totem

Name	Lifetime [years]	U-value [W/m²K]	Description	Location	Surface area [m²]
Flat roof	>= 60	0.1	C4: Proofing sheet polymer bitumen (7mm) C3: EPS board (180mm) C2: Proofing sheet PP-LDPE (0.22mm) C1: CLT panel (160mm)	All roof of the building	5,800

Columns

Regarding the columns, the plan data indicated that there were too many different column dimensions in the project. Therefore, to facilitate the calculations, these columns and beams have been divided into four groups: columns A, B, C and D and beams A, B, C, D and E. These are summarised in the table below.

Table 5: Selection of column types

Name of column	**Dimensions of columns from plans**	**Cross-section area [mm²] (1)**	**Name of element used in Totem**	**Lifetime [years]**	**Cross-section area [mm²] (2)**	**Correction factor [-] = (1) / (2)**
Column A	480mmx600mm	288,000	Glulam column 140x585	>= 60	81,900	3.516
Column B	400mmx400mm	160,000	Glulam column 200x200	>= 60	40,000	4.000
Column C	620mmx950mm	589,000	Glulam column 200x945	>= 60	189,000	3.116
Column D	300mmx360mm	108,000	Glulam column 240x240	>= 60	57,600	1.875

As not all possible column/beam dimensions exist in the Totem software, it was necessary to determine which type of column/beam to select to most realistically represent the situation. From the dimensions of each group of columns/beams, a cross-section area was calculated. Then, the elements in Totem were chosen with dimensions as close as possible to real columns, and with the closest possible cross-sectional area. Once these elements have been selected in the totem software, it will be necessary to take into account a correction factor equivalent to dividing the cross-sectional area of the actual columns by that used in the totem calculations.

In the following table is displayed the inventory of the columns. The real number of columns determined thanks to the plans has been multiplied by the correction factor. This factor applied to the quantity of columns/beams used will, at the end of the analysis, make it possible to get as close as possible to the volume [m³] of wood despite the lack of choice of framework dimensions.

Table 6: Inventory of columns

Floor/Location description	**Length [m]**	**Name of column**	**Correction factor [-]**	**Real amount [-]**	**Input amount in Totem** (correction factor x real amount)
Ground floor	4	Column A	3.516	30	105
		Column B	4.000	74	296
		Column C	3.116	16	50
		Column D	1.875	101	189

Floor/Location description	Length [m]	Name of column	Correction factor [-]	Real amount [-]	Input amount in Totem (correction factor x real amount)
First floor	7	Column A	3.516	36	127
		Column B	4.000	37	148
		Column C	3.116	20	62
		Column D	1.875	196	368
Second floor	3.5	Column A	3.516	33	116
		Column B	4.000	30	120
		Column C	3.116	4	12
		Column D	1.875	166	311

Beams

Similarly to the columns, the beams were divided into 5 groups. The different groups are displayed in the table below. The same method as for the columns was used for the beams below including the calculation of the correction factor that will be used in the inventory further. In the case of the beams here, the plan sections were particularly necessary in order to determine dimensions.

Table 7: Selection of the beam types and calculation of correction factor

Name of column	Dimensions of beams from detailed sections	Cross-section area [mm²] (1)	Name of element used in Totem	Lifetime [years]	Cross-section area [mm²] (2)	Correction factor [-] = (1) / (2)
Beam A	225mmx280mm	63,000	Glulam beam 200x280	>= 60	56,000	1.125
Beam B	300mmx350mm	105,000	Glulam beam 339x360	>= 60	122,040	0.860
Beam C	220mmx500mm	110,000	Glulam beam 200x600	>= 60	120,000	0.917
Beam D	90mmx345mm	31,050	Glulam beam 120x320	>= 60	38,400	0.809
Beam E	90mmx225mm	20,250	Glulam beam 80x240	>= 60	19,200	1.055

Once again, an inventory of each beam, its dimensions and quantities are given in the table below. This inventory is particularly long and is spread over the next two pages.

Table 8: Inventory of the beams

Name of beam	**Location description**	**Length [m]**	**Real amount [-]**	**Input amount in Totem** (real amount times correction factor)
Beam A	Simple beams along the facade	3.2	62	70
	Simple beams in corridor next to concert hall	8.3	2	2
	Simple beams in corridor next to concert hall	5.3	2	2
	Simple beams in corridor next to concert hall	3	9	10
	Simple beams in corridor next to concert hall	6.9	5	6
	Diagonal of the truss in stage 1	3.5	169	190
	Diagonal of the truss in stage 2	3.4	132	149
	Simple beams on second floor	3.2	3	3
	Simple beams on second floor	7.8	2	2
	Diagonal of truss in hotel central mechanical services (4th floor of hotel tower)	5	36	41
	Diagonal of truss in hotel central mechanical services (4th floor of hotel tower)	4.7	40	45
	Diagonal of truss in hotel central mechanical services (4th floor of hotel tower)	4	8	9
Beam B	Simple beams in foyer next to large theatre hall	6.3	4	3
	Horizontal beam of truss in main foyer, next to cultural stairs	18.2	8	7
	Vertical beams of truss (next to cultural stairs)	1.3	72	62
	Horizontal beam of truss in main foyer, above cultural stairs	13.4	8	7
	Vertical beam of truss (above cultural stairs)	1.3	64	55
	Horizontal beam of truss above exhibition space	13	9	8
	Vertical beam of truss (above cultural stairs)	1.3	48	41
	Outside beam on the roof of Foyer (direction bb)	18.5	2	2
	Outside beam on the roof of Foyer (direction bb)	4	8	7
	Outside beam on the roof of Foyer (direction aa)	3.2	21	18
Beam C	Horizontal beam of truss in stage 1	23.2	12	11
	Horizontal beam of truss in stage 2	18.8	12	11
	Horizontal beam of truss in hotel central mechanical services (4th floor of hotel tower)	32	12	11
	Horizontal beam of truss in hotel central mechanical services (4th floor of hotel tower)	17.5	20	18

Name of beam	**Location description**	**Length [m]**	**Real amount [-]**	**Input amount in Totem** (real amount times correction factor)
Beam D	Windows frame of north facade	0.9	26	21
		1.8	16	13
	Windows frame of east facade	2.3	2	2
		3.6	2	2
		1.8	82	66
	Windows frame of south facade	1.8	26	21
		0.9	12	10
	Windows frame of west facade	1.8	56	45
Beam E	Slats of north facade	12.6	23	24
		4.6	15	16
		5.5	10	11
		11.3	11	12
		5.9	10	11
		26.4	8	8
	Slats of east facade	19.3	1	1
		9.4	6	6
		4.9	6	6
		6.7	21	22
		13.2	20	21
		16.3	61	64
		9.5	6	6
		8.4	66	70
	Slats of west facade	18.9	14	15
		11.4	22	23
		10	11	12
		28.7	22	23
		18.8	22	23
		16.3	23	21
	Slats of south facade	16.3	21	22
		8.4	16	17
		11.9	6	6
		18.9	1	1
		14.6	13	14
		10.2	8	8

Technical elements

For the technical elements, from the document of the carbon budget of White, they mention the use of a heat pump. This contributes to the production and storage of heat of hot water. No specific information was available about the number of heat pump present in the project. But according to some website, in the case of passive house, each square meters requires 2-10 watts. Since the projects is 27,687 m² and if we take the average i.e. 6 watts, it needs 166.122 kilowatts (kW) powered by the heat pump. The heat pump available in Totem is a heat pump of 3-10 kW. If we consider that it will power in average 6 kW. Then the building needs an amount of 28 heat pump to power it.

Table 9: Inventory of technical elements

Name	Lifetime [years]	Description	Amount [-]
Heat pump	20	Heat pump, Metals and Plastics (3-10 kW). Production and storage (heating and hot water)	28

In the carbon budget document, they also mention the presence of photovoltaic panels on a large majority of the roof contributing to the production of most of the electricity. Unfortunately, Totem does not yet have a photovoltaic panel element in the software, so this could not be taken into account in the calculations.

b. Energy use

Thanks to a document published by DETAIL magazine, it was possible to obtain precise data on the energy consumption of the Sara Cultural Centre. These data can be found in the Annex 24. A total consumption of 92.5 kWh/m²y was calculated. This includes 64.4 kWh/m²y for heating, 6.1 kWh/m²y for cooling and 22 kWh/m²y for electricity. Additional information on the U-values of the various building components was also provided, to support the choice of materials when they were implemented in the software. These values had to be adapted in megajoules per year in order to be input in the software. To do this, megajoules is equal to kilowatt-hours times 3.6.

$$92.5 \times 3.6 = 333 \, [MJ/y]$$

$$64.4 \times 3.6 = 231.84 \, [MJ/y]$$

$$6.1 \times 3.6 = 21.96 \, [MJ/y]$$

$$22 \times 3.6 = 79.2 \, [MJ/y]$$

This was implemented into the LCA software to consider the energy consumption of the building in terms of CO2eq.

5. Results

The result of all these data encodings is 40.41 mPt/m². This is a very low score compared with the other buildings from TOTEM library (Totem 2024). This is displayed on a scale of the buildings of reference in Figure 33.

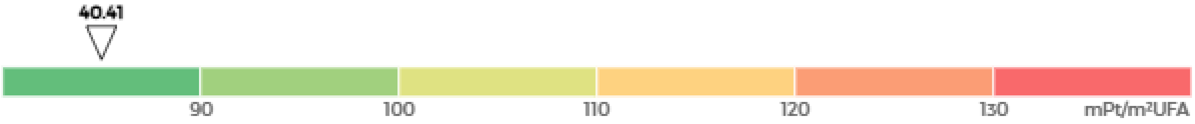


Figure 33: Environmental score of the Sara Cultural Centre generated by the Totem software

Since the focus is on the carbon impact of the building, it is possible to display the impact by indicator and thus show the quantity of carbon equivalent emitted by the building over its lifetime. According to Totem, in terms of carbon emissions, the impact of the building would be about 375 kgCO2eq/m² and its impact compared with the other indicators is displayed in Figure 34. This climate change indicator of the building represents 24% of its environmental impact.

At the scale of the entire building, i.e. multiplying this result by the usable surface area of 27,687m², we obtain:

$$375\ [kgCO2eq/m^2] \times 27{,}687\ [m^2] = 10{,}382.625\ [tonCO2eq]$$

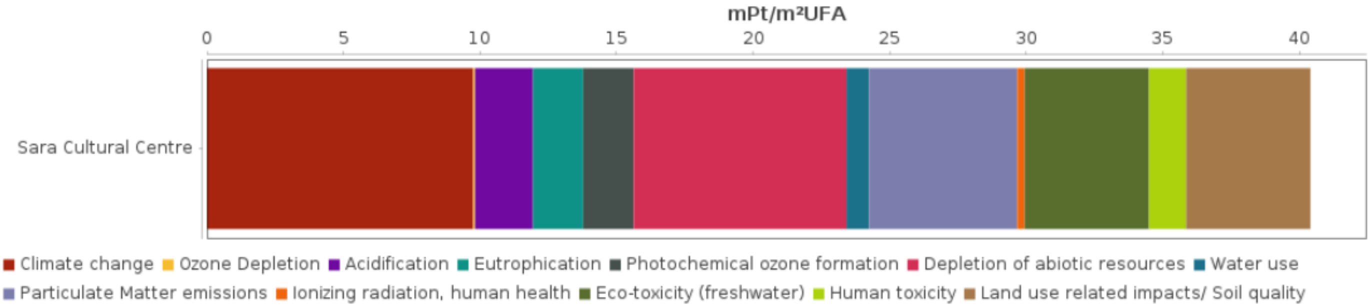


Figure 34: Impact per indicator of Sara Cultural Centre calculated by Totem

This value is very far from the caron budget published by white and mentioning carbon emissions of 5,631 tonnes of CO2eq.

Figure 35 shows the impact per element category of the Sara Cultural Centre. This graph is useful for determining which elements have the greatest influence on the building's environmental impact. From this, it is noticeable that the floors represent the vast majority, accounting for more than 50% of the overall impact. Other important elements are the walls and the openings. Note that this graph represents not only carbon emissions, but also a lot of other environmental impact factors.

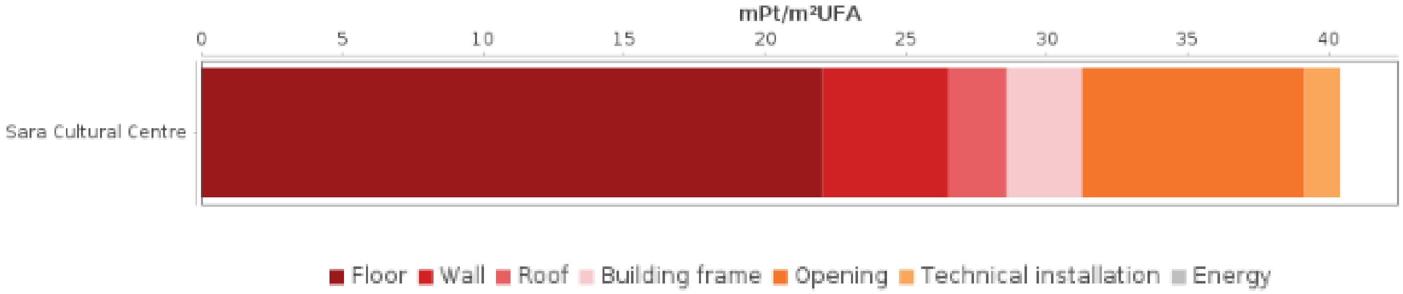


Figure 35: Impact per element category of Sara Cultural Centre calculated by Totem

At first, it may be worth analysing the relative contribution of each floor to distinguish the most polluting type. This can be seen in the Table 10. This indicates that the floor with the greatest impact is the CLT floor with a contribution of 27.91%, followed by the uninsulated concrete floor with 24.16%. In terms of carbon emissions, the CLT floors emit the biggest amount of carbon with 2,898.168 tons of CO2eq, then the insulated concrete floor with 2,508.030 tons of CO2eq and finally the uninsulated concrete floor with 668.808 tons of CO2eq. However, a quantity of 17,320 m² of CLT floor was used for only 11,600m² for the concrete floor. It is therefore more interesting to compare their impact per FU. According to the results, the insulated concrete has a bigger specific impact with 0.22 tonCO2eq/m² than the CLT floors with 0.17 tonCO2eq/m².

Table 10: Relative contribution of each floor to total impact by Totem

Material	**FU [m²]**	**Carbon emissions [ton CO2eq]**	**Specific impact = carbon emissions per FU [tonCO2eq/m²]**	**Relative contribution [%]**
Uninsulated concrete floors	3,760 [m²]	668.808	0.18	6.4
Insulated concrete floors	11,600 [m²]	2,508.030	0.22	24.16
CLT floors	17,320 [m²]	2,898.168	0.17	27.91

In order to understand which material represents the greatest impact of each component, Totem provides pie charts showing the contribution materials, as shown in Figure 36 and Figure 37. It can be seen that for the insulated concrete wall, it is the concrete (70%). This is logical, as it represents the thickest layer of the floor. But also, concrete is known for being a polluting material emitting a significant amount of CO2 and contributing to a large part of the global carbon emissions (United Nations Environment Programme 2022) (Lehne and Preston 2018).

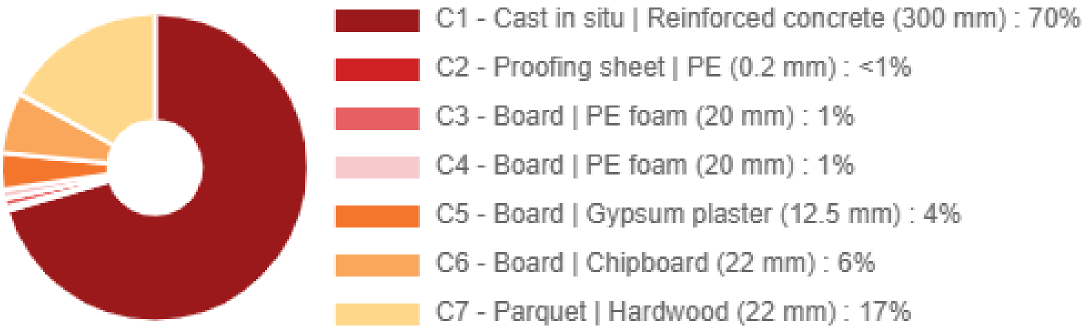


Figure 36: Impact per component of insulated concrete floor

When doing the same for the CLT floors, which is also the biggest thickness in the layers of the floor, CLT only represents about 50% of the floor's environmental impact. In this case, the carpet tile also has a significant impact of more than 25%. Therefore, for a similar specific impact and relative contribution, concrete has a greater impact than CLT.

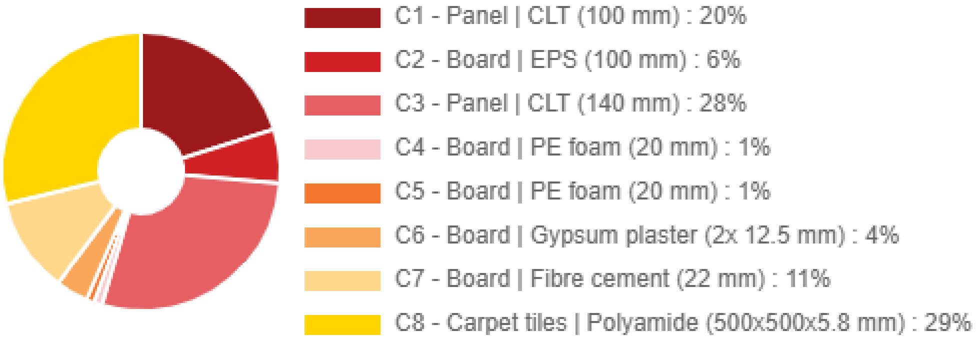


Figure 37: Impact per component of CLT floors

In a second time, wall also have a significant impact and are composed of CLT. Therefore, it can be interesting to analyse the relative contributions of both types of external walls. Similarly to the floors, we note that the overall contribution of timber walls (3.52%) is greater than that of terrazzo walls (1.66%). However, the specific impact of timber walls (0.08 tonCO2eq/m²) is significantly lower than that of terrazzo walls (0.31 tonCO2eq/m²).

Table 11: Relative contribution of each wall to total impact by Totem

Material	**FU [m²]**	**Carbon emissions [ton CO2eq]**	**Specific impact = carbon emissions per FU [tonCO2eq/m²]**	**Relative contribution [%]**
Terrazzo external walls	562 [m²]	172.775	0.31	1.66
Timber walls	4,462 [m²]	365.058	0.08	3.52

In the same way as for the floors, looking at the impact of each material on the components in Figure 38, it is clear that for the terrazzo wall, the reinforced concrete contributes the most to its impact (38%), followed by the terrazzo (33%). Again, terrazzo is a composite material mainly made of cement like concrete. It is therefore coherent that it contributes in large part to its impact (United Nations Environment Programme 2022).

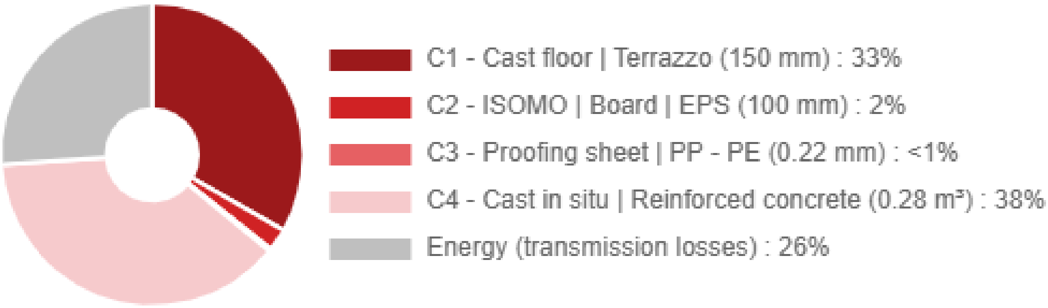


Figure 38: Impact per component of terrazzo external wall

In the case of the timber external wall in Figure 39, the CLT clearly accounts for the biggest part of the contribution (30%) in terms of material. The rest of the contribution is divided between the insulation (18%), the finishing wood planks (8%) and the battens (3%). The contribution of wood materials is clearly lower than that of cement.

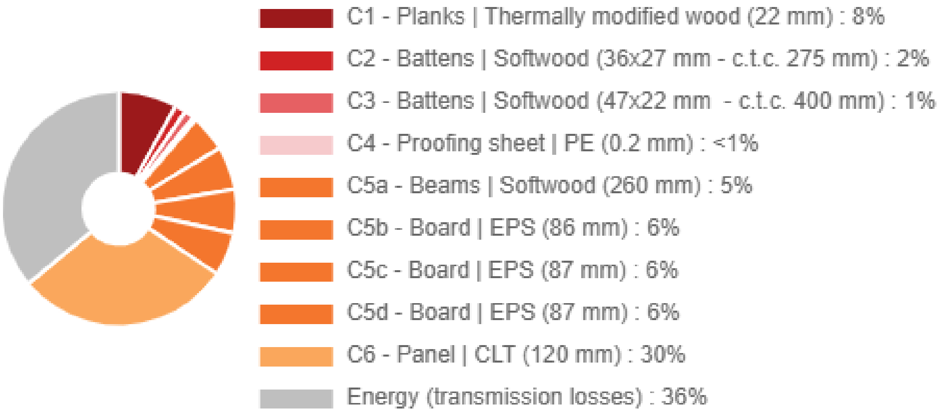
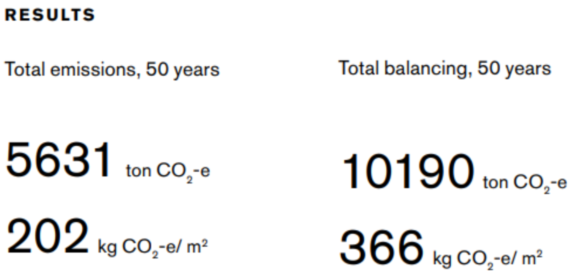


Figure 39: Impact per component of timber external wall

Once the results established by Totem have been analysed, they should be compared with those published by White. From White's results, the total emissions of the building after 50 years of life is 5,631 tons of CO2eq. Besides this, they considered that thanks to the biogenic carbon stored in the wood and the electricity generated by the photovoltaic panels, an amount of 10,190 tons of CO2eq would balance these final emissions as shown in the figure below:



RESULTS

Total emissions, 50 years	Total balancing, 50 years
5631 ton CO_2-e	10190 ton CO_2-e
202 kg CO_2-e/ m²	366 kg CO_2-e/ m²

Figure 40: Carbon budget of Sara Cultural Building published by White

This would result in:

$$5{,}631\ [tonCO2eq] - 10{,}190\ [tonCO2eq] = -4{,}559\ [tonCO2eq]$$

But where does this difference come from? A first assumption is that the carbon budget of White mention nowhere the impact of the maintenance, the replacement, the deconstruction/demolition, the waste transport, the waste processing and the waste disposal. But these are all life stages that were considered in the Totem's calculations. And they account for up to 40% as shown in the graph below from the Totem's environmental footprint calculations.

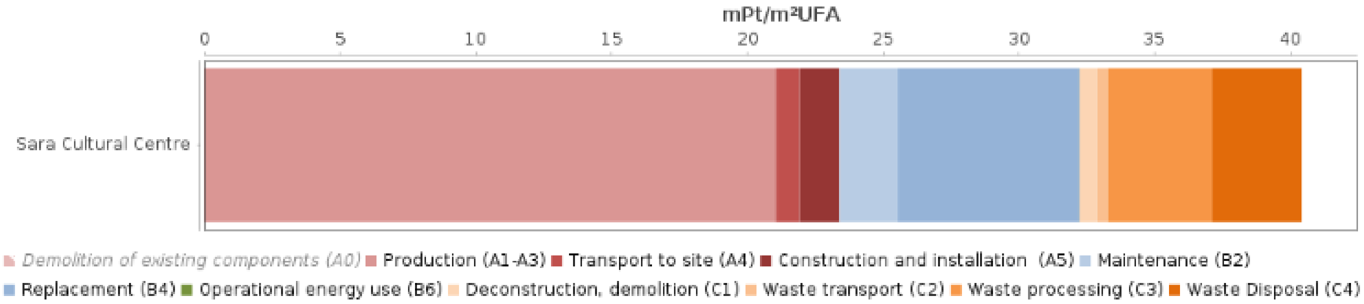


Figure 41: Impact per life cycle stage of Sara Cultural Centre calculated by Totem

This highlights the importance of establishing a unified methodology so that everyone can speak the same language and compare buildings reliably (Younis and Dodoo 2022). But according to the Eurocodes, all the life stages of the buildings should be considered to have the global "picture" of the GHG emissions fluctuating in a building project (Petrović, Eriksson and Zhang 2023). In other words, the calculation method used by Totem would be more realistic than the one used by White for the Sara Cultural Centre.

For example, the Sara cultural centre is equipped with photovoltaic panels. If these technical installations are to last as long as possible, they need to be maintained, otherwise they will certainly not last the 50 years of the building's life. This means that they will generate maintenance carbon emissions. This must be taken into account when assessing the building's life cycle.

Even if the graph in Figure 41 does not only consider carbon emissions, it may still be worth adding the 40% that has not been taken into account to the value of carbon emissions provided by White to check whether these values are getting closer:

$$\frac{100}{60} \times 5{,}631 = 9{,}385\ tons\ of\ CO2eq$$

Indeed, this value is already closer to the value calculated with Totem and may explain a large part of the difference between the two.

As for the negative impact estimated by White due to carbon sequestration and the electricity generated by the photovoltaic panels, this could not be taken into account in Totem's calculations and must therefore be integrated manually. If we consider the 12,200 m³ harvested for the construction of the Sara cultural centre, and that there is an average material loss of 15% during the manufacture of CLT, then the quantity of wood used in the building can be calculated.

$$\frac{85}{100} \times 12{,}200\ [m^3]\ =\ 10{,}370\ [m^3]$$

Then, knowing that 1 m³ of CLT stores 985 kgCO2eq, it is possible to approximate the amount of carbon stored in the final volume of wood.

$$10{,}370\ [m^3] \times 985\ [\frac{kgCO2eq}{m^3}] = 10{,}214.450\ [tonCO2eq]$$

Consequently, 10,214.450 tonnes of CO2eq would be captured in the building's EWP. This is a rough estimate, as there are EWP panels other than CLT in this building, which can explain why this value is a little higher than that calculated by White.

Finally, the final result of the carbon footprint can be calculated using the sum of emissions from all stages of life and carbon sequestration.

$$10{,}382.625\ [tonCO2eq]\ -\ 10{,}214.450\ [tonCO2eq] = 168.175\ [tonCO2eq]$$

This can also be considered considering the usable surface area:

$$\frac{168{,}175\ [kgCO2eq\ ]}{27{,}867\ [m^2]}\ =\ 6.035\ [kgCO2eq/m^2]$$

This is definitely lower than the value from another passive house made with CLT detailed in Figure 24 in page 26.

6. Conclusion

6.1. Discussion

First, the research presented in the thesis highlights several key factors that currently prevent CLT from becoming a standard construction material, despite its recognized environmental benefits. One significant barrier is the prevailing reliance on traditional materials such as concrete and steel, which are deeply entrenched in construction practices and regulations. This confidence is due in particular to a fear of the resistance of wood in the event of fire, which is the result of tragic events in history. Additionally, challenges related to market acceptance, investment cost for the production line creation, and supply chain issues particularly in regions with limited forest resources, hinder the widespread adoption of CLT. Furthermore, the lack of comprehensive building codes and regulations that support the use of CLT can impede its integration into mainstream construction.

Besides the evolution of CLT in the construction sector, this document explores the factors that enable a building to achieve the carbon-negative status. Indeed, the main reason for this is that the choice of sustainable materials, particularly those with high carbon sequestration potential, is fundamental. CLT is an excellent example, as it not only has a lower embodied carbon footprint than conventional materials such as concrete and steel, but also stores significant amounts of carbon, around 1,000kg of CO2 per cubic metre. This phenomenon of carbon sequestration is part of a natural mechanism known as biogenic carbon. Another influential factor is good building insulation, combined with energy production from the building itself using techniques such as photovoltaic panels or heat pumps. This allows it to reduce the operational energy use and achieve passive house status. A good combination of the two can result in the final sum of carbon emissions being negative because less carbon has been released than has been absorbed or avoided.

However, in the case of bio-sourced uses such as CLT, sustainable forest management is essential to preserve biodiversity and ensure that forests continue to sequester carbon effectively. It involves careful planning and monitoring to balance the harvesting of trees with the health of ecosystems, preventing deforestation and encouraging reforestation. By prioritising local and diverse species, sustainable practices strengthen the resilience of forest ecosystems while helping to mitigate climate change.

The Sara Cultural Centre is assessed using the 'cradle-to-grave' approach. This is the most realistic method of assessing a building, taking into account all stages in its life cycle. This approach is also recommended by European standards, as defined in EN 15978, and is implemented in Totem, an LCA software. Additionally, a framework has been established to guide the accurate assessment of a building's carbon footprint, ensuring consistency and reliability in the evaluation process.

In conclusion, the Sara Cultural Centre has a significantly lower environmental footprint compared to other buildings in the Totem library, highlighting the positive impact of using bio-based materials like CLT. In terms of carbon emissions, the Centre also has a very low final impact compared with other lambda CLT buildings but rather similar to other passive CLT buildings. In other words, this leaves little doubt as to the positive outcome of this building. However, the result calculated using Totem did not lead to a negative carbon footprint, contrary to White's claim, although it was close to 0. This is primarily due to the non-consideration of White for the building's EOL. It is though crucial to account them as a building does not simply disappear at the end of its useful life. According to one of the architects, it is difficult to estimate what will happen after 50 years of use. As the building is largely made up of prefabricated elements, it could be dismantled and reused elsewhere (see in Annex 9.3). Nevertheless, the carbon emission of such a transport would not be zero. If we take the example of two buildings made of the same amount of wood and therefore sequestering the same amount of carbon. But one only lasts 25 years, while the other lasts 50 years. The carbon emissions of a building that has only been in operation for 25 years would be much lower than those of a 50-year-old building. This would result in a much lower final carbon emission count for the 25-year building than for the 50-year building. However, given the carbon emissions generated by the construction phase alone (see Figure 24), it is clearly better to extend the life of buildings as much as possible and avoid building new ones.

Moreover, the risk with labelling a building as carbon-negative might suggest that its construction is beneficial to the environment, solving more problems than it creates. While this building indeed has a better impact than most other buildings constructed today, it is always preferable to avoid constructing new buildings altogether. The construction of these buildings requires sustainable forest management, otherwise it could lead to increased deforestation and exacerbate another critical problem. Therefore, achieving a negative carbon footprint is possible, but involves many factors that need to be considered over and above the construction of the building itself.

6.2. Research limitations

In this research, several limitations were encountered that could affect the final assessment of the Sara Cultural Centre's environmental impact.

Firstly, and this is probably the biggest limitation, no photovoltaic panels could be integrated into the software because it does not yet allow this. This would have been very interesting to analyse, as White has stated that this energy production contributes a negative carbon emission of -39 kgCO2eq/m².

Moreover, some elements such as inner walls, stairs, foundations, balconies and electrical services were not included. For the inner walls, it is mainly because of lack of information to estimate their composition and their quantity. For the rest, they are not yet included in TOTEM. This means that the environmental impact of the building may be underestimated. Yet the carbon emissions result still exceeds the value provided by White.

In addition, there were very precise values for the building's energy consumption, which could be integrated directly into the software to determine its impact. However, it was impossible to consider the energy mix of the city/country in which the project was being carried out.

The project was therefore analysed using Belgium's energy mix while Skellefteå is powered entirely by renewable energy, which could skew the results. But the energy use made a very small contribution to the final assessment result. Thus, this did not have a significant impact on the analysis, but this could be the case for projects with higher energy consumption.

The minimal transport involved in the construction of the Sara Building could not be taken into account in TOTEM, which considered an average Belgian construction transport cost for carbon emissions. Nonetheless, it was specifically mentioned that all the timber used for this project was harvested within a 60km radius of the site and that the number of deliveries by truck was reduced by 90%. The share of transport in the final software result was not significant, so this did not considerably overestimate the result.

Lastly, the analysis was limited to carbon emissions, overlooking other significant environmental impacts such as land use, particulate matter emissions, and water use, which are also crucial to consider.

6.3. Critical reflections

The exploration of CLT buildings presents a promising avenue for sustainable construction, yet it also raises several critical considerations.

Firstly, the longevity of carbon storage in wooden structures is contingent upon the preservation of the wood itself. Therefore, it is imperative to design CLT buildings with a strong emphasis on wood preservation techniques and to implement rigorous maintenance practices. This ensures that the carbon sequestered within the timber remains stored for the longest possible duration, thereby maximizing the environmental benefits of such structures.

Moreover, there is an urgent need to establish standardized practices for assessing the carbon footprint of buildings. A unified methodology would facilitate meaningful comparisons between different structures and promote transparency in environmental claims. This standardization is essential for stakeholders, including architects, builders, and policymakers, to make informed decisions based on reliable data.

Additionally, the continuous improvement of LCA tools is crucial. These tools should be adaptable to various climatic and contextual conditions, allowing for a more nuanced understanding of a building's environmental impact. Expanding the range of materials and technical options available within these assessments can further enhance the accuracy and relevance of LCA results.

Furthermore, enhancing the use of EWP like CLT in countries that are not currently leaders in this domain, such as Belgium, is essential. The case of the Sara cultural centre building is further proof that Nordic countries such as Sweden have been using it for much longer than the rest of Europe. In fact, the workers on the project were already familiar with this construction technique (see Annex 9.3).

These nations must work to improve their wood markets for construction, fostering a greater acceptance and integration of sustainable materials in building practices. This can be achieved through targeted policies and educational initiatives that raise awareness about the benefits of using wood in construction. By developing a robust domestic wood industry, such countries can reduce their reliance on traditional materials, promote local economies, and contribute to global sustainability goals.

Finally, the study of new wood preservation techniques and treatments that improve the durability and fire resistance of CLT would make its use inevitable. By ensuring that it can withstand various environmental conditions while maintaining its structural integrity and carbon storage capabilities would improve even more its sustainable benefits. Another aspect could be researching the potential of hybrid construction methods that combine CLT with other materials (e.g., steel, concrete) to optimize structural performance, reduce carbon footprints, and address specific engineering challenges in diverse building types.

7. Declaration of Generative AI and AI-assisted technologies in the writing process

In the course of writing this thesis, I utilized AI-based tools to assist with various aspects of the writing process. These tools were particularly helpful in generating initial drafts, refining language, and ensuring clarity, structure and coherence in the presentation of ideas. While the AI provided valuable support, I maintained full responsibility for the content, critical analysis, and final revisions of the thesis. The use of AI was carefully managed to complement, rather than replace, the rigorous academic standards expected in this work.

8. References

Arenas, Nathalia Fonseca, and Muhammad Shafique. “Reducing embodied carbon emissions of buildings – a key consideration to meet the net zero target.” *Sustainable Futures* 7 (June 2024).

Beijia, Huang, Gao Xiaofeng, Xu Xiaozhen, Song Jialing, and Geng Yong. “A Life Cycle Thinking Framework to Mitigate the Environmental Impact of Building Materials.” *One Earth*, 26 11 2020: 564-573.

Belgique, Société Royale Forestière de. *Les forêts de Belgique.* 2024. https://srfb.be/informations-on-forests/les-forets-de-belgique/ (accessed June 22, 2022).

Brandner, R., G. Flatscher, A. Ringhofer, G. Schickhofer, and A. Thiel. “Cross laminated timber (CLT): overview and development.” *European Journal of Wood and Wood Products*, 01 05 2016: 331-351.

Brandt, Kristin, Alex Wilson, Donald Bender, James D. Dolan, and Michael P. Wolcott. “Techno-economic analysis for manufacturing cross-laminated timber.” *BioResources*, 9 August 2019: 7790-7804.

Cassela, Carly. *First Study of Its Kind Finally Reveals How Dying Trees Affect Earth's Carbon Cycle.* 3 September 2021. https://www.sciencealert.com/first-of-its-kind-study-finds-dead-trees-worldwide-release-more-carbon-than-fossil-fuels (accessed June 24, 2024).

CEN. “Eurocode 2: Design of concrete structures - Part 1-1 : General rules and rules for buildings.” Norm, Brussels, 2004.

Cremonese, Lorenzo, et al. “Making Sense of Techno-Economic Assessment & Life Cycle Assessment Studies for CO2 Utilization: A guide on how to commission, understand, and derive decisions from TEA and LCA studies.” Study report, Institute for Advanced Sustainability, Postdam, 2020.

Espinoza, Omar, Vladimir Rodriguez Trujillo, Maria Fernanda Laguarda Mallo, and Urs Buehlmann. “Cross-Laminated Timber: Status and Research Needs in Europe.” *BioResources*, 16 November 2015: 281-295.

Falk, Andreas, Philipp Dietsch, and Joachim Schmid. *Cross Laminated Timber – A competitive wood product for visionary and fire safe buildings.* Proceedings of the Joint Conference of COST Actions FP1402 & FP1404, Division of Building Materials, KTH Royal Institute of Technology, Stockholm, Sweden: European cooperation in science and technology, 2016.

Frank, Lam. “Modern structural wood products.” *Progress in Structural Engineering and Materials* 3, no. 3 (2001): 238-245.

Friggens, Nina L., Alison J. Hester, Ruth J. Mitchell, Thomas C. Parker, Jens-Arne Subke, and Philip A. Wookey. “Tree planting in organic soils does not result in net carbon sequestration on decadal timescales.” *Global Change Biology* 26, no. 9 (Septembre 2020): 5178-5188.

Fundació Mies van der Rohe. *Sara Cultural Centre.* 2024. https://miesarch.com/work/5577 (accessed June 6, 2024).

Giacometti, Alberto, and Hilma Salonen. "Innovation Dynamics in Wood Construction in Sweden and Finland." working paper, Nordregio, 2023.

Green, Michael, and Jim Taggart. *Tall wood buildings: design, construction and performance.* Second and expanded edition. Edited by Ria Stein. Basel: Birkhäuser, 2020.

Harrington, Jonathan J. "Hierarchical modelling of softwood hygro-elastic properties." *Library of University Of Canterbury*, 2002.

Head, Marieke, Michael Magnan, Werner A. Kurz, Annie Levasseur, Robert Beauregard, and Manuele Margni. "Temporally-differentiated biogenic carbon accounting of wood building product life cycles." *SN Applied Sciences* 3, no. 1 (January 2021).

Holl, Karen D., and Pedro H. S. Brancalion. "Tree planting is not a simple solution." *Science* 368, no. 6491 (June 2020): 580-581.

Hout Info Bois. "Enquêtes - Etat de la construction bois en Belgique." Survey, 2022.

Jeleč, Mario, Damir Varevac, and Vlatka Rajčić. "Cross-laminated timber (CLT) – a state of the art report." *Journal of the Croatian Association of Civil Engineers* 70, no. 02 (2018): 75-95.

Kwok, Alison, Hannah Zalusky, Isabel Rivera, Lindsay Rasmussen, and Hannah Mckay. "Whole Building Life Cycle Assessment of a mass timber multifamily residential structure." TallWood Design Institute, 2019.

Lehne, Johanna, and Felix Preston. *Making Concrete Change: Innovation in Low-carbon Cement and Concrete.* London: The Royal Institute of International Affairs, 2018.

Lugt, Pablo, Joost Vogtlander, John Alexander, Ferry Bongers, and Hal Stebbins. *The Potential Role of Wood Acetylation in Climate Change Mitigation.* Delft, 2014.

Oh, Jae-Won, et al. "Comparative CO2 emissions of concrete and timber slabs with equivalent structural performance." *Energy and Buildings* 281 (2023).

Östman, Birgit, Joachim Schmid, Michael Klippel, Alar Just, Norman Werther, and Daniel Brandon. "Fire design of CLT in Europe." *Wood and fiber science: journal of the Society of Wood Science and Technology* 50 (2018).

Petrović, Bojana, Ola Eriksson, and Xingxing Zhang. "Carbon assessment of a wooden single-family building – A novel deep green design and elaborating on assessment parameters." *Building and Environment* 233 (April 2023).

Puettmann, Maureen, Arijit Sinha, and Indroneil Ganguly. "Life Cycle Assessment of Cross Laminated Timbers Produced in Oregon." *CORRIM*, February 2018.

Quesada, Henry, Robert Smith, and Günter Berger. "Drivers and Barriers of Cross-Laminated Timber (CLT) Production and Commercialization: A Case Study of Western Europe's CLT Industry." *BioProducts Business*, March 2018.

Ravenscroft, Tom. "White Arkitekter unveils mass-timber Sara Kulturhus Centre in Skellefteå." *dezeen.* 8 10 2021. https://www.dezeen.com/2021/10/08/sara-kulturhus-skelleftea-sweden-white-arkitekter/ (accessed April 12, 2024).

Reid, Hannah, et al. "Using wood products to mitigate climate change: a review of evidence and key issues for sustainable development." Technical report, 2004.

Ricardo Gherardi Hein, Paulo. "Genetic and environmental control of microfibril angle on eucalyptus wood: its effects on wood traits and implication for selection." PhD thesis, Universite´Montpellier II - Sciences et Techniques du Languedoc, Montpellier, 2011.

Sala, Serenella, Alessandro Kim Cerutti, and Rana Pant. *Development of a weighting approach for the environmental footprint.* Luxembourg: Publications Office of the European Union, 2018.

Sara Kulturhus. *Sara Cultural Centre – wood, sustainability and Spider-Man!* n.d. https://www.sarakulturhus.se/sv/ett-klimatklokt-hus/sara-kulturhus-tra-hallbarhet-och-spider-man/ (accessed 6 3, 2024).

Sezer, Ahmet Anil, and Anna Frederiksson. "Environmental impact of construction transport and the effects of building certification schemes." *Resources, Conservation and Recycling* 172 (2021).

Swedish wood. *The CLT Handbook.* Stockholm: Swedish Forest Industries Federation and Swedish Wood, 2022.

Too, Judy, Obuks A. Ejohwomu, Felix K. P. Hui, Colin Duffield, Oyegoke Teslim Bukoye, and David John Edwards. "Framework for standardising carbon neutrality in building projects." Edited by Jian Zuo. *Journal of Cleaner Production* 373 (Novembre 2020).

Totem. 28 June 2024. https://www.totem-building.be/pages/home.xhtml (accessed August 08, 2024).

Totem. "Environmental profile of buildings." 2023.

United Nations Environment Programme. "2022 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector." Nairobi, 2022.

Wainwright, Oliver. "Isn't it good, Swedish plywood: the miraculous eco-town with a 20-storey wooden skyscraper." *The Guardian*, 2021.

Wålinder, Magnus. "Building Materials, Advanced Course." *KTH Technical University of Stockholm.* 2022. https://canvas.kth.se/courses/35919.

White Arkitekter. "Cultural Centre and Hotel in Skellefteå." *DETAIL*, December 2021: 58-67.

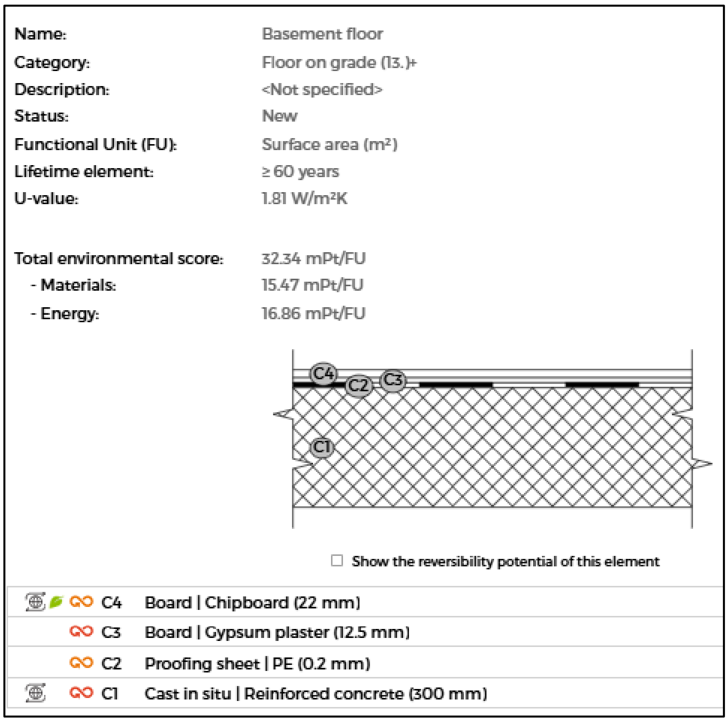
White. "Sara Culture Centre Carbon budget." Report of carbon budget, Skellefteå, 2021.

Wieruszewski, Marek, and Bartłomiej Mazela. "Cross Laminated Timber (CLT) as an Alternative Form of Construction Wood." *Drvna industrija* 68, no. 4 (2017): 359-367.

Younis, Adel, and Ambrose Dodoo. "Cross-laminated timber for building construction: A life-cycle-assessment overview." *Journal of Building Engineering* 52 (July 2022).

9. Annexes

9.1. Elements



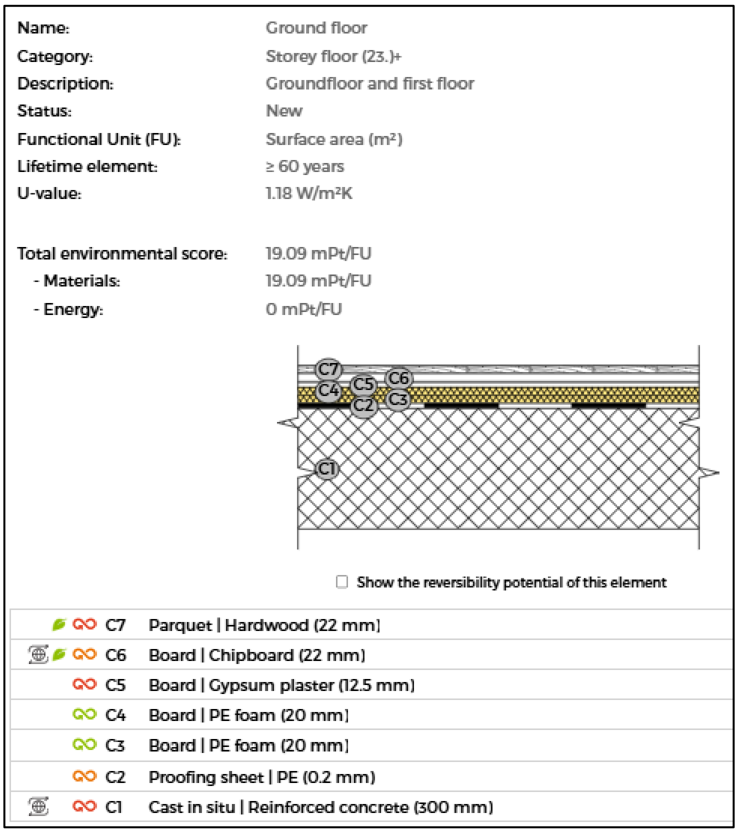
Name: Basement floor
Category: Floor on grade (13.)+
Description: <Not specified>
Status: New
Functional Unit (FU): Surface area (m²)
Lifetime element: ≥ 60 years
U-value: 1.81 W/m²K

Total environmental score: 32.34 mPt/FU
- Materials: 15.47 mPt/FU
- Energy: 16.86 mPt/FU

☐ Show the reversibility potential of this element

C4	Board | Chipboard (22 mm)
C3	Board | Gypsum plaster (12.5 mm)
C2	Proofing sheet | PE (0.2 mm)
C1	Cast in situ | Reinforced concrete (300 mm)

Annex 1: Basement floor



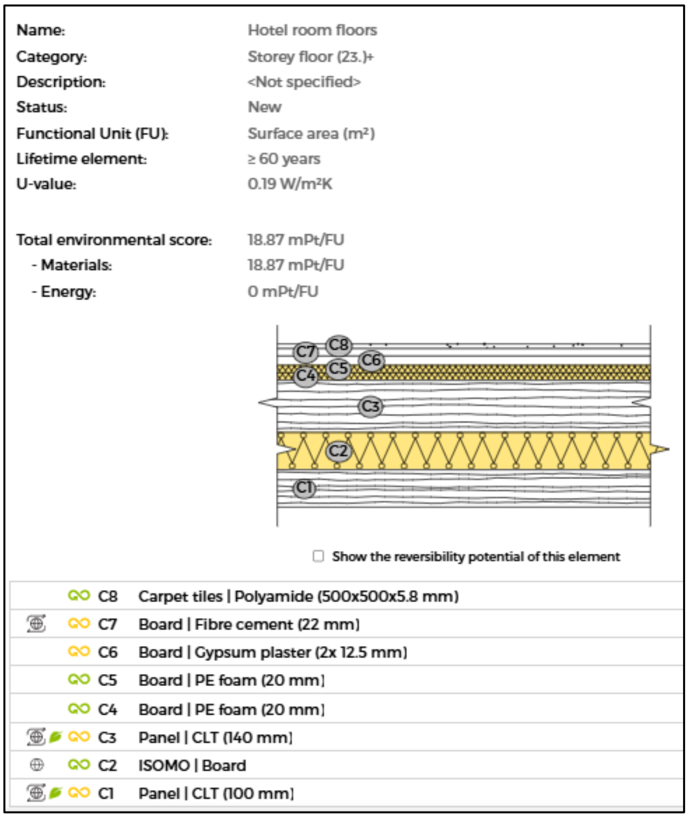
Name: Ground floor
Category: Storey floor (23.)+
Description: Groundfloor and first floor
Status: New
Functional Unit (FU): Surface area (m²)
Lifetime element: ≥ 60 years
U-value: 1.18 W/m²K

Total environmental score: 19.09 mPt/FU
- Materials: 19.09 mPt/FU
- Energy: 0 mPt/FU

☐ Show the reversibility potential of this element

C7	Parquet | Hardwood (22 mm)
C6	Board | Chipboard (22 mm)
C5	Board | Gypsum plaster (12.5 mm)
C4	Board | PE foam (20 mm)
C3	Board | PE foam (20 mm)
C2	Proofing sheet | PE (0.2 mm)
C1	Cast in situ | Reinforced concrete (300 mm)

Annex 2: Storey floors on the cultural centre

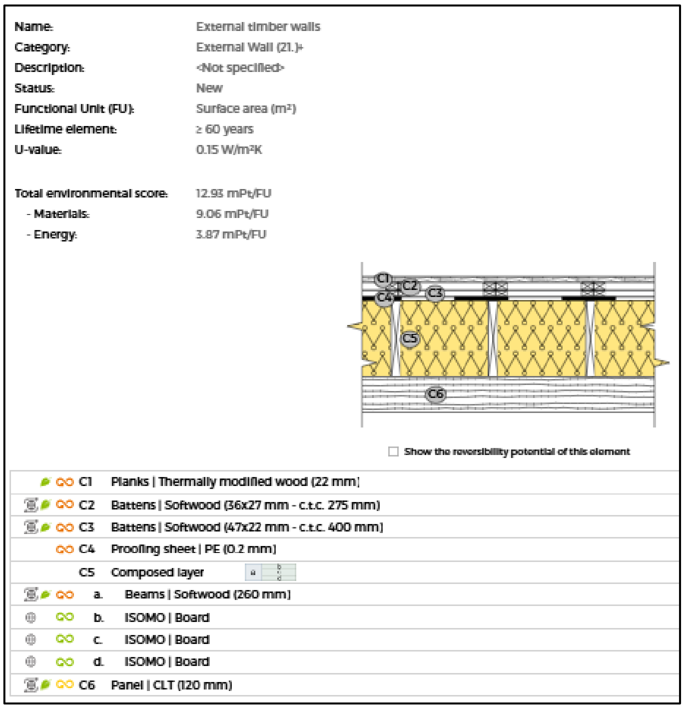


Name:	Hotel room floors
Category:	Storey floor (23.)+
Description:	<Not specified>
Status:	New
Functional Unit (FU):	Surface area (m²)
Lifetime element:	≥ 60 years
U-value:	0.19 W/m²K
Total environmental score:	18.87 mPt/FU
- Materials:	18.87 mPt/FU
- Energy:	0 mPt/FU

☐ Show the reversibility potential of this element

C8	Carpet tiles | Polyamide (500x500x5.8 mm)
C7	Board | Fibre cement (22 mm)
C6	Board | Gypsum plaster (2x 12.5 mm)
C5	Board | PE foam (20 mm)
C4	Board | PE foam (20 mm)
C3	Panel | CLT (140 mm)
C2	ISOMO | Board
C1	Panel | CLT (100 mm)

Annex 3: Storey floors of the hotel rooms

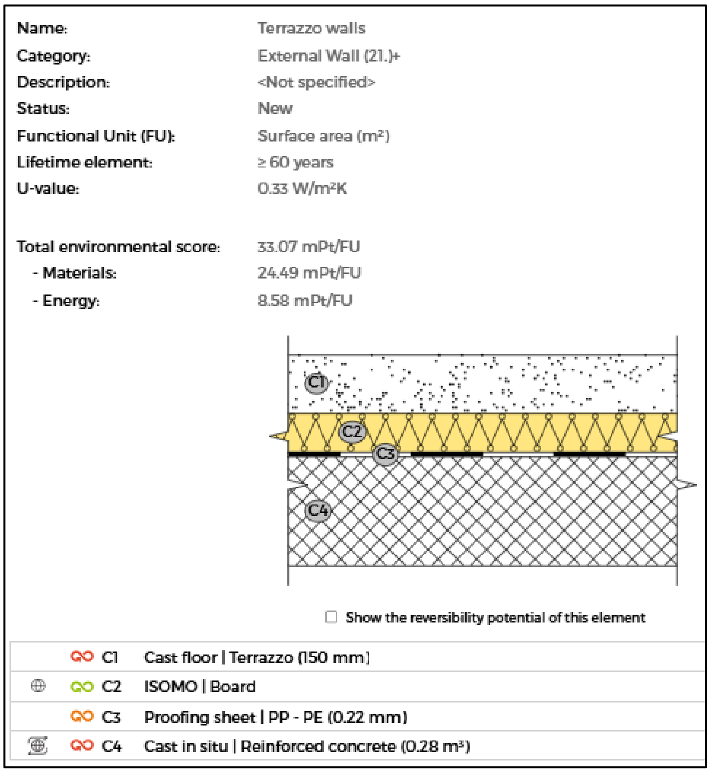


Name:	External timber walls
Category:	External Wall (21.)+
Description:	<Not specified>
Status:	New
Functional Unit (FU):	Surface area (m²)
Lifetime element:	≥ 60 years
U-value:	0.15 W/m²K
Total environmental score:	12.93 mPt/FU
- Materials:	9.06 mPt/FU
- Energy:	3.87 mPt/FU

☐ Show the reversibility potential of this element

C1	Planks | Thermally modified wood (22 mm)
C2	Battens | Softwood (36x27 mm - c.t.c. 275 mm)
C3	Battens | Softwood (47x22 mm - c.t.c. 400 mm)
C4	Proofing sheet | PE (0.2 mm)
C5	Composed layer
a.	Beams | Softwood (260 mm)
b.	ISOMO | Board
c.	ISOMO | Board
d.	ISOMO | Board
C6	Panel | CLT (120 mm)

Annex 4: External timber walls of cultural centre

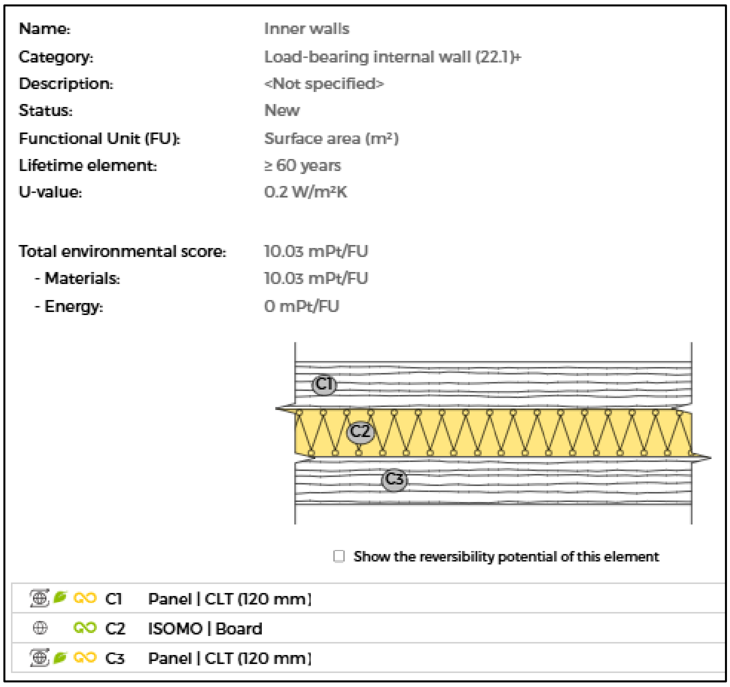


Name:	Terrazzo walls
Category:	External Wall (21.)+
Description:	<Not specified>
Status:	New
Functional Unit (FU):	Surface area (m²)
Lifetime element:	≥ 60 years
U-value:	0.33 W/m²K
Total environmental score:	33.07 mPt/FU
- Materials:	24.49 mPt/FU
- Energy:	8.58 mPt/FU

☐ Show the reversibility potential of this element

∞	C1	Cast floor | Terrazzo (150 mm)
⊕ ∞	C2	ISOMO | Board
∞	C3	Proofing sheet | PP - PE (0.22 mm)
⊕ ∞	C4	Cast in situ | Reinforced concrete (0.28 m³)

Annex 5: External terrazzo wall from the cultural centre

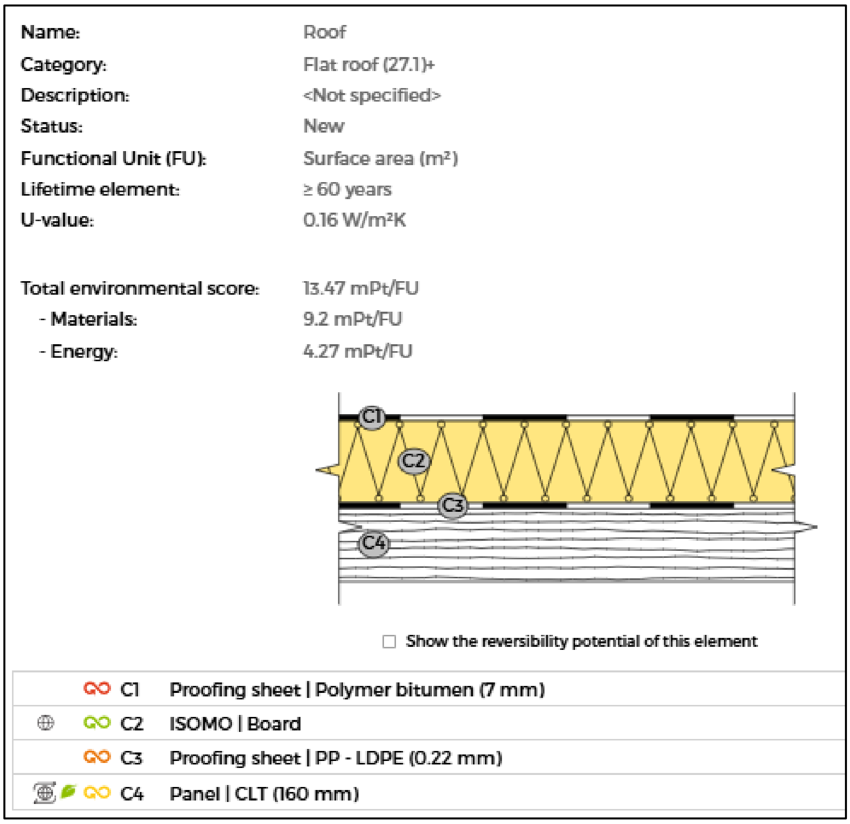


Name:	Inner walls
Category:	Load-bearing internal wall (22.1)+
Description:	<Not specified>
Status:	New
Functional Unit (FU):	Surface area (m²)
Lifetime element:	≥ 60 years
U-value:	0.2 W/m²K
Total environmental score:	10.03 mPt/FU
- Materials:	10.03 mPt/FU
- Energy:	0 mPt/FU

☐ Show the reversibility potential of this element

⊕ ∞	C1	Panel | CLT (120 mm)
⊕ ∞	C2	ISOMO | Board
⊕ ∞	C3	Panel | CLT (120 mm)

Annex 6: Inner walls from hotel rooms

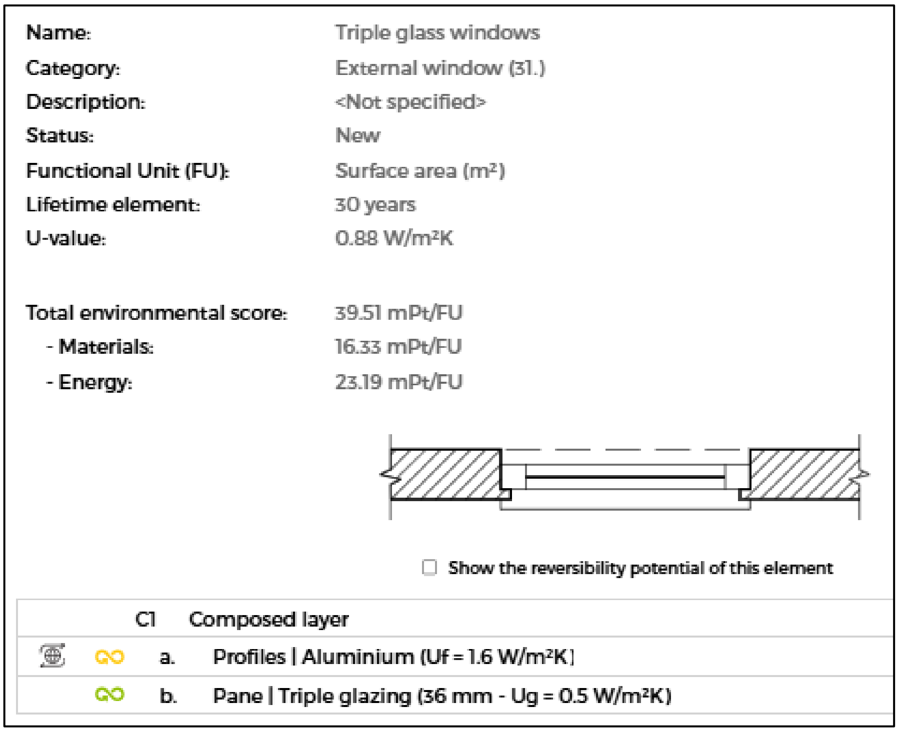


Name:	Roof
Category:	Flat roof (27.1)+
Description:	<Not specified>
Status:	New
Functional Unit (FU):	Surface area (m²)
Lifetime element:	≥ 60 years
U-value:	0.16 W/m²K
Total environmental score:	13.47 mPt/FU
- Materials:	9.2 mPt/FU
- Energy:	4.27 mPt/FU

☐ Show the reversibility potential of this element

C1	Proofing sheet | Polymer bitumen (7 mm)
C2	ISOMO | Board
C3	Proofing sheet | PP - LDPE (0.22 mm)
C4	Panel | CLT (160 mm)

Annex 7: Roof

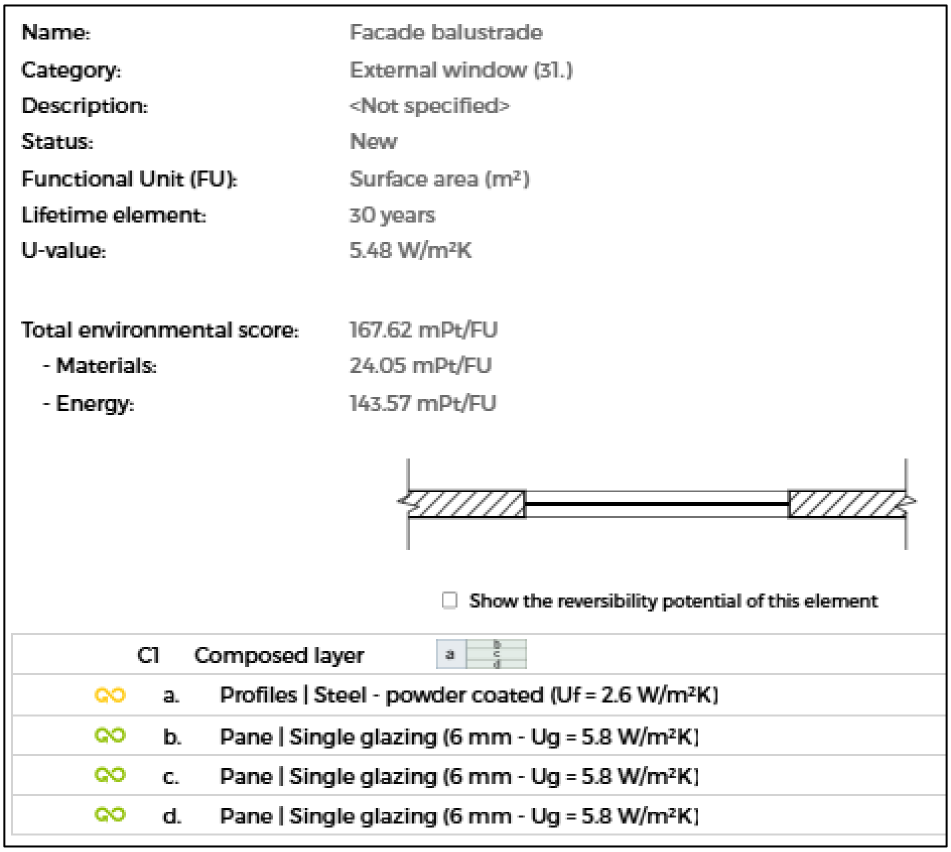


Name:	Triple glass windows
Category:	External window (31.)
Description:	<Not specified>
Status:	New
Functional Unit (FU):	Surface area (m²)
Lifetime element:	30 years
U-value:	0.88 W/m²K
Total environmental score:	39.51 mPt/FU
- Materials:	16.33 mPt/FU
- Energy:	23.19 mPt/FU

☐ Show the reversibility potential of this element

C1	Composed layer
a.	Profiles | Aluminium (Uf = 1.6 W/m²K)
b.	Pane | Triple glazing (36 mm - Ug = 0.5 W/m²K)

Annex 8: Triple glass windows with aluminium frame



Name: Facade balustrade
Category: External window (31.)
Description: <Not specified>
Status: New
Functional Unit (FU): Surface area (m²)
Lifetime element: 30 years
U-value: 5.48 W/m²K

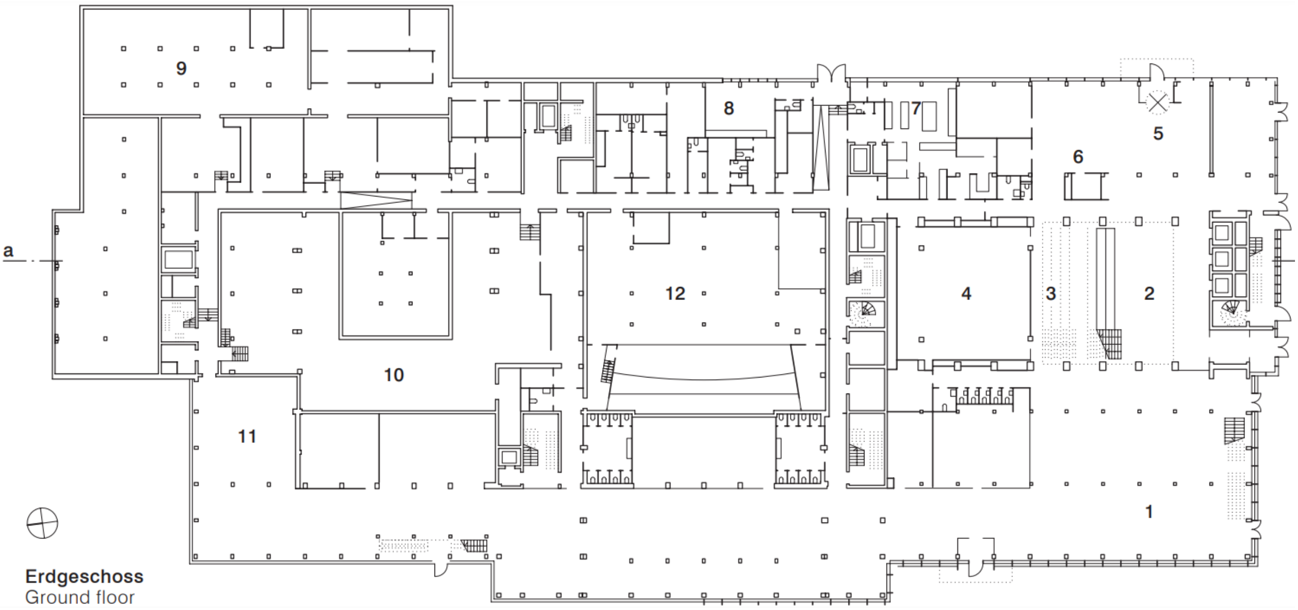
Total environmental score: 167.62 mPt/FU
- Materials: 24.05 mPt/FU
- Energy: 143.57 mPt/FU

☐ Show the reversibility potential of this element

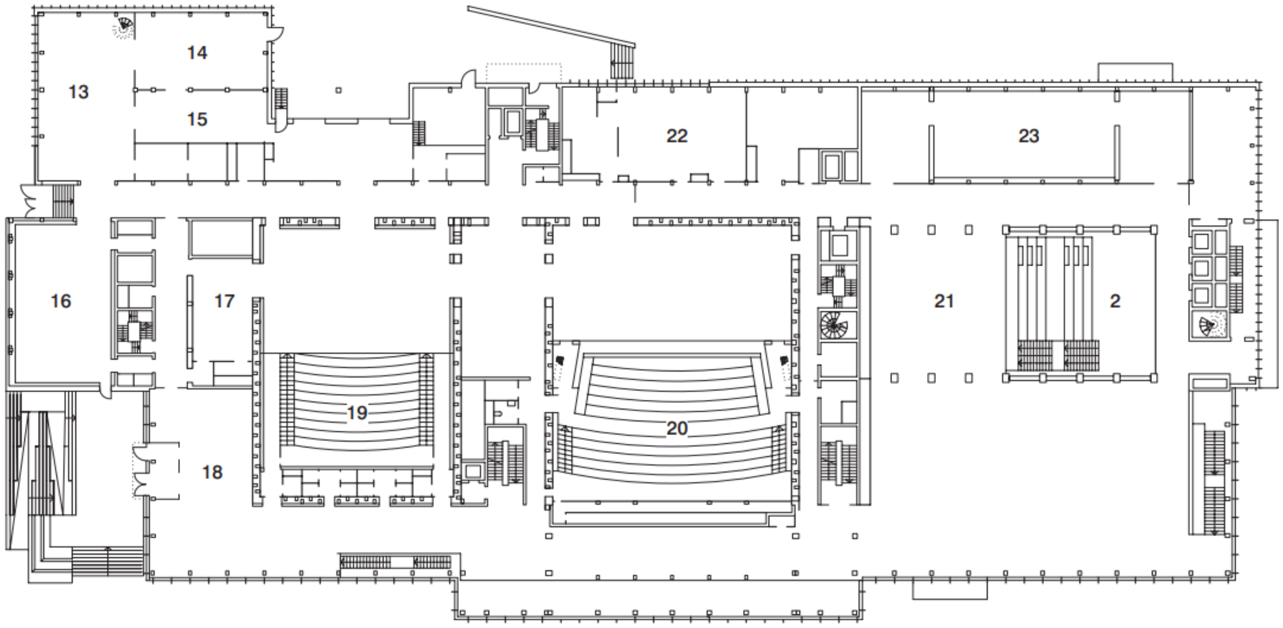
C1	Composed layer
a.	Profiles | Steel - powder coated (Uf = 2.6 W/m²K)
b.	Pane | Single glazing (6 mm - Ug = 5.8 W/m²K)
c.	Pane | Single glazing (6 mm - Ug = 5.8 W/m²K)
d.	Pane | Single glazing (6 mm - Ug = 5.8 W/m²K)

Annex 9: glass wrapping the hotel tower creating the double skin

9.2. Building composition

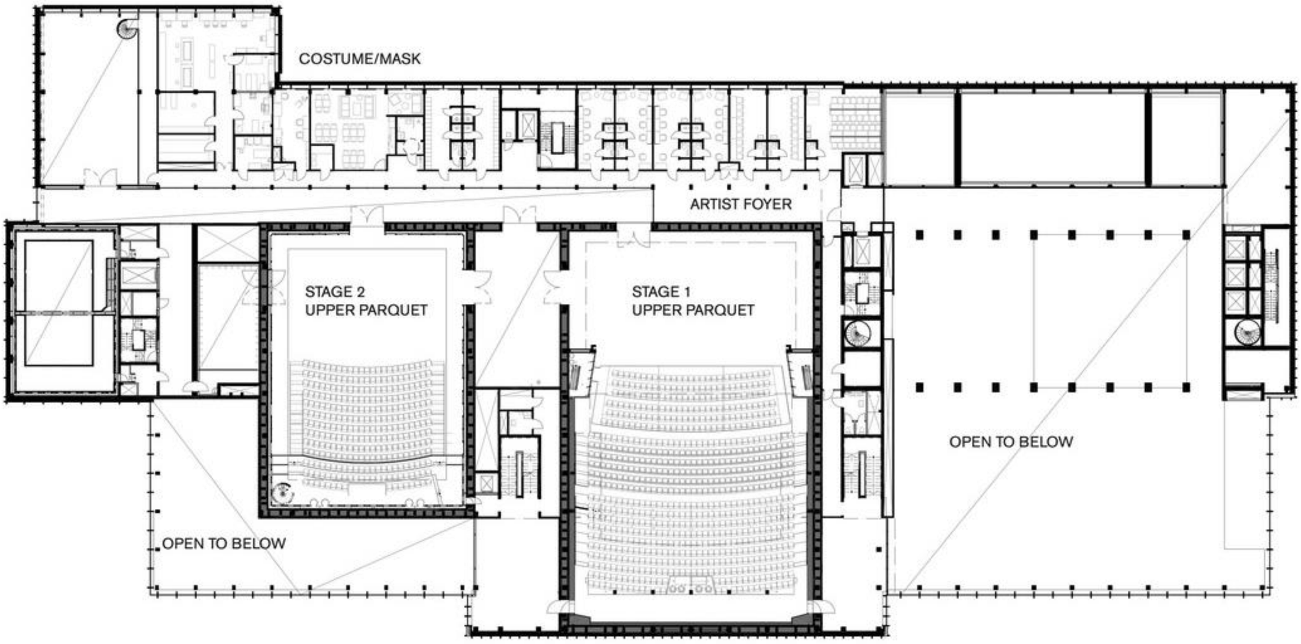


Annex 10: Ground floor. Provided by DETAIL magazine

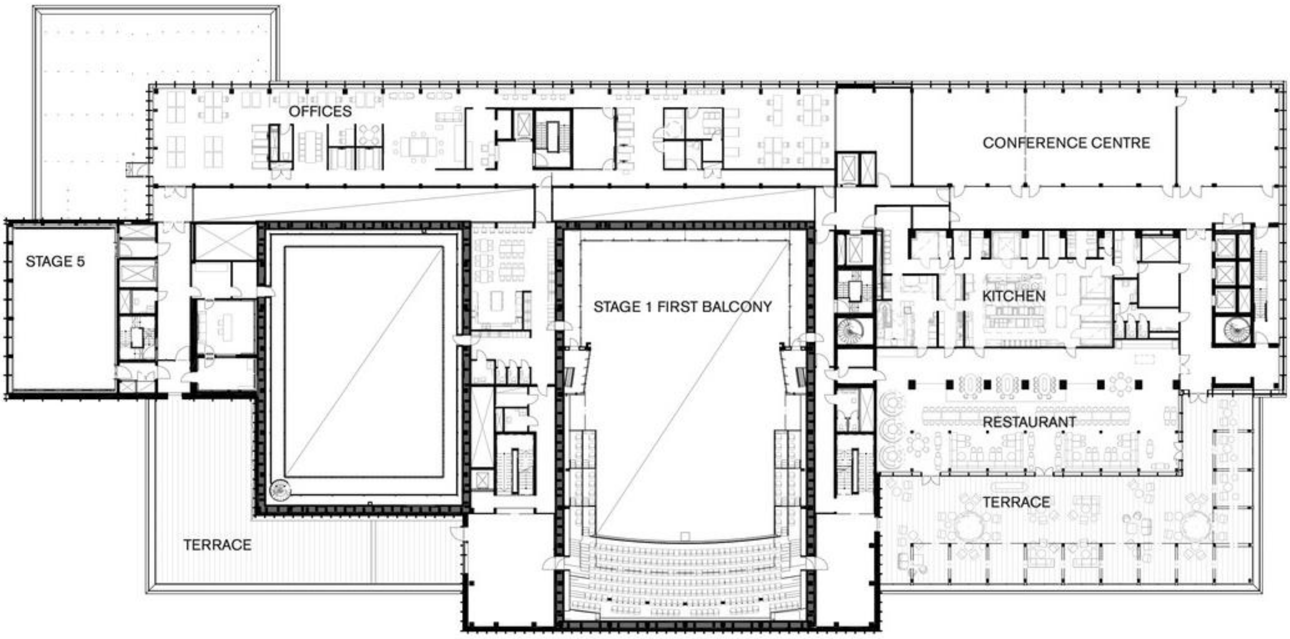


1. Obergeschoss
First floor

Annex 11: First floor. Provided by DETAIL magazine

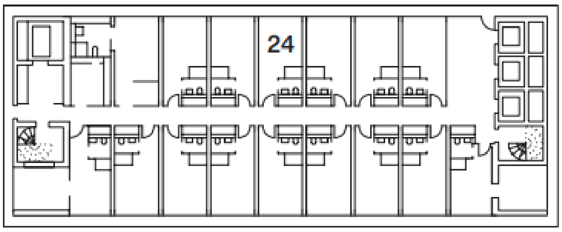


Annex 12: Second floor. Provided by White



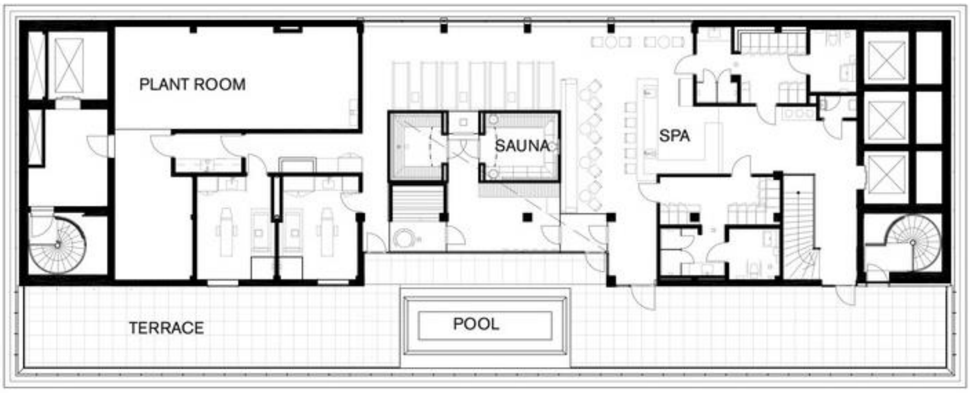
Annex 13: Third floor. Provided by White

Floor plans
scale 1:750
1 Library
2 Main foyer with cultural stairs
3 Wardrobe
4 Matinee stage
5 Hotel lobby
6 Reception
7 Hotel kitchen
8 Hotel auxiliary room
9 Central mechanical services
10 Ventilation station
11 Library stack
12 Storage rooms
13 Studio
14 Carpentry
15 Smithy
16 small theatre hall
17 Auditorium
18 Foyer
19 large theatre hall
20 Concert hall
21 Upper foyer
22 Kitchen
23 Exhibition space
24 Hotel room

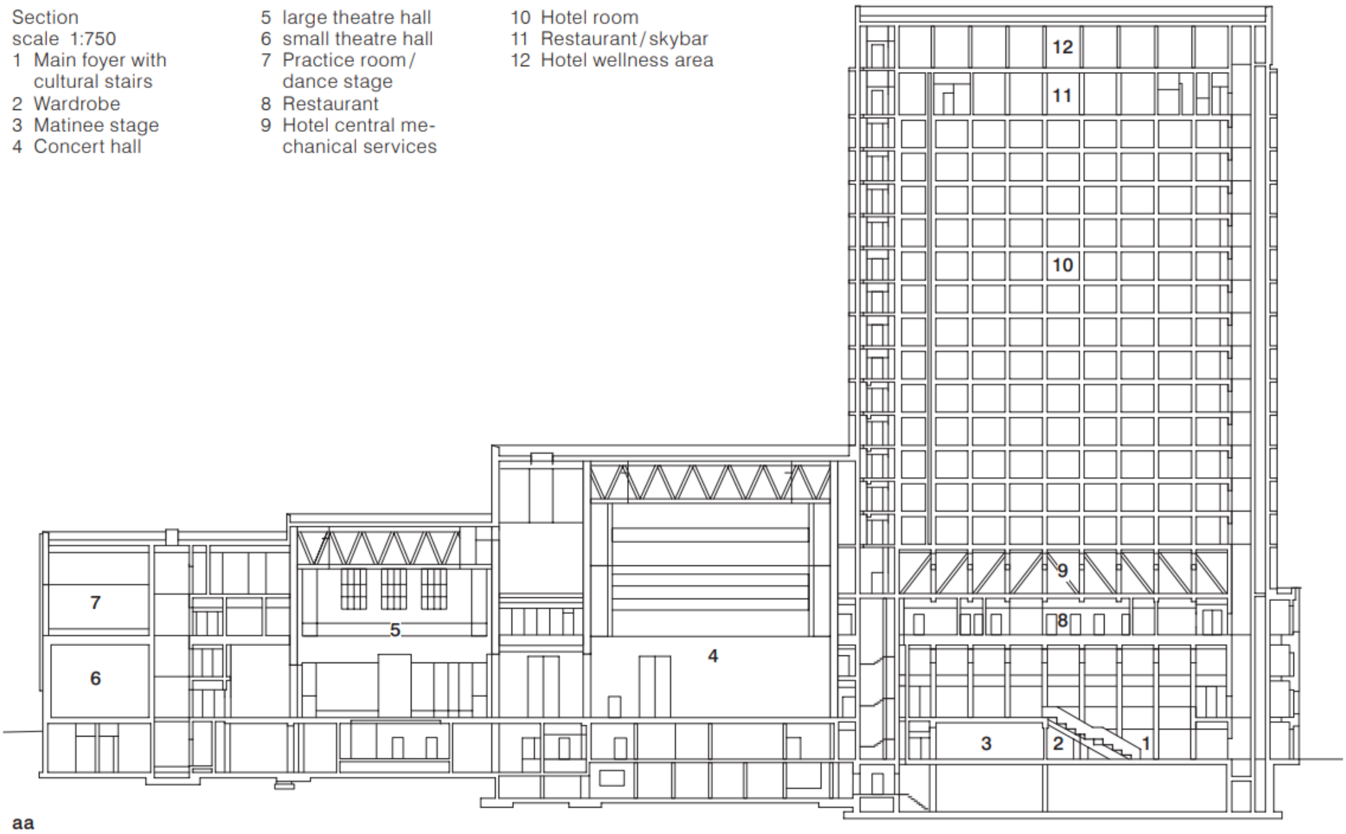


6.–18. Obergeschoss
Sixth to eighteenth floor

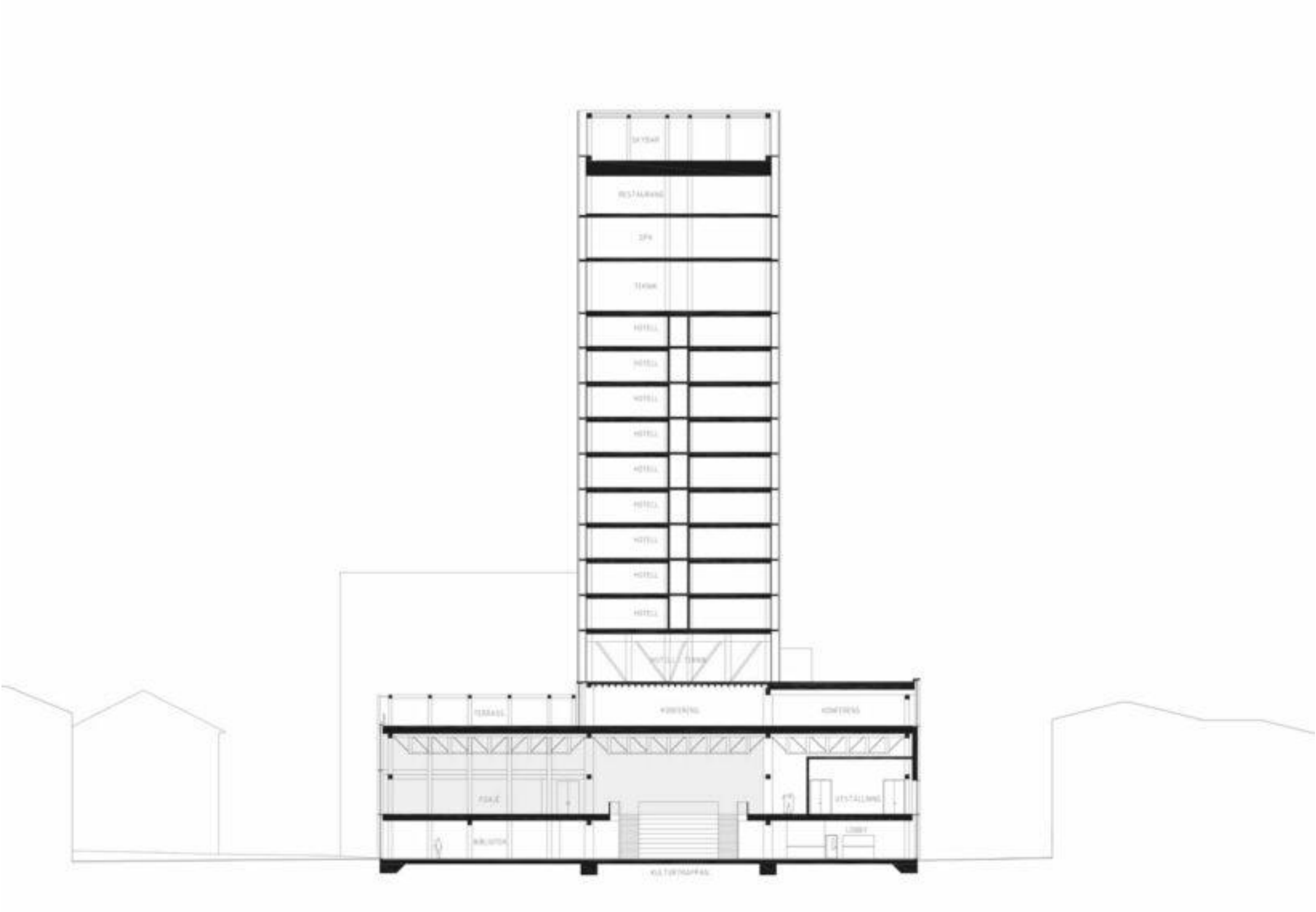
Annex 14: Sixth to eighteen floors. Provided by DETAIL magazine



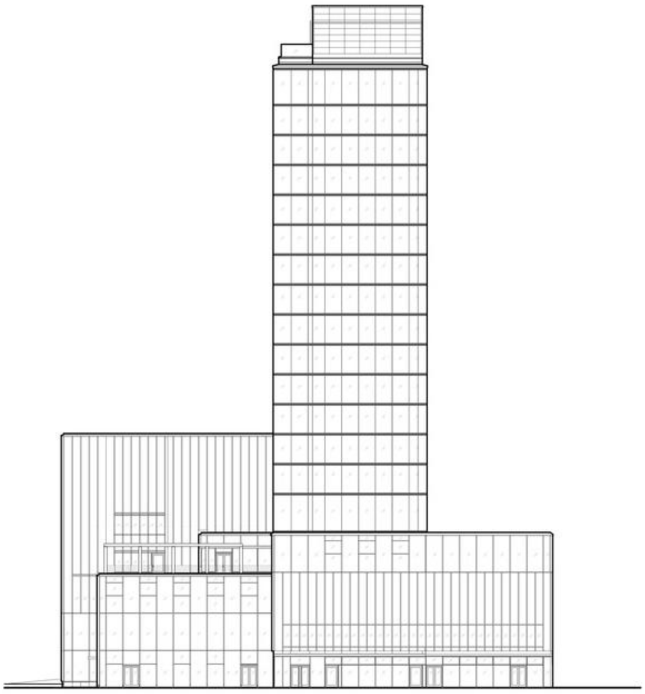
Annex 15: Nineteenth floor. Provided by White



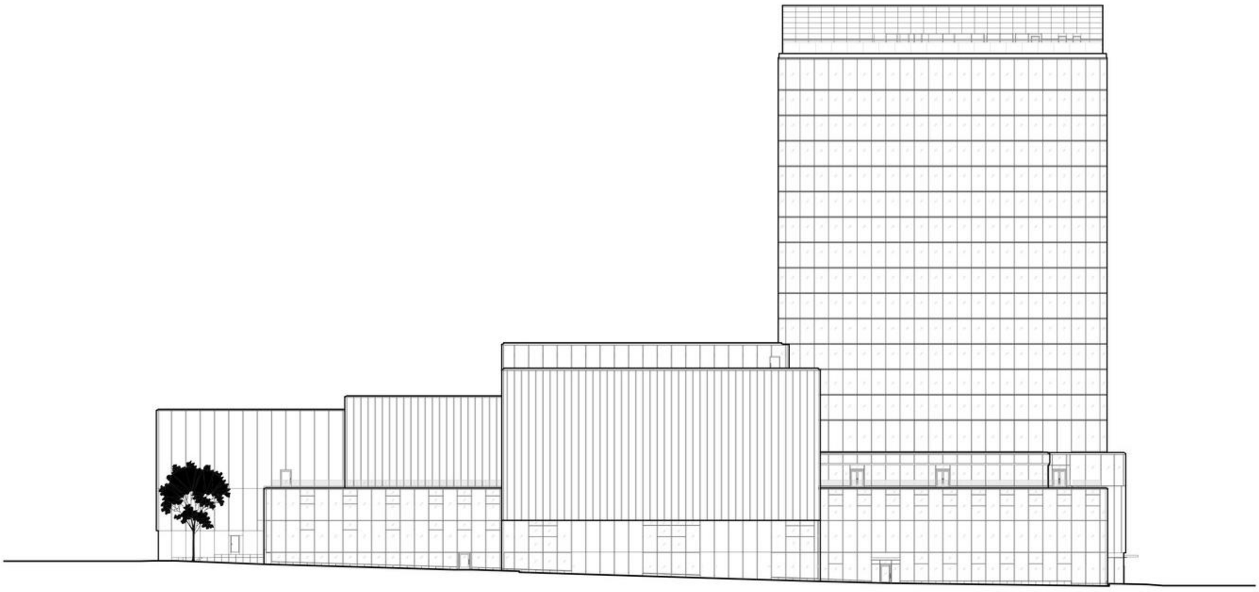
Annex 16: Section aa. Provided by DETAIL magazine



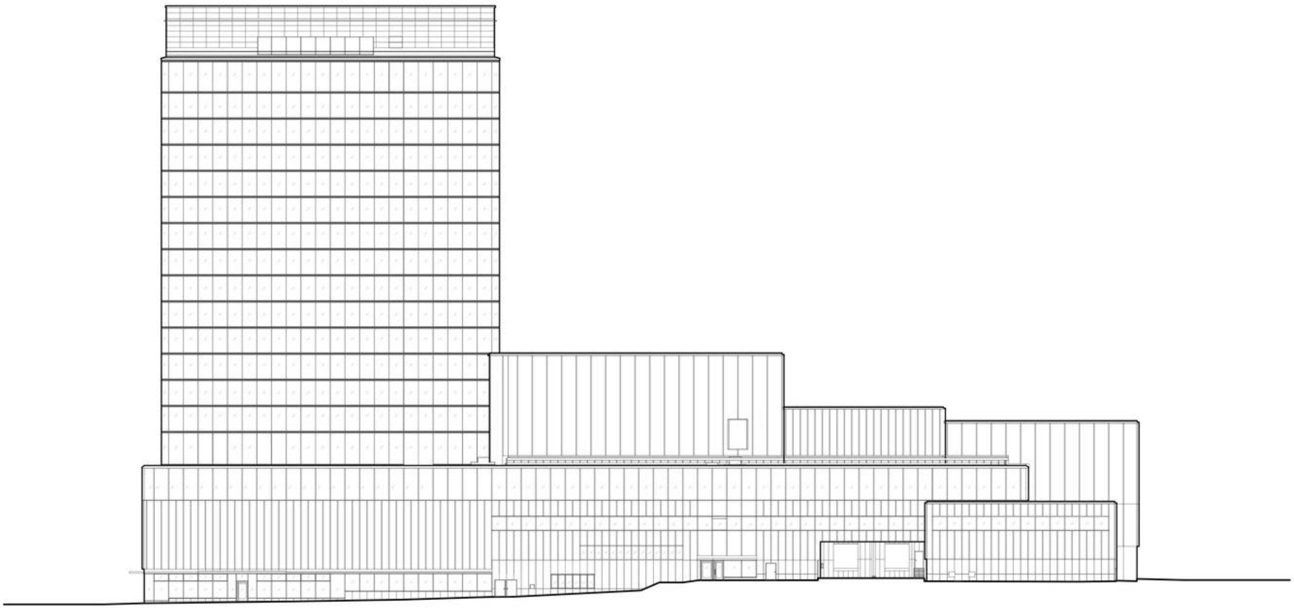
Annex 17: Section perpendicular to section aa. Provided by White



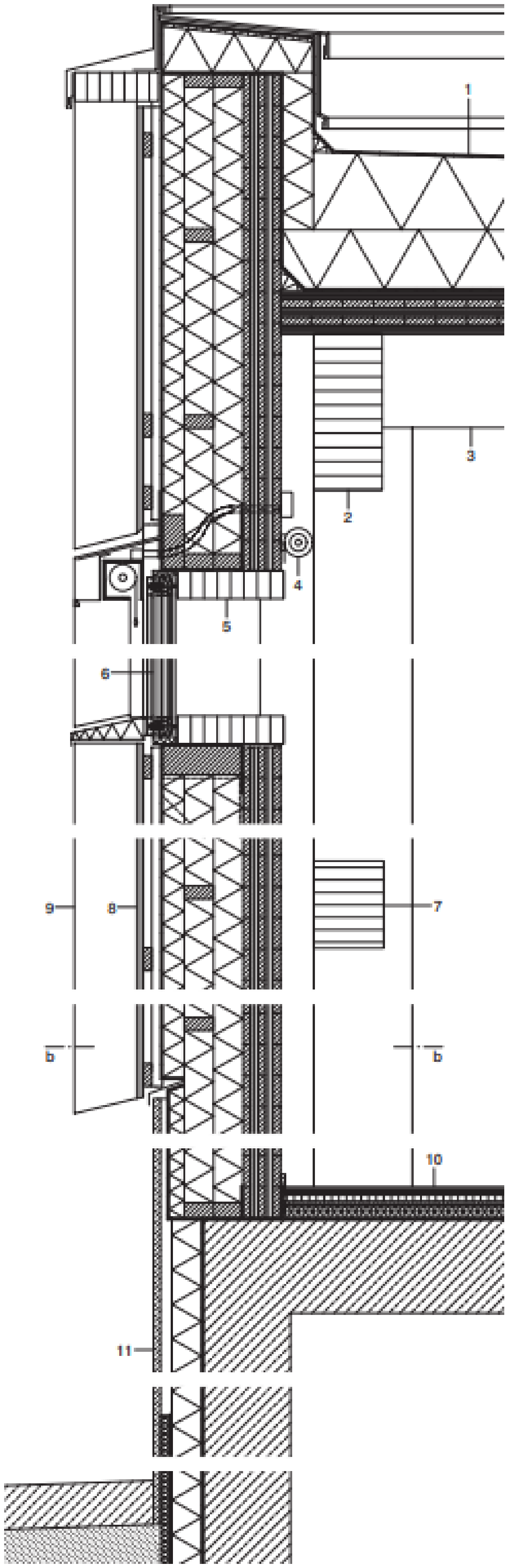
Annex 18: South facade. Provided by White

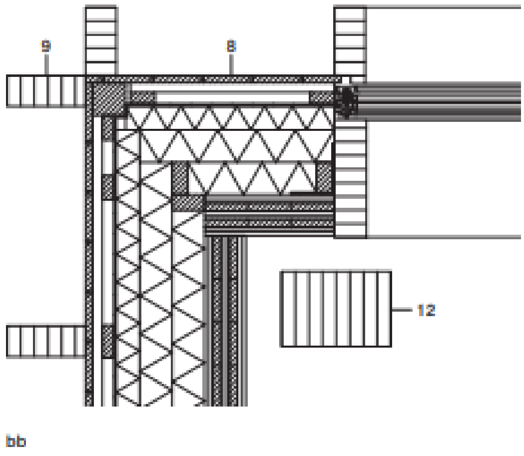


Annex 19: West facade. Provided by White



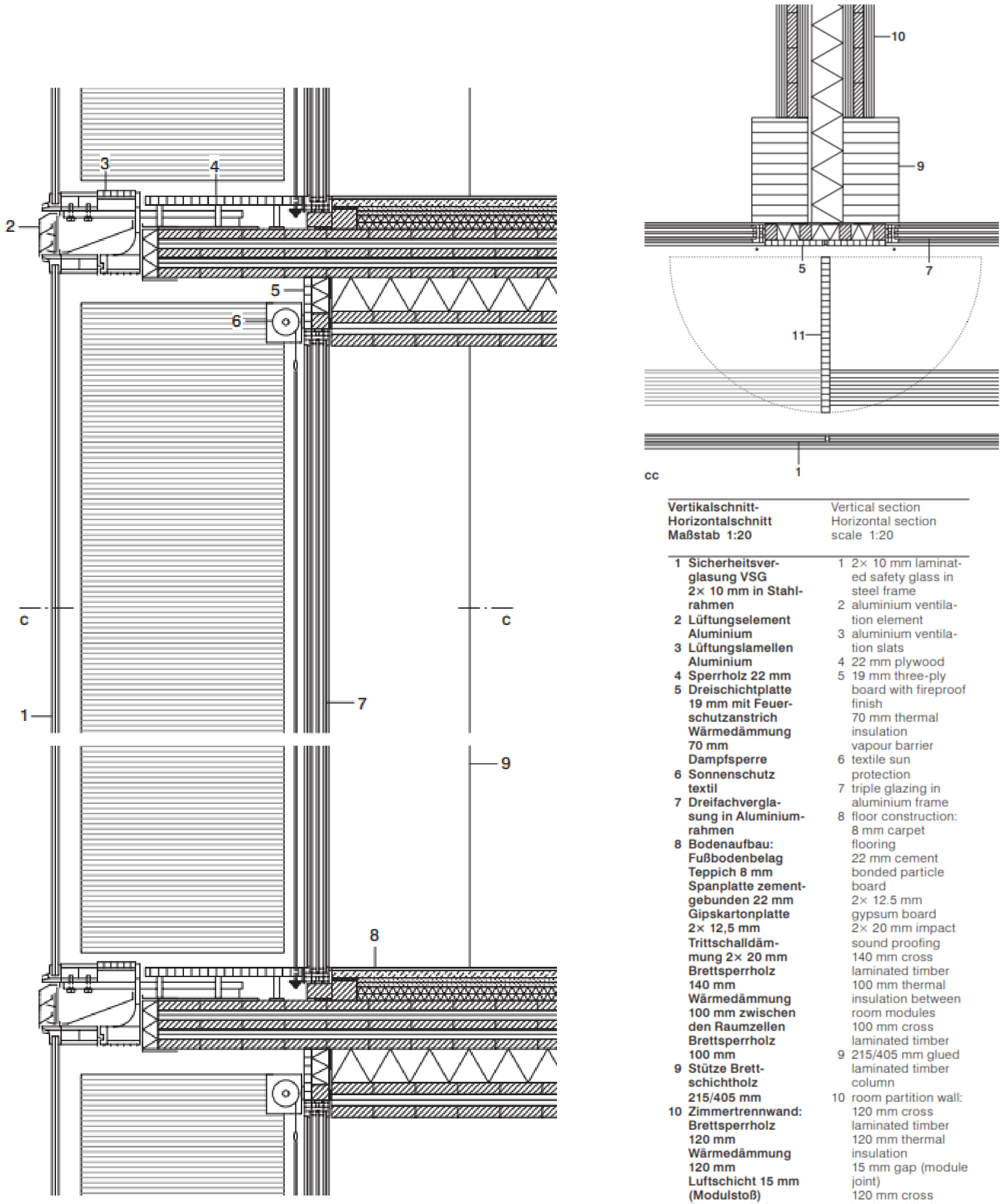
Annex 20: East facade. Provided by White





Vertikalschnitt • Horizontalschnitt Maßstab 1:20	Vertical section • Horizontal section scale 1:20
1 Dachaufbau: Abdichtung Bitumen Gefälledämmung EPS 250–50 mm Wämedämmung EPS 180 mm Dampfsperre Brettsperrholz Fichte 160 mm	1 roof construction: bituminous sealant; 250–50 mm EPS insulation to falls 180 mm EPS thermal insulation vapour barrier; 160 mm spruce cross laminated timber
2 Träger Brettschichtholz Fichte 500/220 mm	2 500/220 mm spruce glued laminated timber beam
3 Unterzug Brettschichtholz Fichte 300/350 mm	3 300/350 mm spruce glued laminated timber downstand beam
4 Sonnenschutz innenliegend	4 interior sun protection
5 Brettschichtholz 90/345 mm	5 90/345 mm glued laminated timber
6 Dreifachisolierverglasung in Aluminiumrahmen	6 triple insulation glazing in aluminium frame
7 Riegel Brettschichtholz Fichte 225/280 mm	7 225/280 mm spruce glued laminated timber crossbar
8 Fassadenaufbau: Holzschalung Fichte druckimprägniert 22/145 mm Lattung 28/70 mm Konterlattung/Hinterlüftung 34 mm Dampfbremse Holzständerkonstruktion, dazwischen Wärmedämmung dreilagig 260 mm Brettsperrholz Fichte 120 mm	8 facade construction: 22/145 mm spruce cladding, pressure treated 28/70 mm battens 34 mm counterbattens/back ventilation; vapour barrier timber frame construction 260 mm inlaid 3-ply thermal insulation 120 mm spruce cross laminated timber
9 Lamelle Brettschichtholz 90/225 mm	9 90/225 mm glued laminated timber slat
10 Bodenaufbau: Dielenboden Fichte 25 mm Spanplatte 22 mm Gipskartonplatte 12,5 mm Trittschalldämmung 2× 20 mm PE-Folie Stahlbeton 300 mm	10 floor construction: 25 mm spruce floor boards 22 mm particle board 12.5 mm gypsum board 2× 20 mm impact soundproofing PE foil 300 mm reinforced concrete
11 Wandaufbau Sockel: Fassadenbekleidung Terrazzoplatte 20 mm Hinterlüftung Wärmedämmung 100 mm Dampfsperre Stahlbeton 280 mm	11 wall construction, pedestal: 20 mm terrazzo panel facade cladding; back ventilation 100 mm thermal insulation vapour barrier 280 mm reinforced concrete
12 Stütze Brettschichtholz 320/220 mm	12 320/220 mm glued laminated timber column

Annex 21: Vertical and horizontal detailed section of cultural centre. Provided by DETAIL magazine



Vertikalschnitt Horizontalschnitt Maßstab 1:20	Vertical section Horizontal section scale 1:20
1 Sicherheitsverglasung VSG 2× 10 mm in Stahlrahmen	1 2× 10 mm laminated safety glass in steel frame
2 Lüftungselement Aluminium	2 aluminium ventilation element
3 Lüftungslamellen Aluminium	3 aluminium ventilation slats
4 Sperrholz 22 mm	4 22 mm plywood
5 Dreischichtplatte 19 mm mit Feuerschutzanstrich Wärmedämmung 70 mm Dampfsperre	5 19 mm three-ply board with fireproof finish 70 mm thermal insulation vapour barrier
6 Sonnenschutz textil	6 textile sun protection
7 Dreifachverglasung in Aluminiumrahmen	7 triple glazing in aluminium frame
8 Bodenaufbau: Fußbodenbelag Teppich 8 mm Spanplatte zementgebunden 22 mm Gipskartonplatte 2× 12,5 mm Trittschalldämmung 2× 20 mm Brettsperrholz 140 mm Wärmedämmung 100 mm zwischen den Raumzellen Brettsperrholz 100 mm	8 floor construction: 8 mm carpet flooring 22 mm cement bonded particle board 2× 12.5 mm gypsum board 2× 20 mm impact sound proofing 140 mm cross laminated timber 100 mm thermal insulation between room modules 100 mm cross laminated timber
9 Stütze Brettschichtholz 215/405 mm	9 215/405 mm glued laminated timber column
10 Zimmertrennwand: Brettsperrholz 120 mm Wärmedämmung 120 mm Luftschicht 15 mm (Modulstoß) Brettsperrholz 120 mm	10 room partition wall: 120 mm cross laminated timber 120 mm thermal insulation 15 mm gap (module joint) 120 mm cross laminated timber
11 Verschattungselement Mehrschichtplatte 32 mm	11 32 mm plywood shading element

Annex 22: Vertical and horizontal detailed section of hotel rooms. Provided by DETAIL magazine

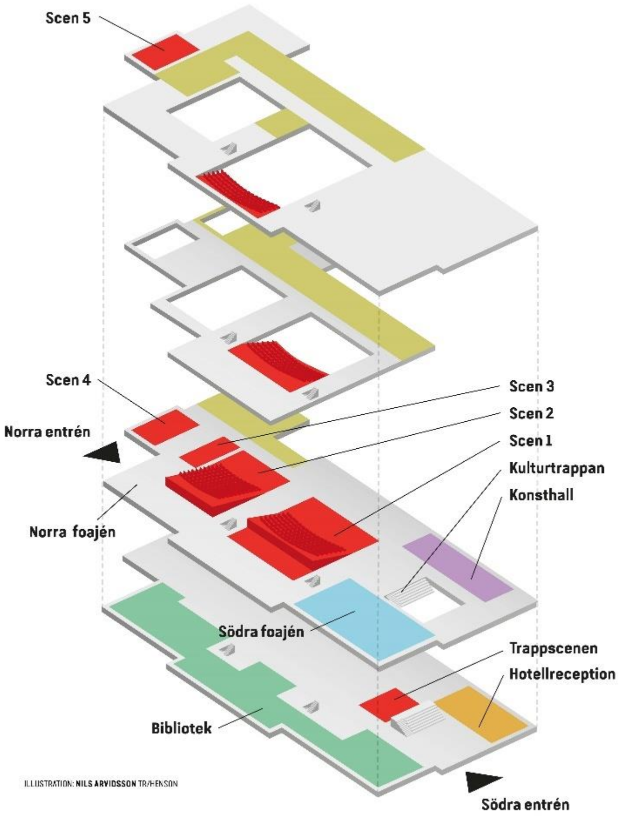
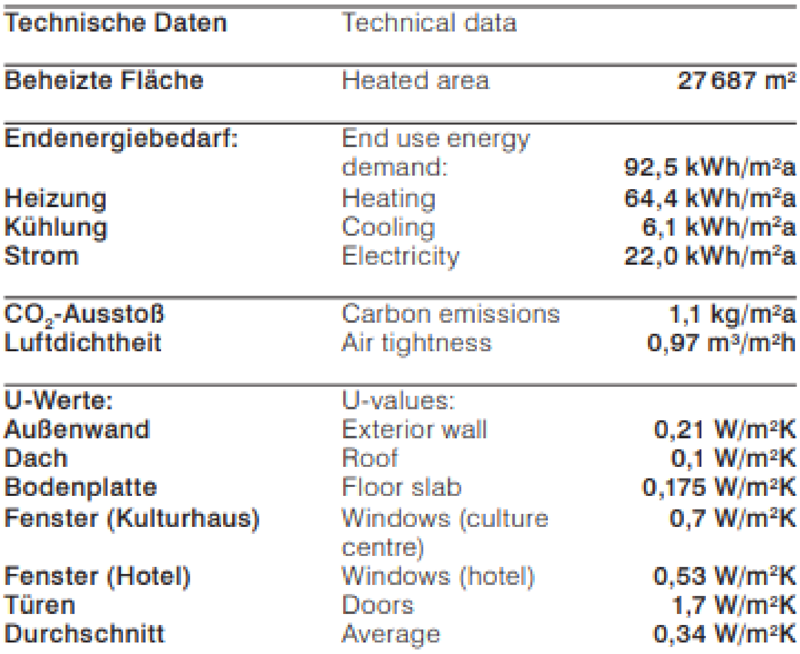


ILLUSTRATION: NILS ARVIDSSON TR/HENSON

Annex 23: Decomposed structure describing the different level. Provided by Sara Kulturhus



Technische Daten	Technical data	
Beheizte Fläche	Heated area	27 687 m²
Endenergiebedarf:	End use energy demand:	92,5 kWh/m²a
Heizung	Heating	64,4 kWh/m²a
Kühlung	Cooling	6,1 kWh/m²a
Strom	Electricity	22,0 kWh/m²a
CO_2-Ausstoß	Carbon emissions	1,1 kg/m²a
Luftdichtheit	Air tightness	0,97 m³/m²h
U-Werte:	U-values:	
Außenwand	Exterior wall	0,21 W/m²K
Dach	Roof	0,1 W/m²K
Bodenplatte	Floor slab	0,175 W/m²K
Fenster (Kulturhaus)	Windows (culture centre)	0,7 W/m²K
Fenster (Hotel)	Windows (hotel)	0,53 W/m²K
Türen	Doors	1,7 W/m²K
Durchschnitt	Average	0,34 W/m²K

Annex 24: Technical data. Provided by DETAIL magazine

9.3. Interview with Robert Schmitz

Question 1: Is it possible to provide 3d model and composition of all the elements of the building. In order to use a LCA software and calculate the environmental impact of building. I also need to know the number of users and the heated volume of the building.

Answer: The LCA was carried out by the contractor, HENT, so you would have to contact them to get the information about it. The 3d model is too heavy so I cannot send it but you can find precise details, plans and section in the DETAIL magazine describing the composition of walls and connections.

Question 2: What made you decide that you wanted to build your building with CLT? What was your knowledge about wood construction?

Answer: Sweden is already large established in wood construction. Long tradition of working with timber. 94, Sweden embarked in the EU, they changed in the fire safety regulations, contractors were then allowed to build multi-storey buildings with a timber structure. Then, more and more complex of building made of CLT. Strong knowledge in prefab, so it was easy to go from that to use timber. People safety first and not the building safety first, the goal was just that the building could still perform and withstand within a certain amount of time.

Question 3: Do you think that it possible to reach such good carbon budget with the same kind of structure but in another context? Like in Belgium for example? A country with less resources in wood? You said in an interview: "We think it could probably go twice around the world and still be carbon neutral", how?

Answer: Yes, it is possible. The issue is more about, how is it transport to the site of the project. Wood would still be low emissions. The transport would have a bigger part in the emissions, but you could use biofuel shipping to reduce the carbon emissions. For the case study of Sara building, it was very local. It Could be interesting to see what happened if you place the culture center in Belgium and see the impact of the transport on the building carbon emissions.

Question 4: What difficulties did you encounter during the project? Was it more complicated than a conventional build?

Answer: It was a pilot project or research project put in real life. We had to make in real life what we studied in theory. We must convince the client at first because it was the first time such a high building was constructed in wood; we could prove it in theory, but nobody did that before. We had to make very detailed analysis and projection to prove the feasibility. We worked closely with engineers in order to make it feasible.

But HENT, the contractors already worked on another high timber building Mjøstårnet (the highest timber building), so the workmen already had a good experience of working with wood.

Question 5: How have you managed to reduce the energy consumption of the use of the building?

Answer: The project is powered by the river, with hydro power, and district heating. Skellefteå is 100% clean energy provider so the energy that powers the building is green.

Question 6: I looked at the carbon budget of the building, and I was wondering why you did not take into account the end of life of the building?

Answer: We calculated the carbon footprint for 50 years of use, but we don’t know what is going to happen after that. Therefore, we did not take it into account. You could say that you would dismantle the building, and it would be somewhere else in 50 years. Everything is prefab, so it could still be used for a future life.

Question 7: Do you know what is the expected amount of user in the building?

Answer: 1500 people could be expected in the theatre, and 1000 people in the hotel. So, in total about 2000-2500 people at the same time.