TOWARDS LOW CARBON BUILDINGS

A CASE STUDY IN SWEDEN

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Master thesis in Energy-efficient and Environmental Buildings
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Lund University

Lund University, with eight faculties, several research centres, and specialized institutes, is the largest research and higher education establishment in Scandinavia. The main part of the University is situated in the small city of Lund, which has about 112 000 inhabitants. Some departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280-degree programmes and 2 300 subject courses offered by 63 departments.

Master Programme in Energy-efficient and Environmental Building Design

This international programme provides knowledge, skills, and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals who will significantly contribute to and influence the design, building, or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants' behaviour and needs, their health and comfort, as well as the overall economy.

The degree project is the final part of the master's programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Summary

This study evaluates the carbon emission performance of a newly constructed building in Helsingborg, a Scandinavian city that aims to achieve carbon neutrality by 2030. Two distinct life cycle assessment (LCA) calculations are used, one cradle-to-cradle using the ZEB-Complete method and one including only production and construction stages based on a joint study between KTH and Boverket. Both LCA results indicate that the building emits 35 kg CO_2e/m^2 less than the average office building in Sweden but falls short of reaching carbon neutrality.

The research emphasizes the importance of building materials as the primary contributor to carbon emissions throughout the life-cycle of a building, superseding the impact of operational energy. To attain carbon neutrality, reducing emissions from building materials is essential. According to the study, conventional construction materials are unlikely to contribute to carbon reduction, necessitating a swift shift in practices.

While efforts are being made to reduce operational energy emissions by developing carbon capture and storage (CCS) technology, the research highlights the significance of addressing carbon emissions from building materials. The results demonstrate the potential for substantial emission reductions when biobased building materials are utilized.

In addition, various climate compensation measures were implemented in this thesis to assess a newly constructed building's potential for carbon neutrality. The effectiveness of multiple measures, such as the substitution of insulation layers with straw, the replacement of columns, slabs, core walls, stairs, and beams with cross-laminated timber (CLT) panels, the conversion of wood into biochar, and the implementation of a green roof combined with solar panels on the entire roof area, was examined. Despite the extensive implementation of these measures, the most favourable scenario obtained an emissions level of 28 kg CO_2/m^2, demonstrating remarkable proximity to the carbon neutrality objective. However, it is essential to observe that the potential for emission reduction is substantially greater when a building is designed to attain carbon neutrality.

The research acknowledges the complexities of accounting for biogenic carbon, biochar, and end-of-life scenarios in carbon emissions assessments. Avoiding double counting and assessing carbon release uncertainties can be challenging. To accurately convey the complex dynamics associated with these factors, it is necessary to take the timing of carbon emissions released into account. Researchers can contribute to advancing the understanding and accurate accounting of carbon emissions throughout the life-cycle of buildings by developing comprehensive and transparent methodologies.

The research identifies the dominance of financial factors in construction projects as an impediment to environmental concerns. By instituting carbon emission thresholds for building materials, the industry can transition toward selecting materials with smaller carbon footprints, mitigating their effect on climate change. Nonetheless, this transition requires budgetary adjustments and a broader transformation within the construction industry, which includes raising awareness, promoting education, and encouraging collaboration. By adopting these adjustments, the construction industry can significantly contribute to reducing carbon emissions and promoting sustainable development.

In addition, the study emphasizes the need to expand the system boundaries when evaluating the carbon neutrality of buildings, considering transportation, infrastructure, and the impact on the surrounding environment as a whole. The environmental impacts resulting from buildings' locations and potential trade-offs with the citywide surrounding should be examined.

According to the study, to obtain an extensive comprehension of the environmental impact of buildings, it is essential to consider system boundaries and external dependencies.

Abstract

This study comprehensively evaluated the global warming potential of an office building in a newly built Scandinavian neighbourhood seeking to reach sustainability. The primary objective of the research was to support the city authorities of Helsingborg by providing valuable insights into actual carbon emissions at the building level and proposing measures to minimize these emissions to achieve climate neutrality by 2030.

Life cycle assessment (LCA) calculations, based on the ZEB (Zero-Emission Building) complete method, were utilized to accomplish these aims. The results were then compared to those of other recently built office buildings with comparable construction specifications. Thereafter, the current gap to carbon neutrality and possible potential for improvement were estimated.

The study showed that, compared to similar buildings, the case study building performs better than the average value in carbon emission. With a comprehensive calculation and quantification to assess the climate impact of the study building, the gap to carbon neutrality of this building is about 500 kg CO_2e/m^2 with the average European emission value for electricity, and about 400 kg CO_2e/m^2 with the Helsingborg municipality emission value for energy. With the extensive implementation of these measures, the most favourable scenario demonstrated remarkable proximity to the carbon neutrality objective. However, it is essential to observe that the potential for emission reduction is substantially greater when a building is designed to attain carbon neutrality. Building materials contribute significantly to carbon emissions, exceeding the impact of operational energy consumption. A rapid transition away from conventional building materials becomes essential to achieve carbon neutrality.

In addition, carbon emissions can be effectively reduced by modifying building systems and materials, especially using biobased materials. However, additional research is necessary to address the complexities of accounting for biogenic carbon, end-of-life scenarios, and the potential difficulties of double counting negative carbon emissions.

This study concludes with essential considerations for attaining carbon neutrality in future construction projects. The results highlight the importance of prioritizing sustainable building materials and investigating carbon capture and storage technologies, such as biogenic carbon and biochar. Ultimately, the construction industry can effectively contribute to carbon neutrality objectives by placing environmental impact alongside financial concerns. Obtaining carbon neutrality in the building industry necessitates a multifaceted strategy that incorporates energy efficiency, low-carbon materials, and sustainable urban planning while taking into account the broader environmental context.

Preface

This study concludes our two-year studies in a master's program called “Energy-efficient and environmental building design” at Lund University, based on the Helsingborg campus in Sweden. It was conducted during the spring semester of 2023.

Acknowledgement

We want to express our profound gratitude to our supervisor, Ricardo Bernardo, for his valuable assistance and unwavering availability in resolving doubts and issues encountered along the way. His extensive consultation and thorough review, which sometimes extended beyond working hours, have been instrumental in the successful completion of this thesis.

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In addition, we would like to show our gratitude to Stora Enso for letting us use their data related to CLT calculation.

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I wish to extend my gratitude to my parents, family, and friends for their unrelenting support and unwavering belief in my ability to complete my master's degree and successfully culminate my studies with a thesis. I would like to express my profound appreciation to Lund University for granting me the opportunity to pursue these courses with the aid of a partially sponsored scholarship. Additionally, I would like to extend my sincerest thanks to my thesis partner, whose diligence and perseverance greatly contributed to the successful outcome of our collaboration.

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I would like to thank my wife and daughter for their understanding and support over the past two years. Time spent with loved ones is priceless, and it is hard to sacrifice it when study and work come to steal it.

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Lastly, thank you, Tuan, for your seriousness and rigour at work, but more importantly, your light spirit, smile, and kindness.

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Terminology and Abbreviations

A_{temp}	Heated floor area
BIM	Building Information Modelling
BTA	Gross floor space/area
CLT	Cross-laminated-timber
CO_2e	Carbon Dioxide equivalent
DH	District Heating
DHW	Domestic Hot Water
EBC	The European Biochar Certificate
EGA	Erik Giudice Architecture
EPD	Environmental Product Declaration
GHG	Green House Gases
GW	Glass Wool
GWP	Global Warming Potential
kg CO_2e	Kilogram of Carbon Dioxide equivalent
KTH	Royal Institute of Technology based in Stockholm
LCA	Life Cycle Assessment
LOA	Rentable Area
PV	Photovoltaic
SGBC	Swedish Green Building Council
SP	Solar Panel
UN	United Nations
ZEB	Zero Emission Building

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Terms and definitions

Ancillary (to something)

Providing necessary support to the main work or activities of an organization (Oxford University Press, 2023)

Biogenic carbon

Biogenic carbon emissions are carbon that originates from biological sources such as plants, trees, and soil (Harris et al., 2017)

Carbon sink

Natural repositories absorb carbon, thereby removing it from the atmosphere and offsetting carbon emissions. It mainly comprises the sea, forests, and soil (EEA Glossary, n.d.).

Climate action

Swedish Green Building Council terminology for initiatives that reduce, avoid, or limit greenhouse gas emissions.

Climate compensation

A method performed outside of the production system that avoids, decreases, or eliminates the appropriate amount of greenhouse gas emissions to offset all or part of the climatic effect.

Climate-neutral

Not influence the greenhouse effect (also known as being zero carbon or having a net zero climatic impact).

Embodied environmental impact

Overall environmental effect of sourcing, shipping, processing, and manufacturing of all raw materials, fuels, and objects used to create a good or service (EESC Glossaries, n.d.)

Global warming potential

Global warming potential is defined as the cumulative radiative forcing, both direct and indirect effects, over a specified time horizon resulting from the emission of a unit mass of gas related to some reference gas (IPCC, 1996).

Life Cycle Assessment

Life cycle assessment is the compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle" (ISO 14040:2006, n.d.).

Renewable energy sources

Renewable energy is energy derived from natural sources that are replenished at a higher rate than they are consumed. Sunlight and wind, for example, are such sources that are constantly being replenished (United Nations, n.d.).

1 Introduction

1.1 Background

Global warming and climate change are two of the most critical global challenges of our day, with the consequences becoming increasingly apparent in recent years. Between 2010 and 2019, average annual global greenhouse gas emissions reached their most significant levels in human history (IPCC, 2022a). Rising temperatures, melting ice caps, increasing sea levels, and severe weather events have resulted from the alarming increase in emissions.

Climate change has already impacted the planet, with certain regions experiencing droughts, floods, wildfires, and other natural disasters. Such catastrophes are frequently disastrous, causing relocation, food shortages, and the spread of illnesses. Limiting global warming to 1.5°C by IPCC is out of reach unless greenhouse gas emissions are reduced rapidly and significantly across all sectors (IPCC, 2022b).

The Sustainable Development Goals (SDGs, 2015), Paris Agreement (United Nations, 2015), and other frameworks have been established by the United Nations to address environmental impacts and reduce emissions. The European Green Deal seeks to attain carbon neutrality by 2050, with net greenhouse gas emissions reduced by 55 % by 2030 (European Commission, 2019). For a sustainable economy, the initiative seeks to strike a balance between emissions reduction, economic development, and job creation.

Some governments are also acting to combat climate change. The Swedish government, for example, has set a target of reaching carbon neutrality by 2045, with certain Swedish cities, notably Helsingborg, aiming to do it by 2030 (Emina Pasic, 2022). Cities are taking various actions to reduce carbon emissions, including boosting renewable energy use, supporting green transportation, and applying circular economy ideas.

1.2 Oceanhamnen

Oceanhamnen (Figure 1) is a new Scandinavian neighbourhood constructed on reclaimed harbour territory behind Helsingborg Central Station. The city has designed this area with an emphasis on sustainability and seeks to achieve climate neutrality by 2030, which is a more ambitious goal than current building regulations and practices (Helsingborg municipality, 2017). This level of engagement toward carbon neutrality presents a significant challenge for the still-in-development district of Oceanhamnen to create fair and relevant criteria and validate if such ambitious goals are achievable.

Figure 1, Oceanhamnen neighbourhood at Helsingborg

The challenge becomes even more pressing in light of the impending construction of new district quarters. These future development phases will include buildings and additional landfill, public areas, squares, and marinas, thus making it essential to adopt a scientific approach to requirements, calculation methodology, decision-making, and follow-up procedures for climate-neutral buildings.

1.3 Office building – Prisma

This thesis focuses on the life cycle assessment of Prisma, an office building built in the first phase of construction of the Oceanhamnen district, with Wihlborgs as the main contractor of this building. Designed by

Erik Giudice Architects, Prisma boasts an innovative design inspired by the prominent cities of Europe. Strategically positioned in the forefront of Oceanhamnen, Prisma offers convenient access to various modes of public transportation, including trains, buses, and boats, within walking distance of Helsingborg C. Prisma has a total usable area of 16 711 m^2, with eight-level and a basement for car parking and technical rooms. The construction type of Prisma is prefabricated steel beams and columns, designed by Scandinavian Weld Tech (SWT), and prefabricated slabs and roof structures, designed by COWI company. Additionally, the building has been certified with a Gold grade according to Miljöbyggnad standards (Wihlborgs, 2021). According to their calculation, the building's primary energy was 54 kWh/(m^2.year), while BBR26's requirement is 80 kWh/(m^2.year) (BBR26, 2018). In addition, Miljöbyggnad's requirement for specific energy use for gold level is 52 kWh/m^2, and the building's calculation achieved 43 kWh/m^2 (Miljöbyggnad 3.0, 2018).

1.4 Definition of carbon-neutral buildings

There are a variety of strategies and definitions for achieving carbon neutrality in building design, with different countries and organizations adopting their approaches. For example, Canada has its "Zero Carbon" framework, while Sweden has its "NollCO_2" definition. Both of these aims to achieve a state in which buildings, during their life cycle, balance the carbon emissions with climate payback measures that mitigate such impacts (Satola et al., 2021). Additionally, Norway has its "Zero Emission Buildings" strategy, which promotes very energy-efficient building design with a large share of local renewable energy production (Razna & Tasnia Aive, 2022).

According to Razna and Trasnia Aive, the impact of these strategies on building design varies significantly depending on which definition is used (Razna & Tasnia Aive, 2022). Some strategies may involve only the purchase of carbon credits, while others may require a much more energy-efficient building design with a significant share of renewable energy production. Achieving such ambitious goals on-site can be extremely difficult and may require innovative design solutions and cutting-edge technologies.

1.5 Objectives

The thesis includes a detailed analysis of the carbon emissions associated with one office building during the first construction phase in Oceanhamnen. It includes the emissions associated with the construction materials, processes, and operational energy use in the entire building life cycle. The result of this analysis was compared to the carbon neutrality target to determine the extent of the gap between the actual carbon footprint of the construction and the target.

Furthermore, the thesis work investigated design alternatives for reducing greenhouse gas emissions in the case-study building.

The study will attempt to answer the following questions:

- What is the performance comparison of the building under investigation and other buildings built with similar regulation requirements?
- What is the carbon emission gap to reach carbon neutrality?
- Which learning outcomes from this case study can be used for the following construction phases regarding requirements and design guidelines?

1.6 Boundaries (limitations)

Due to time constraints, this study will focus on analyzing the carbon emissions of only one office building constructed in the first phase of Oceanhamnen. As a result, the findings may not be representative of the entire district. However, the study serves as a starting point for conducting a more in-depth life cycle assessment during the design of future construction stages of the neighbourhood.

This thesis will be exclusively concerned with the environmental impact of the investigated building, and will therefore employ the Life Cycle Assessment (LCA) methodology. Life Cycle Cost (LCC) and other economic considerations are important factors in the decision-making process for sustainable products and systems; however, they will not be included in this thesis as the objective is to provide a comprehensive understanding of the environmental impact throughout the building's entire life cycle.

Life Cycle Assessment (LCA) is used to evaluate the environmental impact of buildings, mainly through embodied and operational CO_2e emissions under the Global Warming Potential (GWP) indicator. However, a comprehensive LCA should consider other environmental factors like toxicity, air quality, and resource depletion. This study only focused on GWP and did not provide an optimal design option for certifications due to geographical factors. The study also did not consider other factors like Indoor Environmental Quality (IEQ), daylight assessments, and ventilation system design. Only PV panels were considered for renewable energy integration, and social or ecological issues were not addressed. More research is needed to examine sustainability in the construction sector and address these issues.

1.7 Disposition

The report commences with a comprehensive introductory section that sets the stage for the ensuing discussion. This section outlines the topic under investigation, provides relevant background information, and establishes the problem statement that the research seeks to address. Additionally, the introduction presents the research questions, aims, and objectives that guide the study.

Following the introduction, the report describes the methodology employed to achieve the research aims. This section outlines the research design used, including the theoretical framework underpinning the study. It also details the empirical research conducted to gather data and insights on the subject matter.

The results section of the report details the findings that were obtained during the study. This section presents the data gathered and analysed and describes the key patterns, themes, and trends that emerged from the data. The results section also provides an objective assessment of the strengths and limitations of the research.

The report's discussion section reflects on some of the key points, challenges, and contradictions encountered during the research process. This section provides an opportunity to explore the findings' implications and consider their broader significance for the subject area under investigation.

Finally, the conclusion presents the most significant findings and implications derived from the study. It summarizes the main points of the report and provides recommendations for future research in the field. Overall, the report provides a rigorous and comprehensive analysis of the subject matter and contributes to our understanding of this important area of research.

1.8 Contribution

Throughout this study, both authors, Victor-Antoine Delorme, and Huynh Tuan Tran, were actively involved in all aspects of the research. It included collaborating closely to handle and analyse data and information and conducting life cycle assessment (LCA) calculations. Together, they thoroughly searched for relevant literature and information on the assessment certification and carbon emissions calculations required for the study.

Victor-Antoine Delorme took the lead in conducting calculations related to the new options for the building that would help to reduce carbon emissions. At the same time, Tuan Huynh Tran was primarily responsible for data handling and delving into the building information in detail to obtain the most accurate and realistic data possible. All calculations and results were agreed upon by both authors, who collaborated closely to ensure the study was conducted rigorously and objectively.

Furthermore, the two authors divided the report writing process equally, with each author taking responsibility for drafting specific chapters. Tuan Huynh Tran was responsible for structuring the report, editing the text, and creating illustrations, while Victor-Antoine Delorme handled the figures, tables, and finalization process. The authors worked together closely throughout the writing process, ensuring that the report was cohesive and effectively communicated the study's findings.

In the final stages of the study, both authors analysed the results and drew conclusions based on their discussions. They critically assessed the findings and identified the key implications and recommendations for future research in the field. Overall, the collaborative approach adopted by the authors ensured that the study was conducted thoroughly and rigorously and that the findings were effectively communicated to the reader.

2 Literature review

2.1 Policies and framework

According to the European Green Deal, the European Union aims to achieve climate neutrality by 2050 (European Commission, 2019). It means that the EU will have a net-zero greenhouse gas emissions balance, which requires reducing emissions to the extent possible and offsetting any remaining emissions through carbon removal or sequestration. The Green Deal also includes a target to reduce EU greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels (European Commission, 2019).

Sweden, a state member of the EU, has been at the forefront of climate action and has set ambitious goals to reach carbon neutrality. In 2017, the Swedish parliament adopted a climate law that targets net-zero greenhouse gas emissions by 2045 (United Nations, 2017). This goal is more ambitious than the EU's target, and Sweden aims to achieve it without purchasing carbon credits from other countries.

Sweden has implemented various measures to reach this goal, including investing in renewable energy, expanding public transport, promoting energy-efficient buildings, and introducing a carbon tax. Sweden is also phasing out fossil fuels in transportation and aims to have a fossil-free vehicle fleet by 2030.

Sweden has set a target date of 2045 for achieving net-zero greenhouse gas emissions (United Nations, 2017), while the EU has set a target date of 2050. The nation is making progress toward its objective by investing in renewable energy, energy-efficient buildings, and a carbon price. The establishment of an impartial Climate Policy Council ensures accountability and openness. Additionally, Swedish municipalities have established their carbon neutrality standards, and the Neutral Cities 2030 program, which involves 23 cities and six agencies, began in 2019 (Emina Pasic, 2022).

2.2 Climate impact

Climate change is one of our most significant global challenges, and its impact on the environment and society is becoming increasingly apparent. The release of greenhouse gases, such as carbon dioxide, methane, and nitrous oxide, is the primary driver of climate change. These gases trap heat in the atmosphere, leading to rising temperatures, more frequent extreme weather events, and other negative consequences.

To understand the role that different sectors play in contributing to climate change, it is helpful to distinguish between two types of emissions: embodied emissions and operational emissions. Embodied emissions refer to the greenhouse gas emissions associated with producing and transporting goods and services. For example, the embodied emissions of a building include the emissions from the extraction of raw materials and processing, producing, and transporting the materials to their final destination (Ibn-Mohammed et al., 2013). On the other hand, operational emissions refer to the emissions directly associated with using goods and services. For example, the operational emissions of a building include the emissions from heating, cooling, and lighting, and are often influenced by people's behaviours (Darby et al., 2016).

Both embodied and operational emissions are important to consider when assessing the impact of different sectors on the environment. Based on previous studies, most building constructions focused on lowering operational effects (Ramesh et al., 2010). The building's operational impacts were found to be greater than its embodied impacts. However, recent studies show that embodied emissions can be augmented by the reduction of operational energy, especially in low-energy design. As a result, embodied emissions can account for up to 46% of total building emissions (Anand & Amor, 2017). Furthermore, according to several studies from ZEB Research Centre and SINTEF energy (Graabak & Feilberg, 2011), with the increase of renewable energy production, especially hydropower based, it is strongly indicated that CO_2 emission of electricity will be reduced by 90% towards 2050, and is extrapolated to be zero by 2070 (Dokka, Lien, et al., 2013). Therefore, embodied emission from materials is more of a concern regarding climate-neutral buildings.

Material consumption is the largest contributor to embodied carbon in buildings, with cement and steel utilization increasing by 4% per year from 2000 to 2015 due to construction in swiftly developing economies (IEA, 2018). Concrete, which is the most used for building framing in many countries, with China, India, and South-East Asia are the most considerable contributors, is considered the most significant climate impact material due to large CO_2e emission in the process, along with energy-intensive use and chemical reaction (Miller & Moore, 2020). Innovative composite materials with substantial carbon reduction are being manufactured, but their market share is presently negligible. Biomaterials such as wood, hemp, and fibre are renewable, sustainable, and minimally energy-intensive to produce and process. These materials can contain approximately 50% carbon by dried mass (Breton et al., 2018), but they represent only about 19% of the residential construction industry in Europe. Achieving the objectives of the Paris Agreement and the Sustainable Development Goals (SDGs, 2015) will necessitate significant changes in the production of concrete and cement, as well as in the planning, construction, and management of cities (Lehne & Preston, 2018).

2.3 Carbon neutral definitions

In recent years, the concept of carbon neutrality has received a great deal of attention, particularly in the disciplines of sustainability and climate change. Multiple organizations and institutions have formulated their definitions of carbon neutrality, which can lead to confusion and inconsistency. However, it has been proposed that the most inclusive definition of carbon neutrality considers all emissions generated by a product or process, including indirect or embodied emissions, and offsets them through carbon removal or reduction strategies (Europa, 2019). This method assures that the carbon trace is reduced to zero, resulting in a zero-emissions balance. Such an approach provides a more accurate representation of the environmental impacts of a product or service and prevents the transfer of emissions to other stages of the product's life cycle. To ensure consistency and transparency in reporting and measurement, it is crucial to establish a standard, all-encompassing definition of carbon neutrality that can be applied across various sectors and countries.

Carbon neutrality is an internationally defined and calculated concept with varying definitions and calculations. The NollCO2 definition from the Swedish Green Building Council, the White Arkitekter definition, and the Zero Emission Building (ZEB) definition from the Norwegian Research Institute are three commonly used carbon-neutral definitions in Sweden. Razna and Tasnia Aive have studied these three definitions and concluded that ZEB is the most inclusive carbon-neutral definition, encompassing the greatest carbon emissions throughout a building's life cycle (Razna & Tasnia Aive, 2022).

2.4 KTH study

A team of researchers from KTH completed a study in 2021 using the detailed findings of the commissioned research conducted for the Swedish Housing Agency as part of the Swedish Housing Agencies and the Procurement Authority's government assignment "Assignment to promote reduced climate impact in public procurement of construction, civil engineering, and real estate contracts" to produce reference values for climate impact for new buildings. Based on analyses of nearly seventy buildings' climate impact during construction (modules A1-A5), reference values for the climate impact of apartment buildings, offices, preschools, schools, and single-family homes have been developed. The results indicate a significant variation among building types but provide a solid foundation for developing various limit values in, for instance, procurement or developing the regulatory framework for climate declarations (Malmqvist et al., 2021).

According to Boverket, limit values for climate emissions will be improved gradually from 2027 to 2043 with thorough evaluation per step. Figure 2 shows Boverket’s plan about when and how to put the limit value for climate declaration on buildings.

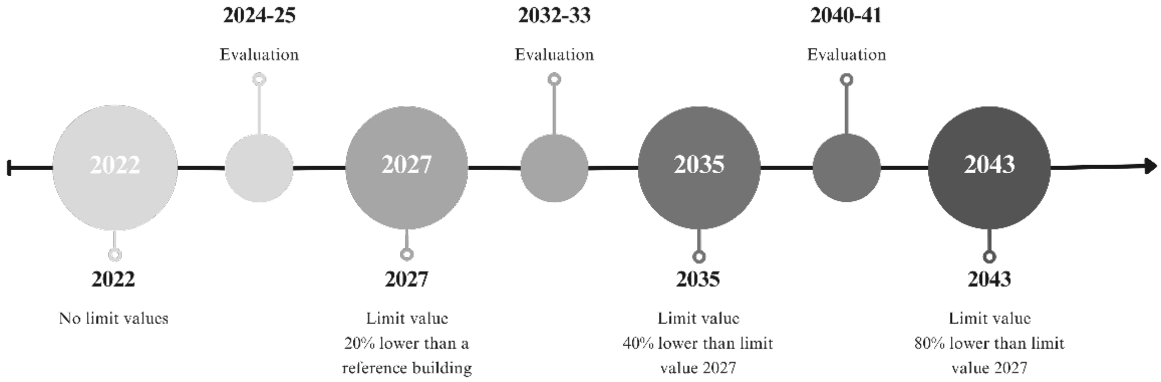

Figure 2, Timeline to put limits value from 2027 to 2043 (Adapted from Boverket, 2019).

Therefore, the KTH study has applied two system limits for 2022 and 2027 for assessment, and the results are shown in Figure 3 for the system limit 2022 and Figure 4 for the system limit 2027.

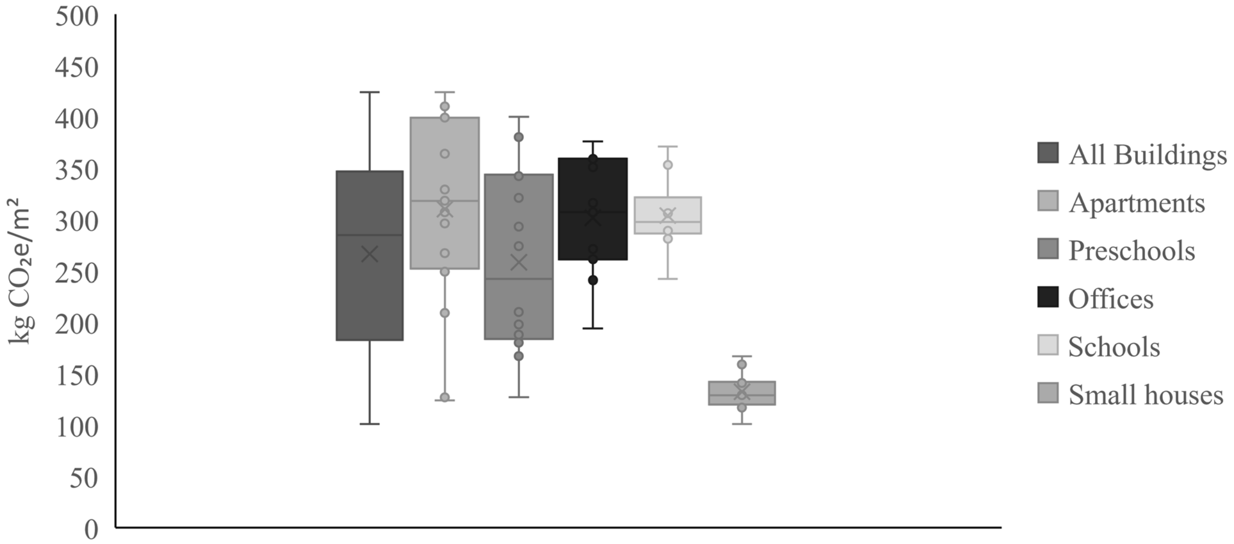

Figure 3, KTH study results about Climate impact module A1-A5 for different building types and all buildings with system limits according to climate declaration for 2022 (Malmqvist et al., 2021).

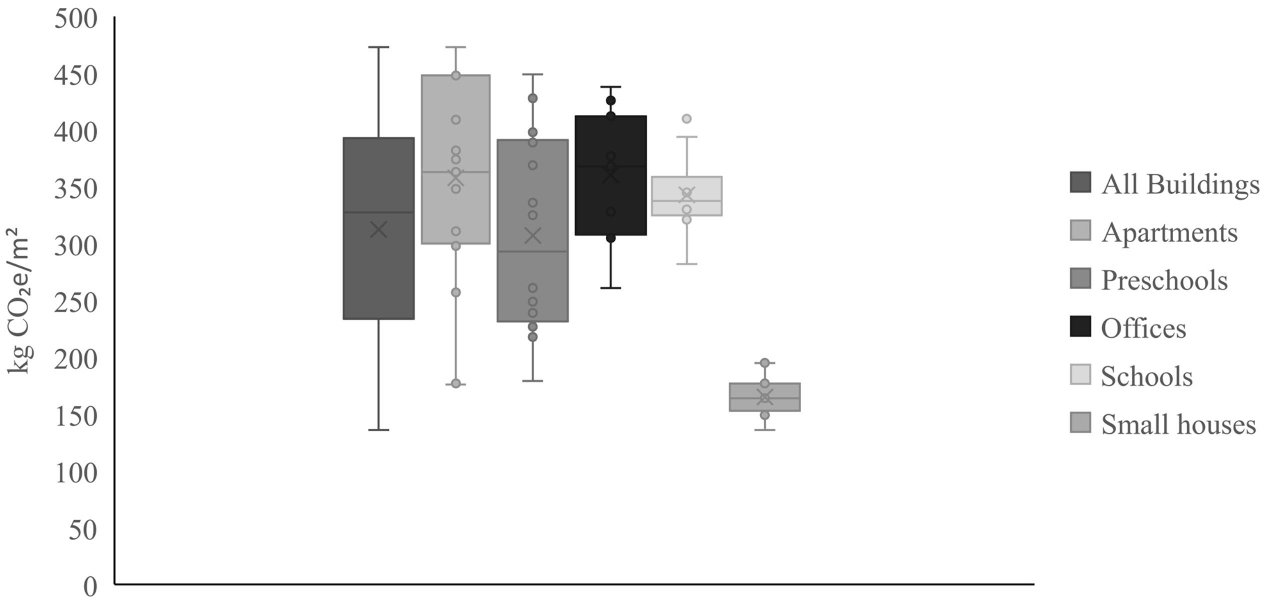

Figure 4, KTH study results about Climate impact module A1-A5 for different building types and all buildings with system limits according to climate declaration for 2027 (Malmqvist et al., 2021).

2.5 Life cycle assessment (LCA)

Life Cycle Assessment (LCA) is an extensively utilized methodological framework for evaluating the environmental impacts of products and services. It is a comprehensive and integrative approach that considers the entire life cycle of a product or service, from basic material extraction to refuse disposal. As environmental concerns develop and businesses strive to reduce their environmental footprint, the significance of life cycle assessment (LCA) increases.

The methodology of an LCA assessment includes four major phases: goal and scope definition, inventory analysis, impact evaluation, and interpretation (As shown in Figure 5). Determining the purpose of the study and the boundaries of the system under investigation constitutes the goal and scope definition phase. In the inventory analysis phase, the inputs and outputs of the system are quantified. The impact assessment phase evaluates the system's environmental impacts, while the interpretation phase interprets the results and communicates them to stakeholders (Hernandez et al., 2019).

In terms of buildings, LCA calculation follows some European standards like EN 15804, which is an essential rule for construction products (EN 15804, 2019), and EN 15978, which is an LCA calculation method for building (NS-EN 15978, 2011). These standards provide a well-established and consistent framework for Environmental Product Declaration (EPDs) and LCA calculation. The details of the four phases of an LCA calculation following European Standards are as follows:

- *Goal and scope*: Defining functional unit, system boundaries, allocations, and assumptions.
- *Inventories (LCI):* Collecting and integrating information regarding the transfer of materials and energy into a variety of products.
- *Impact assessment (LCIA):* Assessing the environmental impacts of various flows of material and energy are assigned to different environmental impact categories.
- *Interpretation:* Interpreting the results from both life cycle inventory analysis and impact assessment.

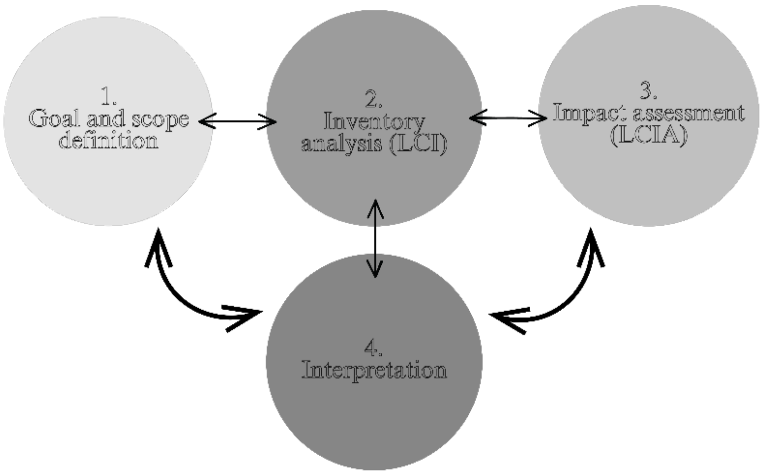

Figure 5, Four major phases of an LCA assessment

In the impact assessment, the process for assessing buildings is divided into four modules A, B, C, and D, with subdivisions in each of them, as shown in Table 1:

Module A1-A3, Product stage: Consists of the extraction and processing of primary materials, the processing of secondary materials, the transportation of materials to the manufacturer, and the production of goods. Waste management and disposal of by-products are included in this procedure.

Module A4-A5, Construction stage: Include emissions from deliveries and vacant reruns. Construction equipment emissions and water and energy use on the construction site. Emissions caused by material loss during transportation and refusal of treatment during construction.

Module B1-B7, Use stage: Considering emission during building usage time. Modules B1 to B5 are related to building structures, B6 is related to emissions of operational energy use, and B7 is associated with emissions of operational water use.

Module C1-C4, End of life stage: These modules are accounted for the treatment process of products after they finish their lifetime. The output of these modules considers demolition, dismantling, sorting, and transportation of waste, its treatment and disposal, and recycling possibility.

Module D, Benefits and loads beyond the system boundary: This module is supplementary information, which aims to provide data on environmental benefits regarding reuse, recycling, and other secondary use.

Table 1, Environmental impact assessment (LCIA) in buildings (BRE global, 2018)

Building life cycle																Supplementary information
Product			Construction		Use stage							End-of-life				Benefits and loads beyond the system boundary
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw materials supply	Transport	Manufacturing	Transport	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction, demolition	Transport	Waste processing	Disposal	Re-use, Recovery, Recycling potential

LCA is a potent tool for evaluating environmental impacts, but its limitations must be considered. One limitation is that LCA is a time-consuming and costly procedure that requires substantial resources and specialized knowledge (Meex et al., 2018). Another limitation is that LCA results can be highly sensitive to the study's underlying assumptions and data, resulting in ambiguous outcomes. Additionally, LCA may not encompass all of a product or service's environmental impacts, especially those that are challenging to quantify.

As environmental concerns continue to grow, life cycle assessment (LCA) is anticipated to play a more prominent role in sustainability assessments. Future directions for LCA research include the development of more standardized and harmonized methods for data collection and analysis, integrating LCA into decision-making processes, and incorporating social and economic impacts into LCA studies. In addition, LCA studies must become more transparent and accessible to stakeholders, such as consumers, policymakers, and industry stakeholders.

2.6 Zero Emission Building definition (ZEB)

Zero Emission Building (ZEB) standards, which are developed by the Norwegian Research Centre on Zero Emission Building and contributed by the works of the International Energy Agency (IEA) and the Energy Performance Building Directive (EPBD), are a comprehensive set of guidelines and performance metrics that define the requirements for a building to emit zero or nearly zero greenhouse gases (BRE global, 2018). These standards typically emphasize, among other factors, energy efficiency, renewable energy production, and low-impact building materials.

The objective of ZEB standards is to create buildings that reduce their environmental impact and provide occupants with healthy and comfortable indoor environments. While ZEB standards can differ by region, climate, and building type, they generally emphasize using eco-friendly materials, energy-efficient systems, and cutting-edge technologies. As the demand for sustainable building practices continues to increase, the significance of ZEB standards will likely grow.

Net zero energy building (net ZEB)

The term 'net zero energy building' (net ZEB) was coined to highlight the concept of an annual equilibrium between energy imported from and discharged to the energy infrastructure – as opposed to an autonomous building (Sartori et al., 2012). Thus, a net zero energy building generates the same quantity of energy from renewable sources (e.g., PV, solar thermal collectors) as it consumes. This net ZEB balance can be graphically depicted, as shown in Figure 6. A net ZEB balance is attained by reducing energy demand (X-axis) through energy efficiency measures and by generating enough electricity or thermal energy to earn sufficient credits (y-axis) to offset the energy required for operation.

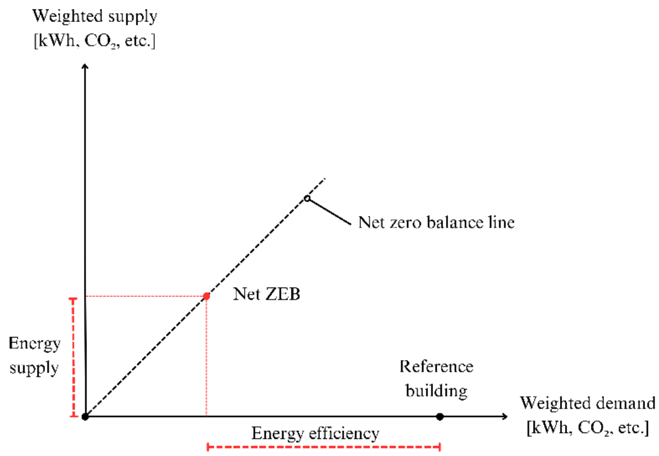

Figure 6, Net zero balance concept (Adapted from Sartori et al., 2012)

Zero Emission Building (ZEB)

Zero Emission Building, or ZEB, is designed to operate without emitting any greenhouse gases. These buildings accomplish their objective through a combination of energy-efficient design, renewable energy sources, and low-impact building materials. As society strives to reduce its carbon footprint and mitigate the effects of climate change, ZEB is gaining popularity. They promote a healthier and greener world through their environmentally responsible and sustainable approach to construction. In addition, ZEB is intended to provide occupants with comfortable and healthful living environments while reducing energy costs over time. ZEB will play a pivotal role in attaining a greener and more sustainable future as governments and organizations throughout the globe strive for more sustainable construction practices.

The central concept of ZEB is that, depending on how the system boundary is defined, various building types can be included at varying ambition levels. The lowest level should be straightforward to attain with fewer resources to encourage more people to construct environmentally favourable structures. Despite the fact that buildings vary in terms of climate, size, and other factors, a smaller apartment building, for instance, may meet the higher standards more easily than larger, more complex buildings (ZEB, 2017).

In the ZEB definition, rather than energy demand and generation, as in the net ZEB, the equilibrium is measured in terms of associated greenhouse gas emissions throughout the building's lifespan. In addition, to accomplish carbon-neutral buildings, the ZEB definition requires maximal climate impact minimization via intelligent material selection, well-considered design, and innovative solutions that address both built-in climate impact and energy requirements (Wiik et al., 2018).

ZEB ambition level definitions and system boundaries

Figure 7 indicates different levels of ZEB and their system boundaries.

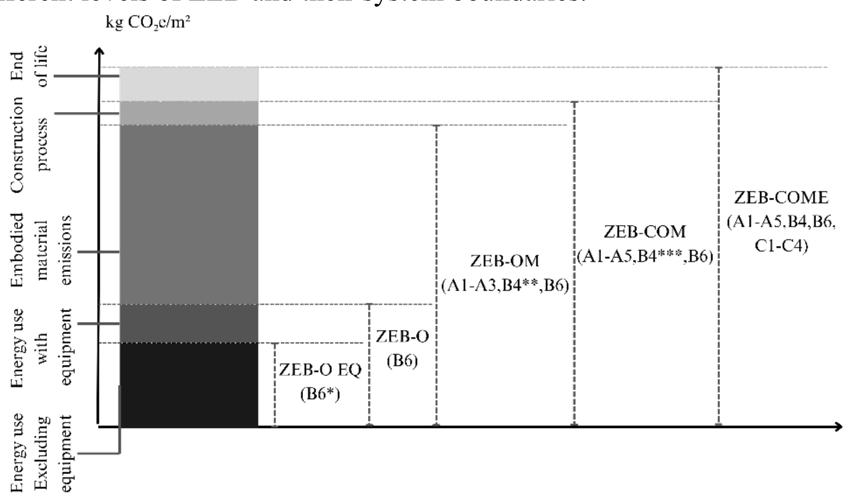

Figure 7, ZEB ambition levels (Adapted from Dokka et al., 2013).

These system boundaries, according to NS-EN 15978, can be interpreted at different stages of LCA:

- *ZEB-O÷EQ:* Emissions associated with operational energy use "O", excluding energy consumption for equipment and appliances (EQ), be offset by the generation of renewable energy (B6*).
- *ZEB-O:* All emissions associated with operational energy "O" must be offset by the generation of renewable energy. The "O" encompasses all operational energy consumption (B6).
- *ZEB-OM:* The emissions associated with all operational energy "O" and embodied emissions from materials "M" must be offset by the generation of renewable energy. The M comprises the product phase of materials (A1 – A3) and scenarios for the replacement phase (B4**). Note that B4** in ZEB-OM only evaluates scenarios related to the production of replacement materials. The replacement material transportation (A4), installation (A5), and end-of-life processes are not included in B4. Table 2 and Figure 7 depict the purview of materials to be included in M.
- *ZEB-COM:* This is identical to ZEB-OM but also includes emissions from the "C" phase of construction. The phases included in C are the transport of materials and products to the construction site (A4) and construction installation procedures (A5). B4*** in ZEB-COM is expanded to include the replacement material's transportation (A4) and installation (A5). B4 *** does not cover the end-of-life processes of substituted materials.
- *ZEB-COME:* This system boundary is similar to ZEB-COM, plus, it takes into consideration emissions of the end-of-life C phase, including deconstruction/demolition (C1), transport (C2), waste processing (C3), and disposal (C4).
- *ZEB-COMPLETE:* A comprehensive emission analysis of a complete life cycle, including all phases from A to C. If relevant and available, D phase, which benefits beyond the system boundary, can also be included as additional information, according to NS-EN 15978.

Table 2 demonstrates the relationship between the ZEB ambition levels and the modular lifecycle stages outlined in NS-EN15978. The light green boxes indicate the mandatory life cycle stages for different ZEB ambition levels. Module D is supplementary information for ZEB-COMPLETE.

Table 2, Description of ZEB ambition levels according to NS-EN 15978:2011 (Fufa et al., 2016).

ZEB ambition level	**Building life cycle**																
	Product			Construction		Use stage							End-of-life				
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
	Raw materials supply	Transport	Manufacturing	Transport	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction, demolition	Transport	Waste processing	Disposal	Re-use, Recovery, Recycling
ZEB-O÷EQ											*						
ZEB-O																	
ZEB-OM									**								
ZEB-COM									***								
ZEB-COME																	
ZEB-COMPLETE																	

* Does not include operational energy of electrical equipment.

** Does not include transport to the building site (A4), installation into the building (A5), or end-of-life treatment of the replaced materials.

*** Does not include end-of-life treatment of the replaced materials.

NB: Biogenic carbon should only be included at a ZEB-COME or ZEB-COMPLETE level.

According to NS-EN 15978, embodied emissions from technical equipment and appliances should be included. Therefore, the "M" in ambition levels ZEB-OM, ZEB-COM, and ZEB-COME refers to emissions from building construction materials and components, excluding emissions from fixed furniture, sanitary equipment, telecommunication, automation, and outdoor installations.

All levels, except ZEB-O/EQ and ZEB-O, include emissions from materials. To maintain calculation consistency, emissions from equipment and appliances should also be included in the material inventory for embodied emission accounting in subsequent ambition levels ZEB-O and higher, as operational energy use for these levels includes equipment and appliances. Appendix table 29 provides a recommended list of included building materials and components according to NS 3451: 2009 (*NS 3451:2009*, n.d.).

2.6.1 Calculation methods

Functional unit

ZEB utilizes LCA calculations based on EN 15978, ISO 14040, and ISO 14044 to analyze climate-neutral buildings. According to ZEB, the functional unit of an analyzed building is one m² of heated floor area (Atemp), with a service life of 60 years. Norwegian EPDs are preferred in LCI. However, if there are no accessible data, Ecoinvent generic data for LCI is used.

Energy per occupant is recognized as a complementary indicator of energy efficiency (Green Power Alliance, 2010). It is recommended that the results from emission analysis for ZEB include both the emissions allocated per square meter per year of the estimated service life of 60 years and per user per year, when possible.

System boundaries

The tangible boundaries of the ZEB Centre are defined by the building itself on the construction site. It implies that the emission analysis should only include materials that are actively used in the building. Materials used for technical installations are only considered if they are contained within the building's physical boundaries. Electrical transmission lines and district heating systems located outside the structure are not included. Components located outside the building but within the boundaries of the building site and contribute to on-site energy production, such as photovoltaic panels and supplementary equipment, should be included. With life cycle boundaries, the specific emissions analysis is dependent on the ZEB ambition level. Therefore, the embodied emissions analysis should state the ambition level and system boundary (Fjola Kristjansdottir, 2014).

Figure 8 demonstrates different options for system boundaries, according to ZEB (Marszal et al., 2011).

The Norwegian ZEB Research Centre has utilized the following limits for the production of electricity and thermal energy (Dokka, Lien, et al., 2013):

- Level III in Figure 7 has been selected for the local production of renewable electricity. That implies the electricity production device for a building must be located on-site, but renewables (such as biofuels) may be used off-site to produce electricity.

- For thermal energy production, level IV has been selected. Thermal energy production for the building (or complex of buildings) can occur either on-site or off-site, but emissions from the actual energy mix must be considered. Total system losses from the production site to the structure must be considered.

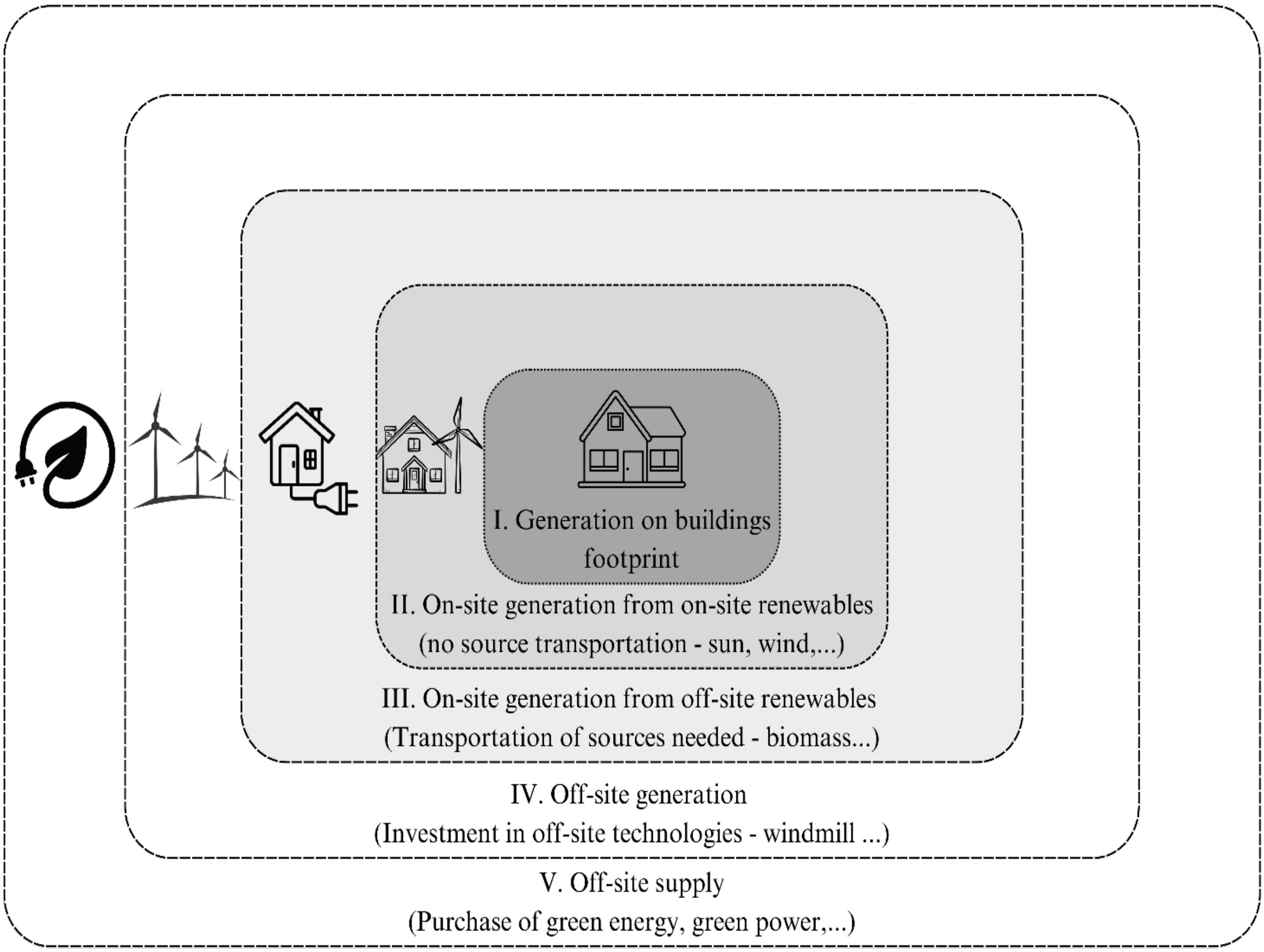

Figure 8, Illustration of different levels of possible system boundaries (Marszal et al., 2011)

Unlike thermal energy, electricity is a high-quality form of energy that can be utilized for most of the building's requirements, including heating, ventilation, illumination, appliances and technical equipment, fans, and turbines. Heat exported from a building or area (cluster of buildings) to a district heating system or neighbouring buildings (off-site) can also be considered. However, thermal energy exports (annually) should not exceed imports due to their inferior energy quality and limited transportability.

Emission data for materials (Life cycle inventory)

The current status in Norway is that there is a continuously increasing availability of Environmental Product Declarations (EPDs) for building materials and components. However, for EPDs, the background life-cycle analysis report is not always openly accessible as it is owned by the study commissioner, who usually produces the product or service. It can make it challenging to gain transparent information on the methodology applied for the EPD. Therefore, if there are no accessible data, Ecoinvent generic data, which is a Swiss-based European database, for LCI is used because of its accessibility, consistency, and transparency.

Uncertainty analysis of emission data

Calculating building emissions necessitates a critical analysis of data and solid quality assurance practices. This is also particularly crucial when comparing various solutions and strategies. Depending on the integrity of the input data, the distinction between two separate bearing systems, for instance, could be negligible. If the data quality is deemed to be high, minor differences between systems can be assumed to be credible. However, if the data quality is deemed to be low, relatively large differences are required to make a reasonable presumption about the differences between the systems. Frequently, results from life-cycle assessments are presented without an evaluation of the analysis's uncertainty. In such instances, a discretionary assessment of the uncertainty is required (Geisler et al., 2005).

Transport and construction process (A4 and A5 categories)

The ambition level of ZEB governs emissions considerations in modules A4 and A5, with a required compensation level for emissions.

When measuring the impact of all construction processes, from earthwork, transport of commodities, and construction labourers to construction equipment, generic data accounting and detailed LCI calculation data should be used. For each input of material and output of refuse, precise distance information travelled, and mode of transport should be collected, including intermediate conveyance between regional facilities. The use of generic datasets for transport per tonne/kilometre is permissible unless transport is anticipated to be significant. Transport-related waste should also be included.

The construction phase is mainly relevant for ZEB-COM, ZEB-COME, and ZEB-COMPLETE, as the choice of materials has a minor influence on the construction process (Wittstock et al., 2011). All A5 processes are generally negligible, at least for filtering and simplifying LCAs.

When calculating for the construction and installation stage A5, it is necessary to account for the production, storage on-site, and transportation of ancillary materials, as well as the individual energy consumed during installation and waste production until the end of the waste stage based on LCI data. Although the transportation of workers to and from the construction site was not considered per Section 7.4.3.2 (NS-EN 15978, 2011), studies have shown that the transportation details of workers, as well as the electricity and fuel consumed during each commute, have a significant impact on the calculations at this stage and should therefore be taken into account (Fjeldheim et al., 2015). The current approach, according to the ZEB Research Center, is to assume a 10% loss for the building materials during the construction installation stage due to a lack of relevant data (Inman et al., 2015); However, additional research in this area could suggest a more concrete value for the loss during this stage (Dokka, Lien, et al., 2013).

Replacements and refurbishments (B4 and B5)

All buildings undergo renovation and refurbishment throughout their lifetimes, during which various building components and materials are either replaced or repurposed. This process significantly impacts a building's emissions over its lifetime. Using reclaimed building materials to reduce new emissions is always advantageous, which can then be excluded from the emissions analysis. However, this is contrary to EN15978 (2011), which states that the emissions attributed to the previous use should be considered in proportion to the material's or component's estimated technical duration. If a structure is completely renovated, its lifespan is restored to 60 years.

The number of replacements of a product, components, and elements used in buildings should be calculated according to NS-EN 15978, 2011, using the following formula:

Number of replacements of product (j) = E [ReqSL/ESL(j) -1] (Fufa et al., 2016)

ReqSL is the required service life of the building,
ESL is the estimated service life,
j is the product,
E rounds the factor to the nearest whole integer.

PV systems that generate renewable electricity to mitigate the building's emissions do not contribute to greenhouse gas emissions during their operation. PV systems contribute substantially to the embodied emissions of zero-emission structures (Dokka, Houlihan Wiberg, et al., 2013).

Within the PV industry, new technologies, materials, and efficiencies for PV modules are continuously evolving (NREL, 2023). Since the reference study of ZEB is 60 years, any PV systems used within the building limits needed to be replaced once studies related to life-cycle of PV modules show that the amount of material used in PV production is expected to be reduced, at the same time, increase in PV efficiencies (Frischknecht et al., 2015, Bergesen et al., 2014, Mann et al., 2014). Therefore, a 50% reduction of the environmental impacts related to A1-A3 categories can be implemented for the replacement scenario (B4) of PV modules.

End-of-life process (C1 – C4)

It is required by law to transport all waste to waste management stations. In addition, when a new development or demolition project is larger than 300 square meters or when a construction project generates more than 10 tons of waste, a waste management plan is required to separate and recycle at least 60 % of the waste on-site before transporting it to the waste facilities (KDR, 2017).

In general, the different waste fractions should be treated as follows (Fjola Kristjansdottir, 2014):

- Bricks should be reused or crushed as an aggregate substitute.
- Concrete should be reused as an aggregate substitute.
- Wood should be incinerated for energy.
- Metals should be recycled.
- Gypsum should be recycled.
- Glass should be recycled.
- Combustible insulation should be incinerated using energy recovery. Other insulation products should be recycled when possible.
- Plastics should be recycled or incinerated using energy recovery.

According to NS-EN 15804, the end-of-life stage (C1-C4) begins when materials or products are replaced, dismantled, or deconstructed from the construction site and continues until they reach the end-of-waste state (EN 15804, 2019). Products that reach the end-of-waste state during the construction stage (A4-A5) or the use stage (B1-B7) will have their end-of-life evaluated within the stage of the product's life cycle.

C1 – Deconstruction/Demolition

This module covers deconstruction, including disassembly, demolition, and on-site categorising. In the absence of reliable data, it is reasonable to presume that the quantity of energy consumed during the deconstruction phase is equivalent to that of the construction and installation phases (Fjeldheim et al., 2015).

C2 – Transport from construction to waste treatment

This module covers waste transportation to waste processing and disposal facilities.

C3 and C4 – Waste processing and disposal

This module covers waste processing for reuse, recycling, and recovery (C3) and dispersal of waste that has not reached end-of-waste status (C4). The use of generic data for scenarios describing end-of-life treatment (C3 and C4) can be based on current national waste accounts for the principal materials.

2.6.2 CO_2 Conversion Factors

CO_2 factor for grid electricity

Figure 9 displays the results of an analysis by Graabak and Feilberg of various scenarios for European electricity generation through 2050 (Graabak & Feilberg, 2011). In the most optimistic scenario, the average carbon intensity would decline from 361 g CO_2e/kWh in 2010 to less than 31 g CO_2e/kWh in 2050. The results were extrapolated to produce an average value that is representative of a 60-year building tenure, resulting in an average value of 132 g CO_2e/kWh, as depicted in Figure *10* (Dokka, Lien, et al., 2013).

The CO_2 curve in Figure 9 and the average factor of 130 g/kWh are based on various options, assumptions, simplifications, and scenarios. There is currently no official value or consensus on a CO_2e factor for electricity in Norway, but the approach adopted here is consistent with the long-term political objectives for the European electricity system.

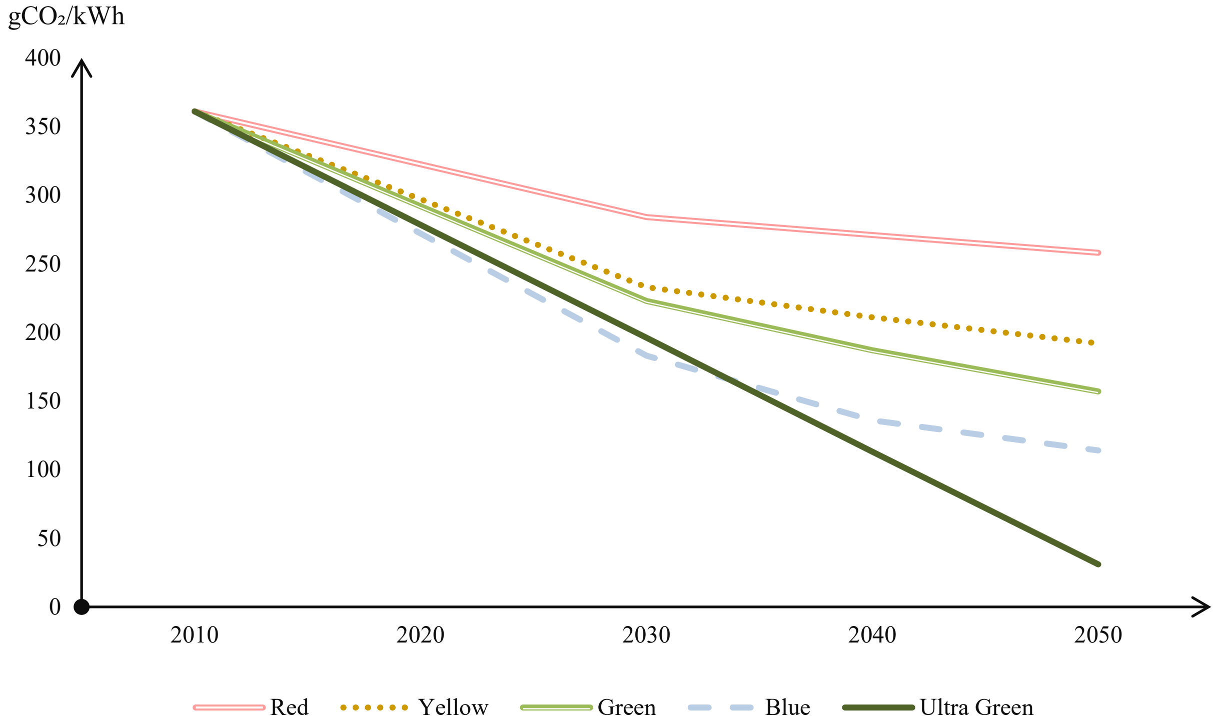

Figure 9, Scenarios of average specific emissions from 2010 to 2050 (Adapted from Graabak & Feilberg, 2011).

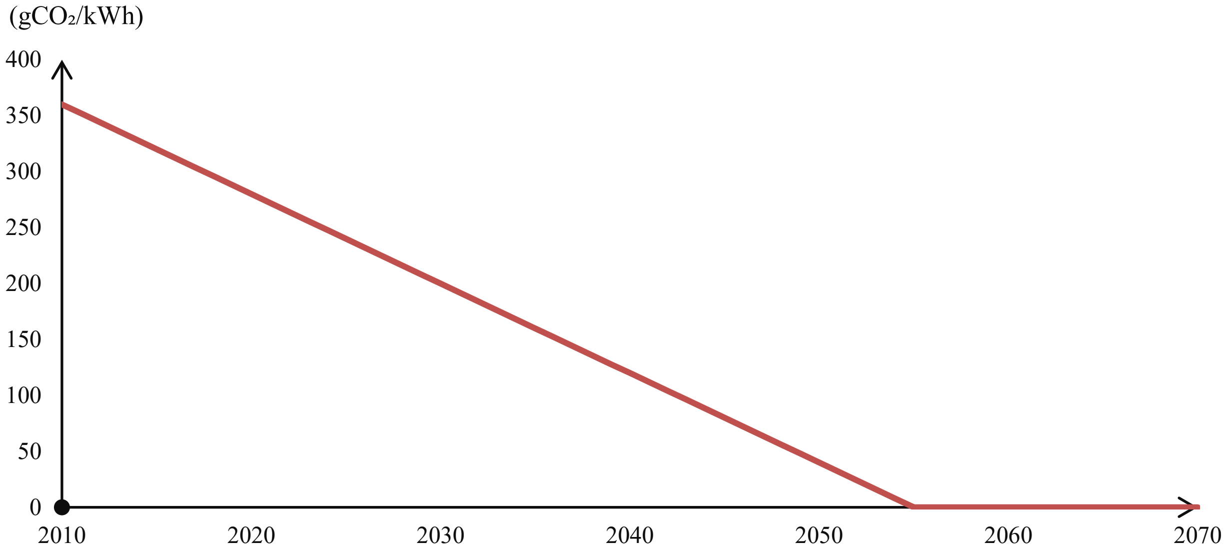

Figure 10, Assumed development for the CO_2e factor for electricity from 2010 towards 2055 (Dokka, Lien, et al., 2013)

CO_2 factor for Bioenergy and Waste incineration

According to (Lien, 2013), district heating should be evaluated based on the actual GHG emissions associated with its production, and not as an emission-free residual heat utilization. Approximately 50 % of the current composition of incinerated waste in Norway is fossil-based.

District heating derived from waste incineration produces comparable greenhouse gas emissions to the combustion of natural gas. (Lien, 2013) estimates that the specific CO_2 emissions from waste incineration are 211 g CO_2e/kWh, based on the present plastic content of waste (approximately 25 %) and current facility efficiencies. District heating companies may use this emission factor if they can demonstrate that their production mix has a reduced emission factor.

Emission factors for different types of biofuels are listed in Table 3.

Table 3, Specific CO_2 emissions from selected biofuels (Lien, 2013)

Biofuel type	**gCO_2/MJ**	**gCO_2/kWh**
GROT (waste from wood harvesting) wood chips	1	3,6
EU wood chips	4	14,4
GROT* pellets/briquettes	2	7,2
EU wood pellets/briquettes**	4 -22	14,4 – 29,2
Wheat straw	2	7,2
Biogas from wet manure	8	28,8
Biogas from dry manure	7	25,2
*GROT = Wood residue **Lower value is using wood as process fuel; upper value is using natural gas as process fuel		

2.6.3 Other requirements

Energy efficiency requirements

The ZEB energy concept is comprised of two design strategies: first, to reduce energy consumption in buildings through energy efficiency measures, and second, to use renewable energy and other technologies to meet the residual energy requirements. These strategies are frequently categorized as either passive or active. Passive strategies relate to the location, layout, massing, and form of the building and its materials, whereas active strategies typically involve technical systems or apparatus to provide building services.

The "low energy house standard" demonstrates compliance with NS 3700 (for residential buildings) (NS 3700, 2013) and NS 3701 (for non-residential buildings) (NS 3701, 2012) as the minimum requirement for energy efficiency in ZEB. These standards establish heating and ventilation demand criteria, with maximum heat loss and thermal bridges, as well as building envelope airtightness.

Indoor Climate Requirements

According to the requirements of the Norwegian building regulations, the indoor climate of a ZEB must be at least as excellent as that of any other building. The ISO 7730: 2005 appendix A requirements for local distress for category B (ISO 7730, 2005) must also be accomplished.

Mismatch production and demand

The mismatch between the energy demand of the building(s) and the on-site energy production can be significant on an hourly, daily, weekly, and annual basis, resulting in grid stress and fluctuating CO_2e emissions. Nevertheless, based on the methods and data currently available, the first approach is to use a constant CO_2e factor with no daily, weekly, or annual variation and to use the same factor for both the import and export of electricity to or from the building(s) (symmetric weighting).

2.7 Biogenic carbon

The term "biogenic carbon emissions" refers to emissions produced by biological sources such as plants, trees, and soil. There is a significant amount of interest in quantifying how plants capture CO_2 during photosynthesis, how it is lost during respiration, how it is stored in biomass (living and dead), and how it is finally biologically sequestered into long-term biological stores in the soil because biogenic carbon emissions are related to the natural carbon cycle. This biogenic terrestrial carbon cycle represents a considerable opportunity for reducing emissions of greenhouse gases (GHG) (Harris et al., 2017).

The process of removing carbon from the atmosphere and storing it in a location where it will remain for an extended period of time is known as carbon sequestration. Carbon sequestration may be natural, in which case the natural processes of the carbon cycle are used, such as the biological fixation mentioned above, or carbon sequestration can be artificial, in which case carbon is compressed and stored. This method is known as carbon capture and storage (Harris et al., 2017). Whereas "carbon storage" refers to the process of sequestering carbon within a product for an extended period of time, which results in an impermanent reduction of CO_2 concentrations in the atmosphere, "carbon sequestration" refers to the process of sequestering carbon within a product for an extended period of time (Arehart et al., 2021). Oxidation, combustion, digestion, and other related processes of biomass degradation may release biogenic carbon into the atmosphere in the form of carbon monoxide (CO), carbon dioxide (CO_2), and methane (CH_4). Biogenic carbon can also be discharged into the environment as a by-product of biomass degradation (Brandão et al., 2013).

Three advantages of using biomaterials are becoming increasingly acknowledged. It can (1) reduce the life cycle GHG emissions associated with material extraction and manufacturing; (2) temporarily store biogenic carbon in the anthroposphere; and (3) limit GHG emissions by substituting other, more emission-intensive building materials. These potential benefits explain why green building rating systems (e.g., LEEDv4) now promote the use of certified-harvested wood products (HWP) and other bio-based, reused, recycled, and local materials to reduce the impacts of the building sector and why several studies argue that wood buildings can achieve lower embodied and operational carbon than conventional buildings (Breton et al., 2018).

Biogenic carbon uptake and release

Two major approaches can be distinguished when assessing the impact of biogenic carbon assimilation and release in conventional LCAs applied to buildings (Hoxha et al., 2020). The '0/0 approach' or 'carbon neutral approach' is based on the premise that the emission of CO_2 from a bio-based product at the end of its existence is balanced by an equal absorption of CO_2 during biomass growth. As a result, there is no consideration of biogenic CO_2 absorption (0) and emission (0). Figure 11 illustrates the method for a wood product used in a structure. In the case of timber recycling, a distinction is made between the forest system, the building system, and a prospective subsequent product system. The following product system is designated as module D. As shown in Figure 11, none of the modules takes biogenic CO_2 into account. In module C, only biogenic methane (CH4) emission is modelled due to its greater impact on global warming than biogenic carbon dioxide (CO_2).

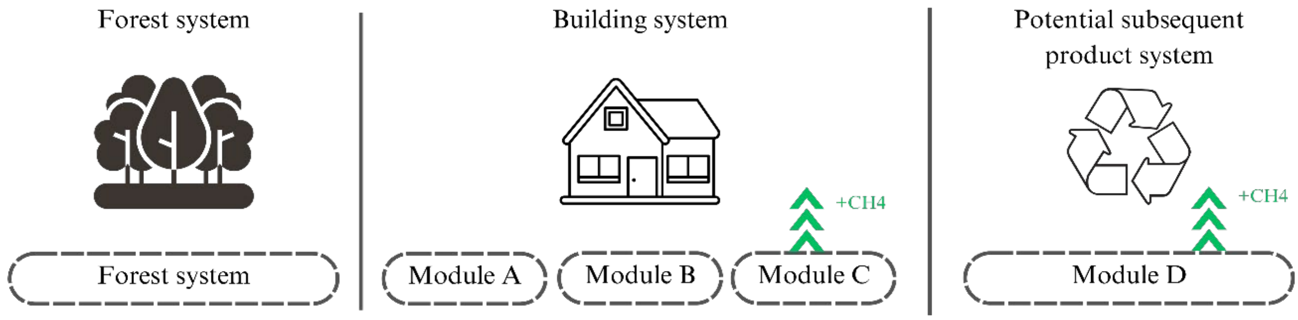

Figure 11, The 0/0 approach to biogenic carbon uptake and release (Hoxha et al., 2020).

The second method, known as the "–1/+1" method, entails monitoring all biogenic carbon fluxes throughout the building's life cycle. In this approach, both biogenic CO_2 uptake (–1) and release (+1) are considered, as well as biogenic carbon transfers between the various systems. Figure 12 depicts this example. The forest's absorption of biogenic CO_2 is conveyed to the building system and reported as a negative emission in module A. After a building's life cycle, biogenic carbon dioxide (or carbon monoxide or methane) is discharged, or the carbon content is transferred to a subsequent product system (in the case of recycling). In both cases, module C reports a positive emission. When using this strategy, it is important that the biogenic carbon balance for all product systems be negative. The primary advantage of the '–1/+1 approach' over the '0/0 approach' is that it provides an overview of all biogenic carbon flux. However, there is a risk of biased and misleading results if only the product and construction effects are considered.

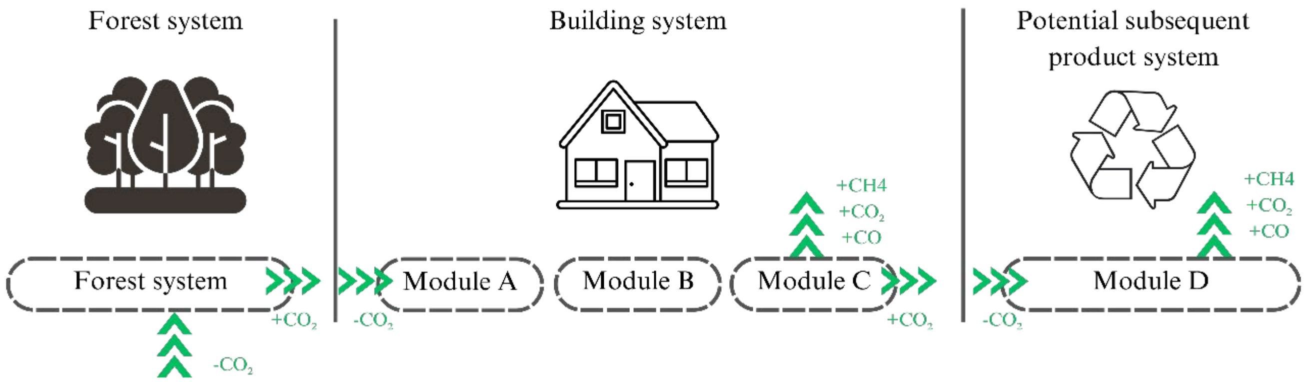

Figure 12, The -1/+1 approach to biogenic carbon uptake and release (Hoxha et al., 2020).

However, when bio-based materials and products are incorporated into the LCA of a building, evaluating only the production phase can result in significant deviations from a comprehensive LCA (Fouquet et al., 2015). End-of-life considerations are equally as important as those made before biomass extraction. An additional difficulty is posed by the fact that bio-based materials belong to multiple systems, each of which can claim the benefit of carbon capture. A timber beam is an example of a harvested wood product that can be included as a forest industry end-product and calculated as such in a forest LCA (Taverna et al., 2007). It is also a bio-based building material that can be utilized in the construction industry (Head et al., 2020). After a building's existence, this product can be used by the energy industry to produce heat or electricity (Müller et al., 2004). The same substance is produced and utilized through cascading logic, and various technical systems (Mehr et al., 2018). If 'double counting' is to be avoided, there must be clarity regarding the multiple uses of the same material. A distribution to the various technical systems must be determined. It is a matter of agreement between the numerous supply chain stakeholders, so there is no apparent solution (Habert, 2013).

The primary criticism of conventional LCA approaches is that they do not account for the impact of the schedule of carbon emissions and the influence of biomass growth rotation periods. When evaluating the impact of bio-based products, this can be problematic. Studies by (Pittau et al., 2018) demonstrate that not all bio-based products are carbon neutral. Timber products, such as processed wood beams or planks, have a long rotation time due to sluggish forest growth, so they cannot be considered carbon neutral in the near future. In contrast, fast-growing bio-based materials, such as fibre and hemp, have a brief rotation period and can mitigate GHG emissions effectively by quickly removing carbon from the atmosphere (Pittau et al., 2018).

Recent publications have revealed that land use significantly impacts carbon sequestration, which has been underappreciated in the scientific literature. If there was no human-managed land, potential vegetation could store 49 % more carbon than it does presently under current climate conditions (Erb et al., 2018). Consequently, the contribution of *land use and land-use change* (LULUC) to carbon sequestration is now a subtopic of the calculation of the Global Warming Score. For instance, harvesting timber reduces forest biomass supplies relative to their potential, which is one of the obstacles to increasing biomass use in the material, product, and energy industries. To maintain and increase carbon sequestration on a global scale, forest managers must keep and increase biomass productivity and stocks.

A closer examination of building LCA and biogenic carbon accounting in EPDs reveals that not all biogenic carbon removals are accounted for in the final product. Figure 13 illustrates the entry and exit points for biogenic carbon in the LCA of a product. Some carbon removals are lost during the process, for instance, as a by-product (pallets, cellulose, or paper) or through combustion. After a building's lifespan, biogenic carbon is released back into the atmosphere, or the carbon content is transported to a subsequent product system (if the material is recycled or otherwise repurposed). In this approach, the biogenic carbon balance should be zero for all product systems (Pittau et al., 2018, Hoxha et al., 2020).

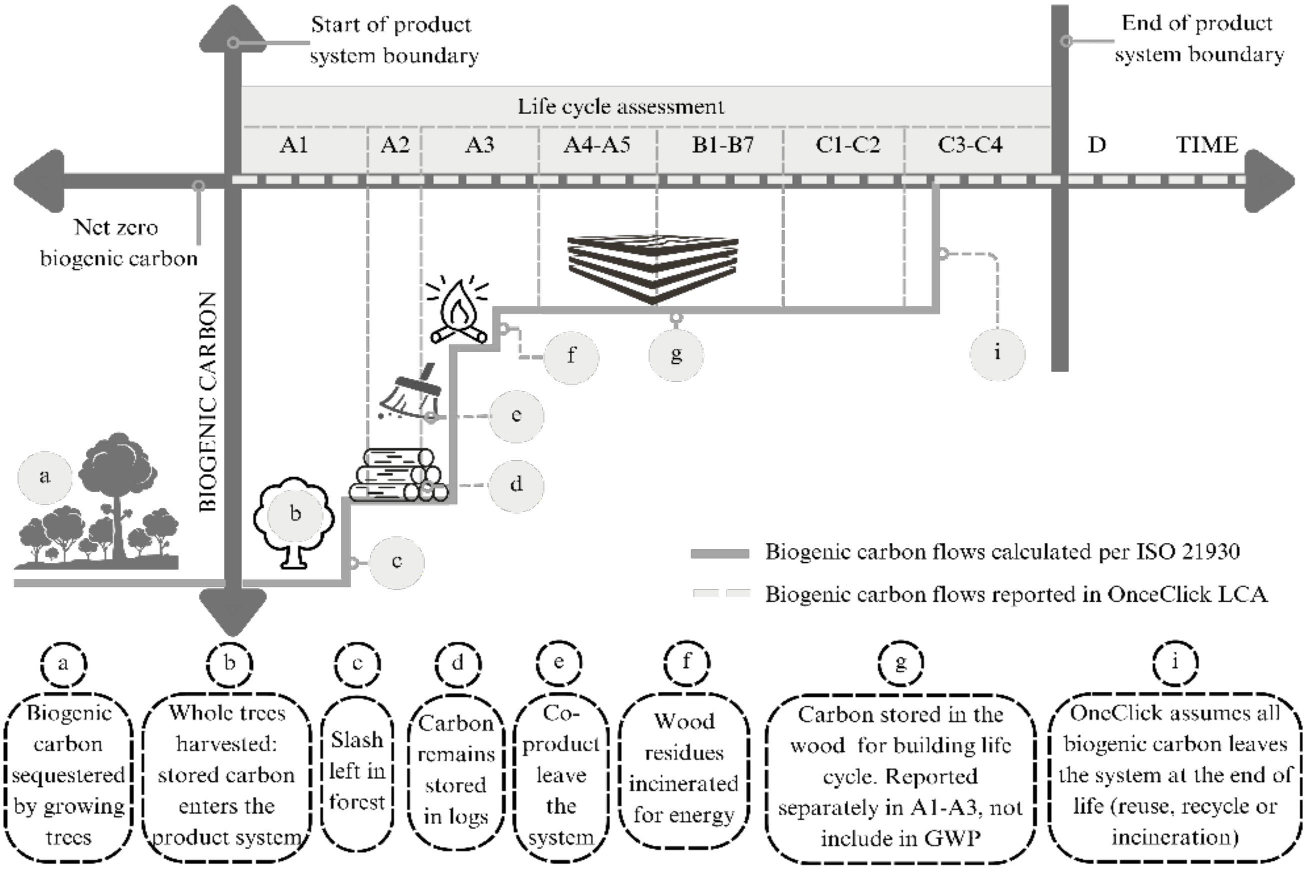

Figure 13, Biogenic carbon flows according to ISO 21930 and reporting in One-click LCA (Woodworks, n.d.)

2.8 Climate compensation measures

2.8.1 Photovoltaics (PV)

Solar panels, also known as photovoltaic (PV) panels, convert sunlight into electricity (Bhatia, 2014). They are a well-known renewable energy technology that has undergone significant efficiency enhancements. In recent years, materials science and manufacturing advancements have led to the development of highly efficient photovoltaic (PV) panels that can generate more energy from the same solar radiation. The ability of a PV panel to convert sunlight into electricity determines its efficacy. The most efficient PV panels on the market today convert approximately 22 % of the sunlight they receive into usable electricity. This is a substantial advance over older PV panel designs, which typically had efficiencies between 10 and 15 % (Jeanne, 2021).

One of the primary benefits of PV panels is their ability to reduce carbon emissions in buildings. By using fossil fuels for heating, ventilation, and electricity, buildings are responsible for a significant proportion of global greenhouse gas emissions (IEA, 2022). By installing PV panels on the roofs or facades of buildings, it is possible to generate renewable electricity that can be used to power the building's operations, thereby reducing the building's reliance on fossil fuels. In addition to reducing carbon emissions, PV panels can also reduce energy costs and increase building proprietors' energy independence (Andreas, 2016). As the price of PV panels continues to fall and their efficacy continues to grow, they are becoming a more appealing option for businesses and homeowners seeking to reduce their environmental impact and save money on energy costs (Louwen et al., 2016). Because of the aforementioned reasons, ZEB stated that, when it comes to PV replacement, the system will need to be replaced once, within the 60-year study period (Fufa et al., 2016). In addition, the replacement scenario (B4) of the PV panels can get a 50 % reduction of the environmental impacts relative to the A1-A3 (Fufa et al., 2016).

According to ZEB, renewable energy production, such as PV panels, should first cover the building's total energy consumption, after which any excess can be accounted for as compensation for the building's climatic impact over its tenure (ZEB, 2017). Given that this is the only climate measure that balances emissions with a system of varying ambition levels, ZEB could be viewed as more ambitious than any other definition (Wiik et al., 2018). The fundamental concept for a building to qualify as climate-neutral is the extreme reduction of its climate impact. Thus, net-zero can only be realized through the production of renewable energy on-site or off-site, a requirement for upgrading to the ZEB-COMPLETE additional ambition level. This implies that the total emissions associated with a building life cycle must be compensated for in all phases A1-A5, B1-B5, B6-B7, and C1-C4 (ZEB, 2017).

2.8.2 Wood

With the benefit stated in the biogenic carbon section 2.7, wood constructions are considered to be utilized in this report. However, some limitations and difficulties like double counting, the impact of time or land use, and land-use change of the carbon sequestration should be considered and discussed later in the report.

Trees remove carbon dioxide (CO_2) from the atmosphere by absorbing it. Half of the dry weight of wood is carbon. Photosynthesis 'waste' produces oxygen, which is essential for existence (Dovetail Partners, 2013). When wood is used for constructing materials, there is a greater potential for carbon sequestration. Consequently, a new "carbon pool" is formed. By constructing a house out of wood, for instance, carbon is retained for as long as the house remains standing. Carbon constitutes approximately 50 % of the dry weight of timber, so estimating the amount of carbon in wood would appear simple. Nevertheless, caution is required when making estimates because many factors substantially impact precision. Among these are the wood's moisture content and the difference between carbon (C) and carbon dioxide (CO_2) at a critical level (Dovetail Partners, 2013).

Cross-laminated timber (CLT) is a form of mass timber that consists of several layers of solid wood panels bonded with a structural adhesive at alternating right angles (Eric, 2022). This material is becoming increasingly popular as a building solution for low-rise to mid-rise buildings, and even high-rise buildings with recent advances in codes and design (Younis & Dodoo, 2022). CLT is a versatile and sustainable material that can be used for structural purposes in building construction, such as floors, roofs, walls, and stairs. CLT has many advantages over conventional materials such as concrete and steel, its high strength-to-weight ratio, thermal and acoustic performance, fire resistance, and low carbon footprint (Hyne Timber, 2019). CLT can also reduce construction time and costs by allowing for prefabrication and rapid on-site assembly.

Carbon constitutes approximately 50 % of the dry weight of wood, which is an important fact to remember. Because the wood used in construction is never completely dried, the moisture inside the wood should be eliminated before calculating the impact of wood in terms of carbon capture (Dovetail Partners, 2013). Depending on the EPDs and the wood type, the moisture content will be different.

CO_2 emissions, or more precisely CO_2-equivalent emissions, are a common topic of discussion when discussing climate-related issues. Possibly as a result, carbon content is occasionally confounded with the CO_2-equivalent of a given quantity of carbon. The molecular mass (sometimes referred to as molecular weight) of carbon is 12, that of oxygen is 16, and that of carbon dioxide (CO_2) is 44. Therefore, the carbon dioxide equivalent of one metric ton of carbon is 3.67 tonnes (44/12 x 1 metric ton). The carbon content must not be confounded with the carbon dioxide equivalent when estimating carbon content; doing so can significantly overestimate the amount of carbon (Dovetail Partners, 2013).

2.8.3 Green roof

Green roofs, also known as vegetative roofs, are gaining popularity in urban areas due to their many advantages. Green roofs are intended to resemble natural ecosystems by integrating vegetation and soil onto roofs. These structures offer several benefits, including stormwater management, a reduction in urban heat island effects, and enhanced air quality. Another advantage of green roofs is their capacity to remove carbon dioxide from the atmosphere, making them an effective instrument for mitigating climate change (Shafique et al., 2018).

On green roofs, a soil stratum serves as the medium for plant growth. The plants then absorb atmospheric carbon dioxide through the process of photosynthesis. Carbon is sequestered in the soil and plant biomass due to this process. As a result, green roofs can act as carbon sinks, reducing the amount of carbon dioxide in the atmosphere and aiding in the fight against climate change. The quantity of carbon sequestered by green roofs can vary depending on the type of vegetation, the depth of the soil, and the local climate (Shafique et al., 2020).

Green roofs are also compatible with other environmentally friendly technologies, such as solar panels. Solar panels are designed to convert sunlight into electricity, serving as a renewable energy source. When combined, green roofs and solar panels can increase the overall energy efficacy of a building. The vegetation on a green roof can reduce the quantity of heat absorbed by the roof, thereby reducing the building's cooling needs and also acting as an additional insulation layer in wintertime (Sookhan et al., 2018). The outer roof heat decrease caused by green roofs can also help increase the PV system efficiency (Shafique et al., 2020). It results in a reduction of the required energy to maintain a comfortable indoor environment. In addition, solar panels can be installed on green roofs, maximizing the available space and reducing the need for a distinct land area for solar installations.

There are many studies about how to quantify the effect of green roofs regarding carbon sequestration. A German study using the Eddy covariance method over an entire annual cycle indicated that the green roof was a carbon sink with an annual cumulative Net Ecosystem Exchange of CO_2 (NEE) equal to -85 g C/m²/year (Heusinger & Weber, 2017). Based on this study, LFM30, which is a local initiative to create a climate-neutral construction and civil engineering sector in Malmö, Sweden, created a guideline about how to quantify the carbon uptake in biomass overground and carbon storage in the ground for different vegetation types (Erlandsson et al., 2022). LFM30 stated that, for green roofs, carbon storage in biomass in a fully grown state was 0.27 kg C/m², carbon storage in the ground was 0.9 kg C/m², and carbon uptake in biomass per year was 0.085 kg C/m². These values will be utilised in this thesis.

2.8.4 Biochar

Biochar is a carbon-based material created through pyrolysis, a thermochemical conversion process. In pyrolysis, organic material is heated in the absence of oxygen, forming a carbon-rich solid residue. The International Biochar Initiative defines Biochar as "the solid material obtained from the thermochemical conversion of biomass in an oxygen-limited environment" (IBI, 2023). Biomass is the organic substance derived from plants and trees, such as timber and wood refuse, from forest management, municipal maintenance, and agricultural and industrial waste. As a result of its ability to enhance soil fertility and crop health when used as a soil amendment, biochar is gaining popularity. In addition, biochar can be used for water filtration, soil detoxification, and as a nutrient source for the soil (Lehmann & Joseph, 2015).

Biochar's ability to function as a carbon sink, sequestering carbon in the soil for hundreds or thousands of years, is one of its most significant advantages. It allows climate change mitigation by decreasing carbon dioxide concentrations in the atmosphere. Utilizing biomass feedstocks that are managed sustainably and grown with minimal inputs can increase biochar's capacity to sequester carbon. In addition, biochar can be combined with other techniques, such as conservation agriculture, to increase carbon sequestration (Jeffery et al., 2017).

Furthermore, studies indicate that when biochar is implemented in green roofs, carbon sequestration increases, and the heat conductivity of the substrate decreases. Firstly, biochar application significantly increased the water-holding capacity of the substrate by 6.6-34.5% and the air-filled porosity (Chen et al., 2018), favouring the plant growth process. Moreover, the application of biochar significantly altered the temperature of roof substrates. During the summer, green roof substrate, including more than 15% of biochar, substantially increased temperature under intense irradiation. Due to its porous structure, the incorporation of biochar could increase water retention (Novak et al., 2009) and reduce substrate temperature via water evaporation (Meng & Hu, 2005). 10 – 15 % biochar addition was found to be optimal for temperature reduction and water retention (Chen et al., 2018). Although biochar can also decrease soil temperature and increase soil moisture in-ground systems, the effects of biochar on soil properties are more pronounced in green roofs (Chen et al., 2018). Additionally, studies show that with 15 % of biochar mixed with soil, biomass and carbon content of plants reached the highest figures, which were 15.92 g / plant for biomass and 32.77 mg/kg of carbon content (Chen et al., 2021).

Biochar is a versatile material with various potential applications. Its use as a soil amendment is a particularly significant one, as it has been shown to improve soil fertility and enhance crop growth. Biochar can also be used in other applications, such as water filtration, soil detoxification, and as a nutrient source for animal feed (H. Schmidt & Wilson, 2014). However, the most significant benefit of biochar is its ability to sequester carbon in the soil, making it a valuable tool in mitigating climate change. Carbon sequestration in biochar can be further enhanced by using biochar in combination with sustainable biomass feedstocks and conservation agriculture practices. Further research is needed to optimize the use of biochar in different applications and ensure its long-term sustainability as a carbon storage option.

2.8.5 Carbon credit

A certificate that may be traded and is known as a "carbon credit" represents the license to release one ton of CO_2 or an equal quantity of another greenhouse gas (tCO_2e) that has been removed from the environment (CFI Team, 2023). This permission is represented by a carbon credit. This enables projects which have fewer carbon emissions to sell their carbon allowances to those that have surpassed the stated limit on the number of carbon emissions they are allowed to produce. This technique acts as a compensatory mechanism that counterbalances the quantity of carbon dioxide and other greenhouse gas emissions that are released into the atmosphere to reduce the impacts of global warming.

The carbon market is governed by countries and international organizations that have established yearly limits on the total quantity of greenhouse gases that may be expelled into the atmosphere. These caps are used to restrict the amount of carbon that can be traded on the market. If a company or project's emissions are higher than the allowed limit, they are required to buy enough carbon credits to make up for the difference. On the other side, they can sell the amount of money they save as credits by going through rigorous regulatory procedures that guarantee their carbon neutrality. To mention, the Gold Standard, VERRA, and Plan Vivo, are just a few of the key organizations responsible for the comprehensive management of this process via various programs and activities. The Verified Carbon Standard (VCS) program, which VERRA introduced, converts each ton of carbon dioxide equivalent (CO_2e) into a VCU (Verified Carbon Unit), which the end-user may buy as a way of offsetting their emissions (Verra, 2022). The Verified Carbon Standard (VCS) program quantifies each ton of carbon dioxide equivalent (CO_2e) into a VCU (Verified Carbon Unit). According to Ecosystem Marketplace, the price of a carbon offset may vary anywhere from US$3 to US$6 per ton. However, this number might change based on the project, location, the carbon standard used, and the project year (Second Nature, 2022). The Swedish market is also actively participating in reducing climate effects via the Voluntary Carbon Offset (VCO) (Hwargård, 2020).

2.9 One Click LCA

OneClick LCA is a cloud-based application that provides a user-friendly and comprehensive solution for life cycle assessment (LCA) and sustainability reporting. One Click LCA was designed by the Finnish company Bionova Ltd to assist building professionals, product manufacturers, and infrastructure developers in measuring, improving, and communicating the environmental performance of their projects (One Click LCA, n.d.). The software utilizes a vast database of environmental impact data to conduct calculations, allowing users to evaluate and compare their design decisions' environmental impact rapidly. The software is routinely updated to incorporate the most recent environmental standards and regulations, ensuring users access to accurate and current data. With its user-friendly interface, customizable reports, and integration with prominent certification schemes, One Click LCA has become an indispensable resource for sustainability professionals around the globe.

One Click LCA is a valuable instrument for sustainable design and decision-making due to its use of EPDs and extensive database. It is essential to note that being EPDs based, One Click LCA enables a more precise and comprehensive analysis of a project's environmental impact. EPDs provide transparent and standardized information about a product's life cycle and environmental performance, which can be used to identify areas for improvement and monitor progress over time. The database of One Click LCA contains thousands of EPDs for a wide variety of products and materials. This enables users to rapidly access accurate and pertinent data for their particular endeavour without extensive research or data collection. In addition, the ability to modify and customize EPD data in One Click LCA provides greater flexibility and precision when evaluating the environmental impact of a project.

One Click LCA undergoes rigorous verification on every EPD added to the database. Each added EPD complies with the European standard EN 15804, the American standard ISO 14040/44, or both. These standards are EPD environmental assessment methods for construction work and services.

2.10 Particular circumstances of Helsingborg's CO_2 emission

Carbon Capture and Storage (CCS) is one of the methods that numerous nations, including Sweden, are developing. CCS is a procedure that entails capturing carbon dioxide (CO_2) from power plant exhaust gases or industrial operations, compressing it into a fluid, and conveying it to a storage site. The captured CO_2 is then injected deep into geological formations, where it becomes stone over time (Swedish Energy Agency, 2022). The government has tasked the Swedish Energy Agency with promoting and deploying CCS in Sweden, intending to attain net-zero greenhouse gas emissions by 2045 and, eventually, negative emissions.

Capture, transport, and storage are the three primary phases of the CCS procedure. Various technologies, including absorption, adsorption, and membrane separation, are used to separate CO_2 from flue gases during the capture phase. Once captured, CO_2 is compressed into a supercritical state to facilitate transportation. In the conveyance phase, compressed CO_2 is transported to either a permanent or interim storage location. Depending on the distance and location of the storage site, this may be accomplished via pipelines, ships, railroads, or tankers (Swedish Energy Agency, 2022).

According to the Swedish Energy Agency's projections for 2021, the nation's overall plan for using carbon storage will aim to store around 3.7 million tons of CO_2 equivalent per year by the year 2030 and 10.7 million tons of CO_2 equivalent by the year 2045 (Swedish Energy Agency, 2022). The decarbonization of the energy industry is an essential endeavour that, per the Swedish carbon capture policy, must be finished by 2030.

In collaboration with the Swedish Energy Agency, Helsingborg started experimentation on carbon storage in 2022 and wants to achieve carbon neutrality for energy production in 2030 (Öresundskraft, 2022). Furthermore, Helsingborg city has a present CO_2 emission value for district heating, district cooling, and energy grids, which are 53 gCO_2/kWh, 78 gCO_2/kWh, and 39 gCO_2/kWh, respectively. Helped with CCS, these values will fall at least to zero in 2030, as stated in the Swedish energy goal (Öresundskraft, 2022).

Figure 14 illustrates the reduction in CO_2 emission from district heating, district cooling, and energy grid production.

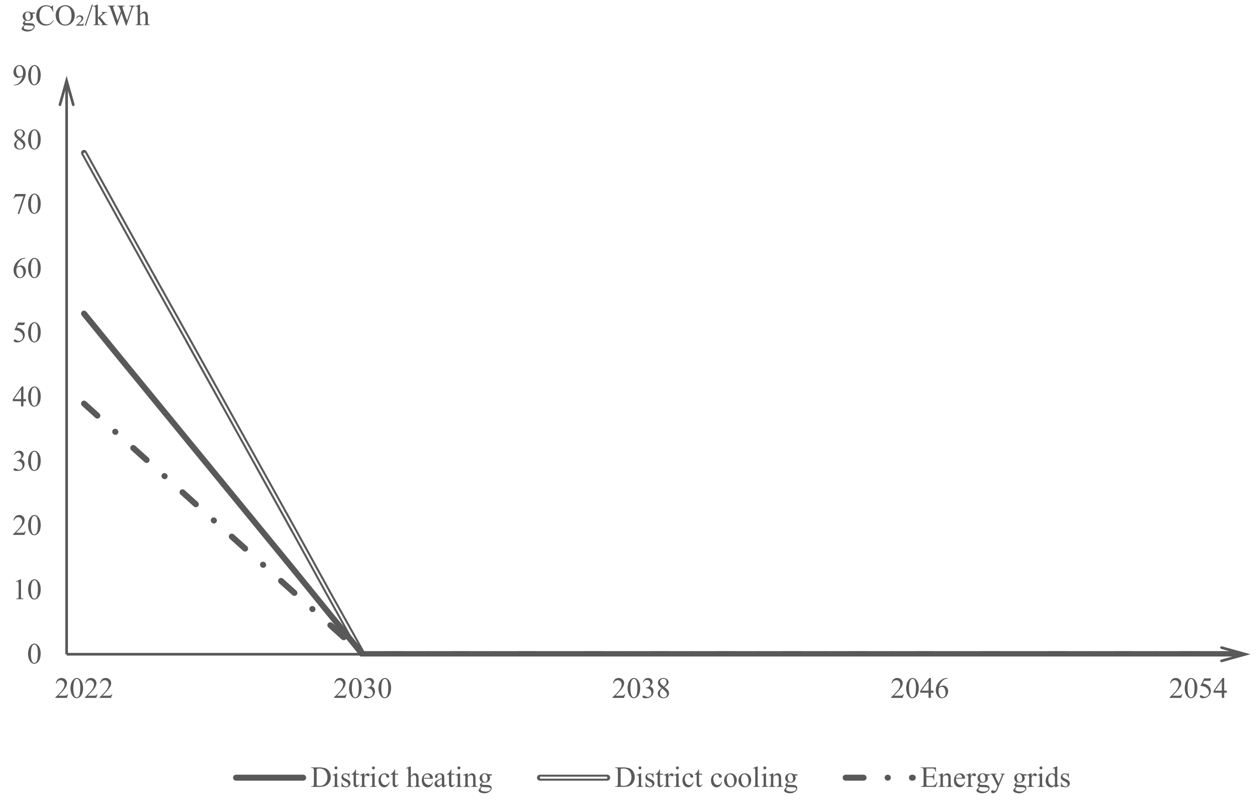

Figure 14, CO_2 emission of different energy production (Öresundskraft, 2022)

3 Method

The methodology was developed around the three main questions of this study addressed in paragraph 1.5. *Figure 15* resumes the different steps performed to achieve these three goals.

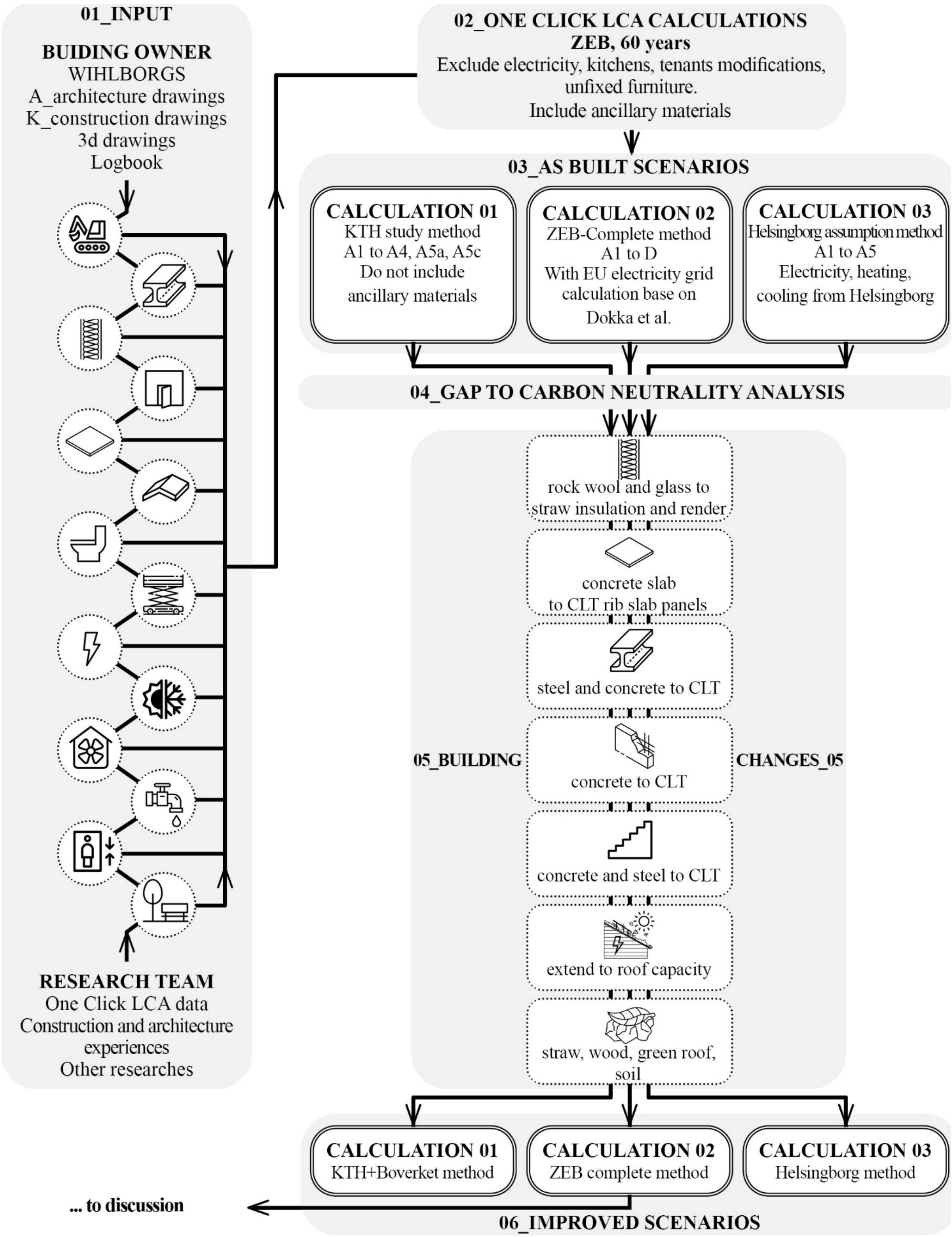

Figure 15, Methodology of the study

3.1 Input

The input provided by the main participant and the building owner of the studied building was the design and construction drawings, the BIM models, and a logbook used to reference the primary material found in the building. Assumptions and calculations were made based on architecture and building experiences acquired through professional work positions. Some data was taken from One Click LCA, and complementary research was done when needed.

The *functional unit* of this study is one m² of heated floor area (A_{temp}), with a service lifetime of 60 years.

An extensive amount of material calculations was made through the spreadsheet program Excel for every analysed section, and building ancillary materials were taken into account and calculated based on the professional construction experience of a team member. Due to the length of this report, Only the important calculations will be shown and explained. To better understand the material calculations, all information for the outer wall materials will be tabled in the Appendices. Furthermore, all materials from the building construction and their associated quantity will also be presented in the report's Appendices.

Groundwork and foundation material

Groundwork and foundation material calculation came from technical drawings, the BIM model, and the logbook. The BIM model was used to find out where was all the footing, while the logbook was used to find the quantity and the provenance of some elements, for example, the amount of steel used or the type and quantity of insulation material.

Since the building is built in an old harbour area, it was assumed that dug soil has to be decontaminated. At Helsingborg, there is a company that does soil decontamination, which is situated ten kilometres from the site location ((NSR AB, n.d.). The quantity of soil dug has been estimated based on the technical drawings, and the transport to the decontamination plant has been considered.

Concrete pilling was calculated based on the number of pilling found in the construction drawings. Figure 16 illustrated the concrete pilling of Prisma building.

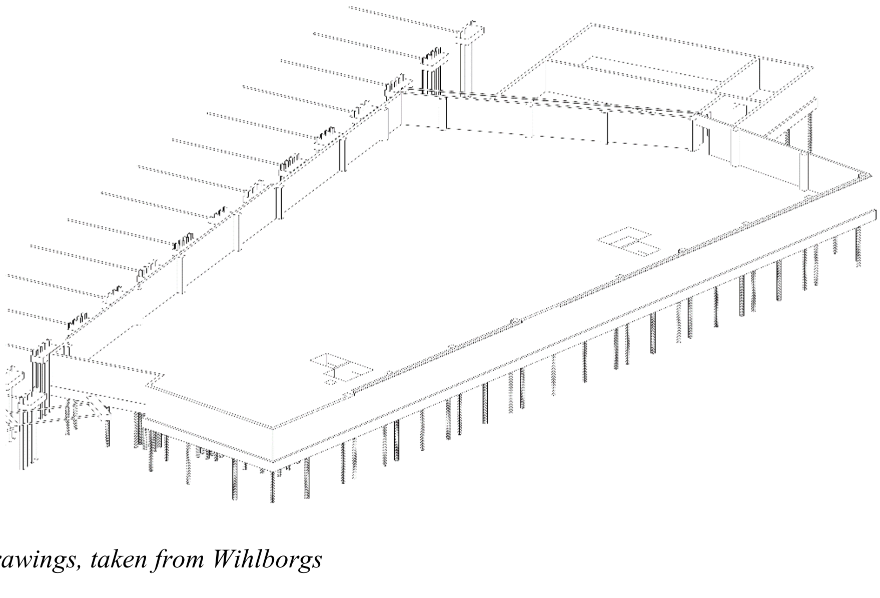

Figure 16, Pilling drawings, taken from Wihlborgs

The length of the pilling was estimated to be ten meters, based on a geotechnical study of the ground in the harbour area of Helsingborg (COWI, 2018). Material calculations for groundwork and foundation can be found in Appendix table 12.

Columns and beams superstructure

Prisma's structural columns and beams are prefabricated and designed by Scandinavian WeldTech (SWT). After assembling on-site, cast-in-place concrete was poured into the columns to enhance the structure further.

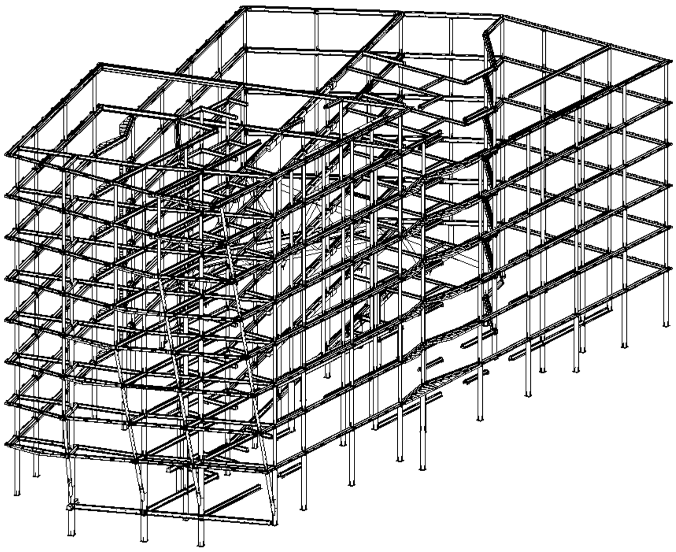

Figure 17, a 3D model of the building structure, taken from Wilhborgs

The columns and beams superstructure material were mostly calculated using a CAD model. With the help of a 3D model, the material volume needed for columns and beams was measured, and the material quantities of the construction were taken. Information about material quantification can be found in Appendix table 13.

Outer walls

The outer wall building material calculations came from the construction drawings and a BIM model. The construction drawings were used to look at the outer wall composition, while the BIM model was utilised to find all types of outer walls and calculate their area. The outer wall material calculation was subdivided into three different details, each of which was studied separately. The first studied detail was the typical socle junction detail, as seen in Figure 18.

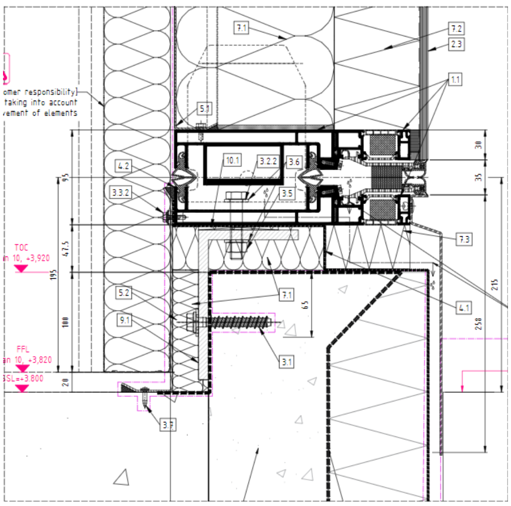

Figure 18, An example of socle detail drawn by Staticus

The socle junction calculations were made for the footprint of the building, which was calculated to be 179 m long. The calculations for the socle junction detail can be found in Appendix table 1.

The second detail studied was the typical floor junction detail, as seen in Figure 19.

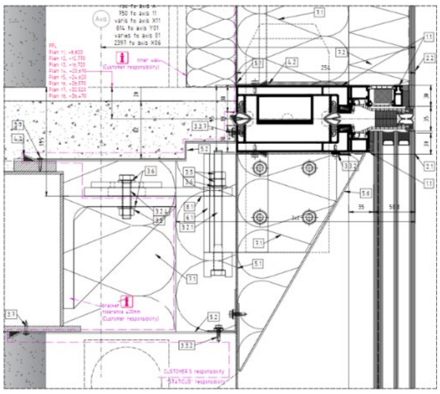

Figure 19, An example of floor junction detail drawn by Staticus

The floor junction calculations were made for all the slab connections above the street floor plan. The materials calculations for the slab junction detail can be found in Appendix table 2.

The third studied detail was the typical building system envelope wall, as seen in Figure 20.

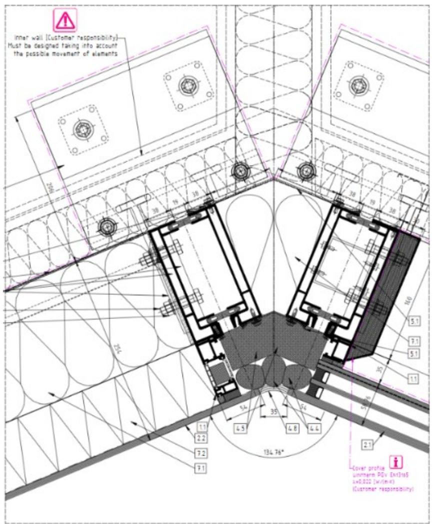

Figure 20, An example of the envelope wall detail drawn by Staticus

The system wall was divided into two main sub-details, the wall sub-detail and the window sub-detail. Both sections are built inner a triangular aluminium frame system attached to floor slabs with bearing brackets. The information on the triple glazes aluminium frame system was available by unit in One Click LCA, while the wall section had to be decomposed and accounted for each material. Figure 21 shows the analysed section.

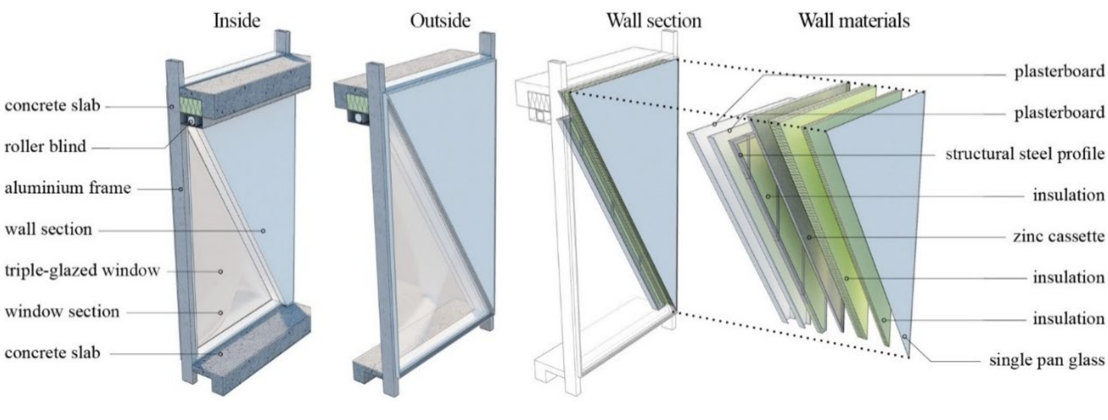

Figure 21, As-built studied outer wall section.

Calculations for the outer wall material can be found in Appendix table 3. When all the material needed for the analysed outside wall section was found, the quantity was adjusted by the square meter of the facade.

The built-in triple-glazed aluminium frame system had to be adjusted for the plain wall sub-section since this last one only had a one-pan glass covering the wall instead of the triple pans that can be found when there is a window. A separate calculation was made to remove the carbon emission of two glass pans from the triple-glazed aluminium frame system. Then, the needed system unit for the wall sub-section was adjusted to consider the carbon emission reduction resulting from a one-pan glass as a finish material instead of the triple-glazed window. The calculation can be found in Appendix table 4.

Specific material sometimes requires their calculations. For example, bearing brackets were needed to attach the triple-glazed aluminium frame system to the floor slabs. The bearing bracket was attached between the structure and the frame system with bolts, washers, and nuts. Two types of bearing brackets were used. Two different calculations (Appendix table 5 and Appendix table 6) were made to find the amount of material for the bearing bracket, and one count (Appendix table 7) was made for what we called the bolt, washer, and nut system. The same kind of calculation was used to find the amount of material for all the structural steel profiles, screws, paint, etc. (see Appendix table 8, Appendix table 9, Appendix table 10). These calculations are based on the technical drawing's information, market product information, and team assumptions. Materials calculations for outer wall materials can be found in Appendix table 3.

Inner walls

The inner wall materials were calculated using technical drawings and a BIM model. The different type of walls and their inner compositions were taken from the technical drawing, while the linear meter for each type of wall was taken from the BIM model. All material was estimated for 1 m² of wall and multiplied by the total number of m² for every type of wall. An example of an inner wall detail drawing can be seen in Figure 22.

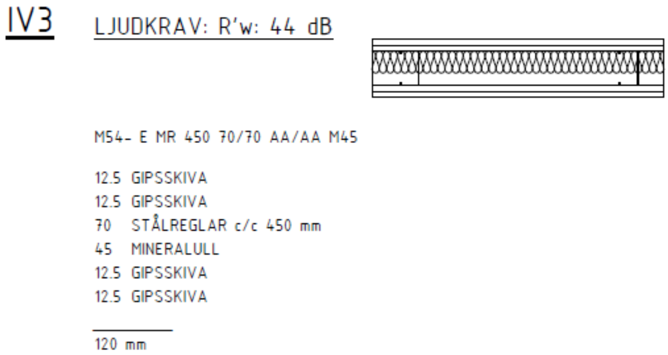

Figure 22, An example of an inner wall detail drawing by EGA.

The material calculation strategies used were similar to the ones used for the outer walls. Each inner wall material was taken into account.

Inner glass partitions and inner doors were calculated based on construction drawings and a BIM model. Using a Revit file, the amount of area for different glass partitions and doors was quantified. Then, depending on the material of the partitions and doors, the amount of material used was assumed based on an EPD retrieved from One-Click LCA. Materials calculations for inner walls can be found in Appendix table 17.

Floor structure

The floor structure was made of prefabricated hollow concrete slab modules designed and produced by COWI as seen in Figure 23. Floor slabs of this building were divided into many different sizes of slab pieces to allow prefabricated production and transporting to the site for construction. All the data and information on the slab, including the weight of the concrete, the reinforcement steel for slabs, and other steel connections, were adopted from the COWI list of components. Material quantities for slab structure can be found in Appendix table 18.

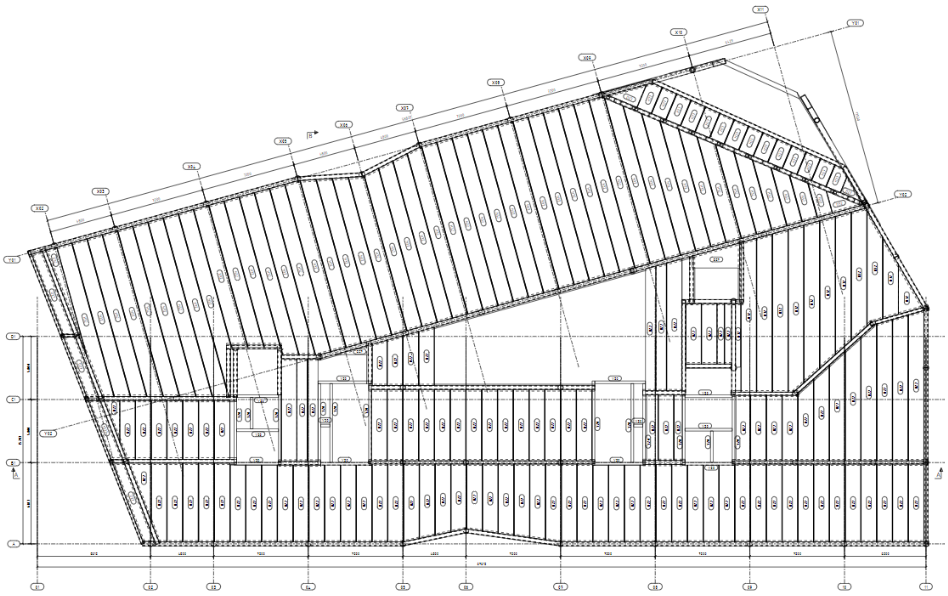

Figure 23, Prefabricated concrete slab design of Prisma building

Outer roof

The outer roof material calculations were based on the construction drawings and a BIM model. The construction drawings were used to find out all types of outer roofs we encountered over the roof slabs, and the BIM model was used to determine their position and area. Six different types of outer roofs were analysed, the generic one with or without solar panels, the terrace roof, the green roof, the underground roof, and the glass roof. Additionally, a calculation was made for outer roof borders and gutter. Figure 24 shows one roof detail. Materials calculations for outer roofs can be found in Appendix table 19.

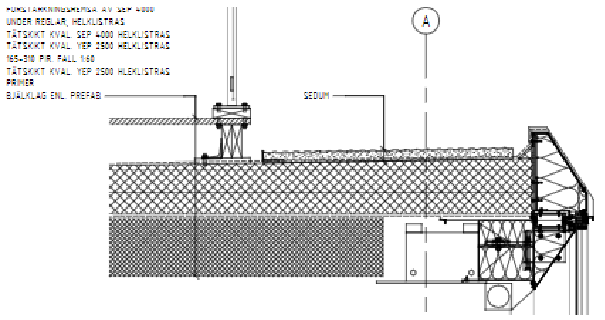

Figure 24, One detail drawing of the outer roof composition

Sanitary equipment

The only inner integrated equipment that was included in the material calculation was the restroom fixtures. This included toilets, sinks, and showers but excluded all other equipment, such as paper distributors or safety assistance equipment. On a larger scale, kitchens as well as special tenants' equipment, were not included in the material calculations. Materials calculations for restrooms can be found in Appendix table 20.

Temporary work

Temporary work includes scaffolding and a temporary elevator. Information about temporary work was provided by the contractors. Materials calculations for temporary work can be found in Appendix table 21.

Electricity energy

Operational electricity for the year 2022 was given by Wihlborgs. The energy production from solar panels that can compensate for the electricity needs of the building was calculated from the given information. Cross-check calculations on electricity calculation were made using System Advisor Model (SAM). The as-built scenario includes the minimum area of solar panels that was needed to be certified by Miljöbygnnad.

Electricity system material was used within OneClick LCA. Information about that system can be found in Appendix table 22.

Heating and cooling

Heating and cooling energy needs were given by Wihlborgs. Heating and cooling system information was calculated and quantified based on a 3D model and a list of MEP drawings. This information can be found in Appendix table 23.

Ventilation system material

Ventilation system material information was calculated based on a 3D model of the building system and a list of drawings regarding system information, as can be seen in Appendix table 24.

3.2 OneClick LCA calculations

One Click LCA was merely one component of the LCA calculation. It must include all information supplied by the city of Helsingborg and take into account specific formulations for energy calculation using the ZEB method. Excel was used to compile the data and extract the desired results.

One Click LCA

The most important GWP calculation was generated using One Click LCA. Materials and their related EPD were chosen in the following order to generate the most accurate results.

Exact material > similar material >
Swedish generic material > Scandinavian generic material > EU generic material

In One Click LCA, it is possible to adjust some elements of the material EPD, such as transport. Generally, the transport was kept as suggested by the program. However, for the main component of the building, such as precast concrete, steel structure, and aluminium glass frame system, transport impact was adjusted to consider where these elements were fabricated. Since the three factories have easy access to rail and maritime transport, and since the construction site was literally in the Helsingborg harbour, it was assumed that trains and ships would be utilised (

Table 4).

Table 4, Main building element factory location and transport

Main building element factory location and transport

building element	**location**	**train km**	**ship km**
Prefabricated concrete element	Kaunas, Lituania	200	624
SWT system (steel structure)	Rostock, Germany	0	225
Triple-glazed aluminium frame system	Bellengberg, Germany	800	225

3.2.1 LCA as-built scenarios

Carbon emission value for heating, cooling, and electricity

Heating and cooling carbon emissions calculations come from the data that was available for Helsingborg in One Click LCA. ZEB does not use a linear decrease of carbon emission through the years like the one used for electricity production, as seen in section 2.3.

For the Helsingborg calculations, the adjusted numbers explained in section 2.10 was applied. The numbers are based on the assumption that the energy production of Helsingborg will be carbon neutral in 2030 (Öresundskraft, 2022).

As seen in section 2.3, ZEB uses a European electrical grid average with a linear decrease in carbon emission to zero in 2060. The result from Dokka was extrapolated for the studied project using the year the studied building was functional as a starting date (Dokka, Lien, et al., 2013).

Figure 25 shows the extrapolated average of carbon emissions for the European electricity grids based on Dokka's study (Dokka, Lien, et al., 2013).

With a starting date of 2010, the European electricity grid average value was 132 g CO_2e/kWh. The extrapolated number used for the studied project in 2022 has a starting date was 74 g CO_2e/kWh, similar to the 75 g CO_2e/kWh used by Razna and Tasnia (Razna & Tasnia Aive, 2022). This number was also extrapolated from 2022 as a starting year, as shown in Figure 25.

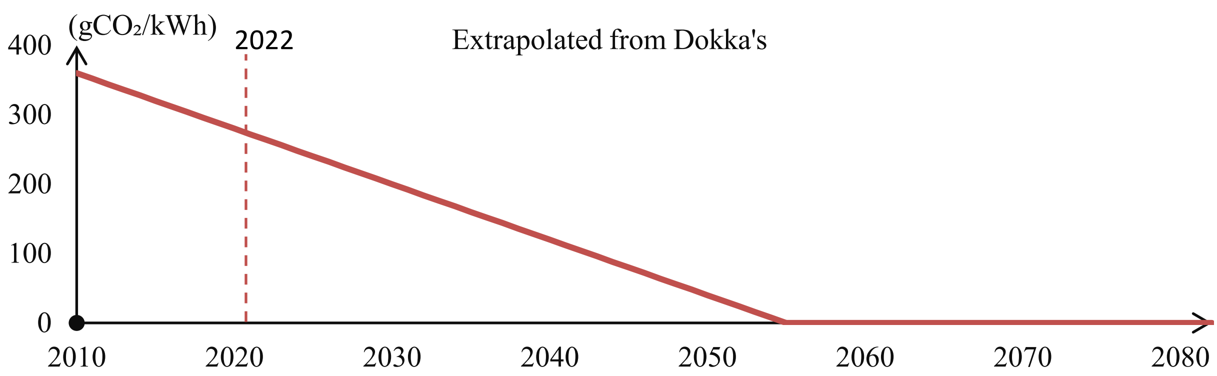

Figure 25, Extrapolated electricity grid average, following ZEB methods.

ZEB considers energy from solar panels to be carbon-free. It means that the amount of kWh/hour produced annually by the solar panel system is removed from the amount of kWh/h needed annually by the building. Some calculations were made to look at if the as-built scenario has a carbon emission reduction by having a solar panel system. The first calculation was to find out how much g CO_2e would be emitted annually if the Helsingborg electricity grid was the only electricity supplier for Prisma. The annual electricity needed is 282 706kWh. The electricity grid average value use was 74 g CO_2e/kWh. The total annual carbon emission was 20 800 kg CO_2e per year. The as-built scenario includes 320 m² of solar panels, which total 57 940 kWh per year. The reel electricity needs to become 224 766 for a total of 16 537 kg CO_2e annually. The solar panel system emitted 827 kg CO_2e per year. When the total electricity needs carbon emission is compared with the real electricity needs carbon emission, the carbon emitted by the total electricity need scenario should be higher.

20 800 kg CO_2e per year >17 736 kg CO_2e per year (16 535 kg CO_2e per year +827 kg CO_2e per year)

It means for the As-builts scenario, that instead of the 74 kg CO_2e/m^2 carbon emission for a scenario without solar panel, the total carbon emitted is 62 kg CO_2e/m^2 with solar panel, with 12 kg CO_2e/m^2 reduction.

Throughout the entire life cycle of the building, the solar panel system has to be changed once. As mentioned in the literature review, ZEB stated that the carbon emissions for the replacement system could be reduced in half (Fufa et al., 2016). This was considered when calculating the carbon emitted by the solar system panel through the entire life cycle of the building.

Calculation 01_ KTH study method

To have comparative numbers with the KTH study, it was necessary to adapt our calculations to their calculation methodology. For example, ancillary material was not taken into account. it was also uncertainty about how A4, A5 energy and A5 spill was calculated. The numbers from our study were not comparable with them for A4 and A5 energy. It is why it was decided to use an average of their number for A4, A5, and A5 energy. Appendix table 28 shows the numbers used for the KTH study.

Calculation 02_ZEB-Complete method

The ZEB-Complete calculation is mostly the same as the standard EN 15804 (EN 15804, 2019). Everything is calculated except integrated fixtures, furniture, tenants, and occupant add-ons. As explained in section 2.6.2, the electricity calculations considered the entire European energy grid and assessed energy produced at the site. Due to time restrictions, the calculation in this study differs slightly from the ZEB calculation. For example, some sanitary equipment was calculated, but the fire emergency system was left outside.

Calculation 03_ Helsingborg assumptions method

The Helsingborg calculation used the ZEB-Complete method but used the Helsingborg energy production carbon emission by g CO_2e/kWh adapted to the early goal of carbon neutrality (2030) through carbon capture and storage technic (see section 2.10).

3.3 Gap to carbon neutrality

After compiling all material in One Click LCA and combining through Exel all LCA calculations, it was possible to find how far the building was from carbon neutrality.

3.4 Design changes

As seen in section 2.2, until recently, emphasis was put more on energy efficiency and less on building materials' GWP impact. Since, Swedish Authorities, through regulation, have increased minimum requirements for building envelope *U*-values and energy efficiency. Parallel to those changes, the average European, Swedish, and local energy grid, as well as cities' energy equipment for distributed heating and cooling, have gained in efficiency and have reduced the emitted carbon (IEA, 2020). It results as it is now the embodied carbon in the building material that accounts for the most significant part of GWP through the life cycle of newly built Swedish buildings. The studied building follows this direction, with this 66 % of carbon emission from materials from the ZEB complete LCA. Building energy requirements will only become more assertive in years to come, accentuating the shift from energy to materials as the biggest carbon emitter. It is why the study focuses on material building changes. Building envelope, superstructure, and slab construction are three of the most important carbon emitters of the studied project.

The first element studied in building change was replacing the glass and stone wool insulation from the outer wall of the building with straw insulation and lime plaster.

Then, the study turned to concrete and steel building structure replacement with CLT structure elements. The goal was to replace steel and concrete with a much lower embodied energy material (Yue Chen, 2012). This change implied designing a preliminary CLT structure where loads are considered. Standard EN 1991-1-1:2002 was used for load calculation, and Calculatis ® (engineering software for timber construction), developed by *Stora Enso* (provider of renewable products in packaging, biomaterials, and wooden construction material), was used for wood sizing calculation (*Stockholm, Sweden, Stora Enso*, 2023). It was decided to keep the same frame as the as-built structure to shorten the time passed on load calculations. By doing that, the new preliminary design structure is not designed to maximize the use of the resources compared to the steel and concrete structure, which professional structure engineers designed with efficiency in mind. Every newly designed structure element is also overdesign since assumptions and calculations on loads were made to meet the most significant load needs. For simplification purposes, since both the steel and concrete structure and the wood structure have steel connectors, anchors, and linked elements, the choice was made to keep the ones used in the as-built scenario for the design change scenario. The wind load and torsion were not taken into consideration due to lack of time and knowledge. However, the new structure was oversized compared to the necessary amount of materials. Therefore, the excess amount of material can compensate with the material needed for bearing wind load and torsion.

Wall envelope modifications

Figure 26 shows the material change that was made on the existing wall. This design change was made in collaboration with Ecococoon and used their technology, which consists of light wood frame modules filled with compacted straw, to replace the wall structure and the insulation. The one-pan glass outside finish of the as-built outer wall scenario was replaced by an outside wood finish.

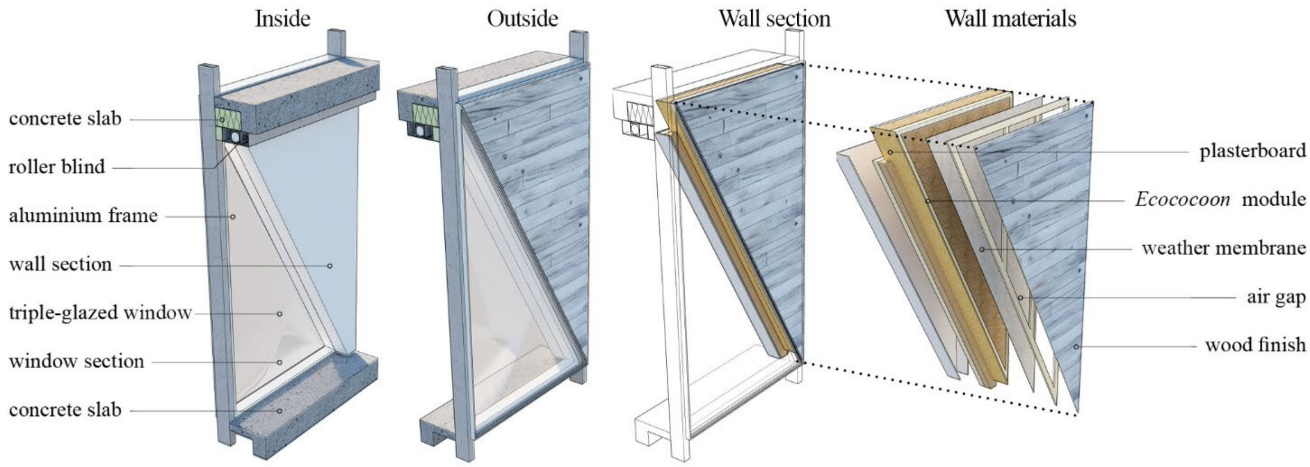

Figure 26, Improved studied outer wall section.

The heat conductivity of straw differs from rock wool insulation which implies designing the new wall construction nine cm thicker than the original wall. It is essential to mention that the team didn't look at any cost for the new measure or losses of m² floor area. When carbon emission thresholds will be implemented on building materials and more robust requirements are implemented on energy use, it will result that more square meters of possible floor area will be used for the building envelope. New material calculations are compiled in Appendix table 11.

Slab modifications

The first structural design change to the CLT structure that was made was the slab design. Slabs loads are relatively easy to calculate compared to the pillar and beam structure, and slabs represent an important part of the building materials. A similar design to the existing concrete slab design was chosen for simplification purposes. The loads applied to the slabs in Calculatis® was the one seen in Table 5.

Table 5, Applied loads on roof and floor CLT slab

Loads apply to CLT slab in Calculatis® based on Standard EN 1991-1-1:2002 for office buildings.

Element	live load kN / m²	Element	dead load kN / m²
Snow	1	Solar panel system	0,15
Roof	1,5	Green roof system	0,5
Floor	3	Innerwall	1
		Floor	1
		Ceiling + ventilation	1
		Roof cover system	1

The engineering software adds to the load calculation the self-load of the CLT slab chosen.

Load and wood sizing calculations for the new CLT slab were made for two lengths, 13,5 meters, and 6 meters, two representative sections of the floor plan, as seen in Figure 27. Each slab type accounted for approximately 50 % of all floor areas.

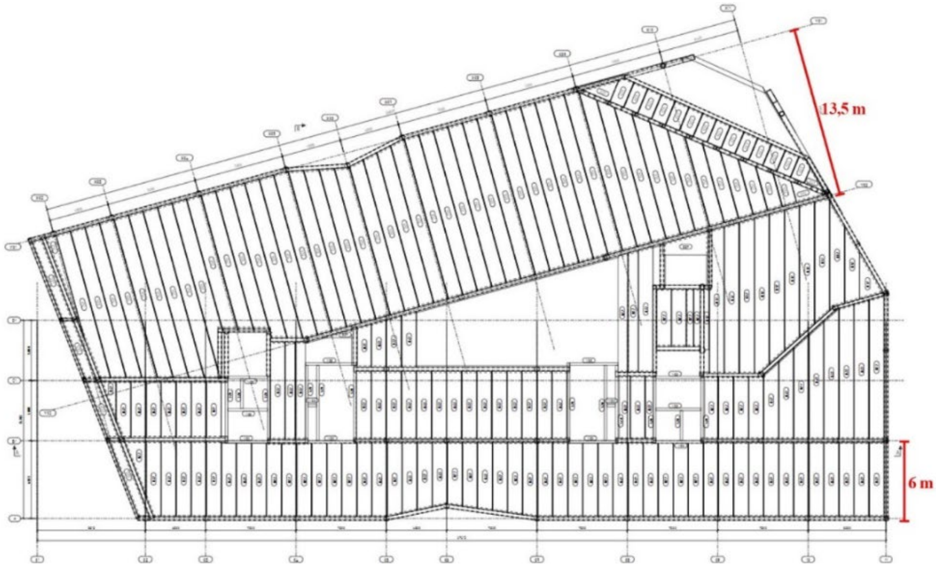

Figure 27, Typical floor plan showing concrete slab modules

To save material and have a slab panel as long as 13,5 *m*, a CLT rib slab panel was chosen. It is important to remember that the new wooden elements are preliminary designs, should eventually be properly designed with the ventilation system in mind, and can use less material when designed by a professional structural engineer. For the calculations, the rib slab panels used were as seen in Figure 30.

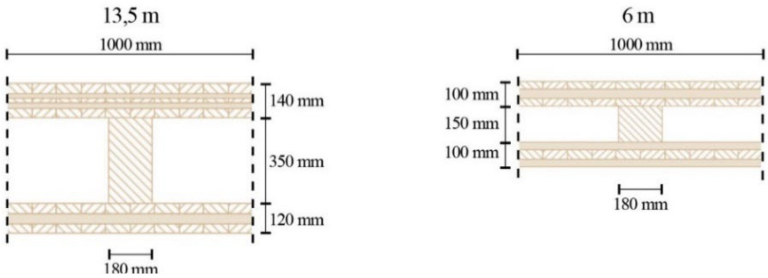

Figure 28, CLT rib panel slab sizing by Calculatis®

Side beams can be perforated to allow pipes, ventilation, etc. A rib slab panel can also be designed without the under CLT panel if necessary for the ventilation system. The material needed for both modules was then normalised by m² to simplify the wood calculation needed for every floor and roof slab. Figure 29 emphasizes the CLT floor and roof slab in the building. Slab calculation can be found in Appendix figure 1 and Appendix figure 2.

Figure 29, Floor and roof CLT slab changes

Structure modifications

CLT replacement was then extended to all the building's structural parts. The beam sizing was calculated using the load coming from the slab, as seen in Figure 30.

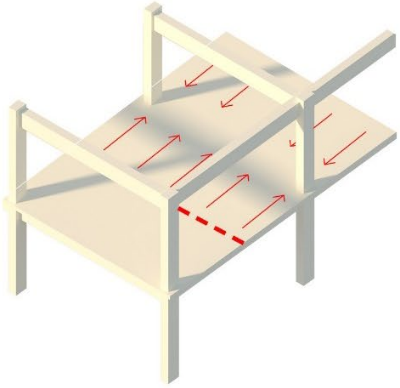

Figure 30, Calculated loads from slab to beam

The slab loads were passed to the beam, and the calculation was made for the most significant beam covert area. Simplification was made to accelerate the process. When beams were by the side of the building's outer wall, it was assumed that the load for the outer wall would not be higher than the half slab, which was not taken into account, as shown in Figure 31, only two sizes of pillars were designed with the most significant possible load for each of them.

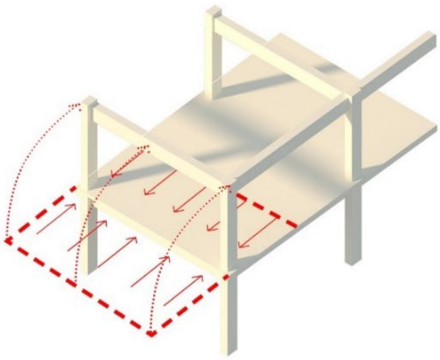

Figure 31, Calculated loads for beam surrounding the studied building

Figure 32 shows the preliminary design of the CLT superstructure replacement. Beam calculation can be found in Appendix figure 3 and Appendix figure 4.

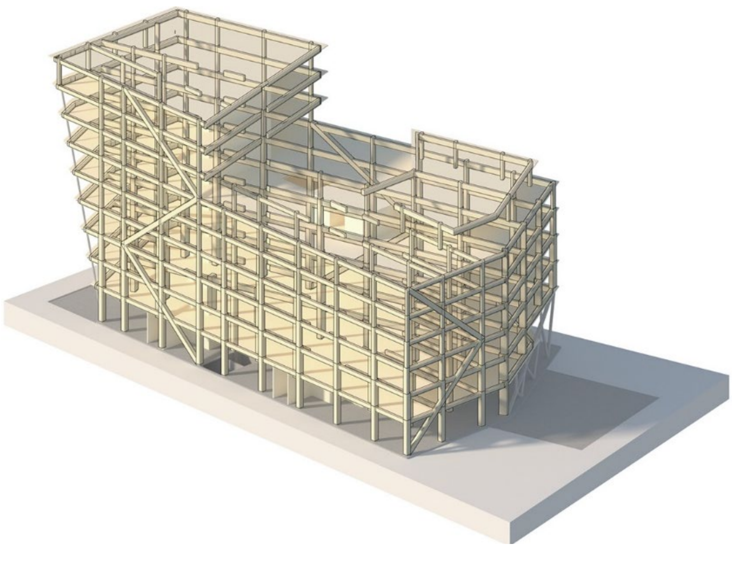

Figure 32, Superstructure, CLT pillars, and beams changes

The calculations for the pillars' sizing considered two loads, one coming from the beam and one from the pillar, which was passed to the supporting pillars, as seen in Figure 33.

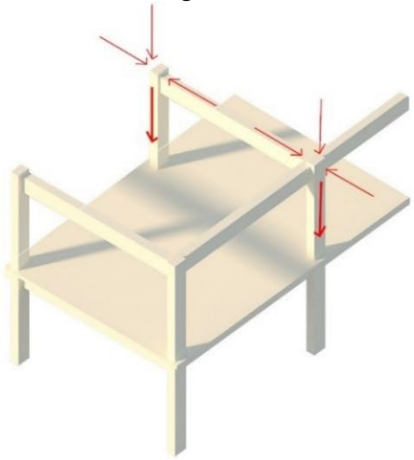

Figure 33, Calculated loads for pillars

Simplification was made on pillar calculation, and only two-floor areas were considered for pillar sizing design, with the most significant possible load for each of them. One floor area was 7,5 m by 13,5 m, and the other was 7,5 m by 6 m. Pillars were designed for every floor to take into consideration load accumulation. Calculations for the pillars can be found in Appendix figure 5 to Appendix figure 13. Caution should be taken while looking at the Calculatis sizing sheet in the Appendices section. For pillars C14 13.5, C13 6, C13 13.5, C12 6, C12 13.5, C11 6, C11 13.5, C10 6, and C10 13.5, because of sizing restriction through the calculator program, the load was divided by two; therefore, two calculated pillars should be considered instead of one.

Core walls modifications

The concrete core walls were the third structural element that was replaced with CLT panels. Similar load calculations as the pillars and beam structure were made for the new CLT wall. The new CLT core wall can be seen in Figure 34. The core wall sizing calculation for the ground floor can be seen in Appendix figure 14.

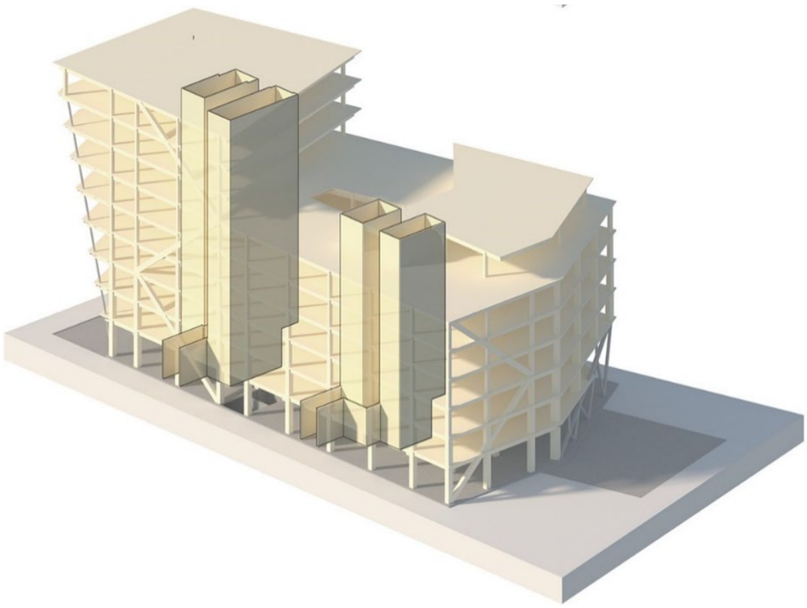

Figure 34, Core wall, CLT wall changes

Stair's modifications

The emergency staircases were the last structure that was replaced with CLT. The same panel thickness as the core wall was chosen for the stairs structure to ensure fire requirements. The new stair design can be seen in Figure 35.

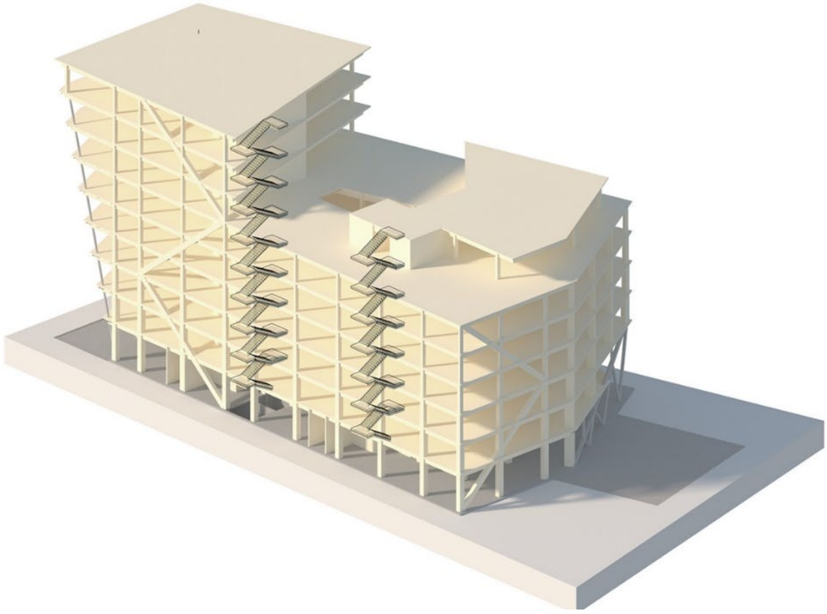

Figure 35, Staircase, CLT stairs change

The total amount of wood resulting from the design change to CLT element was 4915 m^3. This quantity of wood was used in One Click LCA to replace all the concrete and steel structures that were removed for the design changes in an improved scenario. Figure 36 shows the complete structural change that was made. It can be noticed that two structural steel element was kept where the as-built design was complex.

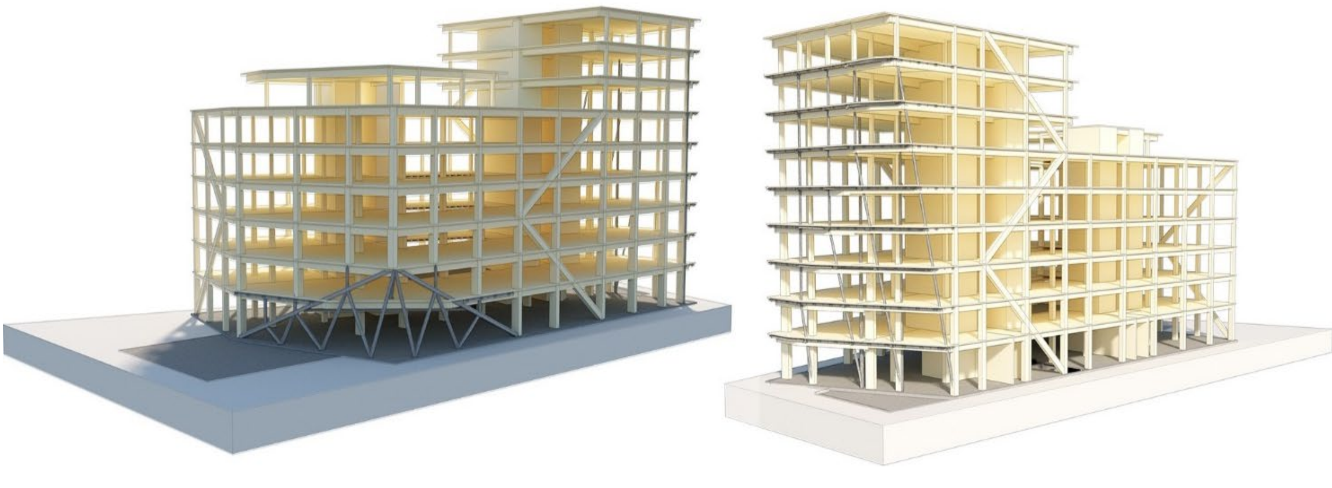

Figure 36, Improved scenario superstructure

Green roof and solar panels

Solar panels and green roofs should be considered in the northern regions of Europe to reduce carbon emissions from buildings. As stated in section 2.8.3, while embodied carbon from the equipment and the maintenance of the solar panels can be a concern, they are also generating carbon-free energy. Green roofs act as an extra layer of insulation and reduce de facto energy use in buildings. It also has the potential to be used as a carbon sink when biomass is discharged properly. When both green roofs and solar panels are built together, solar panels are generally more efficient. Therefore, a case implemented a full green roof, which was 1 045 *m²*, on the roof area was evaluated in terms of carbon emission.

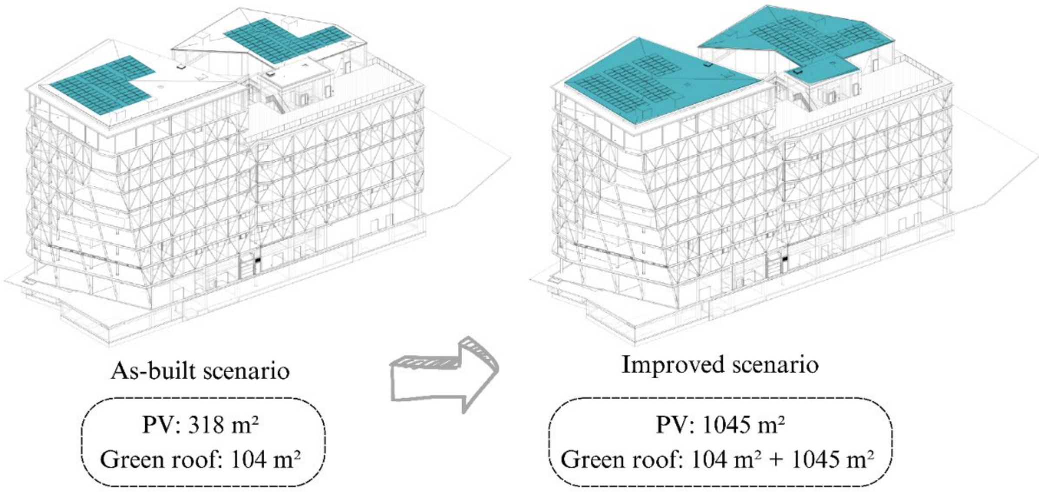

Figure 37, Solar panels and green roof changes

A similar redesign was also applied to the PV panel, with full potential, on the roof. To account for the carbon emission from electricity, and see if it was wise to extend the solar panel area, comparisons with the total electricity needs carbon emission numbers were made. As explained in the as-built scenario, the solar panel system section's total carbon emission for the annual electricity needed was 20 800 kg CO_2e. With the improved scenario, the solar panel area is now 1045 m² with a total annual production of a total of 189 301 kWh. The real electricity needs become 93 405 for a total of 6 872 kg CO_2e annually. The solar panel system emitted 2 712 kg CO_2e per year. When the total electricity needs carbon emission is compared with the real electricity needs carbon emission, the carbon emitted by the total electricity need scenario should also be higher.

20 800 kg CO_2e per year >9 584 kg CO_2e per year (6 872 kg CO_2e per year +2 712 kg CO_2e per year)

It means for the improved scenario, that instead of the 74 kg CO_2e /m² carbon emission for a scenario without solar panel, the total carbon emitted is now 34 kg CO_2e /m² with solar panel, with 40 kg CO_2e /m² reduction.

Throughout the entire life cycle of the building, the solar panel system has to be changed once. As mentioned in the literature review, ZEB stated that the carbon emissions for the replacement system could be cut by two (Fufa et al., 2016). This was considered when calculating the carbon emitted by the solar system panel through the entire life cycle of the building.

Biochar

The calculation of biochar from straw was based on the data coming from EBC (H.-P. Schmidt et al., 2020). As said in the literature review, carbon can be stored in biochar. To create biochar, biomass is needed. One biochar scenario was to transform the straw implanted as envelope insulation into biomass. A calculation from EBC about crops like hay being transformed into biochar specifies that one ton of biomass is needed to create 300 kg of biochar. It is also explained that around 70 % of the biochar is carbon, as seen in section 2.8. To know the kg CO_2e, the calculated carbon has to be multiplied by a factor of 3,67. The estimated amount of straw used in this design change was 108 tons, which gives 32 tons of biochar for a total of 83 tons of CO_2e [2]. It represents 5 kg CO_2e /m² of carbon stored when the building will be dismantled.

Studies on end-of-life scenarios for CLT and other engineered timber frame technology are not numerous because it is a new technology, and produced materials didn't reach the end-of-life stage. One study from Chalmers has analysed how many times, depending on the type of joint, a CLT panel can be reused through a minimum of 100 years long lifetime (Ljunge & Silfverhjelm, 2022). Based on their result, it was assumed that the CLT would be reused at least one time after the end-of-life of the building. Since the panels were reused once, the A1 to A3 carbon emission for CLT was cut by two in the results. It was also assumed that one day or another, after multiple uses, it may not be possible to reuse this wood again, and it may be transformed into biochar. It is an unverified assumption that will also happen in a significant number of years, where it is unclear if the bond product between all the CLT planks would negatively impact the biochar transformation process. The scenario was considered, and the calculations numbers for wood to biochar can be found in Table 6

Table 6, CLT to biochar

CLT to biochar, density:430 kg/m³, moisture 12 %, ratio 50%						
CLT m³	**dry wood kg**	**wastage ratio**	**biomass ton**	**biochar kg**	**Carbon kg CO_2e**	**Carbon kg CO_2e /m²**
4 915	1 887 009	0,1	1 698	509 492	1 302 263	**78**

As seen in the literature review, biochar can be a good soil amendment. Out of the green roof, the site project has a little space on the street level that can be used for vegetation. Since it is already considered by cities to use biochar in bushes and city green areas, this strategy was used on-site (Råberg et al., 2022). Biochar can also be mixed with green roof substrate to increase the possibility for the roof to act as a carbon sink, as stated in the literature review. Carbon capture numbers for the biochar in the ground and green roof can be seen in Table 7

Table 7, Biochar into the ground and green roof

CLT to biochar, density:430 kg/m³, moisture 12 %, ratio 50%						
position	**area m²**	**thickness m**	**volume m³**	**biochar kg**	**Carbon kg CO_2e**	**Carbon kg CO_2e /m²**
Green roof	1 046	0,1	94	18 819	48 101	**2,9**
Bushes	110	1,5	165	33 000	84 348	**5**

Environmental Product Declarations (EPDs) choice

The last case of this study was to see how EPD choices can affect the CO_2 emission in total. With the help of One Click LCA, it was possible to identify the most material contributor to carbon emission, and some better EPDs were advised. Table 8 shows the original and replaced EPDs in different locations.

Table 8, EPD replacement based on OneClick LCA recommendation

Location	*Original EPDs*	*Replaced EPDs*
Floor slab	Ready-mix concrete for hollow-core concrete slabs, C40/50-C50/60, CEM ll/A-V 52.5 N	Ready-mix concrete, C40/50 (B40 MF45), B45MF40LA - UL62A-B000 - Sjursøya (Unicon AS)
Roof steel beams	Hot-finished steel hollow sections, 7850 kg/m3	Rolled steel profiles, plates, and hollow sections, S235-S700, 7850 kg/m3 (UPB)
Ceiling	Suspended metal ceiling system, 5.901 kg/m2	Steel ceiling system, 6.83 kg/m2 (TAIM)
Concrete pile, foundation	Concrete piles, rectangular, 235x235 mm, C50/60, XC2, XF1, reinforcement 4 st. Ø16 (Skanska)	Precast concrete piles, 235x235 mm, 133 kg/m, HP 235-0416V (Hercules Grundläggning AB, Västerås plant)

3.5 Improved *scenario_LCA calculations*

After completing all the design changes and adjusting the material calculations in One click LCA, new LCA calculations were made for the KTH/ Boverket method, the ZEB complete method, and the Helsingborg method. One scenario was created in the GHW calculation software for every studied design change. All the new results were compiled, and the final three LCA calculation methods for the improved scenario were compared with those obtained for the as-built scenario.

4 Result

4.1 As-built result scenario

Results show calculations based on the KTH/Boverket study, the ZEB-complete LCA, and the Helsingborg energy carbon emissions data. But before introducing them, it was important to acknowledge the carbon emitted for every stage of LCA calculation for the studied building following the ZEB-Complete, as shown in Figure 38.

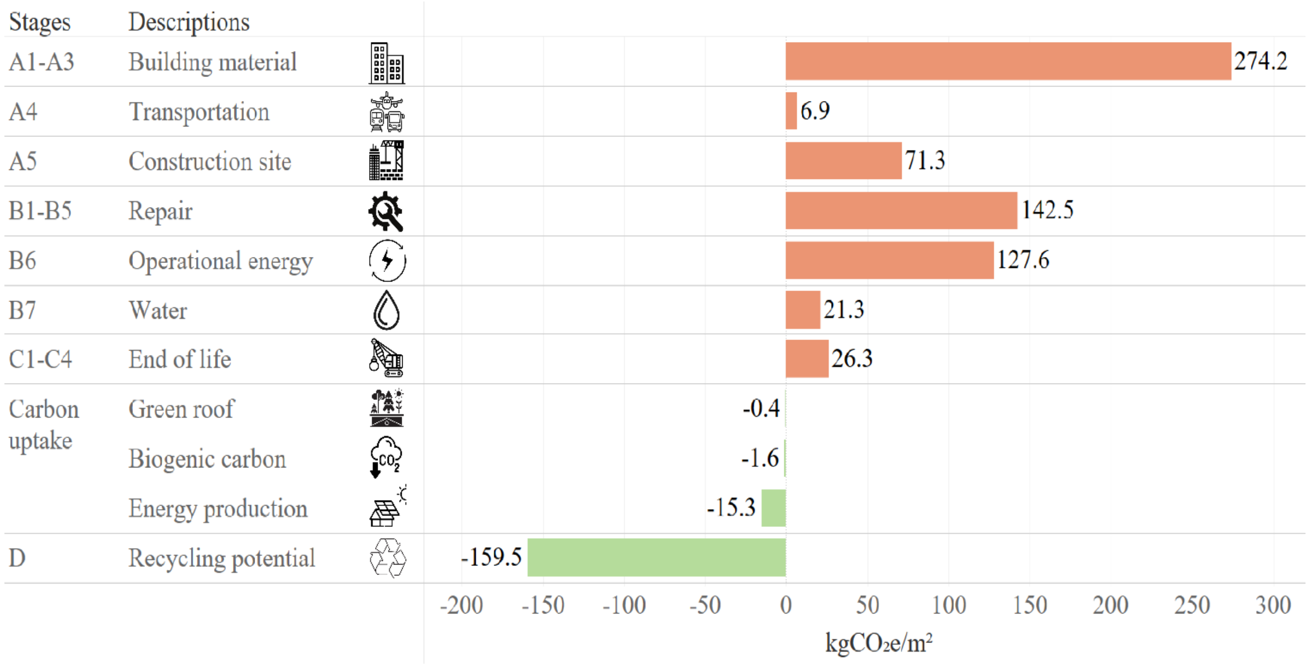

Figure 38, LCA calculation of Prisma following ZEB-Complete level

Figure 38 indicates the carbon emission in the analysed building based on LCA phases with ZEB-Complete level. The highest impact in this building, as shown in Figure 38, was the building material, which is A1-A3 phases in LCA, with 274,2 kg CO_2e/m^2. The following impact was B1 to B5, with 142,5 kg CO_2e/m^2 emission. The impact of operational energy use, which is B6 stage in total, was 127,6 kg CO_2e/m^2. This value will be compensated by the energy production from PV panels, which was -15,3 kg CO_2e/m^2. According to this graph, the most considerable impact of this building is the A1-A3 LCA stages.

Biogenic carbon from the as-built scenario was from all the wood, like interior doors, wood flooring, and piece of wood studs. These types of wood were glued and stuck with other materials, making it hard to recycle them, and in most cases, the end-of-life scenario of these woods will be burnt. According to the ZEB-Complete level, that end-of-life scenario will be seen as releasing the biogenic carbon that was once stored in the wood back into the atmosphere. Therefore, in further study, the amount of original biogenic carbon will be eliminated and not accounted for other types of carbon sequestration.

Figure 39 shows the contribution in carbon emission of different building parts in terms of the A1 to A3 life cycle stage. In total, the building production phase accounted for 274 kg CO_2e/m^2. The highest impact was the horizontal structure, which was slab and ceiling, with 40% in total. The building system was following with 17,9% in carbon emission. Foundation, facade, and superstructure accounted for 8,1%, 13,5%, and 10,8%, respectively, in terms of carbon emission in buildings.

The highest contributor categories, like vertical and horizontal structures and facades, should be redesigned to reduce carbon emissions.

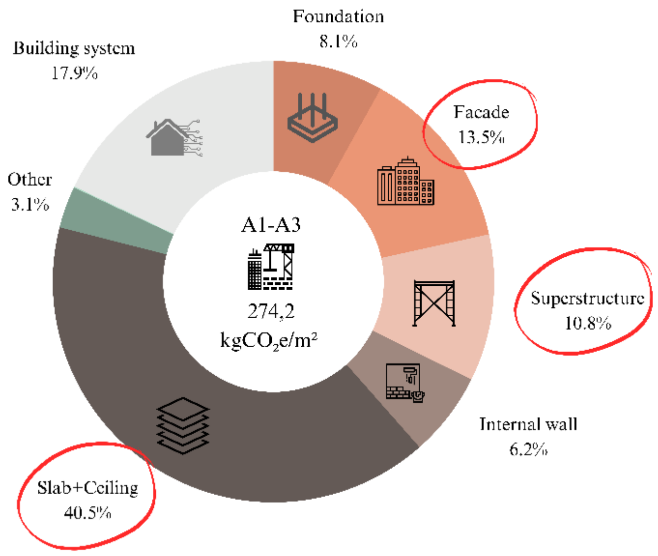

Figure 39, Contribution of different aspects of A1-A3 stages, following ZEB-Complete level

KTH /Boverket study comparison

The next analysed result was the carbon emitted by the building with the calculations of the Boverket /KTH study (See CO_2 Conversion Factors). The total of the CO_2e cast by the studied building during the A1 to A5 life cycle stages is compared with the studied cases of KTH Boverket in Figure 40. The KTH study's average carbon emitted was 360 kg CO_2e/m^2, and the carbon emitted by the studied building was 325 kg CO_2e/m^2. It can be noticed that the study project is situated slightly over the first quartile, which means that the building emitted less carbon than the average of other similar buildings in Sweden.

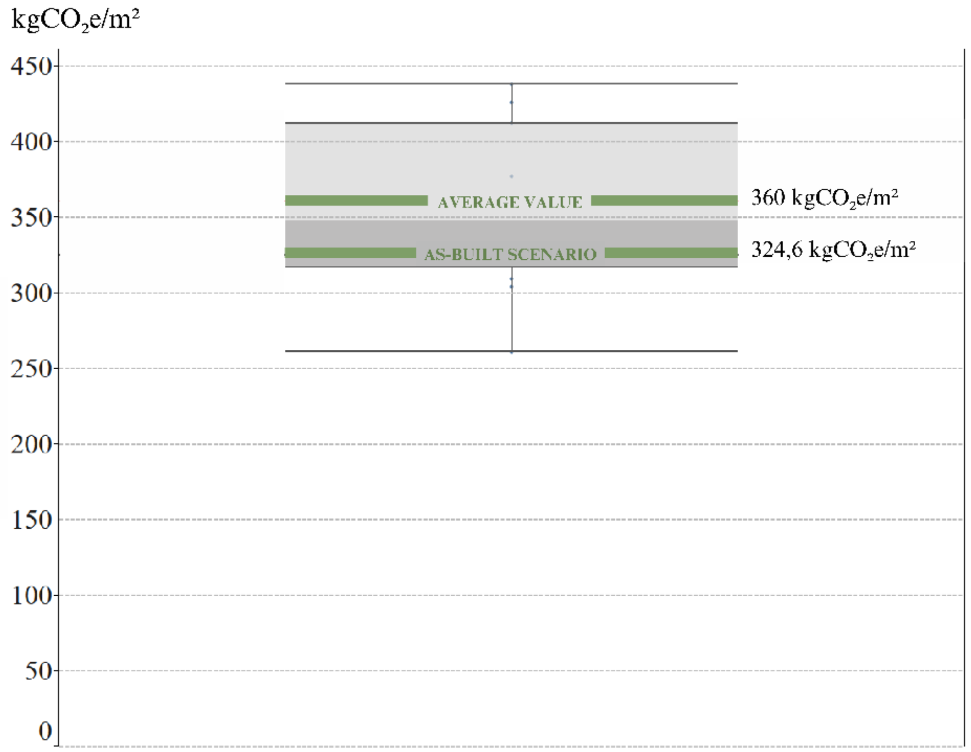

Figure 40, Emission comparison between analysed building and KTH study in a box plot

Carbon neutrality gap

Calculating the complete LCA gives the amplitude of the work that must be done to reduce building carbon emissions. Table 9 resumes the carbon emission calculation for every stage and includes carbon storage.

If carbon neutrality is defined as 0 kg CO_2e/m^2, then Prisma has 494,9 kg CO_2e/m^2 as the gap to the carbon neutrality. This result includes the energy production from PV and the recycling potential of materials in the building.

Table 9, LCA calculation of the building following ZEB-Complete level

Stages	**Description**	**As built (kg CO_2e/m^2)**
A1-A3	Building material	274,2
A4	Transportation	6,9
A5	Construction site	71,3
B1-B5	Repair	142,5
B6	Heating	51,4
B6	Cooling	1,5
B6	Electricity	74,7
B7	Water	21,3
C1-C4	End-of-life treatment	26,3
D	Recycling potential	-159,5
Carbon storage	Green roof	-0,4
	Energy production	-15,3
	Biogenic carbon	-1,6*
TOTAL		**494,9**

**Biogenic carbon will not be accounted for in total*

Helsingborg calculation

The Helsingborg calculation uses the same data as the ZEB complete calculation except for energy. The heating, cooling, and electricity use the Helsingborg data assuming that carbon capture will work as planned and carbon neutrality will be reached in 2030 for energy production. With these changes in energy numbers, the total carbon emissions will be approximately 100 kg CO_2e lower than the ZEB complete LCA calculation, resulting in 395,8 kg CO_2e/m^2. Table 10 illustrates the carbon emission calculation for all stages, including carbon storage.

Table 10, LCA calculation of the building following ZEB-Complete level with Helsingborg value for energy

Stages	**Description**	**As built (kg CO_2e/m^2)**
A1-A3	Building material	274,2
A4	Transportation	6,9
A5	Construction site	71,3
B1-B5	Repair	142,5
B6	Heating	5,8
B6	Cooling	2,3
B6	Electricity	3,0
B7	Water	21,3
C1-C4	End-of-life treatment	26,3
D	Recycling potential	-159,5
Carbon storage	Green roof	-0,4
	Energy production	-0,6
	Biogenic carbon	-1,6*
TOTAL		**395,8**

**Biogenic carbon will not be accounted for in total*

4.2 Design changes

For every design change implemented, a new LCA analysis was made to understand how it impacts the carbon emitted by the building through the 60 years lifespan. Calculating all the changes individually helped to understand where efforts should be put first to reduce carbon emissions in building materials. Table 11 resumes all the implemented measures and their impact on carbon decrease.

Table 11, All implemented measures and their environmental impact following ZEB-Complete level.

Complete LCA	**Cases**	**As-built**	**Scene 1**	**Scene 2**	**Scene 3**	**Scene 4**	**Scene 5**	**Scene 6**	**Scene 7**	**Scene 8**	**Scene 9**	**Scene final**
Stages	Description	Origin	Straw exterior	CLT slab	CLT structure	CLT core	CLT stair	Green roof	Full PV	Best EPDs	Biochar ground	Total
A1-A3	kg CO_2e/m^2	274,2	265,2	246	217,3	263,4	271,8	274,8	279,4	253,8	274,2	152,5
A4	kg CO_2e/m^2	6,9	7,0	3,4	6,9	5,8	6,8	6,9	6,9	6,9	6,9	2,2
A5	kg CO_2e/m^2	71,3	71,3	71,3	70,1	71,3	71,3	71,3	71,5	70,1	71,3	69,1
B1-B5	kg CO_2e/m^2	142,5	143,1	142,5	142,5	142,5	142,5	142,5	145,4	120,9	142,5	120,9
B6	kg CO_2e/m^2	112,3	112,3	112,3	112,3	112,3	112,3	112,3	77,6	112,3	112,3	77,6
B7	kg CO_2e/m^2	21,3	21,3	21,3	21,3	21,3	21,3	21,3	21,3	21,3	21,3	21,3
C1-C4	kg CO_2e/m^2	26,3	26,0	25,2	25,1	25,9	26,2	26,5	26,4	26,3	26,3	23,1
D	kg CO_2e/m^2	-159,5	-159,5	-157,1	-120,0	-154,7	-158,9	-159,5	-161,5	-171,4	-159,5	-126,1
D-Biochar	kg CO_2e/m^2	0	-5,0**	-50,3**	-14,2**	-12,2**	-1,2**	-2,9*	0	0	-5,1*	-7,9*
D-CLT	kg CO_2e/m^2	0	0	-3,2	-0,9	-0,8	-0,1	0	0	0	0	-5
Green roof	kg CO_2e/m^2	-0,4	-0,4	-0,4	-0,4	-0,4	-0,4	-5,5	-0,4	-0,4	-0,4	-5,9
Biogenic carbon[1]	kg CO_2e/m^2	0	-13,3	-133,6	-37,7	-32,4	-3,3	0	0	0	0	-220,3
Total[2]	kg CO_2e/m^2	494,9	481,3	411,0	460,0	474,4	491,6	487,8	466,6	439,8	489,8	321,8
Saving[2]	%	0	-2,7	-17,0	-7,1	-4,1	-0,7	-1,4	-5,7	-11,1	-1,0	-35,0
Total[3]	kg CO_2e/m^2	494,9	468,0	277,4	422,3	441,9	488,3	487,8	466,6	439,8	489,8	101,5
Saving[3]	%	0	-5,4	-44,0	-14,7	-10,7	-1,3	-1,4	-5,7	-11,1	-1,0	-79,5

** Biochar implemented in A1 to A3 stages of the building.*
*** Biochar implemented in the end-of-life stages of the building, made from CLT wood and straw.*

There were two types of biochar in Table 11: biochar implemented in green roofs and landscape, and biochar created from CLT panel and straw building material. The biochar in green roofs and landscape were assumed to be bought and, therefore, accounted for its advantage in terms of carbon reduction. In contrast, biochar created from wood, after the building life cycle was completed, was not included in the calculation to avoid double counting (see 2.7).

Figure 41 shows the changes in every scenario listed, with biogenic carbon's impact. Most of the changes do not significantly reduce carbon emissions, such as a 0,7% reduction for stairs, a 0,6% reduction for green roofs, or 2,5% in straw envelopes. Examining the slabs, superstructure, and solar panel system of a building provides fascinating insights into the effect of their replacement on carbon emissions. The existing steel and concrete superstructure is maintained when the foundation is replaced with Cross-Laminated Timber (CLT) panels, resulting in a 9% reduction in carbon emissions for A1 to A5 and a 17% reduction for the Zero Energy Building (ZEB) Life Cycle Assessment (LCA). In contrast, replacing the superstructure increases the volume of building materials, as the slab is the most significant component. This increases the quantity of biochar that can be

[1] The as-built biogenic carbon was not accounted because it will be released at the end of the life cycle
[2] Biogenic carbon was not accounted for this total and saving
[3] Biogenic carbon was accounted for this total and saving

produced from wood. In addition, the solar panel system's carbon dioxide (CO_2) emissions are mitigated by the reduction in CO_2 emissions caused by solar panel energy production.

According to the aforementioned observations, the selection of replacement materials and systems substantially affects carbon emissions in building construction, with a 6% and 11% reduction in A1-A5 and full LCA, respectively. For instance, substituting concrete surfaces with CLT panels reduces carbon emissions significantly. Furthermore, replacing the superstructure may increase the volume of building materials and the quantity of biochar produced from wood. In addition, the energy produced by solar panels offsets the CO_2 emissions generated during their production, which causes the fact that the PV case had a 1,5% increase in the production stage and a 9,3% reduction in full LCA, highlighting the need to evaluate the environmental impact of building materials and systems over their entire life cycle.

Biogenic carbon plays an essential role in decreasing carbon emissions. The most impactful case was the slab case, with 133,6 kg CO_2e/m² reduction. With biogenic carbon, the final case can reach around -5 kg CO_2e/m² in the A1-A5 stages and 100 kg CO_2e/m² in full LCA, accounting for 220,3 kg CO_2e/m² in carbon reduction.

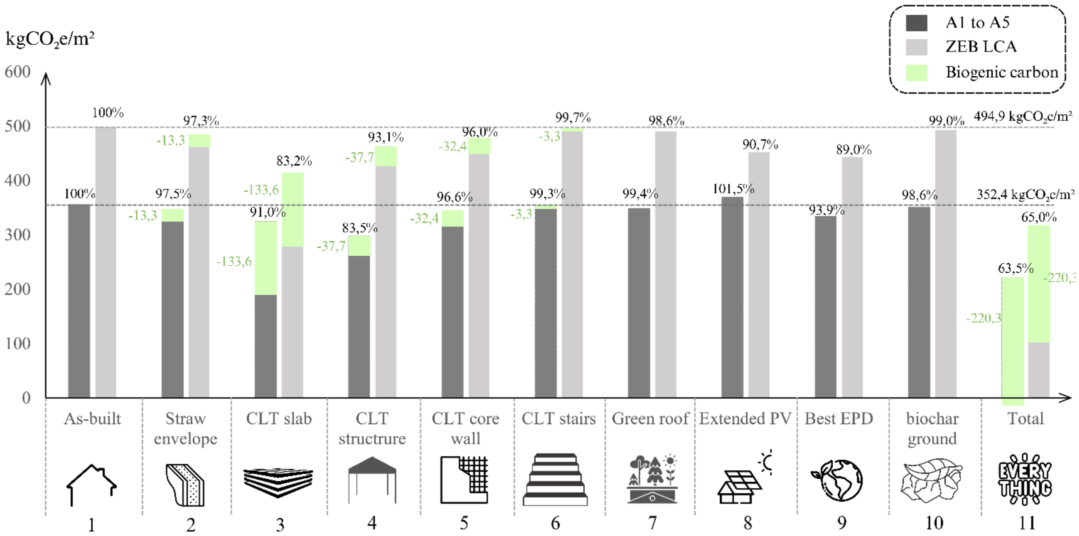

Figure 41, Comparison of each design changes between A1 to A5 and the entire life cycle following the ZEB-Complete method, with biogenic carbon influence.

Figure 42 depicts the environmental impact of various carbon emission reduction strategies, resulting in a cumulative reduction of 393 kg CO_2e/m². Biogenic carbon was the largest contributor to carbon reduction, accounting for 46,7%. Carbon emissions were reduced by 17,8% due to the substitution of concrete slabs with Cross-Laminated Timber (CLT). In addition, selecting sustainable products led to the greatest Environmental Product Declaration (EPD) and reduced carbon emissions by 11,7%. Substituting wood for concrete structures reduced volumes and beams by 7,4% and core walls by 4,2%. Ultimately, the installation of a complete Photovoltaic (PV) system on the roof led to a 6% reduction in CO_2 emissions.

The results of the analysis demonstrate the efficacy of several strategies for reducing carbon emissions in building construction. Significant contributions to the overall carbon reduction were made by biogenic carbon, which was generated predominantly through the use of wood-based materials. The substitution of concrete slabs with CLT panels and the utilization of eco-friendly materials also had a positive effect. Additionally, the substitution of timber for concrete structures and the installation of a complete PV system on the roof contributed to the reduction of carbon emissions.

For the ZEB complete calculation, the carbon emission decrease for the total life cycle of the building without and with biogenic carbon was, for the envelope, 3 % and 6 %, for the combined superstructure elements 11% and 25 %, and for the slab 17 % and 44 %, as seen in Figure 41. Another replacement measure was also experimented such as replacing the concrete and steel staircase system with CLT and extending the green roof and the solar panel to the maximum capacity. The stairs replacement represented only less than 1% or 4 % with biogenic carbon on the green roof and solar panels 11 %. The two last change was ignoring other possible carbon emission decreases.

All the cumulated design changes allowed a 35 % reduction in carbon emission without biogenic carbon and a 79 % reduction considering biogenic carbon.

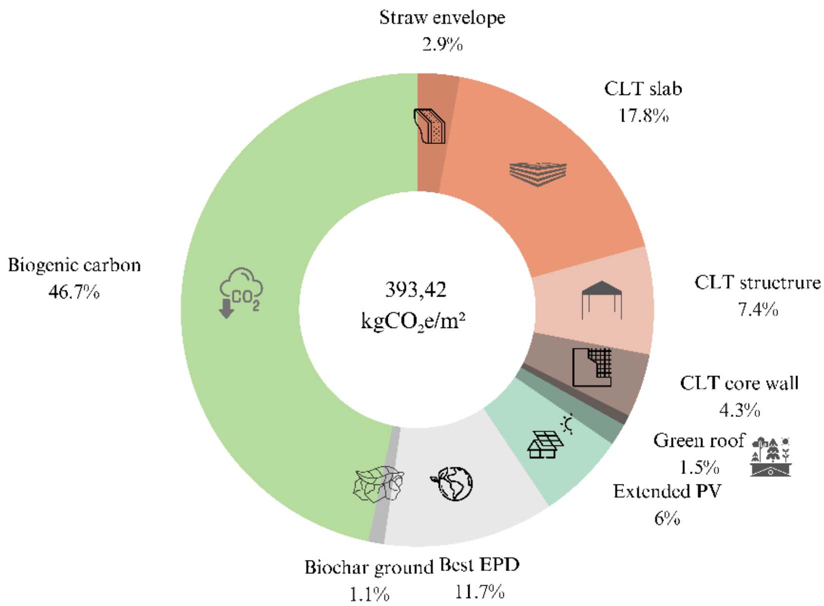

Figure 42, The percentage of different carbon compensation methods implemented in this study

Improved scenario and KTH/Boverket study comparison

With the above findings, the final case, which accounted for all other carbon reduction methods, was then compared with the KTH study once again, and also the original cases to see the improvement, as shown in Figure 43. With all the implemented scenarios, the final case reached 162 kg CO_2e/m^2, corresponding to a 50% reduction compared to the original case.

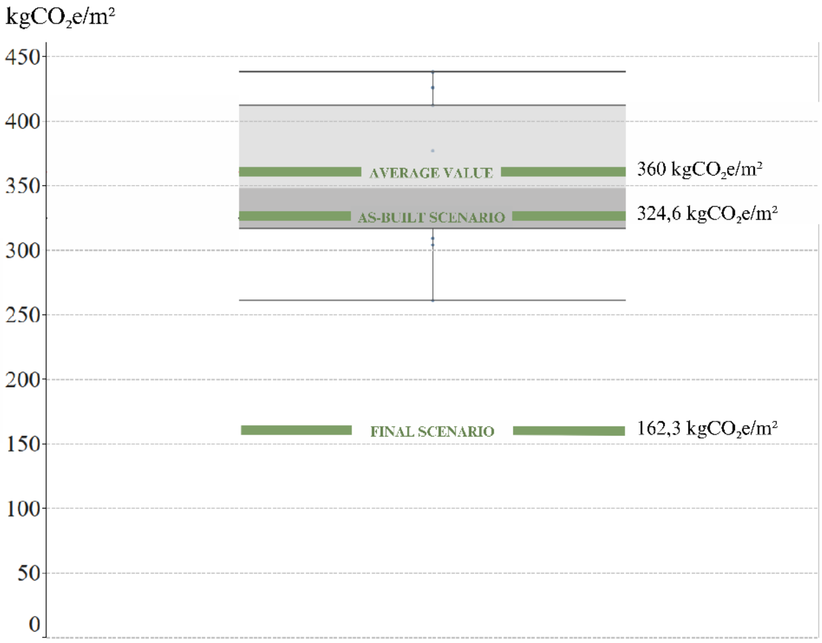

Figure 43, Comparison among KTH study, as-built case, and the improved scenario in terms of CO_2 emission

Improved scenarios with ZEB LCA

When the cumulative carbon emission reductions caused by the design improvements were analyzed, it was found that a decrease of 36% and 80%, respectively, were obtained with and without biogenic carbon reduction.

To avoid counting twice, biochar derived from landscaping, straw, and green roofs were taken into account, but biochar derived from wood construction was excluded. The as-built scenario is compared to the enhanced scenario in Figure 47, which presents a comparative study of the carbon emissions produced by each scenario.

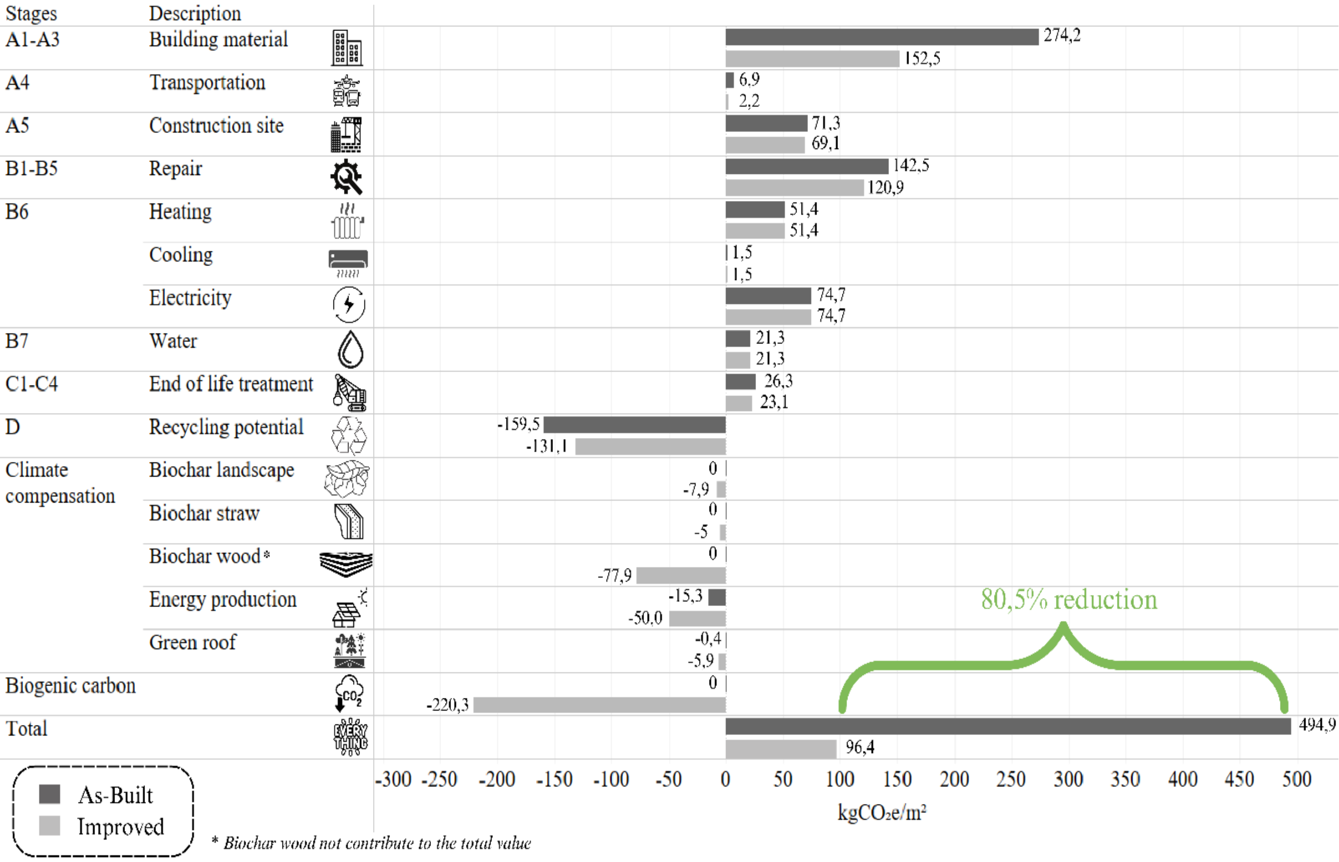

Figure 44, Carbon emission comparison between improved and as-built case, following the ZEB-Complete level

According to the findings, the most significant substantial reductions in carbon emissions occurred between phases A1 and A3, with a corresponding drop from 274 to 152,5 kg CO_2e/m^2. In addition, the recycling potential went from -159,5 to -131,1 kg CO_2e/m^2, which is a negative change. With the help of PV generation, the carbon emissions went from -15 to -50 kg CO_2e/m^2. In addition, the incorporation of a biogenic carbon reduction of 220 kg CO_2e/m^2 made it possible for the final instance to accomplish a decrease of 80,5%, which brought the number of carbon emissions down from 494,9 kg CO_2e/m^2 to just 96,4 kg CO_2e/m^2. It is worth mentioning that without the effect of biogenic carbon, the total CO_2 emission would only reduce from 494,9 kg CO_2e/m^2 to 316,7 kg CO_2e/m^2, corresponding to a 36% reduction.

Improved scenario with Helsingborg energy assumption numbers

The entire climate effect of the enhanced case was compared to the as-built case, followed by the ZEB-Complete level, and then with the value of energy carbon emission from the Helsingborg municipality. This comparison was carried out in the same manner as the previous comparison. Figure 45 shows the climate impact comparison between the final and as-built case, following the ZEB-Complete level, with Helsingborg emission value for energy.

According to the findings, the reduction of the production stage, end-of-life process, and recycling stage were similar to the aforementioned figure. The only difference was the climate impact of operational energy use, including heating, cooling, and electricity.

The result shows that the carbon emission of heating energy was reduced from 51,4 kg CO_2e/m^2 to only 5,8 kg CO_2e/m^2. Similar trends can be seen for the electricity energy data, which had a reduction from 74,7 kg CO_2e/m^2 to only 3 kg CO_2e/m^2. In contrast, cooling energy number showed an opposite trend: an increase from 1,5 kg CO_2e/m^2 to 2,3 kg CO_2e/m^2 when changing to Helsingborg emission value for energy. Therefore, with all the above reduction, this case resulted in a 93% decrease in carbon emission, from 393 kg CO_2e/m^2 in the original case to only 28 kg CO_2e/m^2 in the final case.

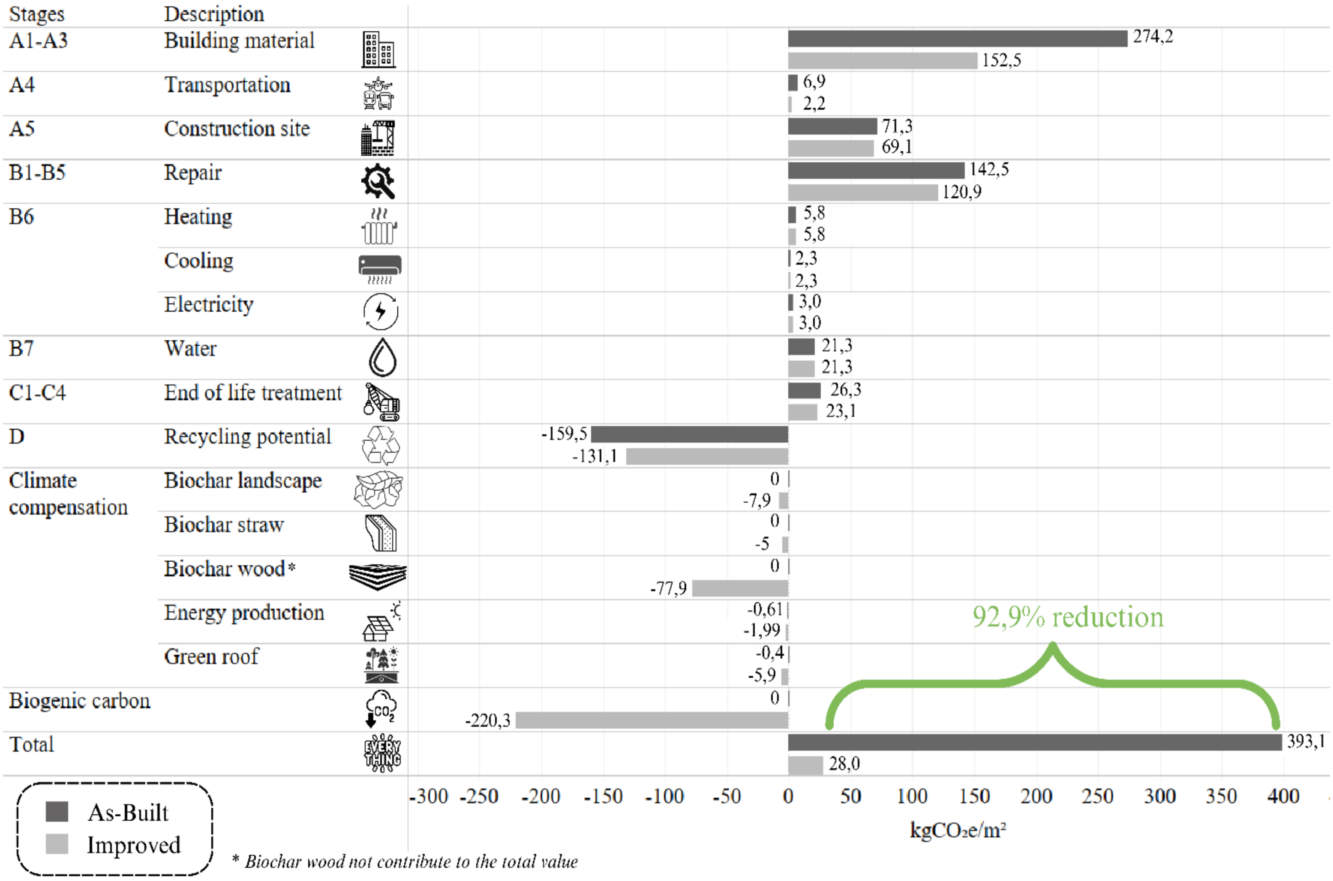

Figure 45, Carbon emission comparison between improved and as-built case, following the ZEB-Complete level, with Helsingborg emission value for energy

The improved building scenario now emits 322 and 102 kg CO_2e/m^2 for the Zeb complete calculation and 248 and 28 kg CO_2e/m^2 for the Helsingborg assumptions calculation.

4.3 Annual cumulative carbon emission from the building life-cycle

One important way to look at the result is to see when the carbon emission will be released through the life cycle of the building. Figure 46 shows the carbon release of a building during 150 years to see the climate impact of the building during the entire life cycle, the carbon emission of wood construction in the case that wood will be reused in another construction, and the continuous carbon capture if wood can turn into biochar.

With the as-built case, the building starts at 342 kg CO_2e/m^2. During the life cycle, the building emitted carbon through the use phase, including operational energy use, replacement, and refurbishment of different materials. Then, in the year 2082, it reached the end of the life cycle after 60 years, with around 470 kg CO_2e/m^2. After the dismantling phase, all possible recycling scenarios were accounted for. That led to a drop from 470 to around 400 kg CO_2e/m^2 and remained the same for the next 90 years.

With the help of all improved methods, the improved case started at the very low value of -27 kg CO_2e/m^2. Then, similar to the as-built process, the building also emitted carbon during its use phase and finally reached its end with around 70 kg CO_2e/m^2 after 60 years. After all the recycling possibilities, the carbon emission is now reduced to 50 kg CO_2e/m^2. Assuming the biogenic carbon inside the wood will not be released for the next building life-cycle, the carbon sequestration remained unchanged for 60 years. In addition, if the wood was used to create biogenic carbon, an amount of CO_2 that was supposed to be released back into the atmosphere is now stored inside the biochar and continues to be captured for thousands of years. So, instead of releasing back 220 kg CO_2e/m^2 biogenic carbon, now the released carbon was only around 120 kg CO_2e/m^2.

Figure 47 shows a similar result with cumulative carbon emission during 150 years, following the ZEB-Complete method, with both the average European and Helsingborg value for the carbon emission of the energy.

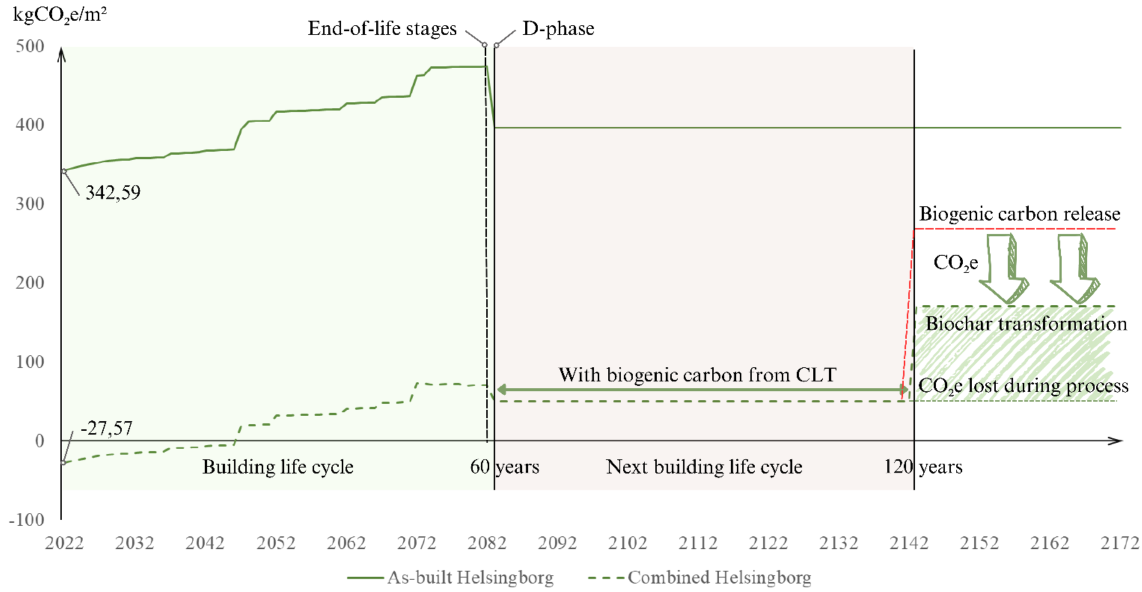

Figure 46, Annual cumulative of carbon emission during two building life-cycles, following ZEB method with Helsingborg value for carbon emission of operational energy.

Similar trends compared to the Helsingborg case can be seen in the ZEB case. With the original case of ZEB, the building started with 342 kg CO_2e/m^2 and ended with around 580 kg CO_2e/m^2. Then the carbon emission was reduced to around 500 kg CO_2e/m^2 due to the recycling process. With the improved case of ZEB, the building began with -27 kg CO_2e/m^2 and end with 140 kg CO_2e/m^2 after 60 years. Then the emission was diminished to around 120 kg CO_2e/m^2. With the same assumption as Helsingborg's case, the biogenic carbon in wood will be captured and stay for 60 years. Then that carbon will be released around 120 kg CO_2e/m^2 due to the biochar transformation process, and the rest will remain in the biochar, keeping the carbon for more than 120 years.

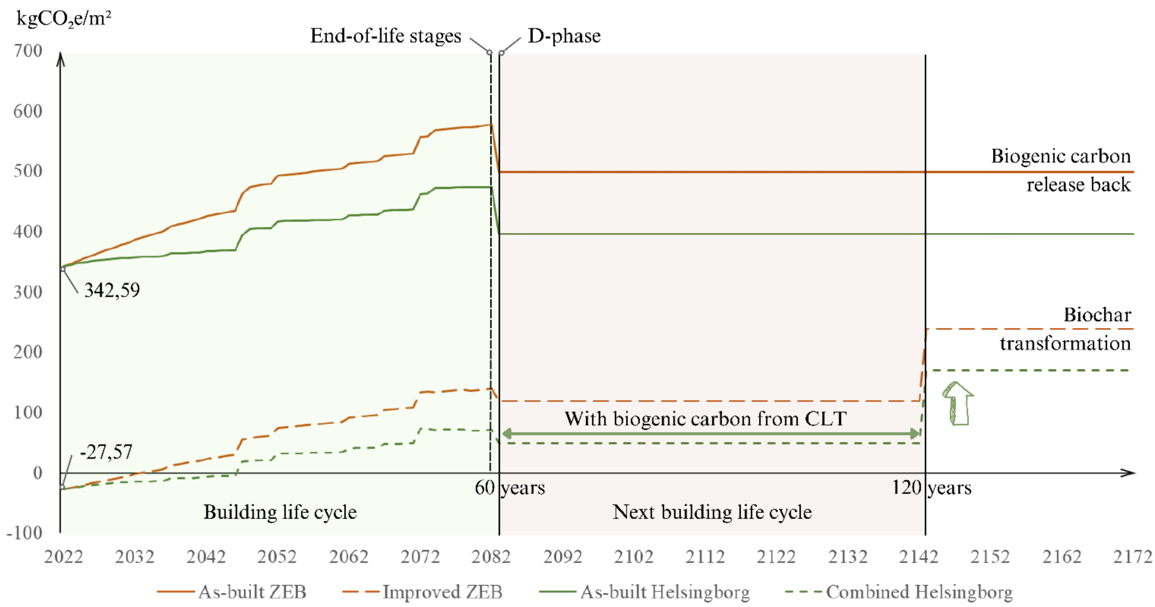

Figure 47, Annual cumulative of carbon emission during two building life cycles, following the ZEB method with both average European value and Helsingborg value for carbon emission of operational energy

In the best scenario, where the Swedish carbon capture plan succeeded, and Helsingborg goes carbon neutral on energy in 2030, the studied building dismantled after 60 years can claim to have emitted 50 kg CO_2e/m^2 at least until the end-of-life of the CLT panel itself.

5 Discussion

The buildings sector in Europe emits 36 % of the annual GHG (Europa, 2020), which is addressed in this research by evaluating the carbon emission performance of a newly built building in a Scandinavian neighbourhood constructed on the reclaimed harbour territory at Helsingborg. The city has designed this area with an emphasis on sustainability. It is the goal of the city of Helsingborg to become carbon neutral by the year 2030. Nevertheless, the city needs further facts to understand how to accomplish this lofty objective with fewer than seven years remaining until the deadline. The result of this research seeks to help the authority understand the actual carbon emission at the building level and what can be done to lower it as close as possible to carbon neutrality. To do it, an LCA calculation was made based on the ZEB complete method requirement. It is challenging to see if the findings of this research can be applied at a bigger scale if the LCA result is not compared with other office buildings built with the exact construction requirement. The advantage of using ZEB-Complete is that it is one of the most complete carbon emission calculation methods, but it also has a drawback when comparing the building with others. Because of its high requirements when accounting for building materials, LCA calculations rarely use the ZEB-Complete method.

It is why another LCA calculation was made based on the KTH study. This research made it possible to compare Prisma to eleven other office buildings in Sweden built with the same Boverket requirement. By using similar calculation methods and similar assumptions to the one made by the KTH research team, it was possible to see that our building emitted 35 kg CO_2e/m^2 less than the average 325 kg CO_2e/m^2 from the study. Based on these results, it can be inferred that the findings from this research may be relevant for other office buildings constructed in a compact city frame, adhering to the same Boverket rules. Visualizing the impact of this amount of carbon emission applied to the 16 711 m² of total floor area from Prisma can be difficult without an analogy. For example, driving an average gazoline car around the globe following the equator will emit in average 6853 kg CO_2e (Hill et al., 2019). With the value obtained using the KTH study method, which only considers stages A1 to A5, the building will emit the equivalent of 793 cars travelling around the equator through its lifetime. In other words, it also means driving without stopping for 36 years at 100 km/h. What does it mean when applying it to the ZEB-Complete LCA calculation?

The Zeb-Complete LCA calculation carbon emission results are, of course, higher than the one obtained with the KTH study. With 495 kg CO_2e/m^2, the newly built Prisma building certified Miljobyggnad Gold is far from carbon neutrality. Returning to the car analogy, it means a car travelling around the globe 1 207 times. At 100 km/h speed, it will mean 55 years of driving without rest.

Previously, studies have shown the importance of operational energy in the carbon emission in buildings, as stated in the literature review. What is striking in this research is the importance of the building material as the most significant carbon emission responsible through the life cycle of the building. This follows the literature review section 2.2, which state that due to improvement in energy equipment and energy distribution and better legislation on energy efficiency, and due to the use of more technology and insulation in buildings, it is now the building material stages that have the highest carbon emission through new buildings' life cycle. To be able to achieve carbon neutrality, building materials' emissions have to be strongly reduced. In this study, building materials represent 55 % of the carbon emission and operational energy, with 26%, half of it. If the carbon neutrality goal in 2030 is taken seriously by Helsingborg, these numbers mean that using conventional construction material is probably not a part of the solution to decrease the emitted carbon. A significant shift has to be made fast if cities want to achieve carbon neutrality in the building sector.

Working on reducing carbon emission in building material doesn't means not continuing to work at increasing efficiency in the energy sector. The city of Helsingborg, with the Swedish Energy Agency, is working on developing carbon capture and storage technology (CCS). It is still a young experimental technology, but all hope is put on it to achieve carbon neutrality for energy production. The experimentation started in 2022, and the global Swedish goal from the Energy Agency has quite a high ambition. If they succeed, Helsingborg will have a carbon-free energy sector by 2030. One ZEB-Complete calculation was made with this assumption. Using carbon neutrality by 2030 for operational energy gives a total of 396 kg CO_2e/m^2, a decrease of around 100 kg CO_2e/m^2 in carbon emitted for the operational energy. Building materials now represent 69 % of the carbon emitted and operational energy 7 %. But still, 44 years of driving, depicting 966 travels around the equator, will be necessary to emit the same amount of carbon.

As seen in section 4.1, building systems and foundations represent an important part of the carbon emitted but have not been examined. Most of the building system is ventilation, which has already been designed to be energy efficient to meet Milijobyggnad Guld 3.0 certification. The foundation can hardly be changed since it has to stay in concrete. The three building construction components that have been considered for this study were the change of the slab floor and roof, the facades, and the superstructure by replacing their concrete, steel, glass, and rock wool insulation material with biobased materials. These three building systems together represent 65 % of the emitted carbon for the building materials stages, which is A1 to A3. Biobased material generally has a lower carbon footprint than the four replaced materials, as seen in this result in section 4.2. All tested changes have successfully reduced carbon emissions, even without considering biogenic carbon storage through wood and straw.

With the ZEB-Complete calculation, the carbon emission decrease for the total building life cycle without and with biogenic carbon was, for the envelope, 3 % and 6 %, for the combined superstructure elements, 11% and 25 %, and for the slab 17 % and 44 %, as seen section 4.2. Other replacement measures were also experimented such as replacing the concrete and steel staircase system with CLT and extending the green roof and the solar panel system to the maximum capacity. The stairs replacement decreases carbon emitted by only 1% or 4 % with biogenic carbon, and the green roof and solar panel extension decrease carbon emitted by 11 %. The two last changes ignored other possible carbon emission decreases. It does not include the gain in energy production when combining green roofs and solar panel systems and the decreased energy needs due to a better-insulated roof. Choices in products with lower carbon footprint EPDs than the ones accounted for in the as-built scenario had been made. Looking at the A1 to A5 stages, it is slightly more than a 50 % reduction that was made for the total design change scenarios. It is significant, but it still represents 785 car travel around the equator or 36 years of non-stop driving from carbon neutrality for ZEB-Complete, and 605 car trips around the equator, or 28 years of non-stop driving for the Helsingborg assumptions method, without considering biogenic carbon (Hill et al., 2019).

Biogenic carbon, biochar, and end-of-life scenarios are always difficult to be accounted for because of double counting or carbon release. For example, when you use biochar in green roof substrate or into the ground, who can profit from this CO_2e storage? The company that has transformed biomass to biochar may claim the kg CO_2e reduction as a part of the benefit they bring to the planet. The building owner may also claim kg CO_2e deductions because they have put it into the ground on the land limit of the building. Another example is biogenic carbon in wood. For example, with CLT panels, biogenic carbon is not released while the building stands and when the CLT panels are reused. For this research, the end-of-life scenario for the CLT wood panel was considered. CLT panels were reused through a new building life-cycle. Doing so makes it possible to push back the moment when the wood's biogenic carbon will be released into the atmosphere. Following those two cycles used for CLT panels, one option was to transform this wood into biochar. Here is a risk of double counting because this biochar will be put into the ground where the land owner may claim the benefit, while the biogenic carbon in wood may as well be accounted for when standing in a building. The same double counting can happen for recycled elements. For all of these reasons, accounting for the D phase is delicate.

One of the study results shows when carbon emission will happen through the life cycle of the building. When biobased materials are used, carbon is stored when a massive effort must be made to break down the GHG. Doing it makes it possible to give importance to the time factor. For the Helsingborg LCA method calculation, it means that when the building enters operation, it will be carbon negative with - 28 kg CO_2e/m^2. Carbon emission will then slowly be released and stabilize at year 60 around 50 kg CO_2e/m^2 until the end-of-life of the CLT panel. After, it was assumed that CLT would be transformed into biochar for a final result of around 170 kg CO_2e/m^2, which will be the carbon emitted through 19 years of driving, representing 417 travels around the equator. It is easier to visualise the beginning of the building life span to acknowledge the effort made to reduce carbon emissions as fast as possible. By visualizing the carbon emissions for all the components of the buildings throughout the years, a broader understanding can be gained regarding the fate of the building materials beyond the building's lifespan without the need to address issues related to double counting.

During the research, discussions arose about the importance of the economic factor in construction projects compared to the significance of the environmental aspect. Even today, with climate change impacting more and more the planet and increasing the massive meltdown of biodiversity, it is still the money that, most of the time, wins over the climate impact. The studied project follows the Boverket requirement and the Miljiöbygnnad Guld 3.0 certification, but neither of them gives thresholds on carbon emission by stages. What may happen the day

Boverket introduces carbon emission thresholds on building materials is that suddenly the carbon emission will increase in importance, and budgets will have to adapt. Construction materials will have no choice but to be chosen for their lower carbon footprint budget.

Often in this research, system boundaries are an obstacle when it comes to understanding at a quarter level, a neighbourhood level, or the city level, what does it mean a carbon neutral building. Another forefront discussion that the researchers would like to explore was to look at all the outside elements that have a building dependency on carbon emission. For an office building, it can be where the worker lives, how far they have to travel or if they are using public transport, individual passive transport, or active transport. It is also how much infrastructure is needed to be maintained and built by the city compared to the average building office at Helsingborg. By reducing individual outside space and street dimensions, was the city able to, or plan to, give back a piece of land to nature and increase natural carbon sink into the city territory? It is also essential to get out of the building boundaries to better understand the consequences of the building for the surrounding environment.

Let's consider a fictive situation where a building owner claimed to have built a carbon-neutral office building on the outskirts of the city of Helsingborg. His land was big enough, so the building could be lower and occupy more square meters of land; by doing so, the owner could increase the solar panel system sufficiently to cover the electricity needed, which with other combined measures, resulted in the building's claim of carbon neutrality. The climate-neutral calculation for this building does not show the consequences of its location at the city level. Because of the geographic position of the building, workers may come by car because the building is not close enough to important public transit transport. Another piece of land is then used for parking the cars, and the city had to build a new road to reach the new building. Unfortunately, the new road has cut one of the last pieces of forest still standing in two. The wildlife on one side has lost direct access to a water source, and adding to it, one of the last habitats for another frog species has been destroyed to build this new carbon-neutral building. Taking into account all the surrounding consequences that a building can inflicted to the environment can lead at a so-called carbon-neutral building being more damaging and emitted more carbon dioxide on a bigger scale than the improved case from this study with 248 kg CO_2e/m^2.

6 Conclusion

This thesis examined the life cycle of Prisma, a new building in Helsingborg, Sweden. This research quantifies the global warming potential of an office building to determine how close the building is to the objective of carbon neutrality. This thesis also examines carbon sequestration strategies to see whether the building can minimize carbon emissions during its lifetime by using existing technology and materials, to inform subsequent research and future building design projects.

The findings reveal that building materials play a crucial role in carbon emissions throughout the building's life cycle, which accounted for 55 % of total carbon emissions, surpassing the impact of operational energy, with only 26 % in total. This shift in focus emphasizes the need to reduce emissions associated with building materials to achieve carbon neutrality effectively. Conventional construction materials are unlikely to contribute to this goal, necessitating a rapid and substantial shift in practices within the industry.

While building material carbon emissions must be reduced, operational energy efficiency must also be improved. ZEB utilized an average European value of 74 g CO_2/kWh, which was greater than Öresunkraft's 3 g CO_2/kWh. However, solar panels will no longer be feasible when grid emissions reach zero since their significant use offsets building energy demands. Helsingborg and the Swedish Energy Agency are also investigating electricity generation using carbon capture and storage (CCS). If it works, this experimental system might help the city achieve carbon neutrality by 2030.

A recent study from KTH shows carbon emission of different types of buildings in A1-A5 stages in LCA, which has values from 261 kg CO_2e/m^2 to 438 kg CO_2e/m^2. Compared to that data, the Prisma building, with a value of 325 kg CO_2e/m^2 in A1-A5 stages, falls below the average level compared to the eleven office buildings from the KTH study, principally because Prisma was designed to be an energy-efficient building.

Moreover, various climate compensation measures were implemented in this study to assess the potential of a newly constructed building to approach carbon neutrality. The effectiveness of multiple measures, including the substitution of insulation layers with straw, the replacement of columns, slabs, stairs, and beams with cross-laminated timber (CLT) panels, the conversion of wood into biochar, and the implementation of a green roof combined with solar panels across the entire roof area, was investigated. Despite the comprehensive implementation of these measures, the most favourable scenario achieved an emissions level of 28 kg CO_2/m^2, which equals to a 93 % reduction compared to the original case, demonstrating remarkable proximity to the carbon neutrality target. However, it is important to note that when a building is specifically designed to achieve carbon neutrality, the potential for emission reduction can be significantly higher.

In life cycle analysis, accounting for biogenic carbon, biochar, and end-of-life scenarios presents challenges due to the possibility of double counting or carbon release. Nonetheless, it is essential to consider the timing of carbon emissions, as the use of biobased materials enables carbon storage during periods requiring intensive efforts to counteract greenhouse gas accumulation.

Ultimately, the construction industry can effectively contribute to carbon neutrality objectives by placing environmental impact alongside financial concerns. Obtaining carbon neutrality in the building industry necessitates a multifaceted strategy that incorporates energy efficiency, low-carbon materials, and sustainable urban planning while taking into account the broader environmental context.

7 Future studies

Several prospective areas of future research deriving from this thesis could contribute to greater comprehension and advancements in carbon emissions reduction within the context of sustainable building design and construction. These consist of the following:

Regional and Contextual Analysis

Examining the applicability of the findings to various geographic regions and urban settings. Case studies and analyses conducted in diverse locations can help identify regional obstacles and opportunities for attaining carbon neutrality in dense urban areas.

Impact of Policies and regulatory frameworks

Examining the impact of policy and regulatory frameworks on the reduction of carbon emissions in the building sector. Analyzing the efficacy of extant regulations and identifying policy intervention opportunities to further encourage the adoption of sustainable building practices.

Developing building materials and technologies

Exploring the potential of emergent building materials and technologies to reduce carbon emissions further. Assessing the viability, performance, and cost-effectiveness of novel materials, such as low-carbon concrete alternatives and advanced insulation systems, is the focus of this investigation.

Occupant Behavior and Lifestyle

Examining the impact of occupant behaviour and lifestyle choices on carbon emissions in office buildings. Conducting surveys, interviews, or monitoring studies to determine the impact of occupant behaviour, commuting patterns, and energy consumption practices on the overall carbon footprint of buildings.

Energy efficiency strategies and technologies

Evaluation of the effectiveness of energy efficiency strategies and technologies in reducing carbon emissions. This may entail evaluating the efficacy of energy-efficient HVAC systems, intelligent building automation, and demand response measures in attaining carbon neutrality objectives.

Life Cycle Assessment (LCA) Refinement

Continually enhancing LCA methodologies and tools to provide more accurate assessments of carbon emissions over the entire life cycle of buildings. This includes refining data collection methods, incorporating regional-specific data, and addressing LCA calculation-related uncertainties and limitations.

Social and Economic Consequences

Investigating the social and economic repercussions of the transition to carbon-neutral buildings. Evaluating the cost-effectiveness, economic viability, and social acceptability of sustainable building practices and their long-term effects on occupant health, productivity, and urban sustainability.

Carbon emission of a broader system

Commute times, public transit, and land use all have a role in how much carbon a building contributes to the city as a whole. Having this wider view is crucial for putting sustainability at the forefront of urban planning choices.

Future studies can contribute to the development of strategies and guidelines for attaining carbon neutrality in office buildings within confined city frameworks by addressing these research areas.

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Appendices

Material calculations tables

Appendix table 1, Socle junction material calculation

Socle junction material calculation, Density: steel 7850 kg/m³, zinc 7200 kg/m³ alu, 2710 kg/m³, glue 1,25 kg/L

material	width m	thick, m	length m	area m²	vol, m³	qty/m	Weight Kg/piece	steel kg	zinc kg	alu, kg	glue kg	sealant kg
membrane	0,4		179	**71,6**								
EPDM membrane	0,5		179	89,5								
Steel flashing	0,6	0,002	179		0,2			**1546**				
Foam insulation	0,1	0,050	179	15,2	**0,8**							
Wool insulation	0,3	0,030	179	53,7	**1,6**							
Zinc flashing	0,5	0,002	179		0,1				**967**			
Phonoterm	0,2	0,025	179		**0,9**							
Metal screw			179				**0,001**					
Nails			179				**0,001**					
Insulation glue			179								**5,6**	
Silicone sealant			179									**7,5**
Bearing bracket 02												
aluminium			179			0,5				**182**		
Zinc			179			0,5			**31**			

Appendix table 2, Floor junction material calculation

Floor junction material calculation, Density: steel 7850 kg/m³, zinc 7200 kg/m³ alu, 2710 kg/m³, glue 1,25 kg/L

material	width m	thick, m	length m	area m²	vol, m³	qty/m	Weight Kg/piece	steel kg	zinc kg	alu, kg	glue kg	sealant kg
zinc cassette	0,4	0,002	1449		0,8				**5 477**			
Zinc flashing	0,3	0,002	1449		0,5				**3 912**			
Steel flashing	0,45	0,002	1449		1,3			**10 237**				
Metal screw			1449			18	0,001	**26**				
Silicone sealant			1449									**45**
Bearing bracket 02												
aluminium			1449			0,5	8,1			**5890**		
Zinc			1449			0,5	1,2		**870**			

Appendix table 3, Outer wall material calculation

Outer wall material calculation (glue: 1L=40 m) Density: steel 7850 kg/m³, zinc 7200 kg/m³, glue 1,25 kg/L

Section 2,4 m x 3,95 m	material	width m	thick, m	length m	Area m²	Vol, m³	qty	steel kg	zinc kg	paint kg	glue kg	qty/m²
Plain wall												
zinc cassette	zinc		0,0015			0,007			**50,5**			**11,86 kg**
	metal screw						26	**0,026**				**0,006 kg**
	urethane	0,15	0,005	10,2		**0,008**						**0,0018 m³**
	silicone sealant			10,2								**2,4 m**
Outside part	hard insulation		0,085		4	**0,34**						**0,08 m³**
	soft insulation		0,16		4	**0,64**						**0,15 m³**
	1 pane al, frame											
Inner part	plasterboard				**5**							**1,18 m²**
	plasterboard				**5**							**1,18 m²**
	75 steel profile			17	4			**9,35**				**2,2 kg**
	soft insulation		0,075		4	0,3						**0,07 m³**
	plasterboard screw						78	**0,156**				**0,04 kg**
	plastercoating				**6,25**							**1,5 m²**
	paint				5					**2,11**		**0,5 kg**
Window wall												
Cover frame	Zinc	0,22	0,0015	8		0,0026			**19**			**4,5 kg**
	Linitherm	0,16	0,03	8		**0,038**						**0,009 m³**
	glue			8							**0,25**	**0,06 kg**
	3 panes al, frame											

Appendix table 4, Triple-glazed aluminium frame system

Triple-glazed aluminium frame system material calculation

Section	Comment	Area m²	Triple-glazed al, frame system length m	height m	area m²	GWP kg CO2 e	unit
window	Triple glazes	2920	2,4	3,6	8,6		338
wall	Single glaze	2992	2,4	3,6	8,6		260
Single glaze		2992				74	
Single glaze		2992				74	
3 glazes al, frame system		2992				260	
Adjusted of unit for wall section						112	149
Total unit							**487**

Appendix table 5, Bearing bracket system 01

Bearing bracket system 01, Density: aluminium 2710 kg/m³, zinc 7200 kg/m³

	width m	length m	thickness m	volume m³	qty/unit	alu kg	bolt mm	zinc kg
	0,15	0,3	0,01	0,000 450	1	1,21		
	0,05	0,15	0,01	0,000 075	2	0,41		
	0,2	0,15	0,01	0,000 300	2	1,63		
	0,2	0,3	0,01	0,000 600	3	4,88		
total						**8,13**	930	**1,2**

Appendix table 6, Bearing brack system 02

Bearing bracket system 02, Density: aluminium 2710 kg/m³, zinc 7200 kg/m³

	width m	length m	thickness m	volume m³	qty/unit	alu kg	bolt mm	zinc kg
	0,3	0,25	0,01	0,000 75	1	2,03		
total						**2,03**	270	**0,35**

Appendix table 7, Bolt, washer, nut system 60mm long

Bolt, washer, nut system 60 mm long, (Hilti HUS3-HF), Density: zinc 7200 kg/m³

	material	Zinc (kg)
bolt	zinc	0,060 0
washer	zinc	0,015 0
nut	zinc	0,002 5
total 60 mm		0,075 0
total 1 mm		**0,0013**

Appendix table 8, Structural steel profile (Lindab), analysed section 0,45 m x 3,7 m

Structural steel profile (Lindab), analysed section 0,45 m x 3,7 m, Density: steel 7850 kg/m³

width mm	weight kg/m	length m	weight kg	area wall m²	weight kg/m² of wall
70	0,55	3,6	2,0	1,22	**1,6**
90	0,64	3,6	2,3	1,22	**1,9**
120	0,73	3,6	2,6	1,22	**2,2**
145	0,82	3,6	3,0	1,22	**2,4**

Appendix table 9, Plasterboard steel screw

Plasterboard steel screw, Density: steel 7850 kg/m³

qty	weight/unit kg	width m	height m	area panel m²	weight screw kg/m²
24	0,001	0,9	2,7	2,4	**0,024**

Appendix table 10, Paint, finish and primer

Paint, finish and primer, Density: Acro paint: 1,3 kg/L

width mm	area m²/L	area average m²/L	qty 1 side L/m²	qty 2 side L/m²	weight kg/m² of wall
primer	4 to 7	5,5	0,18	0,36	0,47
finish	6 to 8	7	0,14	0,29	0,37
total				0,65	**0,84**

Appendix table 11, New outer wall material calculations

New outer wall material calculations (glue: 1L=40 m) Density: steel 7850 kg/m³, zinc 7200 kg/m³, glue 1,25 kg/L

Section 2,4 m x 3,95 m	material	width m	thick, m	length m	Area m²	Vol, m³	qty	steel kg	zinc kg	paint kg	glue kg	qty/m²
Plain wall												
Outside part	lime plaster		0,03		4,25	0,1275						**0,03 m³**
	plaster mesh				4,25				**2,55**			**0,6 kg**
	wood ins. panel		0,06		4,25	**0,255**						**0,06 m³**
	silicone sealant			10,2								**2,4 m**
	straw		0,38		4,25	**1,54**						**0,36 m³**
	wood	0,075	0,045	23		**0,08**						**0,02 m³**
	1 pane al, frame											
Inner part	plasterboard				**5,4**							**1,25 m²**
	plasterboard				**5,4**							**1,25 m²**
	75 wood stud			17	4			**9,35**				**2,2 kg**
	vapour barrier				5	0,3						**0,07 m³**
	Wood screw						20	**0,08**				**0,02 kg**
	plasterboard screw						78	**0,156**				**0,04 kg**
	plastercoating				**6,25**							**1,5 m²**
	paint				5					**2,11**		**0,5 kg**
Window wall												
Cover frame	Zinc	0,22	0,0015	8		0,0026			**19**			**4,5 kg**
	Linitherm	0,16	0,03	8		**0,038**						**0,009 m³**
	glue			8							**0,25**	**0,06 kg**
	3 panes al, frame											

Material quantities tables

Appendix table 12, Material quantity for groundwork foundation

Material	Reference	Quantity	Calculation method 01	02	03
Concrete	Drawings, BIM model	488 m³	✓	✓	✓
Steel	Logbook	265 000 kg	✓	✓	✓
EPS	Logbook, drawings	1 000 m²	✓	✓	✓
Concrete piles	Drawings, hercules,se	3 500 m	✓	✓	✓
Radon/ moisture membrane	Assumption	2 500 m²	✓	✓	✓
Aggregate bed	Assumption	530 m³	✓	✓	✓
Aggregate wall	Assumption	116 m³	✓	✓	✓
Concrete (ramp)	Drawings, BIM model	137 m²	✓	✓	✓

Appendix table 13, Material quantity, columns and beams superstructure

Material	Reference	Quantity	Calculation method 01	02	03
Composite steel	BIM model	15,6 m³	✓	✓	✓
Ready-mix concrete C40/50	BIM model	2,5 m³	✓	✓	✓
Ready-mix concrete C30/37	Calculation	114 m³	✓	✓	✓
Steel hollow section	COWI list	9 ton	✓	✓	✓
Steel bars	COWI list	31 780 kg	✓	✓	✓
Concrete	COWI list	1 666 ton	✓	✓	✓
Steel bar	COWI list	6 097 kg	✓	✓	✓
Steel	COWI list	2 133 kg	✓	✓	✓
Steel	COWI list	19 264 kg	✓	✓	✓
Cast asluminium	COWI list	7 731 kg	✓	✓	✓
Concrete stairs system	OneClick, Drawings	72 m	✓	✓	✓

Appendix table 14, Material quantity for outer walls_socle

Material	Reference	Quantity	Calculation method 01	02	03
Glass wool insulation	Drawings	54 m²	✓	✓	✓
EPDM membrane	Drawings	162 m²	✓	✓	✓
Zinc sheet	Drawings	967 kg	✓	✓	✓
Foam insulation	Drawings	15 m²		✓	✓
Extruded aluminium	Drawings	1 546 kg	✓	✓	✓
Zinc	Drawings, Assumption	32 kg		✓	✓
Adhesive	Assumption	6 kg		✓	✓
Sealant	Drawings	7,5 kg		✓	✓

Appendix table 15, Material quantity for outer walls_floor junction

Material	Reference	Quantity	Calculation method 01	02	03
Extruded aluminium	Drawings	5 890 kg	✓	✓	✓
Stainless steel sheet	Drawings	10 237 kg	✓	✓	✓
Zinc sheet	Drawings	9 389 kg	✓	✓	✓
zinc	Drawings, assumption	896 kg		✓	✓
Sealant	Drawings, assumption	45 kg		✓	✓

Appendix table 16, Material quantity for outer walls_envelope

Material	Reference	Quantity	Calculation method 01	02	03
Zinc sheet	Drawings	48 539 kg	✓	✓	✓
Glass wool insulation	Drawings	901 m³	✓	✓	✓
Plasterboard	Drawings, assumption	7 040 m²	✓	✓	✓
Interior paint	Assumption	1 486 kg		✓	✓
Structural steel profile	Drawings	6 586 kg	✓	✓	✓
Plaster coating	Assumption	3 520 m²		✓	✓
PUR insulation board	Drawings	26 m³	✓	✓	✓
Steel screw	Drawings, assumption	110 kg		✓	✓
Foam insulation	Assumption	5,5 m³		✓	✓
Sealant	Drawings, assumption	300		✓	✓
Adhesive	Assumption	171		✓	✓
Aluminium frame glass system	Drawings, logbook	487 unit	✓	✓	✓
Garage door	Drawings	6 m²	✓	✓	✓

Appendix table 17, Material quantity for inner walls

Material	Reference	Quantity	Calculation method 01	02	03
Plasterboard	Drawings	19 521 m²	✓	✓	✓
Structural steel profile	Drawings	16 537 kg	✓	✓	✓
Stone wool insulation	Drawings	4 871 m²	✓	✓	✓
Steel sheet	Drawings	740 m²	✓	✓	✓
Plywood	Drawings	71 m²	✓	✓	✓
Steel screw	Assumption	1 651 kg		✓	✓
Interior paint	Assumption	8 239 kg		✓	✓
Ceramic tiles	Drawings, assumption	680 m²	✓	✓	✓
Joint grout	Drawings, assumption	680 m²		✓	✓
Acrylic sealant	Drawings, assumption	7 385 kg		✓	✓
Fiberboard (MDF)	Drawings	17 m²	✓	✓	✓
Tile adhesive	Drawings, assumption	1 360 kg		✓	✓
Baseboard	Assumption	7 385 m		✓	✓
Plaster coating	Assumption	19 521 m²		✓	✓
Glass partitionning system	Drawings, BIM model	650 m²	✓	✓	✓
Interior wooden doors	Drawings, BIM model	741 unit	✓	✓	✓

Appendix table 18, Material quantity for floor structure

Material	Reference	Quantity	Calculation method 01	02	03
Composite steel	Drawings, BIM model	38 m³	✓	✓	✓
Steel	Drawings, BIM model	5 m³	✓	✓	✓
Concrete	Drawings, BIM model	4 764 ton	✓	✓	✓
Concrete	Drawings, BIM model	650 ton	✓	✓	✓
Hot finished steel	Drawings, BIM model	84 ton	✓	✓	✓
Steel bars	Drawings, BIM model	35 321 kg	✓	✓	✓
Suspended ceiling system	Drawings, BIM model	257 m²	✓	✓	✓
Suspended ceiling system	Drawings	8 848 m²	✓	✓	✓
Suspended ceiling system	Drawings	846 m²	✓	✓	✓
Suspended ceiling system	Drawings	551 m²	✓	✓	✓
Suspended ceiling system	Drawings	36 m²	✓	✓	✓

Suspended ceiling system	Drawings	83 m²	✓	✓	✓
Suspended ceiling system	Drawings	336 m²	✓	✓	✓
Suspended ceiling system	Drawings	407 m²	✓	✓	✓
Glass wool	Drawings	10 100 m²	✓	✓	✓
Ceramic tiles	Drawings	3 324 m²		✓	✓
adhesive	Drawings	3 m³		✓	✓
Tufted carpet	Drawings	4 400 kg		✓	✓
Carpet adhesive	Drawings			✓	✓

Appendix table 19, Material quantity for outer roof

			Calculation method		
Material	**Reference**	**Quantity**	**01**	**02**	**03**
Glass wall system	Drawings, BIM model, logbook	105 m²	✓	✓	✓
Roof membrane	Drawings	1 230 m²	✓	✓	✓
Stone wool insulation	Drawings	1 230 m²	✓	✓	✓
Adhesive	Assumption	60 kg		✓	✓
Softwood timber	Drawings	7,2 m³	✓	✓	✓
Steel screws	Assumption	7 kg		✓	✓
Thermoplastic roof membrane	Drawings	1 732 m²	✓	✓	✓
EPS insulation	Drawings	866 m²	✓	✓	✓
Green roof system	Drawings, BIM model	136 m²	✓	✓	✓
Plywood	Drawings	55 m²	✓	✓	✓
Zinc sheet	Drawings	634 kg	✓	✓	✓
Gutter system	Drawings	1 542 kg	✓	✓	✓
Glass railing	Drawings	52 m		✓	✓
Glass wall system (roof)	Drawings, BIM model	105 m²	✓	✓	✓

Appendix table 20, Material quantity for restrooms

			Calculation method		
Material	**Reference**	**Quantity**	**01**	**02**	**03**
Porcelain sink	Drawings	89 unit	✓	✓	✓
Porcelain WC kit	Drawings	75 unit	✓	✓	✓
Shower	Drawings	3 unit	✓	✓	✓

Appendix table 21, Material quantity for temporary works

			Calculation method		
Material	**Reference**	**Quantity**	**01**	**02**	**03**
soil removed	Drawings, assumption	81 000 m³		✓	✓
Diesel used	Drawings, assumption	6 480 L		✓	✓
Adapted site impact / no el,	OneClick LCA	15 463 m²		✓	✓
Deconstruction scenario	OneClick LCA	16 711 m²		✓	✓
Energy use	Wihlborgs	400 000 kWh		✓	✓
Temporary steel balcony	Wilhborgs + Calculation	390 units		✓	✓
Steel	Wilhborgs + Calculation	20 986 kg		✓	✓
Elevetor 1600 kg	Wihlborgs	1 unit		✓	✓

Appendix table 22, Material quantity for elecricity and litghting

			Calculation method		
Material	**Reference**	**Quantity**	**01**	**02**	**03**
Electricity cabling	One-click LCA	13 100 m²		✓	✓
Concrete	One-click LCA	7 001 kg		✓	✓
Battery lithium-ion	One-click LCA	4 558 kg		✓	✓
Motion detector	One-click LCA	28 kg		✓	✓
LED lighting	One-click LCA	7 657 kg		✓	✓
Cable 1 wire	One-click LCA	3 567 kg		✓	✓
Power cable	One-click LCA	8 887 kg		✓	✓
Electronic acces control	One-click LCA	1 446 kg		✓	✓

Appendix table 23, Material quantity for heating, cooling

Material	Reference	Quantity	Calculation method 01	02	03
EPS insulation	Drawings, 3D model	2 kg	✓	✓	✓
EPS insulation	Drawings, 3D model	172 kg	✓	✓	✓
EPS insulation	Drawings, 3D model	2 kg	✓	✓	✓
EPS insulation	Drawings, 3D model	67 kg	✓	✓	✓
Steel pipes	Drawings, 3D model	28 kg	✓	✓	✓
Steel pipes	Drawings, 3D model	1873 kg	✓	✓	✓
Steel pipes	Drawings, 3D model	1 kg	✓	✓	✓
Steel pipes	Drawings, 3D model	32 kg	✓	✓	✓
Water circulation radiators	Drawings, 3D model	250 kW	✓	✓	✓
Chilled beams	Drawings, 3D model	91 units	✓	✓	✓

Appendix table 24, Material quantity for ventilation

Material	Reference	Quantity	Calculation method 01	02	03
Air handling units	Drawings, 3D model	11 units	✓	✓	✓
Smoke detectors	Drawings, 3D model	4 units	✓	✓	✓
Air diffuser units	Drawings, 3D model	29 kg	✓	✓	✓
Air diffuser units	Drawings, 3D model	53 kg	✓	✓	✓
Air diffuser units	Drawings, 3D model	206 kg	✓	✓	✓
Air diffuser units	Drawings, 3D model	163 kg	✓	✓	✓
Air diffuser units	Drawings, 3D model	811 kg	✓	✓	✓
Lighting controlers	Drawings, 3D model	213 units	✓	✓	✓
Motion sensors	Drawings, 3D model	225 units	✓	✓	✓
Technical sensors	Drawings, 3D model	67 units	✓	✓	✓
Temperature regulators	Drawings, 3D model	227 units	✓	✓	✓
Fire dampers	Drawings, 3D model	94 units	✓	✓	✓
Air filters	Drawings, 3D model	2 units	✓	✓	✓
Rooftop exhaust fans	Drawings, 3D model	3 units	✓	✓	✓
Rooftop exhaust fans	Drawings, 3D model	2 units	✓	✓	✓
Rooftop exhaust fans	Drawings, 3D model	13 units	✓	✓	✓
Temp, measurement sensors	Drawings, 3D model	10 units	✓	✓	✓
VAV damper	Drawings, 3D model	4 units	✓	✓	✓
Technical sensors	Drawings, 3D model	4 units	✓	✓	✓
Technical sensors	Drawings, 3D model	4 units	✓	✓	✓
Ventilation ducting	Drawings, 3D model	1 727 m	✓	✓	✓
Ventilation ducting	Drawings, 3D model	803 m	✓	✓	✓
Ventilation ducting	Drawings, 3D model	738 m	✓	✓	✓
Glass wool	Drawings, 3D model	95 m^3	✓	✓	✓
Glass wool	Drawings, 3D model	217 m^3	✓	✓	✓
Glass wool	Drawings, 3D model	36 m^3	✓	✓	✓
Glass wool	Drawings, 3D model	47 m^3	✓	✓	✓
Ventilation ducting	Drawings, 3D model	530 m	✓	✓	✓
Ventilation ducting	Drawings, 3D model	567 m	✓	✓	✓
Ventilation ducting	Drawings, 3D model	153 m	✓	✓	✓
Ventilation ducting	Drawings, 3D model	153 m	✓	✓	✓

Appendix table 25, Material quantity for water

Material	Reference	Quantity	Calculation method 01	02	03
PP pipes	Drawings, 3D model	795 kg	✓	✓	✓
PP pipes	Drawings, 3D model	249 kg	✓	✓	✓
PP pipes	Drawings, 3D model	228 kg	✓	✓	✓
Floor drains	Drawings, 3D model	53 units	✓	✓	✓
Valves	Drawings, 3D model	721 units	✓	✓	✓
PEX pipes	Drawings, 3D model	178 kg	✓	✓	✓
PEX pipes	Drawings, 3D model	145 kg	✓	✓	✓
PEX pipes	Drawings, 3D model	18 kg	✓	✓	✓
EPS insulation	Drawings, 3D model	15 kg	✓	✓	✓

EPS insulation	Drawings, 3D model	12 kg	✓	✓	✓
EPS insulation	Drawings, 3D model	3 kg	✓	✓	✓
PP pipes	Drawings, 3D model	228 kg	✓	✓	✓
PP pipes	Drawings, 3D model	212 kg	✓	✓	✓

Appendix table 26, Material quantity for mechanics and technologies

Material	Reference	Quantity	Calculation method 01	02	03
Elevator 1 000 kg	Drawings, 3D model	2 units	✓	✓	✓
Elevator 2 000 kg	Drawings, 3D model	2 units	✓	✓	✓
Fire system doors	Drawings, 3D model	517 m²	✓	✓	✓
Interior blind	Drawings, 3D model	2507 units	✓	✓	✓

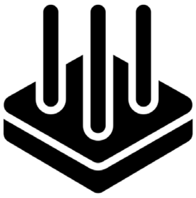
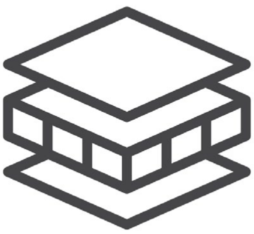
Appendix table 27, Material quantity for landscape

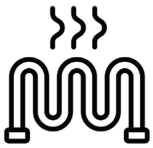
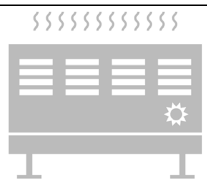
Material	Reference	Quantity	Calculation method 01	02	03
Concrete tiles	Drawings, assumption	270 m²	✓	✓	✓
Aggregate	Drawings, assumption	270 m²	✓	✓	✓
Sand	Drawings, assumption	270 m²	✓	✓	✓
Soil	Drawings, assumption	231 m²	✓	✓	✓

Appendix table 28, Impact of KTH study and other methods

Building ID	Comment	A1-A3	A4	A5 Spill	A5 Energy	A1-A5
		kg CO_2e/m^2	kg CO_2e/m^2	kg CO_2e/m^2	kg CO_2e/m^2	kg CO_2e/m^2
Kon1	KTH study	273	29	10	17	329
Kon2	KTH study	306	35	9	17	367
Kon3	KTH study	349	30	16	17	412
Kon4	KTH study	262	14	11	17	304
Kon5	KTH study	222	13	9	17	261
Kon6	KTH study	309	42	9	17	377
Kon7	KTH study	264	16	12	17	309
Kon8	KTH study	274	30	8	17	329
Kon9	KTH study	353	43	13	17	426
Kon10	KTH study	378	25	18	17	438
Kon11	KTH study	347	33	15	17	412
As-built	**Complete**	**271.7**	**6.9**	**9.4**	**60.4**	**348.4**
Scenario 2	Boverket adjust	267.6	28.2	11.8	17.0	324.6
Scenario 3	straw envelope	265.2	7.0	9.2	59.5	340.9
Scenario 4	wood slab	246.0	3.4	9.1	57.3	315.8
Scenario 5	wood structrure	217.3	6.9	7.8	54.5	286.5
Scenario 6	wood core	263.4	5.8	9.1	59.1	337.4
Scenario 7	wood stair	271.8	6.8	9.3	60.1	348.0
scenario 8	best new EPD	251.3	6.9	8.3	60.4	327.0
Final		134.7	7.9	6,0	13.7	162.3

*Appendix table 29, Recommended list of included materials and components, based on the list of building elements (*NS 3451:2009*, n.d.)*

2, Building Structure			
21, Groundwork and foundations		211	Clearing of land
		212	Excavation
		213	Ground Reinforcement
		214	Support structures
		215	Pile foundations
		216	Direct foundation
		217	Drainage
		218	Equipment and completion
		219	Other elements
22, Superstructure		221	Frames
		222	Columns
		223	Beams
		224	Bracings
		225	Fire protection of load bearing construction
		226	Cladding and surfaces
		227	Equipment and completion
		228	Other
23, Outer walls		231	Load bearing wall
		232	Non-load bearing wall
		233	Glass Façade
		234	Windows and doors
		235	Outer cladding and surfaces
		236	Internal surface
		237	Solar shading
		238	Equipment and completion
		239	Other
24, Inner walls		241	Load bearing wall
		242	Non-load bearing wall
		243	System walls
		244	Windows , doors, folding walls
		245	Skirting
		246	Cladding and surfaces
		247	N/A
		248	Equipment and completion
		249	Other
25, Floor structure		251	Load bearing deck
		252	Slab on ground
		253	Raised/ Built-up Floor, screed
		254	Floor system
		255	Floor surfaces
		256	Fixed Ceiling and surface
		257	Suspended Ceiling
		258	Equipment and completion
		259	Other
		261	Primary construction

26, Outer roof		262	Roof covering
		263	Glass Roof, Roof light, Roof Opening
		265	Cornice, Flashings, Gutters and Downpipes
		266	Ceiling and Internal surfaces
		267	Prefabricated Roof Elements
		268	Equipment and completion
		269	Other
28, Stairs, Balconies, etc.		281	Internal stairs
		282	External stairs
		283	Ramps
		284	Balconies and Verandas
		285	Grandstands and Amphi theatres
		286	Marquees and Canopies
		287	Railings, Handrails and Fenders
		288	Equipment and completion
		289	Other
3, Heating, Ventilation and Air Conditioning			
32, Heating		325	Equiment for heating installations e,g, heatpumps, heater, domestic hot water tanks and exchangers and boilers which are not electrical (see 45),
		329	Other heat installations e,g, Solar thermal collector system
36, Ventilation and Air conditioning		362	Duct system for air conditioning
		364	Equipment for air distribution
		365	Equipment for air treatment
		366	Insulation for air treatment
		369	Other
44, Lighting		442	Lighting fixtures and fittings, cables, cable trays, plug sockets
45, Electric heating		452	Electric heaters to be installed in floor, on walls or roofs
		453	Underfloor heating
		454	Electrical domestic hot water tanks and electrical boilers
		459	Other electrical heating system equiment
49, Other			Photovoltaic system
			Other renewable power systems
6, Other installations			
61, Prefabricated unit		611-619	Prefabricated rooms/ modules excluding technical equiment and fixed inventory that is otherwise excluded from the minimum requirements in this table
62, Passenger and goods transport		621	Lifts/ Elevator

CLT wood sizing calculation by Calculatis®

6 m lenght analyzed section

Prisma Page 1/3

6m ROOF RIB SLAB copy 08.05.2023

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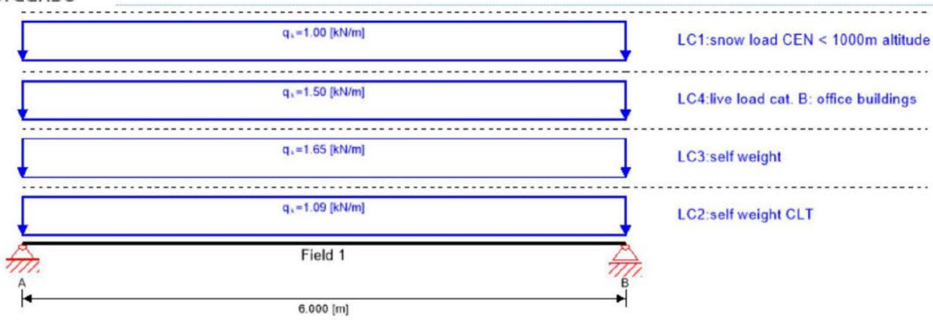
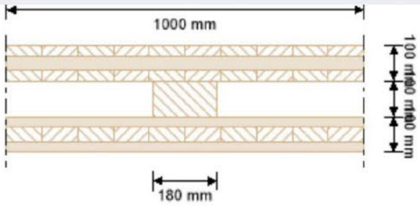


Global utilization ratio									75 %
ULS	52 %	ULS Fire	15 %	SLS	75 %	SLS Vibration	0 %	Support	-1 %

Section: CLT rib panel by Stora Enso: CLT 100 C3s - 18/10 - CLT 100 L3s



13,5 m lenght analyzed section

Prisma Page 1/3

13.5m ROOF RIB SLAB copy 08.05.2023

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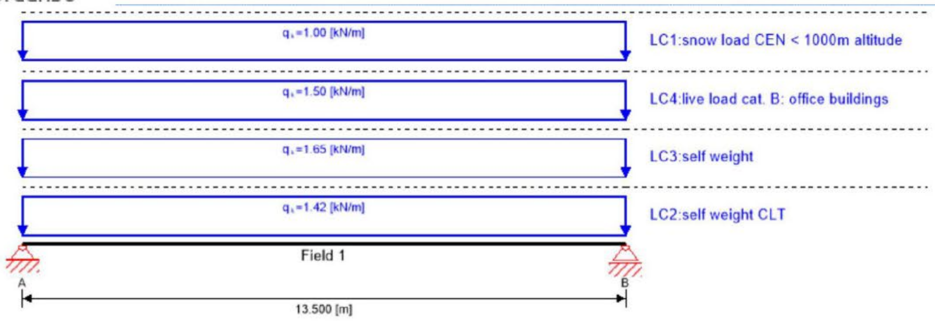
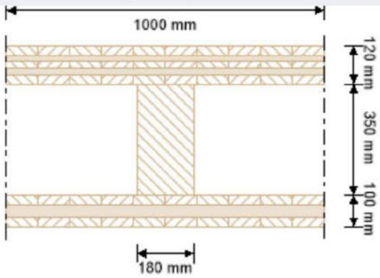


Global utilization ratio									82 %
ULS	32 %	ULS Fire	16 %	SLS	82 %	SLS Vibration	0 %	Support	-1 %

Section: CLT rib panel by Stora Enso: CLT 120 C5s - 18/35 - CLT 100 C3s



Appendix figure 1, Roof slab wood sizing

6 m lenght analyzed section

Prisma Page 1/3

6m RIB SLAB copy 08.05.2023

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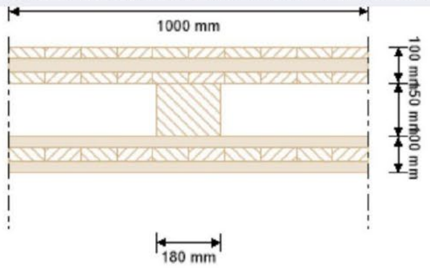
Global utilization ratio									69 %
ULS	68 %	ULS Fire	18 %	SLS	69 %	SLS Vibration	0 %	Support	-1 %

Section: CLT rib panel by Stora Enso: CLT 100 C3s - 18/15 - CLT 100 L3s



13,5 m lenght analyzed section

Prisma Page 1/3

13.5m RIB SLAB copy 08.05.2023

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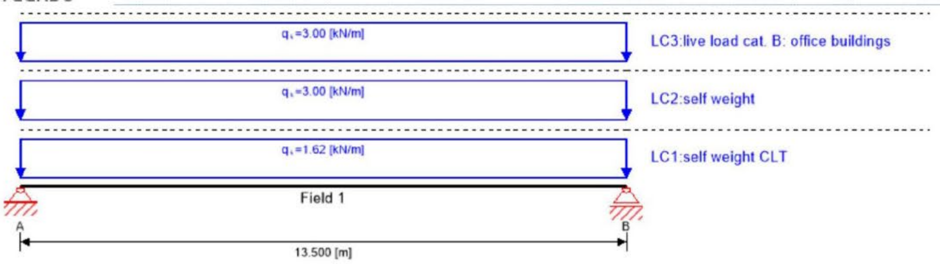
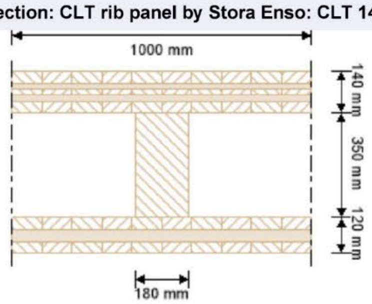


Global utilization ratio									93 %
ULS	50 %	ULS Fire	21 %	SLS	93 %	SLS Vibration	0 %	Support	-1 %

Section: CLT rib panel by Stora Enso: CLT 140 C5s - 18/35 - CLT 120 C3s



Ribs width are reduced by 20 mm for the design

Appendix figure 2, Floor slab wood sizing

6 m lenght analyzed section

Prisma Page 1/1

beam ROOF for 6 m section 08.05.2023

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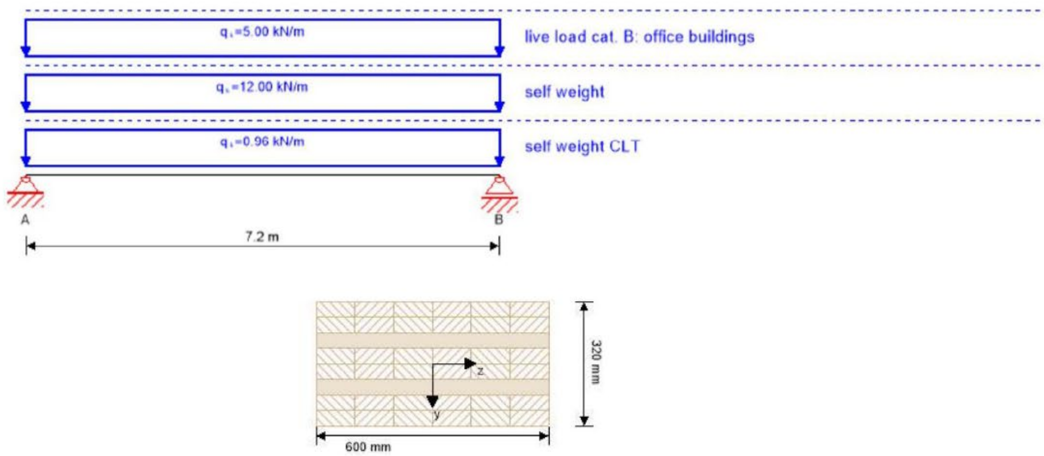


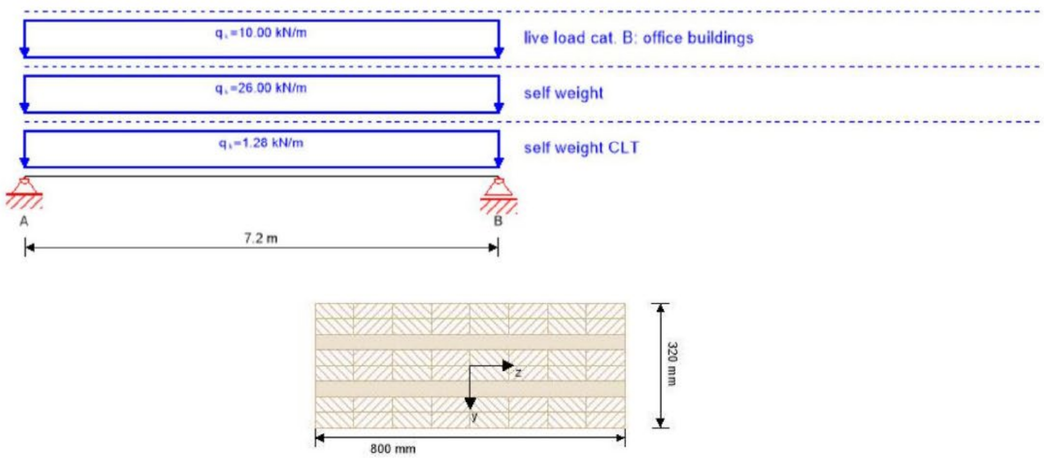
Global utilization ratio			73 %
ULS	73 %	ULS Fire	!

13,5 m lenght analyzed section

Prisma Page 1/1

beam ROOF for 13.5 m section 08.05.2023

Victor-antoine Delorme | Lund University | Designer VD | Checker



Global utilization ratio			85 %
ULS	85 %	ULS Fire	!

Appendix figure 3, Roof beam wood sizing

6 m lenght analyzed section

Prisma Page 1/1

beam FLOOR for 6 m section 08.05.2023

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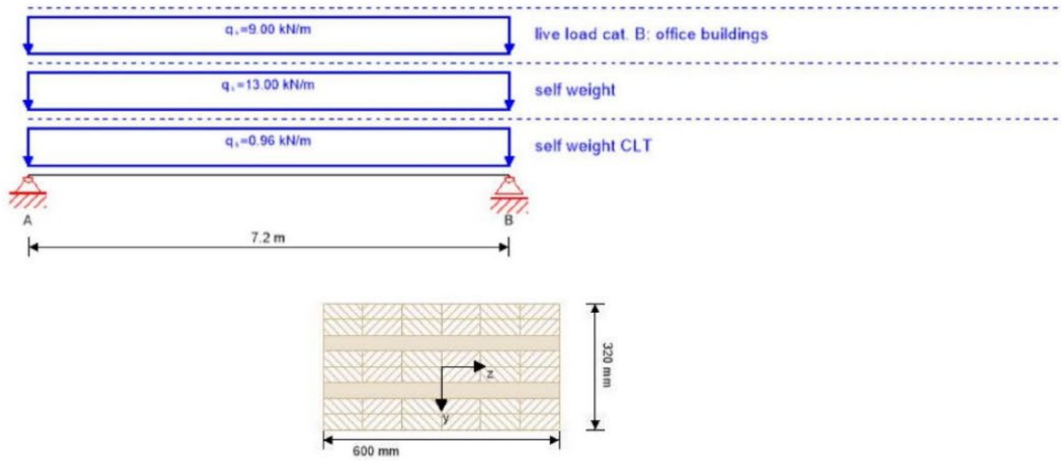


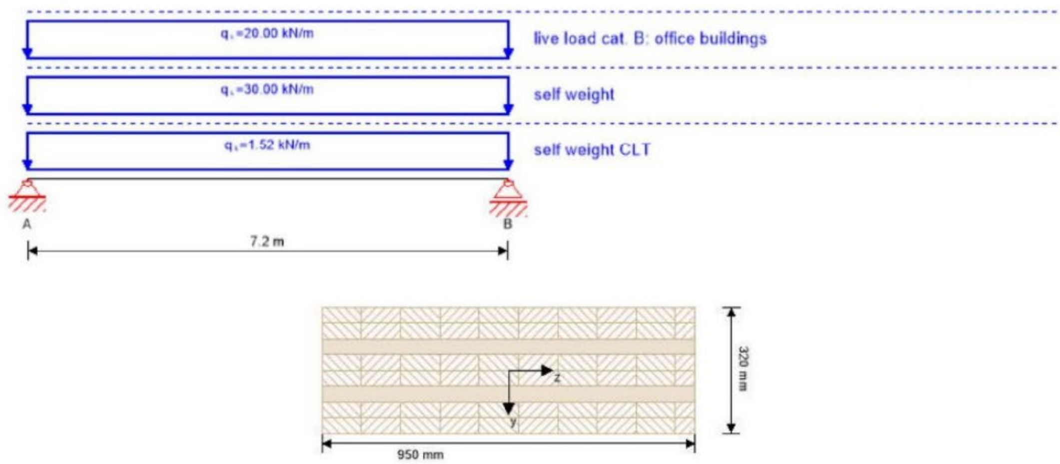
Global utilization ratio			95 %
ULS 95 %	ULS Fire !		

13,5 m lenght analyzed section

Prisma Page 1/1

beam FLOOR for 13.5 m section copy 08.05.2023

Victor-antoine Delorme Lund University Designer VD Checker



Global utilization ratio			85 %
ULS 85 %	ULS Fire !		

Appendix figure 4, Floor beam wood sizing

6 m lenght analyzed section

Prisma Page 1/1

colomn teknik 6m 08.05.2023

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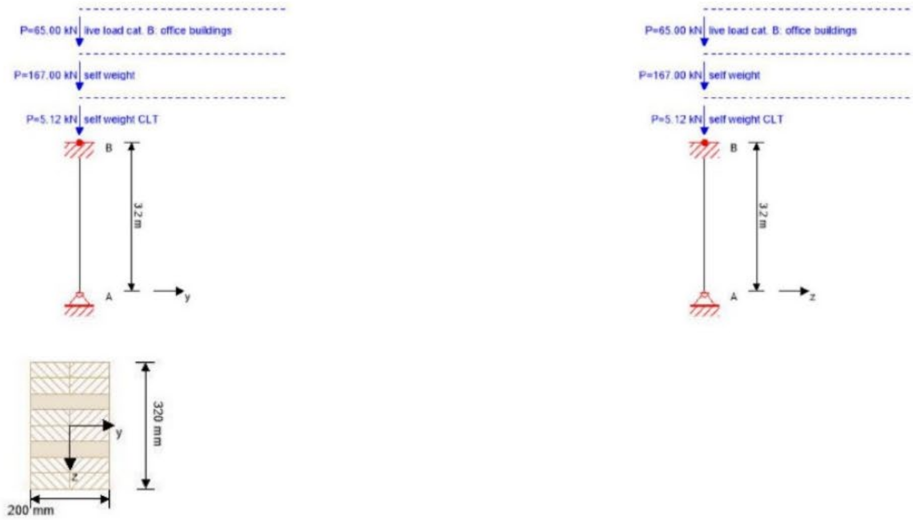

Global utilization ratio			56 %
ULS	56 %	ULS Fire	0 %

13,5 m lenght analyzed section

Prisma Page 1/1

colomn teknik 13,5m 08.05.2023

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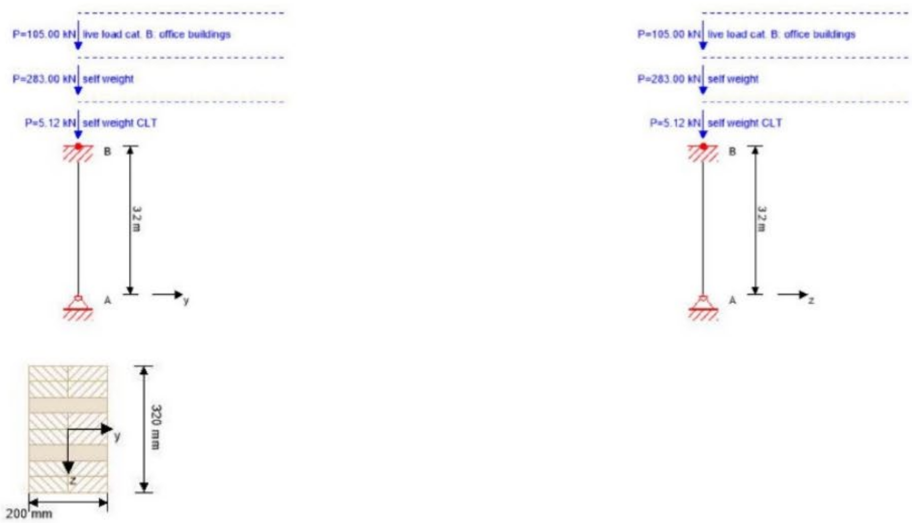

Global utilization ratio			93 %
ULS	93 %	ULS Fire	0 %

Appendix figure 5, Column floor 18, wood sizing

6 m lenght analyzed section

Prisma

c17 6m

Page 1/5

08.05.2023

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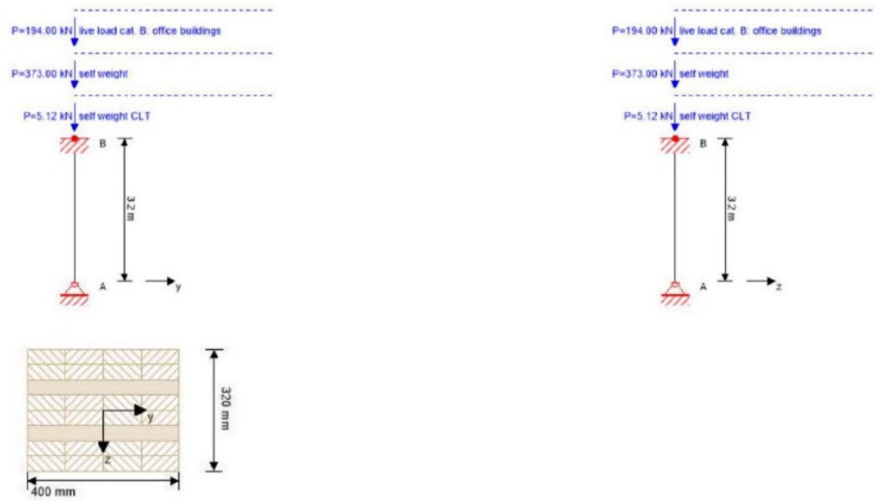
storaenso



Global utilization ratio			63 %
ULS	63 %	ULS Fire	0 %

13,5 m lenght analyzed section

Prisma

c17 13,5m

Page 1/8

08.05.2023

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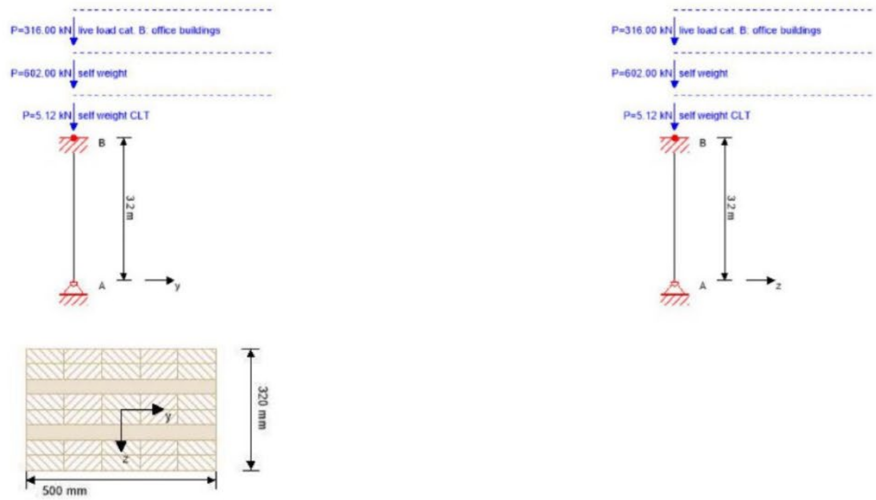
storaenso



Global utilization ratio			81 %
ULS	81 %	ULS Fire	39 %

Appendix figure 6, Column floor 17, wood sizing

6 m lenght analyzed section

Prisma Page 1/5

c16 6m 08.05.2023

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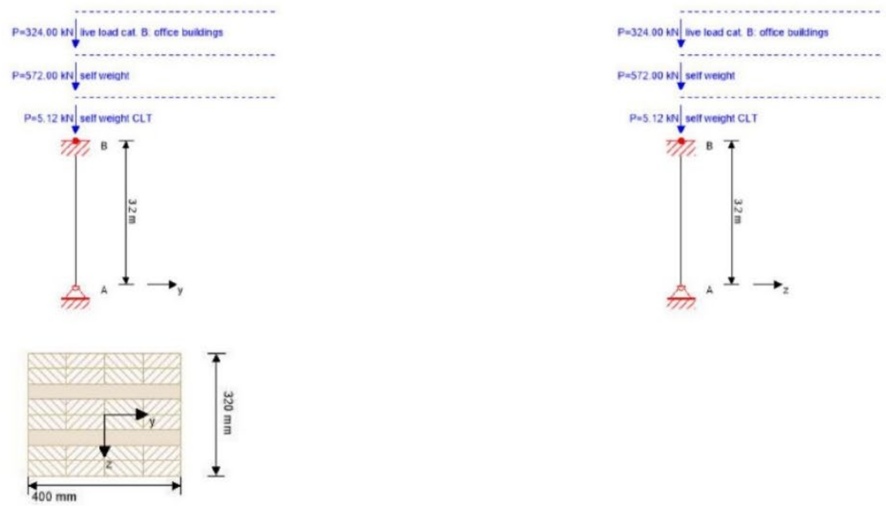


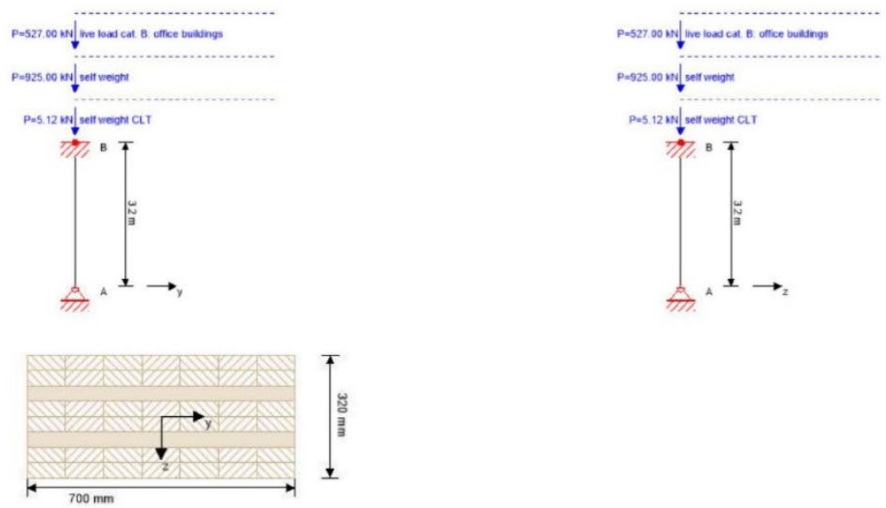
Global utilization ratio				99 %
ULS	99 %	ULS Fire	0 %	

13,5 m lenght analyzed section

Prisma Page 1/8

c16 13,5m 08.05.2023

Victor-antoine Delorme | Lund University | Designer VD | Checker



Global utilization ratio				92 %
ULS	92 %	ULS Fire	43 %	

Appendix figure 7, Column floor 16, wood sizing

6 m lenght analyzed section

Prisma Page 1/5

c15 6m 08.05.2023

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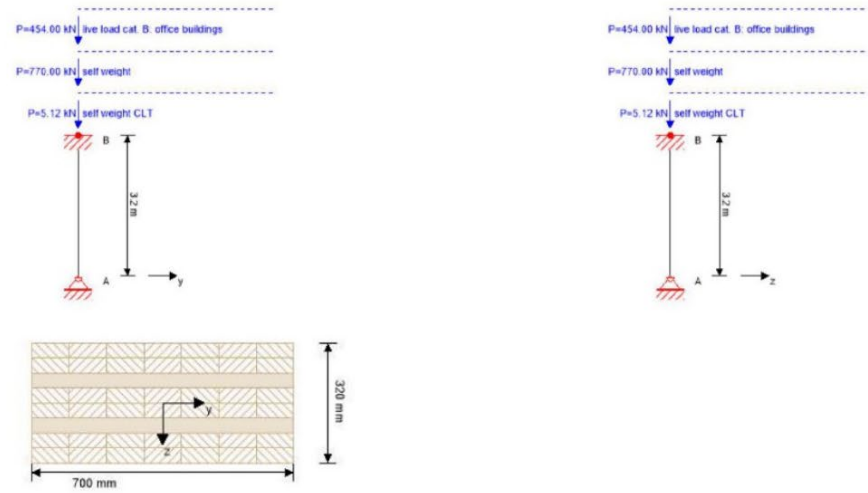

Global utilization ratio				78 %
ULS	78 %	ULS Fire	0 %	

13,5 m lenght analyzed section

Prisma Page 1/8

c15 13,5m 08.05.2023

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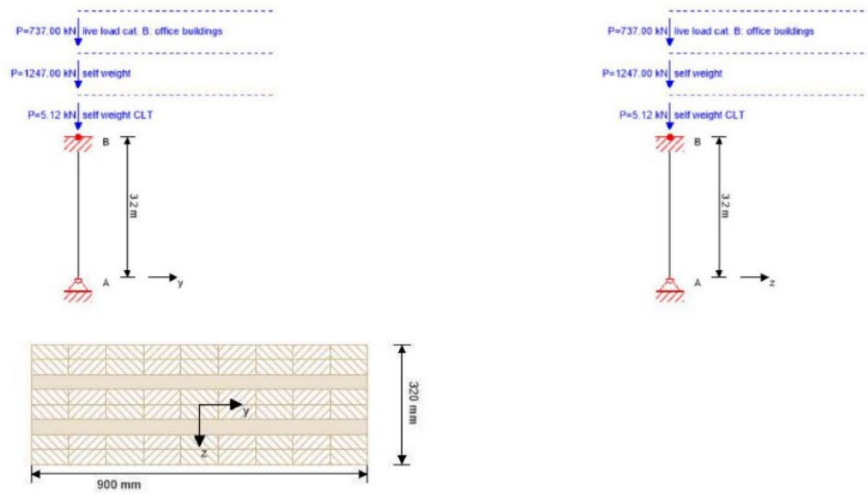

Global utilization ratio				98 %
ULS	98 %	ULS Fire	46 %	

Appendix figure 8, Column floor 15, wood sizing

6 m lenght analyzed section

Prisma Page 1/5

c14 6m 08.05.2023

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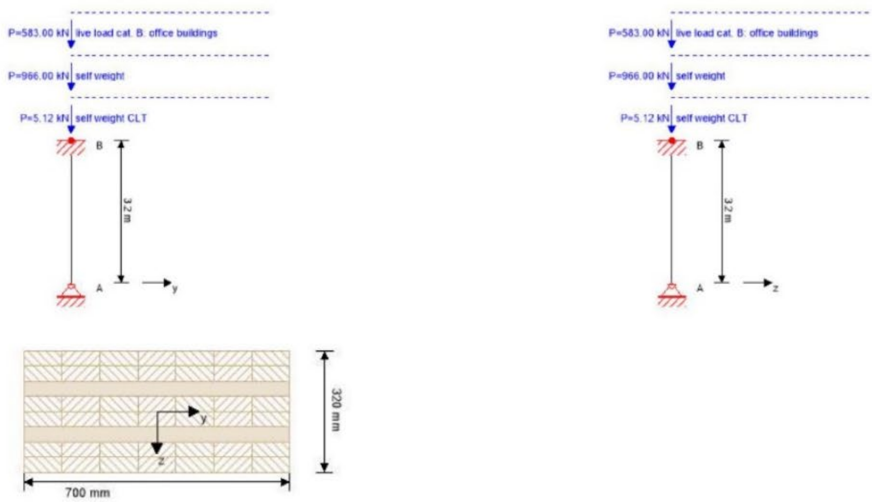
storaenso



Global utilization ratio			98 %
ULS 98 %	ULS Fire 0 %		

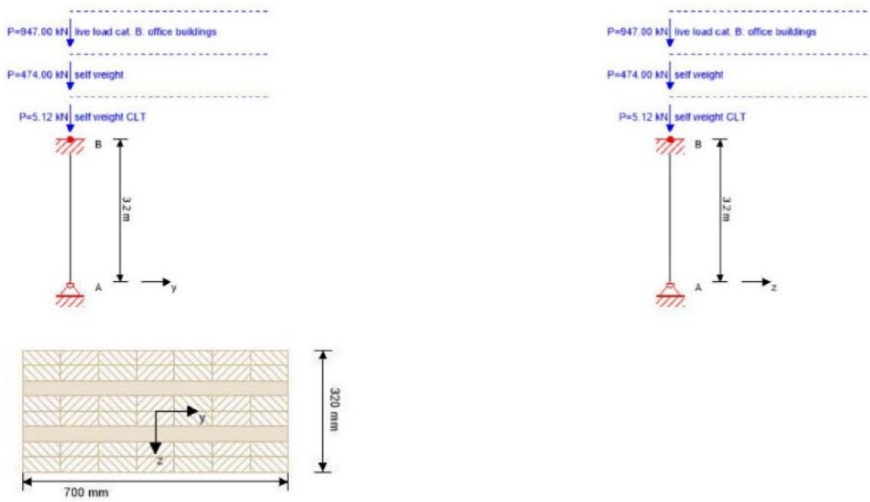
13,5 m lenght analyzed section

Prisma Page 1/8

c14 13,5m 08.05.2023

Victor-antoine Delorme | Lund University | Designer VD | Checker

storaenso



Global utilization ratio			93 %
ULS 93 %	ULS Fire 30 %		

Appendix figure 9, Column floor 14, wood sizing

6 m lenght analyzed section

Prisma Page 1/5
c13 6m 08.05.2023

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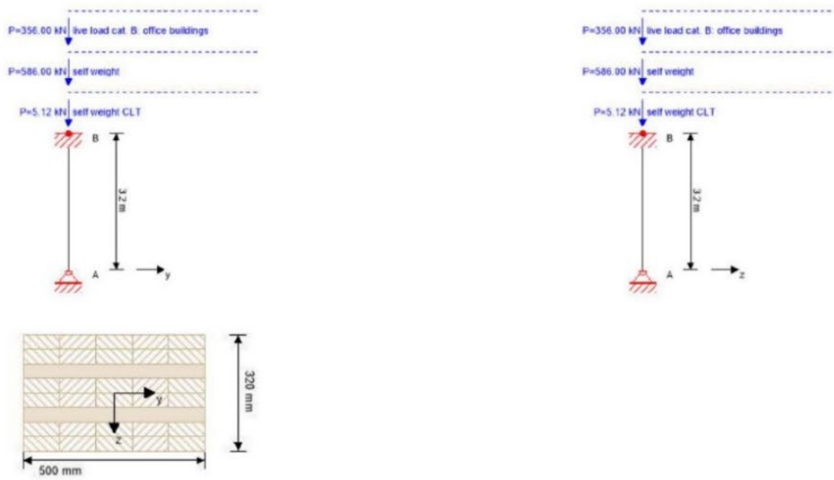
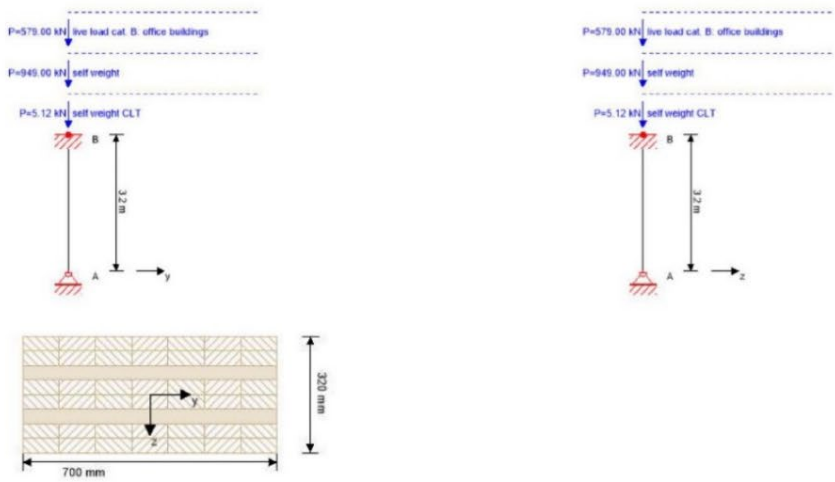


Global utilization ratio			84 %
ULS	84 %	ULS Fire	0 %

13,5 m lenght analyzed section

Prisma Page 1/8
c13 13,5m 08.05.2023

Victor-antoine Delorme	Lund University	Designer VD	Checker



Global utilization ratio			97 %
ULS	97 %	ULS Fire	45 %

Appendix figure 10, Column floor 13, wood sizing

6 m lenght analyzed section

Prisma Page 1/5

c12 6m 08.05.2023

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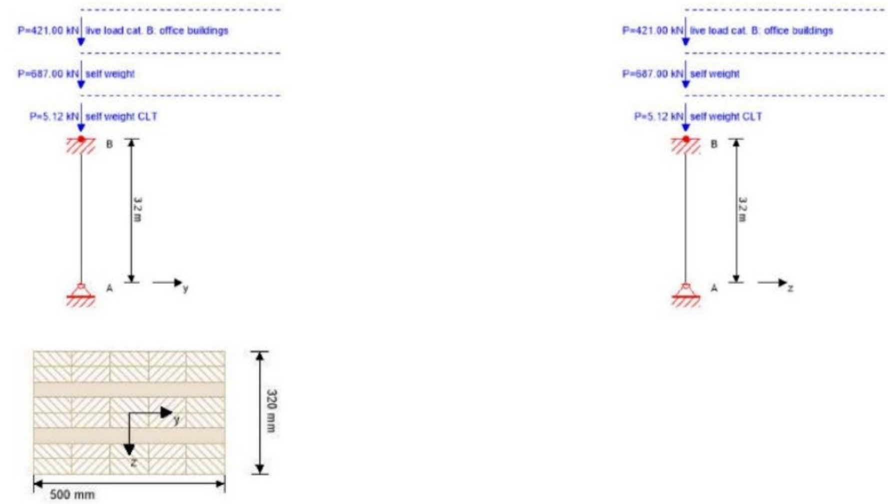


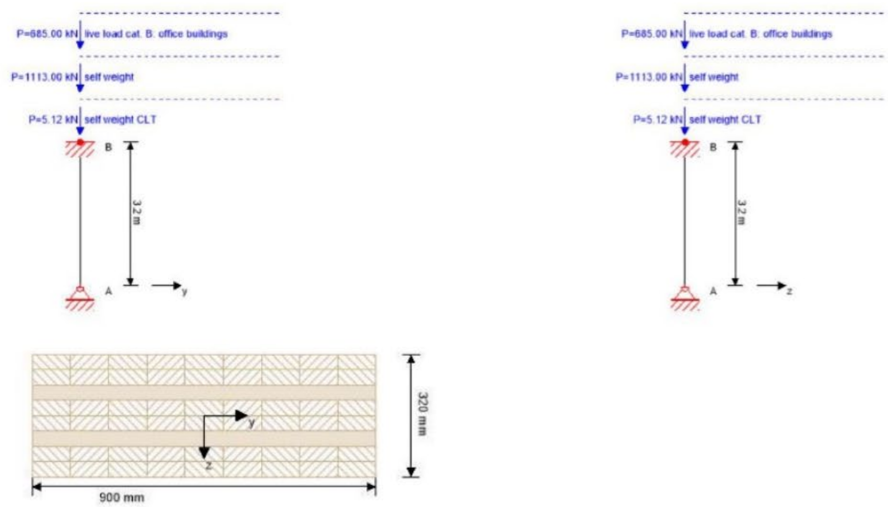
Global utilization ratio			98 %
ULS	98 %	ULS Fire	0 %

13,5 m lenght analyzed section

Prisma Page 1/8

c12 13,5m 08.05.2023

Victor-antoine Delorme Lund University Designer VD Checker



Global utilization ratio			89 %
ULS	89 %	ULS Fire	41 %

Appendix figure 11, Column floor 12, wood sizing

6 m lenght analyzed section

Prisma Page 1/5

c11 6m 08.05.2023

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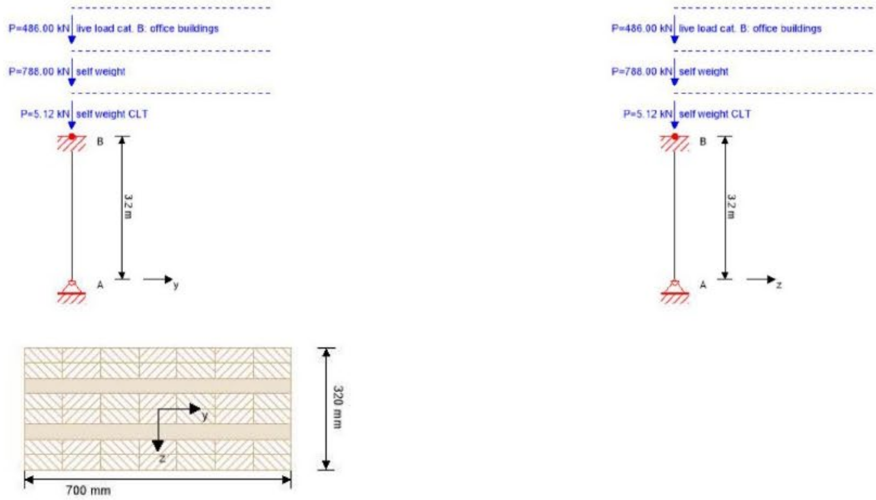


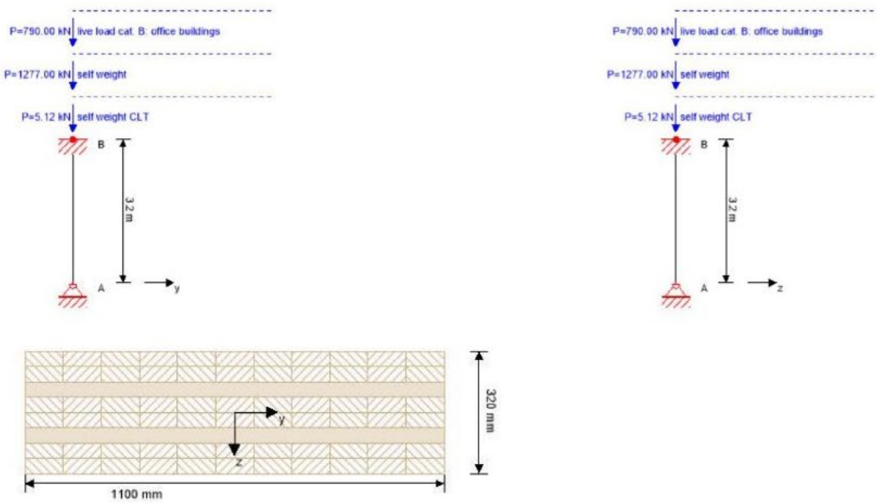
Global utilization ratio				81 %
ULS	81 %	ULS Fire	0 %	

13,5 m lenght analyzed section

Prisma Page 1/8

c11 13,5m 08.05.2023

Victor-antoine Delorme Lund University Designer VD Checker



Global utilization ratio				83 %
ULS	83 %	ULS Fire	38 %	

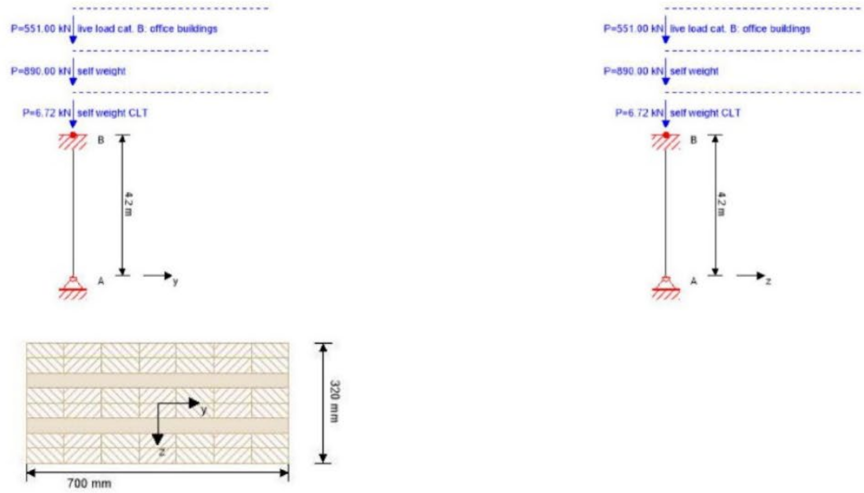
Appendix figure 12, Column floor 11, wood sizing

6 m lenght analyzed section

Prisma Page 1/5

c10 6m 08.05.2023

Victor-antoine Delorme Lund University Designer VD Checker



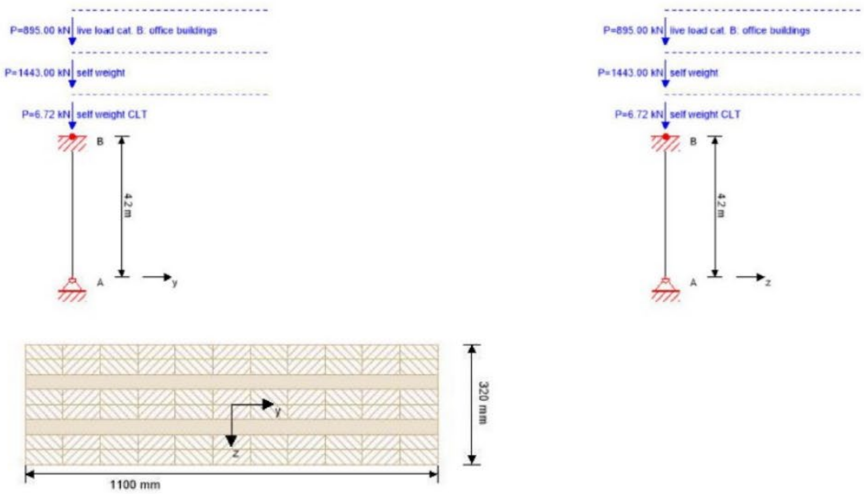
Global utilization ratio			94 %
ULS	94 %	ULS Fire	0 %

13,5 m lenght analyzed section

Prisma Page 1/8

c10 13,5m 08.05.2023

Victor-antoine Delorme Lund University Designer VD Checker



Global utilization ratio			97 %
ULS	97 %	ULS Fire	47 %

Appendix figure 13, Column floor 10, wood sizing

6 m lenght analyzed section

Prisma Page 1/1

CW 10 08.05.2023

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Appendix figure 14, Core wall ground floor, wood sizing

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Department of Building and Environmental Technology