The feasibility of timber as a structural material for mid-rise residential buildings in the Netherlands

A case study-based comparison of concrete, masonry, hybrid-timber and full-timber design variants on environmental and economic impact

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VAN WIJNEN

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by

S.A.L. Stevens

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Cover: Dalston Works, London (Merrick, 2017)

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Preface

This thesis marks the final step in obtaining my Master's degree in Civil Engineering at Delft University of Technology. It has been a journey filled with both personal and professional growth. I have enjoyed my time in Delft, learned a lot about myself and my interests, and built lasting connections and skills. Along the way, I learned to question the status quo, explore new perspectives, and look beyond what is immediately visible. This mindset is reflected in the cover image of this thesis, which features one of the largest applications of timber in apartment buildings. While the timber structure remains hidden from view, the environmental savings achieved through this innovative use of timber are significant.

My research focused on the practical application of timber systems, emphasising the urgent need for solutions to address the various challenges of modern construction. It reflects the interest I have developed over the years and it highlights the impact engineers can have on societal problems.

I would like to thank several people without whom this research would not have been possible. I would like to thank Vincent for his guidance and for the opportunity to perform my research in collaboration with Van Wijnen Engineering. I would also like to thank my colleagues for providing a pleasant working environment and for their willingness to answer my questions. Next to this, I would like to thank Roel, Marc, and Michele for being part of my graduation committee, for their valuable feedback, and for their guidance throughout the process.

Finally, I would like to thank my friends and family for their support throughout my studies. Their advice, ongoing encouragement, and occasional distraction provided the right balance to keep me going during challenging times.

Enjoy reading.

Stan Stevens
Delft, February 2025

Abstract

The construction sector aims to reduce its environmental footprint to address climate change and material depletion, with an increasing focus on reducing embodied carbon. Simultaneously, there is a growing demand for affordable housing in the Netherlands. A significant part of the new housing stock needs to be mid-rise residential, efficient in both material and land use. Bio-based materials, such as timber, which are renewable and have relatively low carbon emissions, could play a key role in reducing embodied carbon for these types of buildings. Since structural systems often account for the majority of a building's embodied carbon, using timber here can offer significant advantages. However, its application in practice remains relatively uncommon in the Netherlands.

Although existing research highlights the potential of timber in structural systems, challenges such as limited knowledge, lack of incentive and financial barriers are often cited as key reasons for its limited adoption. This research aims to address these challenges by exploring and quantifying to what extent a shift toward timber-based structural systems can reduce the environmental footprint of mid-rise residential buildings in the Netherlands, while maintaining economic feasibility. By doing so, this research aims to offer practical insights into the use of timber in construction, addressing knowledge gaps and identifying the conditions for its application in practice.

A comprehensive literature review was conducted on environmental regulations, assessment methods, structural systems, and suitable compositions of structural elements using timber. The insights gathered were applied to a case study, where various redesigns were developed and optimised under different boundary conditions. The environmental impact was quantified by a life cycle assessment using the Paris Proof Indicator (PPI, measured in GWP-GHG). Simultaneously, economic feasibility was quantified by an evaluation of construction costs. The scope of the assessments is limited to the life cycle stages from cradle to practical completion, emphasising the importance of direct impact.

As a result of the assessment of the case-study redesigns, several building concepts provided significant reductions in environmental footprint while being economically feasible. Compared to the original design, hybrid redesign concepts with calcium silicate brick walls and CLT-concrete composite floors can achieve PPI reductions up to 42% while being of equal or lower costs. Concepts with CLT walls and hollow core timber floors can even lead to reductions of PPI up to 55%. Within a 10% increase in costs, a wider range of concepts can lead to similar PPI reductions. All concepts with both CLT walls and CLT floors proved to be economically unfeasible within the stated cost thresholds.

The associated PPI values were found within the range of 82 and 114 kg CO_2-eq./m^2, depending on the building concept. Accounting for design variations between mid-rise residential buildings, research uncertainties, and potential design optimisations, the building concepts researched could align with the Paris Agreement targets up to 2035. As the targets for 2050 are roughly twice as strict, it is unlikely that these are achievable within the researched design strategies. Incorporating reused or recycled materials and/or accounting for the benefits of temporary carbon storage in bio-based materials will likely be necessary to achieve these targets.

Contents

Part I

Research framework

1

Introduction

This chapter will give an introduction to the research topic. In the first section, the research context will introduce the topic and its relevance. After that, the state-of-the-art will give an overview of existing research on the topic, revealing potential knowledge gaps. Finally, the research problem will be stated based on these knowledge gaps.

1.1. Research context

Environmental challenges

One of the leading environmental challenges in the current world is climate change. As many know, human activities have been the leading cause of this, primarily the burning of fossil fuels since the Industrial Revolution. Carbon dioxide and methane emissions are critical drivers for rising temperatures all around the globe, which can lead to various parts of the world becoming uninhabitable within the next century (United Nations, 2024). Especially with the increasing world population and thus demand for housing and agricultural land for food production, this is a major problem. The global construction sector has a significant environmental footprint, contributing considerably to the above-mentioned problems. The industry is responsible for roughly 37% of all CO_2 emissions worldwide (United Nations Environment Programme, 2022), hence the importance of change in this sector.

This 37% of CO_2 emissions can be divided into two categories: embodied carbon and operational carbon. Embodied carbon is all carbon emission that can be related to the extraction, production, transportation, construction, replacement and disposal of materials. Operational carbon is all the carbon emitted for processes during the use stage, such as heating, cooling, lighting, and operating a building. While roughly two-thirds of the current emissions are operational, this number is expected to drop significantly as a result of the energy efficiency actions taken and the change towards the use of renewable energy sources (International Energy Agency, 2023). As a result, embodied carbon will become more dominant, expected to be as high as 40-70% of the total amount emitted by the sector before 2030 (LETI, 2019).

A second environmental challenge is material depletion. The planet only has a certain amount of natural resources, which are currently harvested at high rates. While the resources for concrete are far from depleted, this is different for various metals. For example, iron and aluminium supplies are expected to last no longer than 80 years (van der Lugt, 2020). Contradictory, bio-based materials can give a theoretically infinite supply.

As a result of the challenges and problems mentioned above, the Netherlands, like many other countries, has committed to addressing the environmental problems by signing the recent Paris Agreement. The government aims to reduce the country's primary material demand and CO_2 emissions by at least 50% by 2030, as an initial step toward a 95% reduction in CO_2 emissions by 2050 (Rijksoverheid, 2020).

Non-environmental challenges

Besides the mentioned environmental challenges, there are non-environmental challenges. A housing shortage, labour shortage, and rising costs are all examples of this. To address the housing shortage, the Dutch government has set the goal of building 100,000 houses yearly until 2030 (Ministerie van BZK, 2022). The needed new part of the building stock consists of various building types. According to the responsible ministry, roughly two-thirds of all buildings need to be affordable owner-occupied or rental houses.

From analysing industry-wide research into reaching the building stock goals within the environmental boundaries, it can be concluded that 53% of buildings are expected to be apartment buildings. More specifically, 41% of the expected buildings will be new-to-build apartment buildings (NIBE et al., 2023). While the exact percentage of affordable housing in the new building stock is currently up for political debate, numbers remain significant regardless of the outcome. These building types are anyhow efficient to house many people in a relatively small floor area (Omroep West, 2024). Besides, these types of buildings are very suitable for many locations, among which city centres.

As a result of these non-environmental challenges, building efficiently and cost-effectively is even more critical than before. In addition, environmental regulations are more strict than ever (Rijksoverheid, 2020).

Structural engineering

As indicated before, operational carbon is decreasing and is expected to decline even further. This shows a shift in importance towards embodied carbon. Decreasing embodied carbon for buildings is the next step in reducing the total environmental impact of the construction industry. Structural engineering plays an important role in this. Throughout the design process, structural engineers influence various decisions concerning the material choice, structural systems and layout, construction methodology and potential design for deconstruction (Orr et al., 2021).

When zooming in on the earlier-mentioned apartment buildings, in this case, mid-rise apartment buildings, the origin of the embodied carbon can be related to various elements of a building. In Figure 1.1, this is visualised for the cradle-to-gate phase of a typical mid-rise apartment building in the United Kingdom. On the right-hand side, it is visible that the superstructure and substructure are contributing the most, with a combined contribution of 67%. This combination - often called the load-bearing structure - is divided into more specific elements on the left-hand side of the graph, where the potential of reduction measures is also given (LETI, 2019).

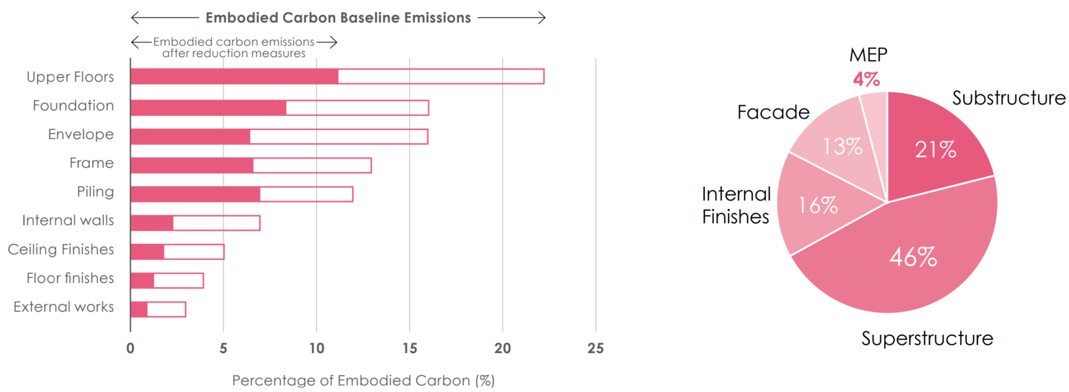


Figure 1.1: Embodied carbon for a medium-scale residential building (cradle-to-gate stage) (LETI, 2019).

According to a design guide of the Institution of Structural Engineers, various strategies exist to reduce embodied carbon. In Figure 1.2, these strategies are shown with their corresponding effectiveness. *Building nothing* has, of course, the highest effectiveness, while *building less* is relatively close to this, with a reduction potential of 80%. These options can only be exploited in a limited way, as many new houses need to be constructed. However, the strategy *building clever* could be very relevant. Design with, for example, low carbon materials and more efficient material use could lead to a reduction of embodied carbon up to 50%: a significant amount (The Royal Institute of British Architects, 2020).

According to the design guide, this strategy can be related to RIBA stages 3 and 4, which are spatial coordination and technical design. Design studies are conducted in these stages, and cost analyses are performed to test architectural concepts. Besides, more in-depth architectural and engineering designs are being developed.

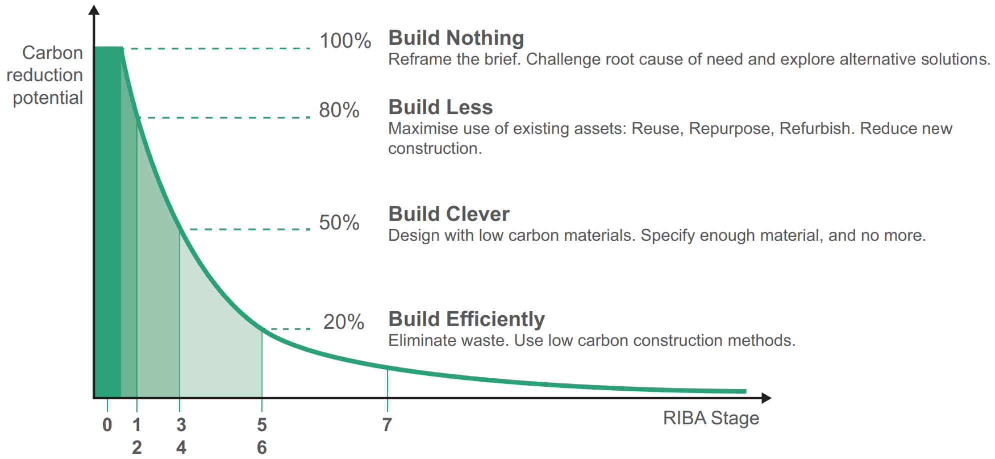


Figure 1.2: Carbon reduction potential, approximately mapped against RIBA Plan of Work (The Royal Institute of British Architects, 2020).

Bio-based materials

From the previous paragraph, it can be concluded that structural engineers could significantly reduce the environmental impact of buildings by selecting low-carbon materials. The earlier cited research by NIBE et al. - which focuses on the Dutch situation specifically - also mentions using low-carbon construction materials as one of their key strategies for building more houses within environmental boundaries. More specifically, they mention using bio-based materials as “the way to go”.

Mentioning bio-based materials and structural elements in one sentence often means using timber. Recent research by Vilnius Gediminas Technical University, aiming to investigate the benefits of sustainable timber construction, studied 169 timber construction projects from the past 25 years (Tupenaite et al., 2023). From this research, various conclusions can be drawn. First, the number of publications significantly increased from 2018 onwards, indicating an increased awareness and importance of this topic. Furthermore, three key benefits can be retrieved from the research:

- Timber construction reduces GHG/CO_2 emissions
- Timber sequestrates/stores carbon
- Timber is a recyclable/renewable material

As stated above, the most mentioned conclusion is that using timber reduces the emission of greenhouse gasses, such as CO_2. The second most mentioned conclusion is that timber stores carbon. In the production stage, the emission of CO_2 is quantified as negative, as timber can store carbon when it grows, contradictory to the energy-intensive extraction and processing of raw materials for non-bio-based materials. Thirdly, the renewable aspect of timber was mentioned often, which is essential in countering material depletion.

According to these conclusions, using timber could counter the environmental problems stated before. However, using this bio-based material, especially structurally, is unusual for regular buildings in the Netherlands (NIBE et al., 2023). With the need to build many apartment buildings within the next decade, structural timber could provide a viable and needed alternative construction material.

1.2. State-of-the-art

This section presents important scientific research into the use and application of timber as a structural material for medium-scale residential buildings, the building type in the highest demand. The given overview will lead to the relevant knowledge gap for this research.

Characteristics of timber

Several studies have shown the potential for timber as a structural material in buildings. The main reason for this is the storage of carbon during tree growth. This leads to negative values during the quantification of carbon emissions in the production stage of a building, indicating storage. When forests are managed sustainably and appropriate end-of-life scenarios are chosen, this could lead to a smaller value for CO_2 emissions in a life cycle assessment than buildings with predominantly concrete or steel.

However, timber has many different material properties compared to regular construction materials. Because of the anisotropic nature of the material, timber has different characteristics in different loading directions. According to a study by the University of Cambridge, timber has a strength parallel to the grain, similar to reinforced concrete. In terms of stiffness, timber is less stiff than concrete and way less stiff than steel. As the density of wood is lower, it benefits structures where a lot of the weight will come from self-weight rather than variable loads (Ramage et al., 2017). Timber is often engineered into mass timber elements to counter the anisotropic characteristics. Multiple smaller elements are glued together in a factory, often in various orientations, creating elements that can address the weaknesses of sawn timber. This engineered wood makes more efficient use of the material and enables constructions to be built higher and more efficiently, as elements can be prefabricated.

While engineered wood has countless appearances in the construction sector, only a few are commonly used for structural reasons. Sawn timber is often used in low-rise buildings when a timber frame load-bearing structure is used. Glue-laminated timber (Glulam) and cross-laminated timber (CLT) - both the result of glueing various saw sections of timber together - are commonly used for higher buildings and larger spans. Glulam is often used for beams and columns, while CLT is used for walls and floors. Laminated veneer lumber (LVL) - the result of combining many thin sheets of wood - is a more homogeneous material, often used in beams, trusses and planks. Figure 1.3 gives an overview of the mentioned types of engineered wood.

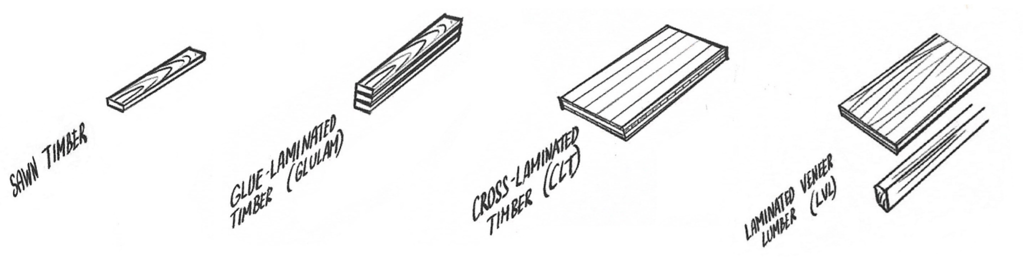


Figure 1.3: Visualisation of the different types of engineered wood and their origin (van der Lugt, 2020).

Research into the potential of timber

Research at Delft University of Technology investigated under which circumstances timber can be a valid alternative construction material. In the study, the number of storeys and floor spans of a cross-laminated timber building were parameterised, and emissions were calculated. Buildings with a relatively small floor span of 3.6m and a storey height of up to 5 storeys could be profitable in the Netherlands - even without considering carbon storage. When carbon storage is considered, spans up to 4.8m or buildings up to 9 storeys could become profitable (Helmond, 2021).

Other studies have shown several advantages of timber as a structural material, such as the possibility for smaller foundations due to the lower mass of superstructures (Luijkx et al., 2021). Buildings with predominantly timber also tend to have a shorter construction time (Waugh-Thistleton-Architects, 2018), provide more options for modifications and have more architectural flexibility than concrete alternatives (Tupenaite et al., 2023). Among the disadvantages due to the lower mass of wood are lower thermal performance, lower acoustic performance and a higher level of attention needed for vibrations (van der Lugt, 2020). Durability is generally relatively low, and fire resistance often requires more attention compared to concrete buildings(Cheng et al., 2023). Finally, construction costs are usually higher than concrete alternatives (Giesekam, Barrett, and Taylor, 2016).

Comparative research

Besides research into timber as a structural material, several studies have compared timber and concrete buildings to a certain extent. Researchers at Tampere University performed a life-cycle assessment of a five-storey high residential building in a local neighbourhood in Finland. In this study, concrete and timber alternatives for the building were designed. All variants were assessed based on all LCA categories. The timber building had a 28% lower carbon footprint than the hybrid building in the production stage (A1-A3). In the construction stage (A5), this was 55% less than the hybrid building and roughly 65% less than the concrete building. In the end-of-life stage (C), concrete had a far smaller footprint than timber building, while timber showed the most potential beyond the life cycle (D). In conclusion, "wood-based hybrid solutions can lead to more rational use of wood, encouraging the development of more efficient buildings" (Rinne, Ilgin, and Karjalainen, 2022).

Another study, performed by the Melbourne School of Engineering, investigated mid-rise residential buildings in various locations in Australia. Greenhouse gas emissions and costs were determined for a cross-laminated timber design and a reinforced concrete alternative. The greenhouse gas emissions of the CLT building in the product and construction phase are roughly 50% lower than those of the concrete building. The benefits in the end-of-life phase for the reinforced concrete building are 18% higher than those of the CLT building. The total life cycle costs of the CLT building are 0.9-1.3% lower compared to the reinforced concrete building (Jayalath et al., 2020).

Finally, a cost comparison between timber and traditional concrete systems for apartments in Australia, performed by the University of Melbourne, confirmed previous findings. Three design alternatives were investigated: a concrete alternative, a timber alternative with a concrete ground floor, and a full timber alternative. The full timber alternative has 10% lower element costs, while the timber with concrete ground floor alternative has 7% lower element costs. Note that construction costs were not taken into account in these numbers. (Ritchie, 2018).

1.3. Research problem

As can be concluded from the state-of-the-art, the use of timber could be a realistic solution to contribute to solving some of the environmental problems in the Netherlands and worldwide. Existing studies have shown potential. However, designing and constructing with new materials and processes is a step into the unknown, leading to more uncertainty, risks and often more costs. More research into the application of timber is essential, as gaining more knowledge about the material can potentially take away obstacles like the ones described above.

For example, little research is available on the earlier-mentioned building type "mid-rise residential", especially not for application in the Netherlands. Country-specific research is important, as the Netherlands' concrete-based industry could lead to significant differences in how economically attractive choosing another material than concrete or masonry is compared to other countries. Besides, comparative studies often only focus on environmental impact rather than economic impact.

In short, a complete analysis of different variants of a mid-rise building where the environmental impact of elements is compared to the economic impact does not exist for this country. This is important, as economic aspects are often leading in decision-making: a more environmentally friendly solution will not be built at all if it is not profitable, especially not for "regular" residential buildings, for which developers do not have a strong incentive to reduce the environmental footprint (Luijkx et al., 2021). So, to enable designers and engineers to choose timber more often, more knowledge is needed on how this can be incorporated profitably.

2
Research approach

This chapter will give the research approach. Derived from the research problem, the research aim and objective will be given first, followed by the scope. After this, the main research question and the sub-research questions will be given. Finally, the methodology and structure of the research will be explained.

2.1. Research aim and objective

The objective of this research is to investigate the feasibility of timber as a structural material for mid-rise residential buildings in the Netherlands. The research aims to explore and quantify to what extent a shift toward timber-based structural systems can reduce the environmental footprint of mid-rise residential buildings in the Netherlands while maintaining economic feasibility.

To achieve this, a case study is performed on a typical Dutch apartment building, originally designed with calcium silicate bricks and concrete as primary structural materials. Redesigns will be made for this building using various timber-based systems, optimising for various boundary conditions. Redesigns will be made in full timber and hybrid timber configurations, ensuring compliance with local building codes. The redesigns will be assessed on environmental impact and economic feasibility.

After this, the validity of the case study results for mid-rise buildings in general is investigated by performing a sensitivity study. Furthermore, by combining all data, the relation between the environmental and economic impact of various structural systems, elements and design strategies will be shown more explicitly. The results are compared to the environmental targets retrieved from governmental goals, aiming to enable structural engineers to make design decisions more quickly and well-founded, with more knowledge about the consequences.

2.2. Research scope

A scope has been defined to ensure this research can be performed within the available time frame. This leads to limitations and focus points, as explained below.

Building type and materials

This research will focus on mid-rise residential buildings with roughly five storeys, a widely used and much-needed building type in the Netherlands. While the inclusion of timber is the main focus point of the redesigns, hybrid variants, including non-bio-based materials, will be investigated as well. However, only prefabricated concrete will be considered for the superstructure, and all modular construction methods will not be considered. The material choices within various design variants will be based on preliminary assessments of elements.

Level of detail

This research will focus on the load-bearing structure. While the superstructure will be the main focus point for optimisation, the substructure will also be considered. In addition to structural elements, changes or additions initiated by a change of structural element will also be considered. For example, when a switch from a concrete wall to a CLT wall means fireproof cladding will be needed to meet similar fire resistance demands, this will be considered. The principle is that the structural and building physics performance of different designs will be similar. The level of detail, as commonly used, can best be described as a combination of preliminary design (VO) and final design (DO).

Assessment

As mentioned, the redesigns will be assessed in terms of environmental and economic impact. While the exact criteria will be determined as part of this research, the limitation of environmental analysis for cradle-to-practical completion has been determined. This has been chosen to focus on direct impact, as, for example, reducing carbon emissions is urgent. Besides, end-of-life scenarios are uncertain in various ways, as technological progression is likely to influence these scenarios to a larger extent than can be predicted at this moment in time. Furthermore, the non-environmental aspects will be included in the cost analysis. Therefore, construction time and the amount of labour required will only be considered indirectly.

2.3. Research questions

Main research question

This research consists of multiple parts, each answering various sub-questions. Answering these sub-questions will contribute to answering the main research question, which is stated below.

"To what extent can a change in structural system towards timber lead to a reduction of the environmental footprint of a typical mid-rise residential building in the Netherlands, while ensuring economic feasibility?"

Sub-research questions

The following sub-research questions will be discussed throughout this research:

Q1 Which methods assess the environmental footprint and economic feasibility of design variants most effectively, and which parameters should be included?

Q2 Which structural systems and elements are suitable for timber or hybrid timber mid-rise residential buildings, and what are their advantages and disadvantages?

Q3 What are limiting structural, environmental and economic factors in the original design of the case study building, and which redesign strategies can be retrieved from this?

Q4 How can the original design of the case study building be adjusted optimally into timber or hybrid timber variants, *within* the existing grid?

Q5 How can the original design of the case study building be adjusted optimally into timber or hybrid timber variants, *beyond* the existing grid?

Q6 Which input parameters are most likely to affect the case study results, and to what extent do they influence the ability to extrapolate these results to mid-rise residential buildings in general?

The sub-research questions will be explained in more detail in the next section, along with the relation between them.

2.4. Research structure and methodology

The research is divided into several parts. Each part consists of multiple chapters belonging to a sub-research question. Figure 2.1 gives an overview of this. Different and/or multiple research methods will be used for each question. In this section, the aim of each part will be explained, and the research methods will be given if applicable.

Part 1 - Research framework

The aim of this part is to introduce the research topic and identify the state-of-the-art and research gaps. Based on this, the research approach has been given and explained further.

Part II - Preliminary research

In this part, research questions Q1-Q2 will be addressed.

The aim of this part is to gather the needed information for the case study on environmental, economic and structural design aspects. Several terms of the research question will be defined, current environmental regulations will be investigated, and other topics will be discussed. This will be done by analysing existing literature. Similarly, economic impact is investigated, and suitable assessment methods are determined for both environmental and economic impact.

To address the second research question, suitable structural systems and elements are identified based on a combination of literature and experience from practice. The build-ups of structural elements will be determined based on existing guidelines and will be assessed in a preliminary manner afterwards. Suitable structural systems will be selected and analysed, and consequences will be given. Interviews with experts from practice will be used to gather more information and validate the already collected data.

Part III - Case study

In this part, research questions Q3-Q6 will be addressed.

The aim of this part is to find efficient redesign variants that are optimised in terms of both environmental and economic impact. To address the third research question, the existing design will be analysed structurally, and environmental and economic impact assessments will be given. To address the fourth and fifth research questions, a twofold case study will be performed, in which redesigns of various materials will be combined into realistic designs that will be optimised under various boundary conditions. Both timber and non-bio-based materials will be used. First, solutions will be explored within the existing grid, meaning that the current building layout - including the heart-to-heart spans of the apartments, will be maintained. Secondly, the solutions will be explored beyond this, meaning that different building layouts will be explored within the site.

Based on the knowledge gathered in Part I, the first design steps will be made with hand calculation to get a rough estimation of the element size for various systems. Later, the redesigns will be modelled, and design software will be used to verify the structural capacity. Technosoft and AxisVM will be used for structural verifications. Depending on which environmental and economic indicators will be used, appropriate software will be selected to quantify the impact. Assessments will be held throughout and after the redesign process, as designing is circular rather than linear. After the final assessment, the resulting data will be analysed and used to answer the relevant research question.

To address the sixth research question, the effect of various input parameters on the outcome of the case study will be investigated. First of all, the uncertainty in input data used for environmental and economic assessment will measured by performing renewed calculations with different input values. After this, the influence of minor changes in dimensional input variables will be investigated. Various research methods will be used depending on which factors will be investigated. The aim is to investigate to what extent the case study results can be extrapolated to mid-rise residential buildings in general.

Part IV - Research outcome

This last part aims to reflect on the research findings, derive conclusions, and suggest recommendations for practical application and future research.

Below, in Figure 2.1, an overview of the structure of the research is given.

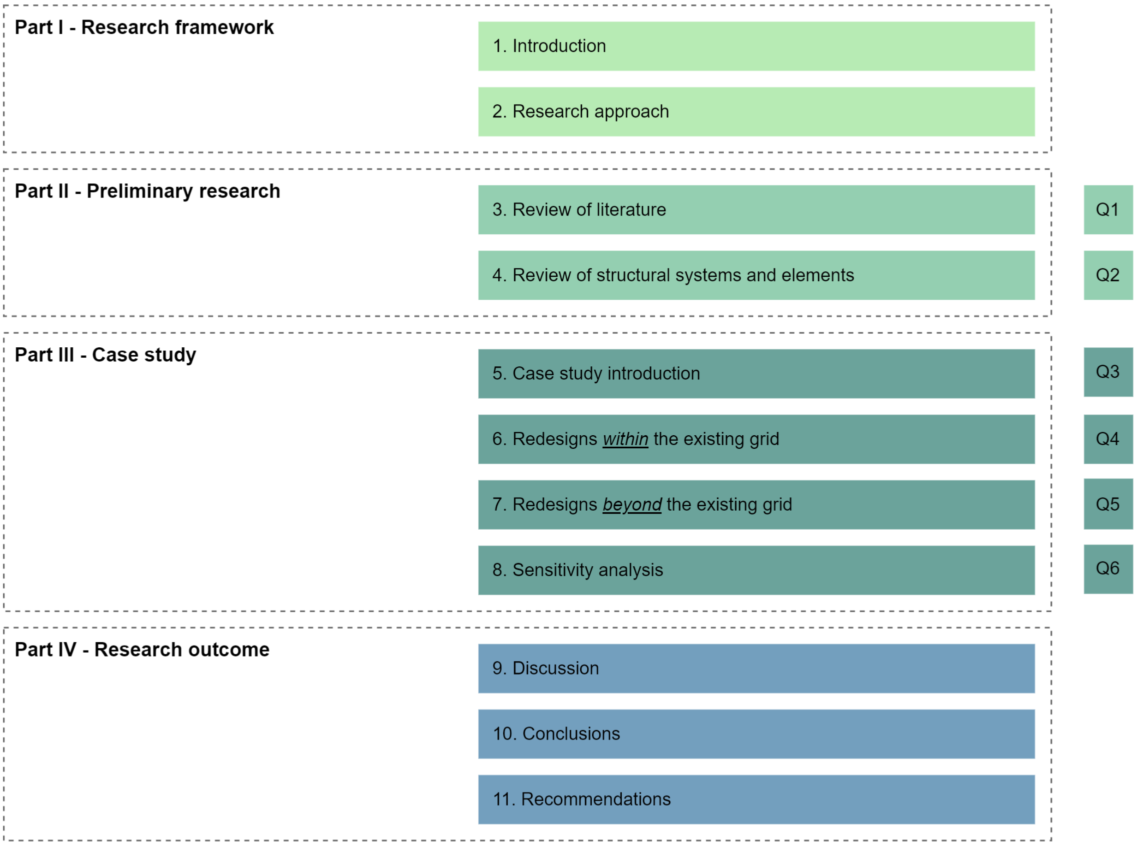


Figure 2.1: Structure of the research, including annotation of which sub-question will be addressed in each chapter.

The structure of the research, as given on the previous page, shows the relation between chapters and sub-questions. To show the relation between individual parts within and between the different chapters, a conceptual overview of the research is given in Figure 2.2.

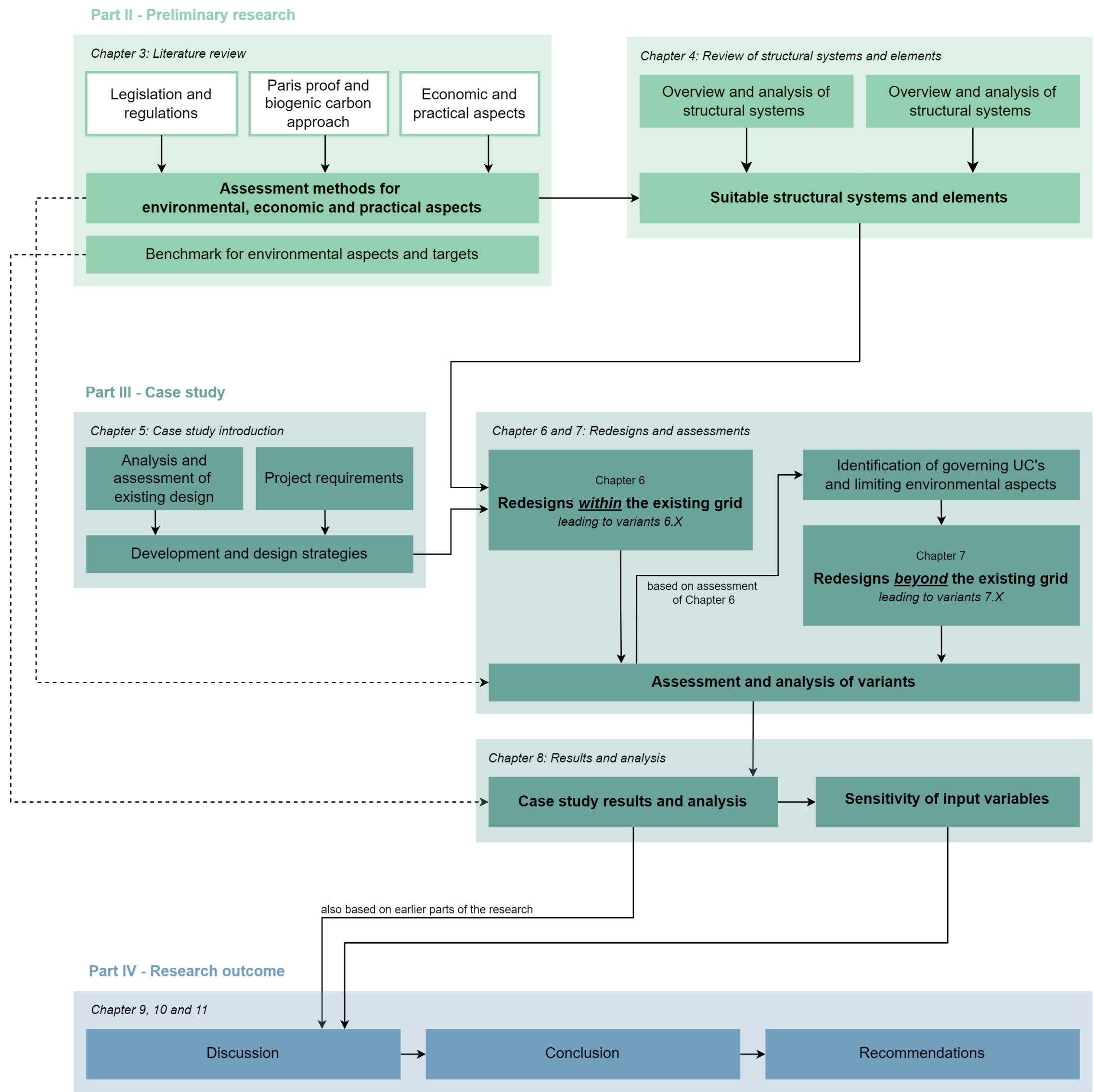


Figure 2.2: Conceptual overview of the research.

Part II

Preliminary research

3

Review of literature

In this chapter, key topics to the research will be reviewed based on literature, with the aim to find suitable assessment methods for both environmental impact and economic feasibility. First, these terms will be defined more clearly. After that, environmental legislation and regulations, the Paris proof approach and the importance of biogenic carbon will be discussed. Based on the above, suitable indicators and assessment methods will be determined, all to address the following research question:

"Which methods assess the environmental footprint and economic feasibility of design variants most effectively, and which parameters should be included?"

3.1. Definitions

This section defines the terms "environmental footprint" and "economic feasibility" - mentioned in the main research question - and provides more context and background information to help make better-substantiated choices regarding quantification methods.

3.1.1. Definition of environmental footprint

As mentioned in the research question, the environmental footprint of mid-rise residential buildings is aimed to be reduced. What an environmental footprint is will be discussed threefold: from the perspective of planetary boundaries, from the perspective of sustainability, and from the perspective of engineering.

Definition 1 - Environmental footprint according to planetary boundaries

Fifteen years ago, the Stockholm Resilience Centre identified nine planetary boundaries to assess the Earth's interrelated biophysical boundaries. According to the Centre, "crossing boundaries increases the risk of generating large-scale abrupt or irreversible environmental changes" (Richardson et al., 2023). Logically, this is something that needs to be avoided.

As of 2023, six of the nine boundaries are crossed or outside safe operating space, being the following:

- Climate change, measured in atmospheric carbon dioxide concentrations
- Biosphere integrity, measured in extinction rate and energy available to ecosystems
- Land-system change, measured in percentage of forests rested intact
- Freshwater change, measured in percentage of human-induced disturbance of water flow
- Biogeochemical flows, measured in phosphate and nitrogen global and regional flows
- Novel entities, measured in percentage of synthetic chemicals released to the environment without adequate safety testing (Persson et al., 2022).

The other boundaries, which are currently within a safe operating space, are:

- Stratospheric ozone depletion, measured in stratospheric ozone concentration
- Atmospheric aerosol loading, measured in interhemispheric difference in Aerosol Optical Depth
- Ocean acidification, measured in the global mean saturation state of calcium carbonate in surface seawater (Richardson et al., 2023)

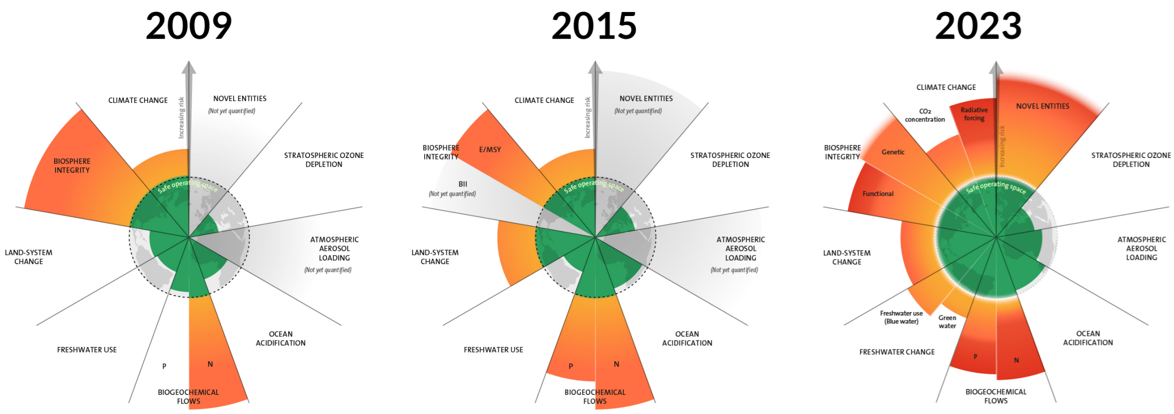


Figure 3.1: The evolution of the planetary boundaries framework, where green indicates a boundary that has not been crossed, and orange indicates an increasing level of being outside of the safe operating space for that boundary (Richardson et al., 2023).

In Figure 3.1, it can be seen that the amount of boundaries that have been crossed has increased over the years. While the building industry's impact on boundary climate change is the most obvious, the activities of the building industry are directly or indirectly related to all boundaries. Therefore, all boundaries can be seen as part of the environmental footprint of a building (NIBE et al., 2023).

Definition 2 - Environmental footprint according to sustainability

Environmental impact and sustainability are terms that are used interchangeably. However, they are not equal. A widely used definition of sustainability or sustainable development is the one created by the Brundtland Commission of the United Nations:

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

According to the commission, four needs are considered: availability of finite resources, clean environment by minimising harmful emissions, social fairness and economic growth (World Commission on Environment and Development, 1987). As can be derived, environmental aspects are only a part of sustainability, next to economic and social aspects. The need for the availability of finite resources and a clean environment by minimising harmful emissions is roughly in line with the boundaries stated by the Stockholm Resilience Centre. However, not all boundaries, especially those related to more significant system changes, are mentioned directly.

Definition 3 - Environmental footprint and sustainable structural engineering

Besides the definition of environmental sustainability, other factors that could be influenced by structural engineers and could lead to a more sustainable building industry should be considered. Already fifteen years ago, Peters et al. defined criteria for sustainable structural engineering: increase a building's service life, design in a flexible way to ensure future use and circularity, limit material use, use sustainable materials, take into account the impact of construction and transport, and use a structural system for more than just load-bearing purposes: the importance of integral design. While this thesis focuses on the effects in earlier life stages, these criteria should be considered in decision-making (Peters et al., 2019).

3.1.2. Definition of economic feasibility

The research question states that reducing the environmental footprint is aimed at “while ensuring economic feasibility”. However, economic feasibility might not be something entirely clear. The Cambridge Dictionary defines feasibility as “the possibility that something can be made, done, or achieved, or is reasonable” (Cambridge Dictionary, 2024).

In this thesis, many design variants will be created. These variants will only be considered or elaborated on when they are competitive already or have a reasonable chance of being economically competitive in the future. This ensures that design variants that at this stage might not be able to compete with existing variants but might be in the future are also taken into account. This process of becoming more economically attractive in the future is due to potential economies of scale. Research by McKinsey & Company has estimated a reduction of costs up to 20% as a result of this (McKinsey & Company, 2019).

Besides these potential cost reductions, benefits could also be achieved in terms of energy-efficient buildings due to timber’s excellent thermal properties (Buchanan and Levine, 1999). Furthermore, if environmental policies evolve and environmental compensation costs are taken into account, for example, via carbon taxes, timber could become more economically competitive in the long term (D’Amico, Pomponi, and Hart, 2020). All of the reasons mentioned above are reasons to at least investigate potential variants that are currently not competitive but might become so in the future.

As mentioned before, sustainability has economic and social aspects next to environmental ones. While economic aspects can be related to all topics mentioned above, this is not true for social aspects. However, social sustainability is not something directly influenced by structural engineers but rather by “manufacturers and constructors, which, together with governing organisations, determine the working conditions and fairness for employees and communities where the building materials originate from” (van Wijnen, 2020). Therefore, this aspect is not considered in this research.

3.2. Environmental legislation and regulations

In this section, an overview of how the Netherlands has set up legislation and regulations to achieve the targets of the Paris Agreement will be given. Existing calculation methods will be explained, and other suggested methods will be discussed.

3.2.1. Paris agreement and Dutch adaptation

To stay within the boundaries mentioned earlier, almost all UN members have agreed to act upon this during the United Nations Framework Convention on Climate Change in 2015. The agreement following from this, often called the Paris Agreement, addresses crucial areas for climate change, most notably setting the goal to “limit the global temperature increase to well below 2 degrees Celsius, while pursuing efforts to limit the increase to 1.5 degrees” (UNFCCC, 2024).

The Netherlands has committed to lower their CO_2 emissions step-wise over the next decennia, with certain decreases in emissions compared to the established baseline of 1990 (Rijksoverheid, 2020). For 2030, that target is a 60% reduction, followed by 70% in 2035 and 80% in 2040. A combination of the historic data for CO_2 and interpolated values between the targets give the graph in Figure 3.2.

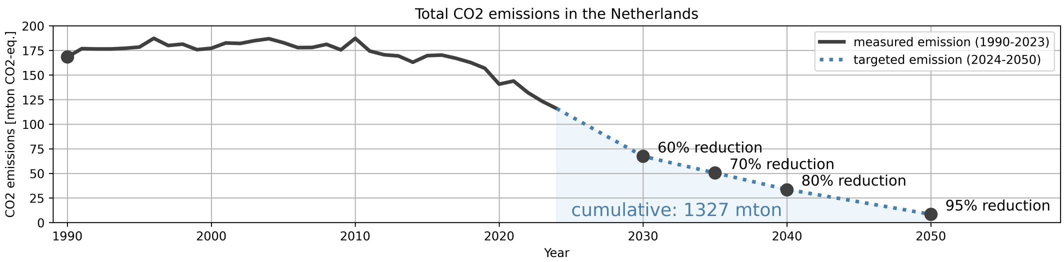


Figure 3.2: Total CO_2 emissions in the Netherlands, measured and targeted values.

Note that for 2050, a reduction of 95% is used rather than 100%, in line with policies (Rijksoverheid, 2020). As can be seen in the graph, a 24% reduction compared to 1990 is achieved at this moment in time: a relatively low percentage at first sight. However, to put these values in perspective, emissions were up compared to this baseline as late as 2016.

3.2.2. Milieu Kosten Indicator (MKI) and Milieu Prestatie Gebouwen (MPG)

The Netherlands has created regulations for various sectors to achieve the set goals. For the building sector, this means that calculations need to be made to quantify the environmental impact of all new buildings. These calculations must be performed according to the life cycle assessment framework, as will be explained in detail later in this chapter. The indicator created for this is named MPG, short for Milieu Prestatie Gebouwen, measuring the impact per square meter of gross floor area per year of the reference service life. To get to an MPG value, first, the value for the Milieu Kosten Indicator (MKI) needs to be determined, which is the total impact of a building. The methods consider various environmental impact categories, each belonging to a different part of environmental impact. To get MKI values, the total values for all environmental impact categories need to be multiplied by monetised weights. This leads to a value in euros: the total environmental compensation cost for that project, or MKI. This can be summarised in the following formula:

$$MKI = \sum_{i,j=1}^{n,m} V_j \cdot E_{ij} \cdot C_i \qquad [euro]$$

where:

V_j	is the volume of element j,
E_{ij}	is the environmental impact of element j for indicator i,
C_i	is the shadow cost for indicator i,
n	is the number of environmental impact categories,
m	is the number of construction elements.

To better compare values between projects or design variants, this value can be divided by its reference service life and its gross floor area, leading to the MPG-value in €/m^2/yr, as described earlier. The MPG can best be summarised in the following formula:

$$MPG = MKI \ / \ A \ / \ RSL \qquad [euro/m^2/y]$$

where:

A	is the gross floor area of the project,
RSL	is the reference service life of the project.

The environmental impact categories used for this are explained later. Currently, 11 impact categories are used, while the maximum MPG value for residential buildings is 0.8. From 2025 onwards, 17 impact categories will need to be used to provide more information. The maximum MPG value will increase to 1.0. This decision and the MPG method itself have been criticised (Belzen, 2024). First of all, the method itself is rather complicated, as other EU countries use methods that are way less complex. MPG outcomes are given in one score, which could be seen as simple and easy to compare; however, it results in a loss of background information on where the impact on the environment originates from. Secondly, a lack of available product data is also an important issue, and besides, not all categories have been thoroughly scientifically based. As a result, the use of bio-based materials is expected to become less favourable, which is contradictory to governmental policies (Bruyn, Bijleveld, and Korteland, 2020).

Considering carbon emission specifically, it is relevant to note that no separate CO_2 assessment is mandatory in the Netherlands, and neither will this be created in the near future (Belzen, 2024). Besides, in an MPG calculation, global warming potential, the indicator reflecting carbon emissions, focuses on whole-life carbon. This means that the combination of embodied carbon and operational carbon is assessed. As a result, achieving lower operational carbon values will allow for higher embodied carbon values, leading to a combined value which is below the limit.

3.3. Paris proof approach and CO_2-budgets

This section will discuss the Paris proof approach and indicator, being an alternative indicator for environmental footprint.

3.3.1. CO_2-budget and Paris proof indicator

In recent research by the Dutch Green Building Council, in cooperation with NIBE and partners, the topics of construction within the planetary boundaries and Paris-proof embodied carbon has been studied (NIBE et al., 2023). A so-called CO_2-budget is the key concept of the study: a budget which reflects the total amount of emissions that is theoretically available to stay within certain limits.

Based on a 2021 IPCC study - The Physical Science Basis - estimated remaining carbon budgets have been determined. Different combinations of maximum allowable temperature increase, combined with likelihoods of occurrence, led to these budgets, as can be seen in Figure 3.3. The available worldwide budgets are given first, and the adjusted budgets for the Netherlands are given afterwards. This budget is based on the Netherlands' share of the worldwide population and is adjusted for 2024 by subtracting emissions from the past years (Statistics Netherlands (CBS), 2024). The choice to take the share of population rather than, for example, the share of GDP will eventually be a political one, for which worldwide consensus needs to be found. This is important, as the Dutch represent only 0.22% of the population but 0.99% of the world's GDP: a significant difference. Population ratio has been chosen for now, as this is more in line with the country's environmental targets, as will be shown later.

Approximate global warming relative to 1850-1900 until temperature limit (°C)	Estimated **worldwide** remaining carbon budgets from the beginning of **2020** (Gton CO2)				
	Likelihood of limiting global warming to a certain temperature limit				
	17%	*33%*	*50%*	*67%*	*83%*
1,5	900	650	500	400	300
1,7	1450	1050	850	700	550
2,0	2300	1700	1350	1150	900

Approximate global warming relative to 1850-1900 until temperature limit (°C)	Adapted estimated remaining carbon budgets from the beginning of **2024** for **the Netherlands**, based on population ratio (Mton CO2)				
	Likelihood of limiting global warming to a certain temperature limit				
	17%	*33%*	*50%*	*67%*	*83%*
1,5	1440	890	560	340	120
1,7	2650	1770	1330	1000	670
2,0	4520	3200	2430	1990	1440

Figure 3.3: Available CO_2-budgets based on IPCC studies, both for worldwide and Dutch situation (Canadell et al., 2021).

In Figure 3.4, the cumulative CO_2 emissions for the period 2024-2050 according to Figure 3.2 is compared to the available budgets according to a 67% likelihood. From this, and Figure 3.3, it can be concluded that achieving the current goals will most likely lead to a temperature increase below 2.0 degrees Celsius - that is, if all countries would take similar actions. Besides, an increase limited to 1.7 degrees is possible (50th percentile), and an increase limited to 1.5 degrees is unlikely (17th percentile).

To achieve the goal of "limiting the global temperature increase to well below 2 degrees Celsius, while pursuing efforts to limit the increase to 1.5 degrees", it could be argued that more strict rules or policies are needed. To stay realistic and not limit the possibility of building more housing, the advice of the Dutch Green Building Council to select the 67% likelihood of staying below a 1.7-degree increase in temperature will be followed in this research (Spitsbaard and Leeuwen, 2021).

The method of using a CO_2-budget does not take into account future effects which are beyond the service life of a building. The method only takes into account the emissions from the source of a material to the completion of a building and, therefore, is more focused on the short term rather than the long term. In practice, emitting more carbon right now and compensating for that in later stages of life is a common strategy. As the Paris Agreement goals need to be realised within the next decades, the method of using a CO_2-budget will be more suitable to assess this (Spitsbaard and Leeuwen, 2021).

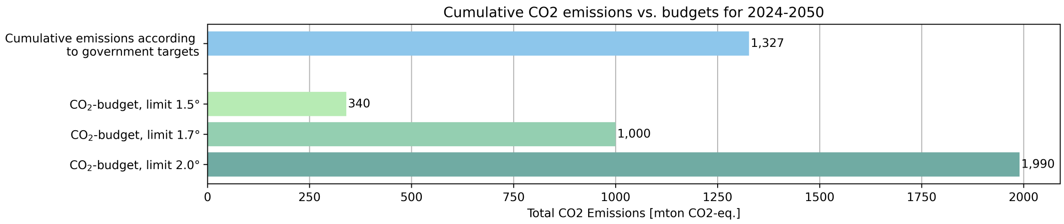


Figure 3.4: Cumulative CO_2 emissions according to policy goals (Figure 3.2) vs. available CO_2-budgets (Figure 3.3).

In fact, the method used is similar to MPG and MKI calculations. However, only life cycle stage A is accounted for, and only the indicator GWP is used. This could best be described in the following formula:

$$PPI = \sum_{i=1}^{n} V_i \cdot E_i \;/\; A \qquad [kg\ CO_2 - eq./m^2]$$

where:

V_i is the volume of element i,
E_i is the embodied carbon per m^3 for element i,
A is the gross floor area of the project,
n is the number of elements.

3.3.2. CO_2-budget for buildings

When following the 67% likelihood of staying below a 1.7-degree Celcius increase, the remaining budget until 2050 is 1000 Mton CO_2. This value, however, is for the country as a whole. The construction sector - and specific projects - can only be awarded a small piece of this. Based on relative shares, the Dutch Green Building Council has determined the available budget for new residential buildings per year. Figure 3.5 shows how this value for available CO_2-budget has been determined. Again, the choices made are political ones, which should be equal globally. For now, the approach of the DGBC will be followed, as this is in line with the policy goals, as shown in Figure 3.4.

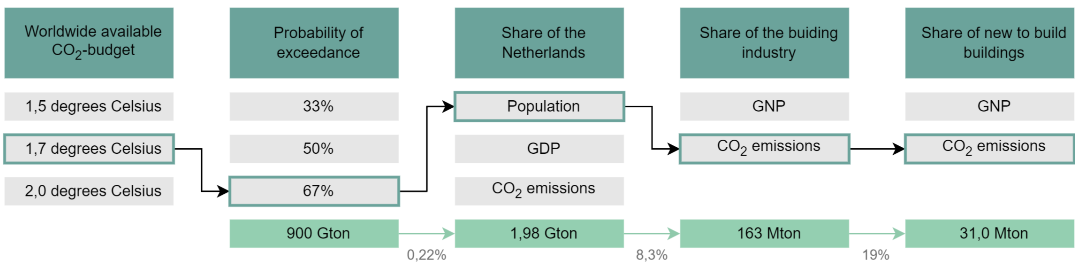


Figure 3.5: Overview of choices made during the allocation of CO_2-budget for new to build residential buildings (NIBE et al., 2023).

After all these steps, as a result of research by the Dutch Green Building Council, a total amount of 31 megatons of embodied carbon will be available for the new residential buildings up to 2050. However, this is for buildings as a whole, including finishing work, installations and other non-load-bearing structures. For this research, only the load-bearing substructure, superstructure and facades will be considered. These parts, according to the study mentioned in the research context, account for roughly 79% of a mid-rise residential buildings' embodied carbon (LETI, 2019). While this division is likely to change in the future, for now, a proportionate linear reduction of budget is assumed. This reduces the available budget to approximately 24 megatons of CO_2-equivalent.

The earlier mentioned research by the DGBC also provides more specific targets to stay within the limits of the Paris Agreement for various building uses. For all these uses, thresholds for embodied carbon are given per m^2 of useable floor space. Within the DGBC research, the available budgets have been determined considering the expected growth in building stock and division between building types. The retrieved values are adjusted for the load-bearing structure as mentioned above and are given in Figure 3.6. Note that many assumptions have been made, leading to a relatively large uncertainty. As can be seen, the current threshold is roughly 130 kg CO_2-equivalent per square meter of usable floor space.

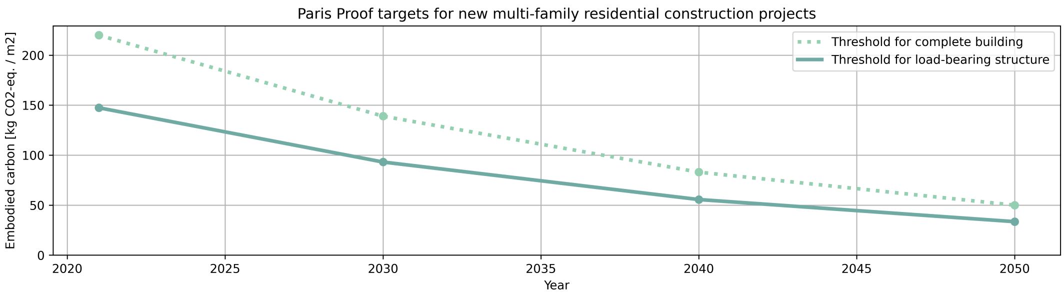


Figure 3.6: Paris proof targets for new-to-build multi-family residential buildings (Spitsbaard and Leeuwen, 2021).

3.4. Quantification methods for environmental aspects

In this section, an explanation of the life cycle assessment framework, which is the leading quantification framework for environmental impact, will be given.

3.4.1. Life cycle analysis framework

Standards and regulations provide a framework to assess the amount a product contributes to crossing the planetary boundaries effectively. ISO 14040 provides an overview of the LCA principles and frameworks, while ISO 14044 provides detailed requirements for execution. For the construction sector specifically, EN 15804 provides the specific sector-related regulations and, for example, how Environmental Product Declarations should be created.

The original version of this standard, published in 2013, is EN 15804+A1. It focuses mainly on the cradle-to-gate life stage, with several optional modules. The update published in 2019, EN 15804+A2, focuses on the whole life cycle. This updated version aligns better with the European Union's environmental goals, consisting of more mandatory impact categories and life cycle modules. Besides, there are stricter requirements for transparency and data quality.

Life cycle stages and indicators

In the framework, different stages or modules can be identified. These stages are shown in Figure 3.7. Which stages or modules need to be considered depends on the scope of the research or project. Four modules can be identified: product and construction stage (A), use stage (B), end-of-life stage (C) and benefits beyond the systems boundaries (D).

Note that modules C and D, representing end-of-life and the benefits beyond the building systems boundary, are mandatory according to EN 15804+A2. These modules are important for a circular economy, as they account for how a material is treated after its lifespan or in a potential further life. In this research, the scope has been defined as *cradle to practical completion*, meaning only the first module is used. This decision has several consequences, as only part of a building's life is considered. For example, accounting for biogenic carbon is more complex, as all carbon uptake is accounted for in the A1 stage. As all carbon release is accounted for in the C3 or C4 stages, leaving this out could give incomplete overviews. This topic will be discussed in a later section.

Besides modules to categorise time, various indicators are used to reflect the planetary boundaries, called impact categories. EN15804-A2 mentions 11 core impact categories and 8 additional, which will become mandatory. The 19 indicators are shown in Figure 3.8 (Nationale Milieudatabase, 2024).

Environmental product declarations

Data about products is needed to calculate impact according to the LCA method. This data, values for all impact categories and (relevant) modules, is standardised in EPDs or *environmental product declarations*. Manufacturers provide these data sheets, which should ensure transparency and easy comparison, as all important input variables are stated. However, when using the Dutch National Database (NMD) to find EPDs and environmental impact data, critical information is often not shown.

This topic has already been addressed in previous research by Wouter van Wijnen. In this research, the calculations of MPG and the use of NMD are described as “a black box”, and the NMD data for timber “proved to be derived from unverified processes” (van Wijnen, 2020). Therefore, recommendations were given to use international data over national data and compare it critically. In this research, this recommendation will be followed. This critical comparison can be seen in later calculations, as will be shown in Appendix A.

Product stage			Construction stage		Use stage							End of life stage				Beyond boundary*
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw material supply	Transport	Manufacturing	Transport	Construction process	Use	Maintenance	Repair	Replacfement	Refurbishment	Operational energy use	Operational water use	Deonsrtuction demolition	Transport	Waste processing	Disposal	Reuse, recovery and recycling potential
Cradle to gate																
Cradle to practical completion																
Cradle to grave																
Cradle to cradle																

Figure 3.7: Overview of life cycle assessment stages or modules according to NEN-EN 15804+A2. Underneath, an overview of various scopes is given.

Core and additional **environmental impact indicators** (NEN-EN 15804+A2)			
Number	Impact category	Indicator	Unit
1	Climate change - total	GWP-total	kg CO2 eq.
2	Climate change - fossil	GWP-fossil	kg CO2 eq.
3	Climate change - biogenic	GWP-biogenic	kg CO2 eq.
4	Climate change - land use and land use change	GWP-luluc	kg CO2 eq.
5	Ozone depletion	ODP	kg CFC 11 eq
6	Acidification	AP	mol H+ eq.
7	Eutrophication aquatic freshwater	EP-freshwater	kg PO4 eq.
8	Eutrophication aquatic marine	EP-marine	kg N eq.
9	Eutrophication terrestrial	EP-terrestrial	mol N eq.
10	Photochemical ozone formation	POCP	kg NMVOC eq.
11	Depletion of abiotic resources - minerals and metals	ADP-minerals&metals	kg Sb eq.
12	Depletion of abiotic resources - fossil fuels	ADP-fossil	MJ, net calorific value
13	Water use	WDP	m3 world eq. deprived
14	Particulate Matter emissions	PM	disease incidence
15	Ionizing radiation, human health	IRP	kBq U235 eq.
16	Eco-toxicity (freshwater)	ETP-fw	CTUe
17	Human toxicity, cancer effects	HTP-c	CTUh
18	Human toxicity, non-cancer effects	HTP-nc	CTUh
19	Land use related impacts/ Soil quality	SQP	dimensionless

Figure 3.8: Environmental impact categories according to NEN-EN 15804+A2.

3.4.2. Global warming potential and biogenic carbon approach

Global warming potential in EN 15804+A2

As stated earlier, one of the most relevant environmental indicators for the building sector is climate change, measured in global warming potential (GWP). In calculations for MKI or MPG, most of the total monetised value can be allocated to this indicator. In EN 15804+A2, GWP is divided into three different indicators, as shown beneath, all having the unit kg CO_2-eq.

- GWP-fossil - Global warming potential from airborne fossil greenhouse gas emissions.
- GWP-biogenic - Global warming potential from airborne bio-based greenhouse gas emissions.
- GWP-luluc - Global warming potential due to land use and land use changes.

By dividing the GWP into several origins, a more clear overview of carbon flows is established. Next to these separate values, two summations are commonly used as indicators:

- GWP-total - Sum of all GWP categories.
- GWP-GHG - Sum of GWP-fossil and GWP-luluc.

As shown, GWP-total is a summation of all three separate indicators. The indicator GWP-GHG - global warming potential from greenhouse gasses, represents the sum of GWP-fossil and GWP-luluc and, therefore, does not account for the sequestrated carbon in GWP-biogenic.

GWP-biogenic: carbon sequestration and cascading strategies

For bio-based materials, carbon sequestrating is one of the key benefits compared to traditional materials. This sequestration, the uptake and storage of carbon by bio-based materials during its growth, is accounted for in the indicator GWP-biogenic. As all storage is seen as temporary, full uptake and full release of carbon is assumed during the life of a building. Therefore, the benefits of carbon storage are not considered when looking at the full life span. As mentioned before, extending the lifetime of a timber product could ensure the storage of carbon for a longer time. Cascading strategies can realise this: high-end products, such as mass timber, are reworked in smaller elements, such as beams, at the end of their lifetime, creating residual value and preventing large-scale carbon release.

At the same time, trees can grow back multiple times before the sequestered carbon is released, leading to a net increase in captured carbon over multiple generations. This net increase only happens when new-to-build timber buildings are not replacing buildings already made from timber. In other words, it is an effective strategy until the market is saturated (Vogtländer, 2010). As this is currently far from true, this strategy could effectively lower the atmosphere's carbon levels in the short term, as explained in Figure 3.9.

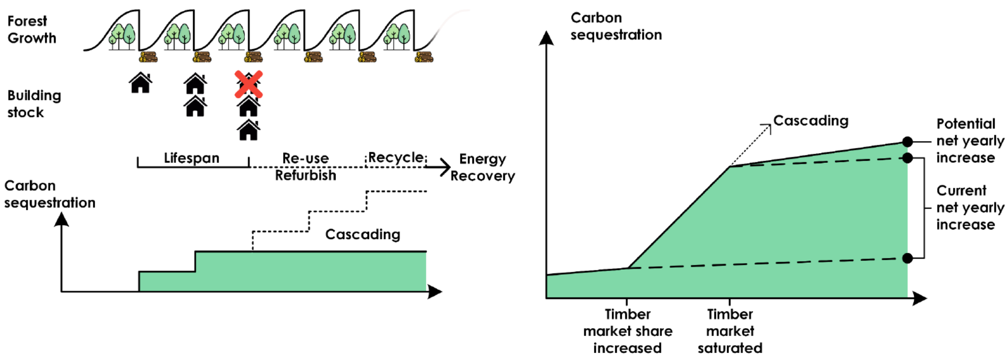


Figure 3.9: Carbon sequestration explained (van Wijnen, 2020).

However, as only the cradle-to-practical completion is considered in this research, only part of the carbon flows is accounted for, namely the carbon uptake, which can potentially lead to misrepresentation. Based on research by Hoxha et al., which investigated various methods used in scientific research to include biogenic carbon for specific scopes, three main ways to take sequestration into account can be identified: the 0/0 approach, the -1/+1 approach, and the dynamic approach.

Approaches to account for biogenic carbon

The 0/0 approach, as shown in Figure 3.10, is the most simple approach, as it does not include biogenic carbon at all. It is based on the assumption that uptake of CO_2 during the biomass growth of a bio-based product is balanced by an equivalent release of CO_2 at the end of its life, as the storage is considered to be only temporary. Note that this approach is currently used in Dutch regulations, according to EN 15804+A1. However, by doing so, the potential benefits of biogenic carbon are discarded.

The -1/+1 approach, on the other hand, does include biogenic carbon. This is the future approach, as described in EN 15804+A2. As visible in Figure 3.11, CO_2 uptake (-1) and CO_2 release (+) are shown in each system, providing an overview of carbon flows. In each system, separated by dotted lines, the biogenic carbon flow balance should be zero. However, as concluded by the earlier mentioned research, “there is a risk of biased and misleading results when only the impact of the product and construction process stages (module A) is assessed, considering the positive effect of biogenic CO_2 uptake without reporting the release at the end of life” (Hoxha et al., 2020). As this is true for this research, the potential benefits of biogenic carbon could be overestimated when this method is used.

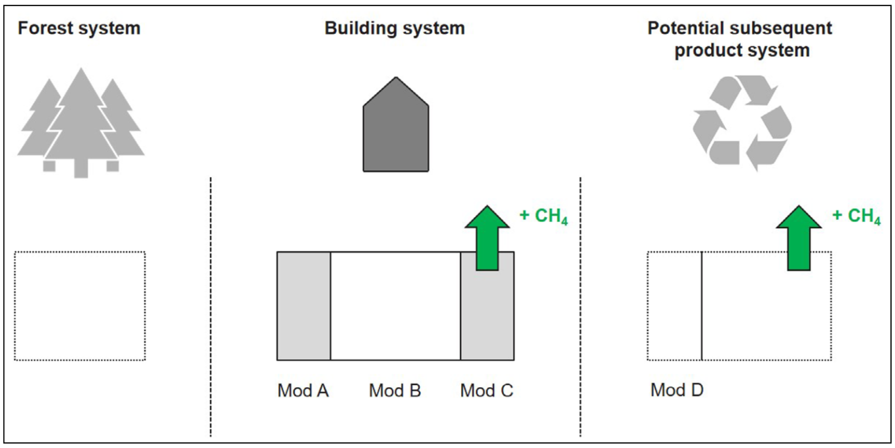


Figure 3.10: The 0/0 approach to model biogenic carbon uptake and release. Dotted lines indicate the product systems that fall outside the building system boundaries (Hoxha et al., 2020).

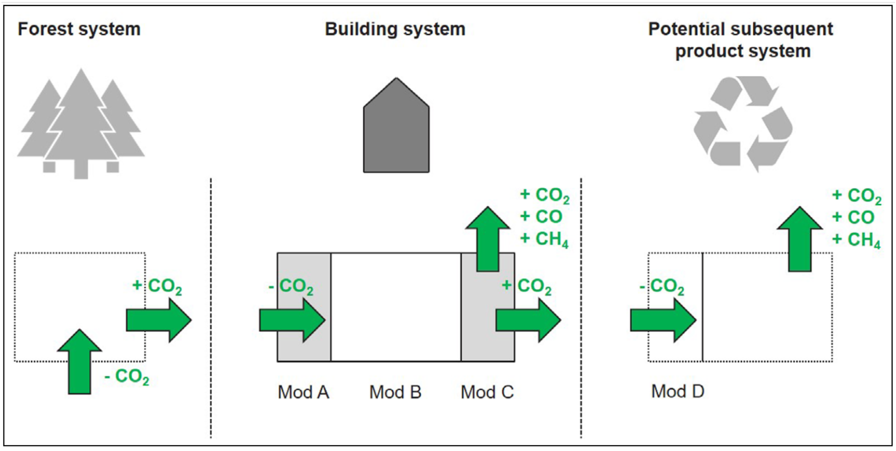


Figure 3.11: The –1/+1 approach to model biogenic carbon uptake and release. Dotted lines indicate the product systems that fall outside the building system boundaries (Hoxha et al., 2020).

Both static methods do not appropriately consider the timing of emissions and the influence of the rotation periods of various biomass growth. The benefits of carbon storage are not valued, as all storage under 100 years is considered temporary and, thus, not effective in the long term. However, when the same amount of biomass has regrown before the carbon of the original biomass has been released into the atmosphere, net storage will be achieved, even if this is for a shorter time period than 100 years.

A dynamic approach, as shown in Figure 3.12, does take time into account. As a result, only a time-equivalent amount of carbon is considered for a certain system. Two scenarios can be considered: one assuming tree growth before harvesting and one assuming regrowth during a building system's life. While conceptually similar, results tend to be significantly different, hence the importance of transparency in calculations (Hoxha et al., 2020). Using a dynamic method - or a simplification of this - could lead to a more accurate inclusion of biogenic carbon for certain scopes. Therefore, it could be useful for this research.

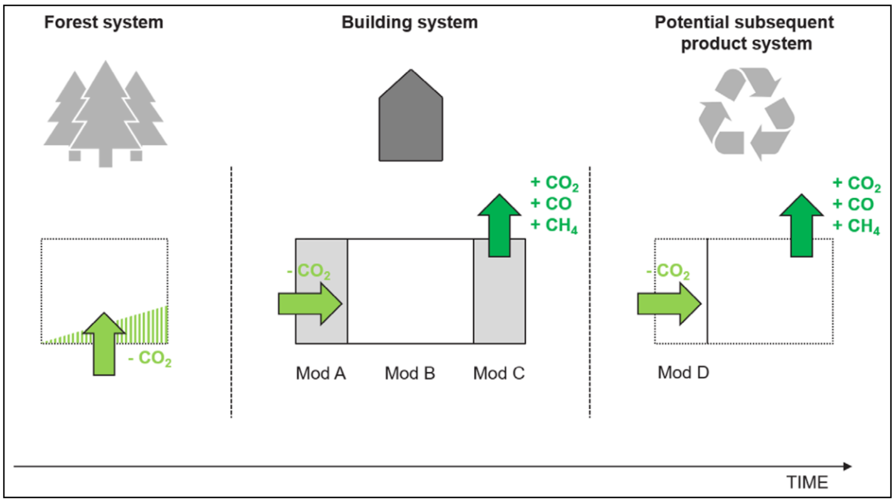


Figure 3.12: The dynamic approach, considering that trees grow before the use of the harvested wood product. Dotted lines indicate the product systems that fall outside the building system boundaries. Note that an approach where tree growth during the building system lifespan could be seen as an alternative to this approach (Hoxha et al., 2020).

Calculation method

In line with the principle of the dynamic approach, the Dutch government ordered independent research, with the main goal of investigating how to quantify the temporal storage of carbon and how to include it in calculation methods (SGS Search Ingenieursbureau B.V., 2022). The following formula is derived from the results of this research:

$$W_{cb,\text{eff}} = V_1 \cdot W_{cb,\text{tot}} \cdot \frac{L_{p1} + V_2 \cdot L_{p2}}{T_{kp}} \qquad [\text{kg } \mathrm{CO_2}\text{-eq.}]$$

where:

$W_{cb,\text{eff}}$ = amount of biogenic carbon that should be considered,
$W_{cb,\text{tot}}$ = total amount of biogenic carbon, as defined in LCA module A,
V_1 = variable related to level of sustainable forestry,
V_2 = variable related to the uncertainty of end-of-life scenarios, default: $V_2 = 0.2$,
L_{p1} = life span of the material's first life,
L_{p2} = life span of the material after its first life,
T_{kp} = critical time period, default: $T_{kp} = 100$ years.

The resulting value represents the amount of carbon uptake during the growth stage of a tree, given for a part equal to the average time carbon is stored in timber elements. This time is equal to a building's first life, combined with averaged time and scenarios for end-of-life. This value cannot simply be added to the results in LCA calculations, as it disrupts the carbon balance. However, this value can be argued as an estimated representation of the benefits of temporary carbon sequestration. It could, therefore, be useful to compare bio-based and non-bio-based products.

In essence, this formula gives a reduction factor to the total amount of biogenic carbon that should be accounted for, which is limited by definition to 1.0. Variable 1 can be assumed to be 1.0 when materials are harvested sustainably, and no abrupt deforestation takes place. Variable 2 accounts for a time period beyond the first life; a higher value indicates more inclusion of a second and further life of an element, resulting in longer carbon storage. In line with the scope of this research, cradle to practical completion, variable 2 should be assumed 0. When assuming a first life span of 50 years, as buildings are generally designed for, the following formula arises:

$$W_{cb,\text{eff}} = V_1 \cdot W_{cb,\text{tot}} \cdot \frac{L_{p1} + V_2 \cdot L_{p2}}{T_{kp}}$$

$$= 1.0 \cdot W_{cb,\text{tot}} \cdot \frac{50 + 0}{100} = 0.50 \cdot W_{cb,\text{tot}}$$

3.5. Quantification methods for economic aspects

In this section, quantification methods and background information for economic aspects are given, as both are important in decision-making - next to the previously discussed environmental impact.

Within this thesis, the economic impact is included in *total building costs* for the load-bearing structure and relevant other elements. These costs consist of material as well as construction costs, similar to the A module of a life cycle assessment. The exact scope for elements, the impact of cost fluctuations, the potential inclusion of environmental impact in costs and other potential benefits will be discussed in the following sections.

Cost classification

In *NEN2699 - Investment and operating costs of property*, terminology and classification methods are given for construction cost and life-cycle costs of buildings and real estate. This standard consists of six levels, each giving certain levels of detail. Depending on the phase of a project, the amount of levels can be selected. In the first level - nine elements or rubrics can be identified. The first seven elements within this level are related to investment costs, while the last two elements are related to life cycle costs.

For this research, only investment costs are considered, which is in line with the goal of the research. To further simplify calculations and to be able to focus more on relevant aspects, only the elements that lead to significant differences between buildings with and without bio-based materials are considered. For example, land costs are not expected to be significantly different for various designs, hence the exclusion of this rubric. Besides, taxes and financing costs are outside the scope of this research, leading to the fact that only construction costs - rubric B - are considered.

In Figure 3.13, an overview is given of the rubrics (level 1), clusters (level 2) and element clusters (level 3) which are considered. Note that all elements within level 3 include material costs as well as construction costs, such as labour and material-related costs. As can be seen, the load-bearing sub- and superstructure are taken into account completely, while other element clusters are only considered partially. The governing principle is that the level of detail is included if it is affected by changes in material.

For example, interior wall finishing is included when extra fire-protective cladding is needed for timber walls to achieve similar protection as conventional concrete walls. When, for example, roof finishing is identical for all design variants and thus not affected by the change of structural material, it is excluded. Note that environmental compensation costs, such as carbon emission costs, are not considered, as this value would only be meaningful when compared to total building costs. For this research, not all the building costs are considered, but only a part of it. Environmental impact is, therefore, completely separated from the economic impact.

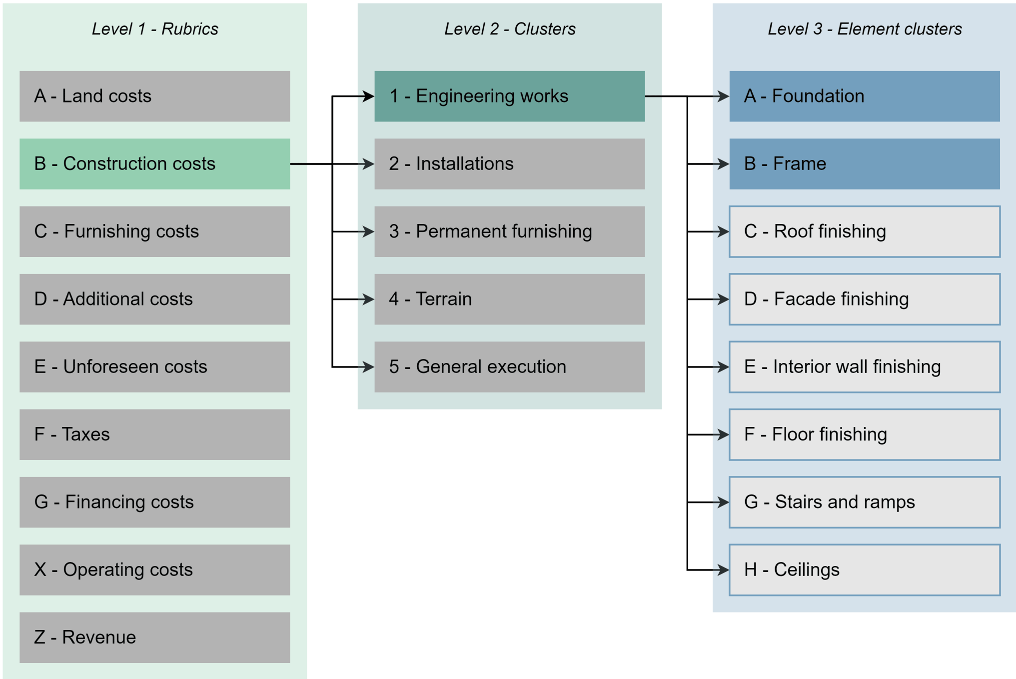


Figure 3.13: Overview of included and excluded levels of NEN2699. Coloured indicates an inclusion, light grey indicates a partial inclusion and dark grey indicates an exclusion. Adapted from NEN2699.

Information sources and cost fluctuations

For this research, *ArchiCalc Begrotingssoftware* will be used as the main source for element prices. This software, designed by building cost advisor Archidat, has over 90.000 registered users within the Netherlands and gives current values for material prices and construction costs for various types of construction works, among which new residential construction projects (*Over Archidat* 2024).

The most recent values - from September 2024 - will be used consequently throughout this research. Besides, during the economic impact assessment, meetings with building costs advisors from contractor branches of Van Wijnen Groep will be held to verify data. However, the ArchiCalc database does not provide sufficient data for mass timber elements. Therefore, an analysis of existing quotes has been made, where data has been gathered and corrected for the relative value of timber at that moment and for inflation compared with September 2024. Based on this, average values for various elements have been determined, as explained in more detail in Appendix A. In this appendix, information about how cost fluctuations are accounted for is included.

3.6. Conclusions

Based on the sections above, several conclusions can be drawn, which will help answer the sub-research question stated at the beginning of this chapter.

Environmental aspects

The following conclusions can be drawn for environmental aspects:

- Environmental footprint is a wide concept, often associated with carbon dioxide emission, but consisting of much more than that.
- Currently, Dutch regulations give thresholds for the environmental performance of buildings for the expected life cycle as a whole, for all indicators combined. According to the life cycle assessment framework (LCA), all stages, including the use stage, are considered. Therefore, the use of the MPG and MKI calculation methods is less suitable for the scope of this research.
- To achieve the Paris Agreement goals, the use of the Paris Proof Indicator (PPI) is a suitable

assessment method, focussing on direct impact by only considering carbon emission for the A-module of the LCA. In line with a net zero effect of carbon uptake and release, using GWP-GHG is best suited.

- Inclusion of temporary carbon sequestration for bio-based materials, however, could provide useful additional information, showing the benefits of sequestration. For this scope, cradle-to-practical completion, only adding a part of the GWP-biogenic to GWP-GHG is most suitable.
- While timber is renewable, there is limited availability on a system level. Limiting the use of timber is desirable to act against potential material depletion.

Economic aspects

The following conclusions can be drawn for economic aspects:

- Within this thesis, economic feasibility is interpreted as being economically competitive or having a reasonable chance of being economically competitive in the future.
- The NEN2699 framework for investing costs of property is suitable to assess economic impact. For this, within this research, only load-bearing elements and elements directly related to changes in load-bearing elements will be considered.
- Environmental compensation costs are a suitable indicator for monetising environmental impact; however, they are more suitable when total building costs are known rather than only the costs of load-bearing elements.

Assessment methods

To conclude this chapter and to answer the sub-research question, several indicators have been selected to assess design variants, based on the conclusions above. By using the following indicators, redesigns can be easily compared to each other, the original design, other projects and established thresholds:

Environmental impact:

- **PPI** in **GWP-GHG** [kg CO_2-eq./m^2 of GFA]
- **PPI** in **GWP-total** [kg CO_2-eq./m^2 of GFA], defined as GWP-GHG + 0.5 * GWP-biogenic
- **Volume of timber** [m^3]

Economic impact:

- **Material and construction costs** [euro/m^2 of GFA]

Note that the definition for GWP-total used in this research differs from the definition in EN 15804+A2. Within this research, this indicator reflects the value of GWP-GHG, including the potential benefits of temporary carbon storage for the selected scope. Without mentioning otherwise, the definition of this research is meant when referring to GWP-total.

4

Review of structural systems and elements

In this chapter, the aim is to find suitable structural systems and elements for timber and hybrid timber residential buildings. To do so, regulations and building codes will first be explored for mid-rise residential buildings specifically to find relevant building requirements. After that, potential structural systems and elements will be investigated to find advantages and disadvantages. Finally, structural elements will be investigated more in-depth by assessing various cross-sections. All contributing to addressing the following research question:

"Which structural systems and elements are suitable for timber or hybrid timber mid-rise residential buildings, and what are their advantages and disadvantages?"

4.1. Requirements for mid-rise residential buildings

Definitions and general characteristics of mid-rise residential buildings

The research question mentions the terms "structural system" and "mid-rise residential building". Within the scope of this research, mid-rise residential buildings are buildings with roughly five stories, specifically for residential purposes. With a structural system, all elements contributing to the gravitational and lateral load-bearing system are intended, as discussed later in this chapter.

In addition to these load-bearing elements, elements related to building physics are often needed when a switch from non-bio-based to bio-based materials is made. These elements will be considered to the extent needed to fulfil the requirements according to national building codes, to a similar level as non-bio-based materials. For example, a concrete floor could fulfil the acoustic requirements due to its mass, while a mass timber floor needs extra insulation to do so. In this case, this acoustic insulation will also be taken into account.

One of the most important characteristics of residential buildings is that many apartments are present within one building. Each apartment needs to be a separate unit, leading to more strict building physics regulations, contrary to, for example, an office building. For this reason, massive walls are often used rather than a column-beam grid with partition walls; the walls and floors need to be unit-separating elements. Combinations of walls and column-beam grids are also frequently used, depending on the size of apartments (Waugh Thistleton Architects, 2024).

Furthermore, residential buildings with five storeys or more belong to consequence class CC2b and the design life span is generally 50 years, leading to the use of specific partial loading and safety factors in design verification, which will be given in later chapters (Nederlands Normalisatie-instituut, 2020). As discussed in the previous chapter, an MPG-score of 1,0 will be the set limit from 2025 onwards (Nederlands Normalisatie-instituut, 2024).

4.1.1. Fire resistance, resilience and design strategies

Fire resistance

When designing in timber, fire resistance is one of the most commonly mentioned concerns related to the material. For fire safety, the Dutch building code states that the fire resistance of the load-bearing structures is a fixed value, depending on the height of the highest floor of a building, as stated below:

- 60 minutes (R60) if h < 7m
- 90 minutes (R90) if 7m < h < 13m
- 120 minutes (R120) if h > 13m

As can be seen, changes of one or two storeys to a design can significantly change the demands for fire resistance. When using timber, three common solutions are used to achieve these demands (INBO, 2022). The strategies, often used combined, are given below:

1. **Over-dimension** of timber, which ensures that after a fire of a certain duration, enough timber is left to ensure structural safety. However, this could lead to large element sizes, which could be argued as an inefficient use of material.
2. **Covering** of timber with (double) gypsum boards or other fire-resistant materials. This leads to timber not being visible and using less sustainable material.
3. Use of a **sprinkler** system, which is often applied in high-rise or public buildings, leading to timber which can be left exposed, but requires extra installations.

Fire resilience

While fire resistance ensures sufficient time to leave a building in case of a fire, this does not mean that a building "survives" a fire. The capability of a building to keep a fire within a compartment, and therefore not expose the rest of the building to the fire, is captured in the concept *fire resilience* (Herpen, 2024). Fire scenarios and fire curves are different for CLT and concrete buildings, as timber is combustible. Only when the permanent fire load of a building is separated from the variable fire load is a fire in a CLT building similar to a fire in a concrete building. This means that exposed timber is unfavourable for fire resilience. Furthermore, for a CLT building to achieve a similar likeliness of burning down compared to a concrete building, installing sprinklers is advised (NTR Focus, 2024).

Fire safety design strategies

Research by Qvist, which compared the economic and environmental impact of material use and fire risk for CLT buildings, published recommendations for fire safety design strategies. For smaller and larger compartments, levels of encapsulation of exposed timber and the potential inclusion of a sprinkler installation have been investigated.

For compartments of 48m2, "it is proposed that only up to 3 storeys a residential building should be fully exposed. For buildings higher than 3 storeys, but lower than 8 storeys, it is suggested to apply 2 layers of fire-rated encapsulation for 70% of the compartment surface. Above this height, a sprinkler becomes preferred over the use of encapsulation" (Qvist, 2022).

For compartments of 140m2, "it is proposed to construct residential buildings up to 3 storeys without additional fire safety measures. For 4-storey buildings, encapsulation is suggested. For a building higher than 4 building storeys, a sprinkler is preferred over the use of encapsulation" (Qvist, 2022).

4.1.2. Acoustic performance and other building physics requirements

Acoustic performance

Besides performance in the case of fire, performance related to acoustics or sound is important, especially for lightweight structures such as timber structures. Within the building codes, there are two main serviceability demands related to this:

- Airborne sound difference (characteristic value), which refers to sound waves that travel through the air, needs to be larger than or equal to 52dB.

- Impact sound resistance (average value), which refers to the noise generated when a force is applied to a surface and causes it to vibrate, needs to be smaller than or equal to 54 dB.

When using timber, there are three ways to achieve the desired levels of performance, according to an advising guide for architects and engineers (INBO, 2022). Again, a combination of the possibilities is used frequently:

1. Acoustic **decoupling** of wall and floor elements by, for example, using a double CLT wall system. However, this decreases the global stability of a building.
2. Use of **cavity walls** and/or **isolation**, which has the consequence of using more materials with higher levels of embodied carbon.
3. **Adding mass** to elements, which acts as a damping layer, often as wet or dry screed floor.

Other building physics regulations

Next to the requirements mentioned above, there are many other building physics-related requirements: thermal performance, performance related to moisture and ventilation, performance related to smoke formation, and much more. While some of these are taken indirectly into account in selecting appropriate cross-sections, these elements are not directly related to structural performance - or are outside the detail level of this research - and are therefore not considered.

4.2. Overview of structural systems

In this section, an overview of structural systems suitable for mid-rise residential buildings, including bio-based materials, will be given. First, gravitational load-bearing systems will be given, after which lateral load-bearing systems will be provided.

4.2.1. Gravitational load-bearing systems

Concepts of structural systems

According to one of the leading architecture firms for timber in the UK, there are four main ways of building with timber: timber frame, modular mass timber, panellised mass timber and post-and-beam mass timber (Waugh Thistleton Architects, 2024). In Figure 4.1, an overview of these systems and their advantages and disadvantages is given, according to their latest handbook on timber buildings. As can be seen, all mass timber solutions are possible for mid-rise buildings, while the use of timber frames is less suitable for load-bearing purposes.

Modular buildings, however, are outside the scope of this research and, therefore, not considered. A combination of panellised and post-and-beam mass timber structures is most likely, depending on the layout of apartments and preferences concerning prefabrication and construction time; apartment separating walls are likely to be panels, while posts and beams are likely to be used for intermediate supports when needed.

Building height vs. structural systems

In figure 4.2, a conceptual overview is given for structural systems of timber buildings for either panellised or post and beam structures. Depending on the building height and use of the ground floor levels, different configurations are advised. Note that this figure also provides solutions for lateral stability, which will be discussed in the next subsection.

As can be seen, the foundation is generally made from concrete, with the timber superstructure on top of that. When a building's ground floor function needs a layout different from the structure above, a concrete table structure is often applied. Besides, a concrete core is common for buildings over 8 storeys to provide sufficient stability. When needed, the addition of mass on the top floors of a building can also contribute to more stability, often used for buildings over 12 storeys. In general, for mid-rise residential buildings, a timber superstructure on top of a concrete foundation will be sufficient for stability.

Key: ●●●● Most advantages; ●○○○ Fewest advantages; ✓ Commonly used; ✗ Less commonly used

		Lightweight timber	Mass Timber Systems		
		Timber frame	Modular	Panellised	Post and beam
Timber products					
Typical Application	Low-rise residential	✓	✓	✗	✗
	Mid-rise residential	✗	✓	✓	✓
	Commercial	✗	✗	✗	✓
Prefabrication		●●○○	●●●●	●●●○	●○○○
Construction time		●○○○	●●●●	●●●○	●●○○
Ease of transportation		●●●●	●○○○	●●○○	●●●○
Layout flexibility		●●●○	●○○○	●●○○	●●●●
Demountability		●○○○	●●●○	●●●○	●●●●

Figure 4.1: Overview of structural systems for timber buildings, including their consequences (Waugh Thistleton Architects, 2024).

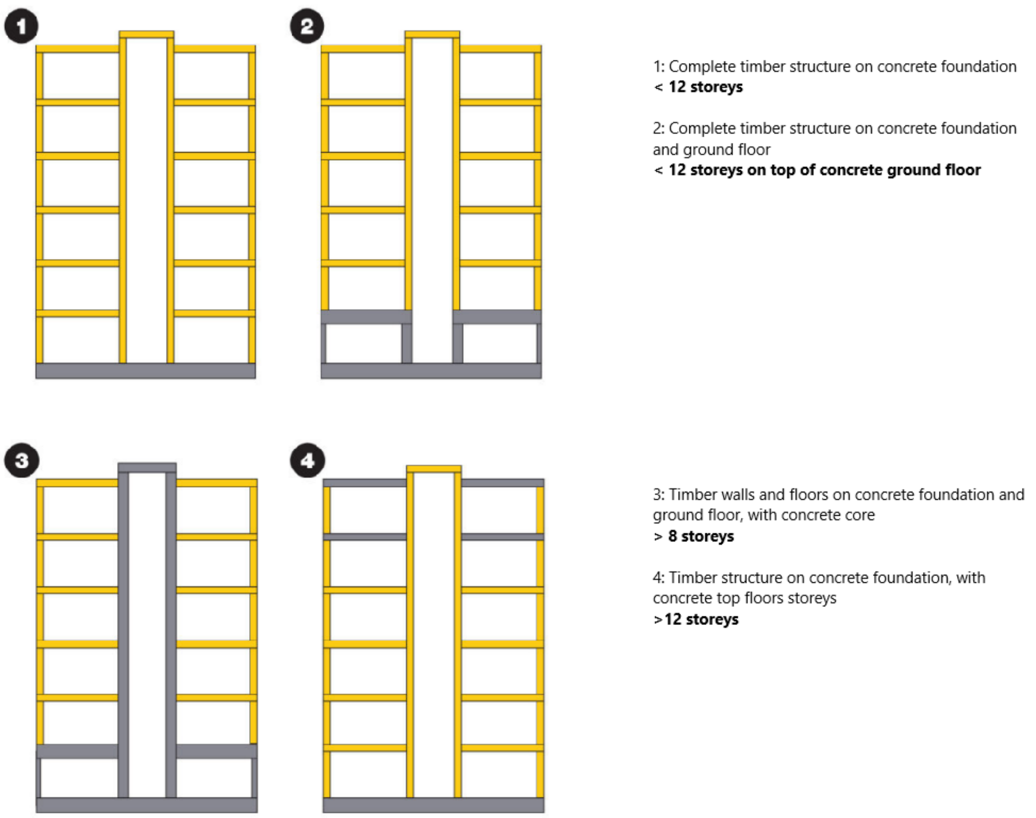


Figure 4.2: Overview of common solutions for stability when using timber, often depending on the number of stories and the use of the ground floor level (Waugh Thistleton Architects, 2024).

4.2.2. Lateral load-bearing systems

As can be concluded from the previous sections, a concrete core is generally not needed for mid-rise residential buildings. To transfer lateral forces, three types of solutions are used, which are given below:

- Moment resisting frames
- Shear walls
- Bracing

Below, each system will be explained in more detail. Besides, in Figure 4.3, these stability systems will be shown conceptually.

Moment frames

In moment-resisting frames, stiff connections between the columns and beams or walls and floors are made. By doing so, the bending resistance of elements will be used to transfer loads. This type of stability system is often used in steel frames or when concrete is poured in situ in combination with reinforcement. When using timber, it is more difficult to achieve moment-resisting connections. When doing so, large connections are often the result.

Shear walls

When using shear walls for stability, solid walls will take loads in shear and bending. This could be applied either in a centralised way by using a core or throughout several places in a building. This type of stability system is often used when concrete walls are used. Cross-laminated timber walls - or even timber frame walls with LVL panels added - can also provide sufficient stiffness to act as a shear wall.

Bracing

When using bracing as a stability system, diagonal elements will work in compression and/or tension. Diagonals provide compression and tension capacity, which can transfer lateral loads to the foundation. These diagonals can be made from both steel and timber and can be applied in various configurations. Steel tension rods can also be used. When applying these elements in both diagonal directions, one of the rods will transfer the lateral forces by tension, while the other rod will not contribute. This mechanism is often used in facades when a large open floor space is needed.

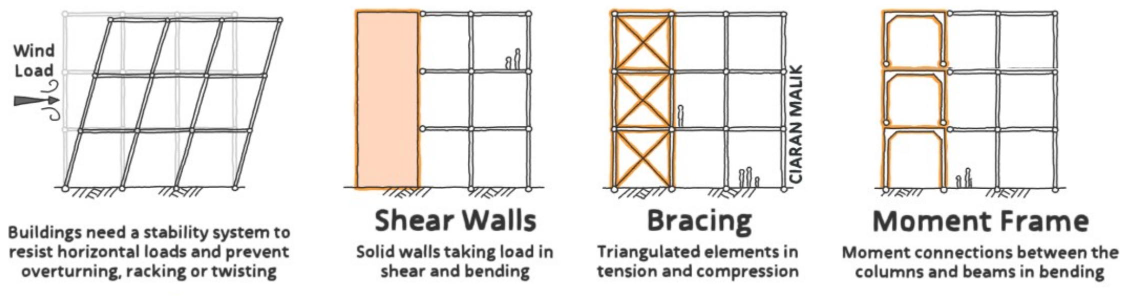


Figure 4.3: Conceptual overview of stability systems used in residential buildings (Malik, 2024).

4.3. Overview of structural elements

In this section, an overview of structural elements will be given. First, this will be done for load-bearing walls and floors, after which line elements such as columns, beams, and diagonals will be discussed.

4.3.1. Vertical load-bearing elements: walls

Load-bearing walls in residential buildings are often apartment-separating walls. Therefore, a minimum airborne sound difference of 52 dB is required. Besides, these walls are often part of the main load-bearing systems, requiring a fire resistance of R90: after 90 minutes, enough structural capacity should be left to prevent failure of the load-bearing system.

Based on literature and experience from practice, three main materials can be identified: calcium silicate brick, concrete, and cross-laminated timber. Some elements are often used as single walls, others as double walls with a cavity in between. Simplifications of cross-sections are given in Figure 4.4. Below the figure, each floor type will be explained further.

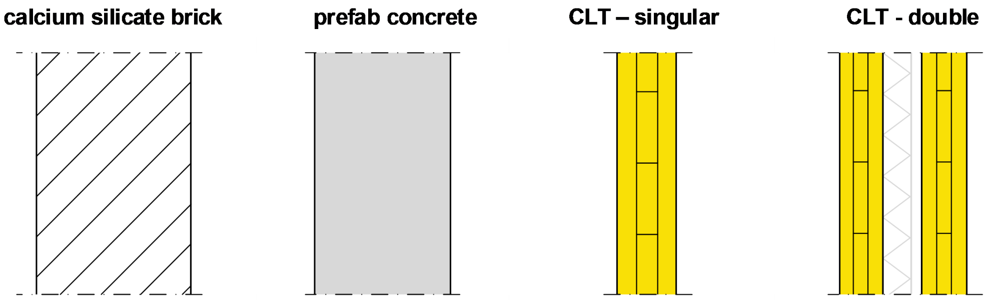


Figure 4.4: Conceptual overview of wall types.

Calcium silicate brick wall

One of the most used wall types in residential buildings is calcium silicate brick. Made from large blocks, this type of wall allows for high architectural freedom. It is often a relatively affordable solution, even though it can be more labour-intensive than, for example, precast concrete. The energy required for production is relatively low, making it environmentally attractive. Various sizes and strengths are available, and the material is categorised into class A1 for combustibility. As a result, sound requirements are governing in dimensioning. This is often achieved by ensuring sufficient mass.

Prefab concrete wall

Concrete is one of the most used structural materials and is also used for walls in residential buildings. Its environmental footprint is relatively high, while labour required on-site is minimal when using precast elements. As it is not widely used in residential buildings of this scale, in-situ concrete is left outside the scope of this research. Like calcium silicate brick walls, combustibility is very low, leading to sound requirements to be governing. Again, ensuring sufficient mass for this is the common dimensioning strategy.

CLT wall - singular

Cross-laminated timber can be used in walls in a single and double way. The single wall system uses less material, thus being more affordable. However, meeting sound requirements is generally higher as no real decoupling between apartments is present. Achieving lateral stability, however, is easier. To meet fire resistance requirements, walls often have two layers of gypsum boarding (25-30mm on each side), significantly delaying the burning time of the timber behind. To meet sound requirements, soundproof insulation is needed on at least one side of the CLT panel - between studs on which the fireproof cladding is added (Herpen, 2024).

CLT wall - double

Cross-laminated timber can also be used in a double wall, with a cavity in between. The system generally uses more material, which is likely more expensive. Besides, stability can be harder to achieve. However, meeting sound requirements is usually easier, as a decoupling between apartments is possible. To meet fire resistance — similar to a singular panel — two layers of gypsum boarding are often used to reduce the timber's burning time. This consideration between thicker gypsum boarding or thicker CLT elements will likely be financial. Usually, a cavity of 60mm is sufficient to achieve acoustic demands (Binderholz, 2024).

4.3.2. Horizontal load-bearing elements: floors

Floor elements in mid-rise apartment buildings are almost always apartment-separating elements. Therefore, floor elements should ensure a minimum airborne sound difference of 52 dB and have an impact sound resistance smaller than or equal to 54 dB. To ensure structural integrity in case of fire, a resistance of level R90 is required.

Based on these criteria - and information gathered from literature and experience gathered from practice - various floor types have been identified. There are - in theory - many options for floors using conventional materials. Concrete wide slab floors, hollow core slab floors, ribbed slab floors, solid slab floors and even concrete-steel composite floors. However, in practice, wide slab floors are used most often for this type of building. For this reason, only this floor type is considered in this research. Note that storey floors are considered, not ground floors.

Three main types of timber alternatives can be identified: cross-laminated timber, hollow core timber, and timber-concrete composites. Many variations are possible within these floors, as will be discussed below. Figure 4.5 gives a schematisation of the mentioned floor types.

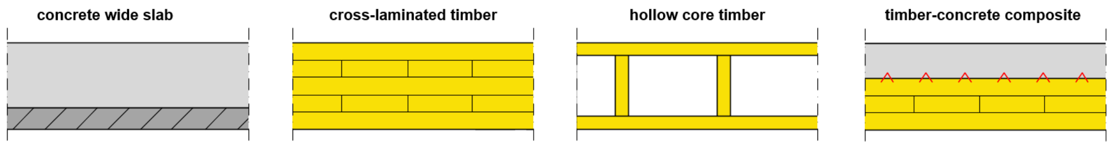


Figure 4.5: Conceptual overview of floor types.

Concrete wide slab floors

Concrete wide slab floors consist of precast elements combined with in-situ cast concrete. Composite action is achieved using steel anchors. Benefits include the fact that installations can be easily worked into the floor, the lack of need for extensive scaffolding, and the high sound and fire-resistance performance. It is relatively affordable but uses many materials with a significant environmental footprint. Usually, sound performance is governing. A floating concrete screed is often applied to achieve sufficient performance, leading to relatively thick elements.

Cross-laminated timber floors

Similar to CLT walls, CLT floors are lightweight compared to conventional materials. Both fire resistance and acoustic performance are important topics to address in the design of floors. To achieve fire protection, gypsum cladding can be added. To achieve sufficient acoustic performance, more weight and insulation need to be applied, often done by including a screed floor. As the elements are massive panels, costs are usually high compared to conventional materials. Besides, limited space for installations is available.

Hollow core timber floors

Hollow core timber floors are floors made from laminated veneer lumber. Similar to the principle of an I-profile, two horizontal panels are connected via many vertical elements, often delivered in box shapes. The span direction is in two ways, and using timber in this way limits the material use. However, due to the low self-weight, additional mass is often needed to fulfil acoustic requirements next to gypsum panels for fire resistance. Due to the cavities of the elements, installations can be included easily.

Timber-concrete composite floor

Timber-concrete composite floors are floors where the timber bottom part of a floor works together with a concrete top layer to increase performance and stiffness. Due to this, the timber sections - which could be CLT or other types of timber - can be reduced in thickness. This often leads to more affordable elements, lower thickness, and more favourable behaviour related to stiffness, such as deflections and vibrations.

4.3.3. Other elements: columns, beams and diagonals

Columns and beams

The load-bearing structure often uses columns and beams next to walls and floors. Both these elements are frequently made of conventional and bio-based materials. Concrete and steel are often used as conventional materials, while glue-laminated timber and laminated veneer lumber are solutions for bio-based materials. One of the most important differences between the materials is the size: timber elements are often much larger than steel or concrete elements. Which materials are favourable depends on many variables, such as costs, available space, environmental impact and material of the structure above. When timber floors are used - and thus self-weight is low - timber beams and columns are often chosen, while steel beams could achieve larger spans within a smaller space.

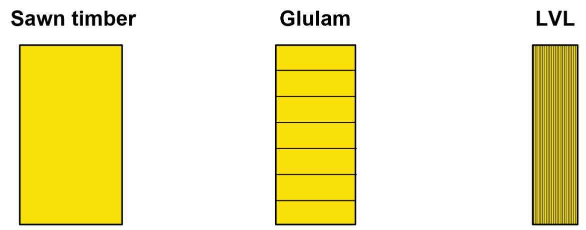


Figure 4.6: Conceptual overview of timber beam types, dimensions based on a design guide by Stora Enso (Stora Enso, 2022).

4.4. Analysis of structural elements

In this section, various structural elements—as discussed in the previous section—will be assessed and analysed to find the most promising elements for redesigns in later chapters. First, load-bearing inner walls will be discussed, followed by floors.

4.4.1. Vertical load-bearing elements: walls

Cross-sections

This section discusses load-bearing inner walls. The thickness of concrete and calcium silicate brick walls is determined based on minimum mass requirements for acoustics. The build-up of both single and double timber walls is determined based on existing handbooks from INBO and Swedish wood and by using Binderholz's design tool. All cross-sections fulfil the following requirements:

- Fire resistance of 90 minutes
- Airborne sound difference larger than or equal to 52dB

Note that the fire-resistance requirements are ensured by using fire-resistant gypsum panels, by having overcapacity for burning timber, or a combination. The suitable cross-sections are given in Figure 4.7. Different combinations of exposed and encapsulated timber are given for single and double CLT walls. CLT element thickness is generally a minimum requirement according to literature; for practical reasons, larger sizes could be chosen. For thermal insulation, hemp fibre is preferred over mineral wool, as a significant reduction in GWP can be achieved for a small increase in price.

Assessment

In Figure 4.8, an overview is given of the assessment of the wall build-ups mentioned before. In the first part, a quantitative assessment is given for thickness, weight, costs and environmental impact. This impact is first given in GWP-GHG, the embodied carbon without including biogenic carbon storage. Besides, GWP-total is given, which does include embodied carbon for 50%. More information about the assessment can be found in Appendix A.

A qualitative assessment is given in the second part for more practical aspects. This assessment should be seen relatively: the most favourable cross-section is awarded a "++", while the least favourable cross-section is awarded a "–". Note that double values are sometimes awarded to give more detail. The following categories are used, which will be explained in more detail in Appendix A:

- Demountability: the possibility of deconstructing the structure at the end of its life.
- Aesthetic benefits timber: the level of exposed timber is often seen as favourable by architects and users.
- Fire resilience: the level of fire resilience, as discussed in the previous sections.
- Complexity of build-up: the amount of (different) layers in the build-up, indicating a more difficult-to-construct section.
- Complexity of connections: the expected complexity of connections with floors; thickness and number of elements are governing for this.

Besides, in Figure 4.9, GWP-GHG and GWP-total are plotted against the costs. Note that the large dots represent the values where temporary carbon storage is not included, while the small dots represent the values where this is included for 50%; a time-equivalent amount to a building's first life span of 50 years.

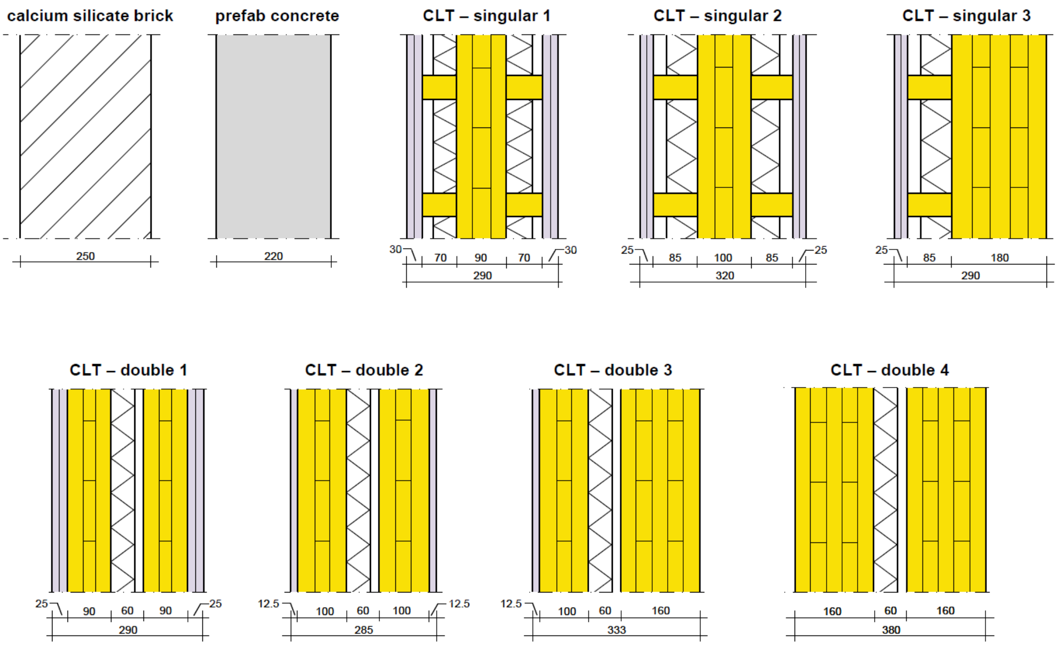
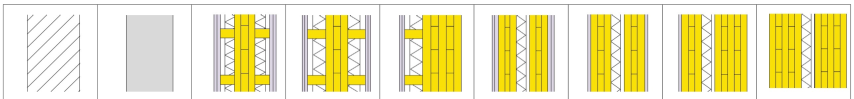


Figure 4.7: Overview of suitable wall cross-sections for inner walls, according to requirements discussed in Section 4.1, based on literature (INBO, 2022) (Binderholz, 2024).



	calcium silicate brick	prefab concrete	CLT singular 1	CLT singular 2	CLT singular 3	CLT double 1	CLT double 2	CLT double 3	CLT double 4
thickness *[mm]*	250	220	290	320	290	290	285	333	380
weight *[kg/m2]*	538	550	98	96	106	122	111	128	145
GWP-GHG *[kg CO2-eq./m2]*	50	71	26	25	27	32	28	32	35
GWP-total *[kg CO2-eq./m2]*	50	71	-17	-24	-46	-36	-48	-66	-85
costs *[euro/m2]*	92	107	206	211	222	270	285	310	335
demountability	-	+	+	+	+	+	+	++	++
aesthetic benefits timber	-	-	-	-	+	-	-	+	++
fire resilience	+	+	-	-	-	-	-	-	-
complexity of build-up	+	++	--	--	-	-	0	0	+
complexity of connections	+	+	-	-	0	0	0	+	+

Figure 4.8: Assessment of suitable wall sections on global warming potential, costs, weight and thickness.

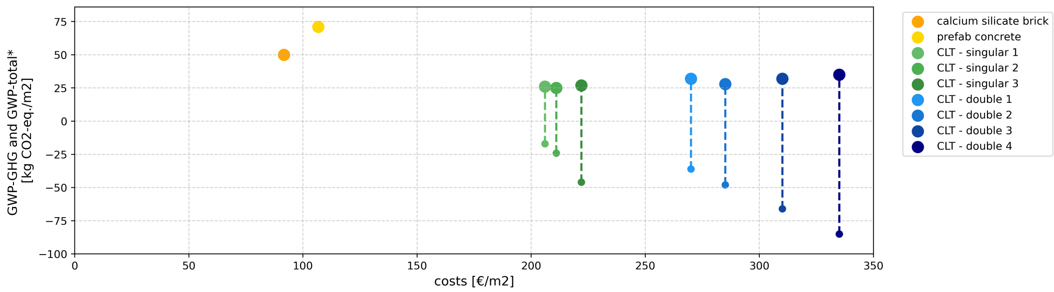


Figure 4.9: Visualisation of costs vs. GWP-GHG and GWP-total for various inner wall types. Note that the large dots represent GWP-GHG, while the small dots represent GWP-total, which is defined as GWP-GHG + 50% GWP-biogenic.

Conclusions

Based on the assessment in the previous section, the following conclusions can be drawn when comparing the different types of elements:

- Prefab concrete walls are a relatively affordable solution. However, they have high levels of embodied carbon. Suitable when thin elements or high self-weight is required.
- Calcium silicate brick walls are often more affordable and have lower levels of embodied carbon than prefab concrete ones. However, more labour on site is needed. Preferable compared to prefab concrete walls for mid-rise residential buildings.
- CLT walls have lower levels of embodied carbon than conventional alternatives and have higher levels of sequestrated carbon. However, costs are 2.0-3.0 times higher, while embodied carbon is 2.0-3.0 times lower.

Between the various CLT walls, the following trends can be seen:

- Whether a single or double wall is selected does not necessarily affect thickness; the level of exposed timber does.
- Within single or double-wall systems, different solutions are relatively close together in many aspects. Thickness and level of exposed timber are likely to be decisive criteria.
- Single walls are favourable when low costs and low levels of material use are important.
- Double walls are favourable in situations where more self-weight is needed, visibility of timber is essential, and/or fire resilience is important. It can also be favourable when - by legislation changes - high levels of carbon storage are prioritised.

A case study will be performed as some consequences of typologies cannot be seen in element sections only. This section will act as input for this.

4.4.2. Horizontal load-bearing elements: floors

Cross-sections

This section discusses suitable floor sections, as given in Figure 4.10. The thickness of the concrete wide slab floor is determined based on minimum mass requirements for acoustics. The build-up of timber floors is determined based on handbooks from INBO and Swedish wood and by using Binderholz's design tool. All floor elements fulfil the following requirements:

- Fire resistance of 90 minutes
- Airborne sound difference larger than or equal to 52dB
- Impact sound resistance smaller than or equal to 54 dB

Note that the thickness of the structural layers is based on general spans of 5.0-6.0 meters, as is most frequently used. In reality, different designs will lead to different spans, which could favour any of the floor build-ups, with most requiring a slightly different thickness. For insulation, which is included for thermal reasons only, hemp fibre is preferred over mineral wool, as a significant reduction in GWP can be achieved for a small increase in price.

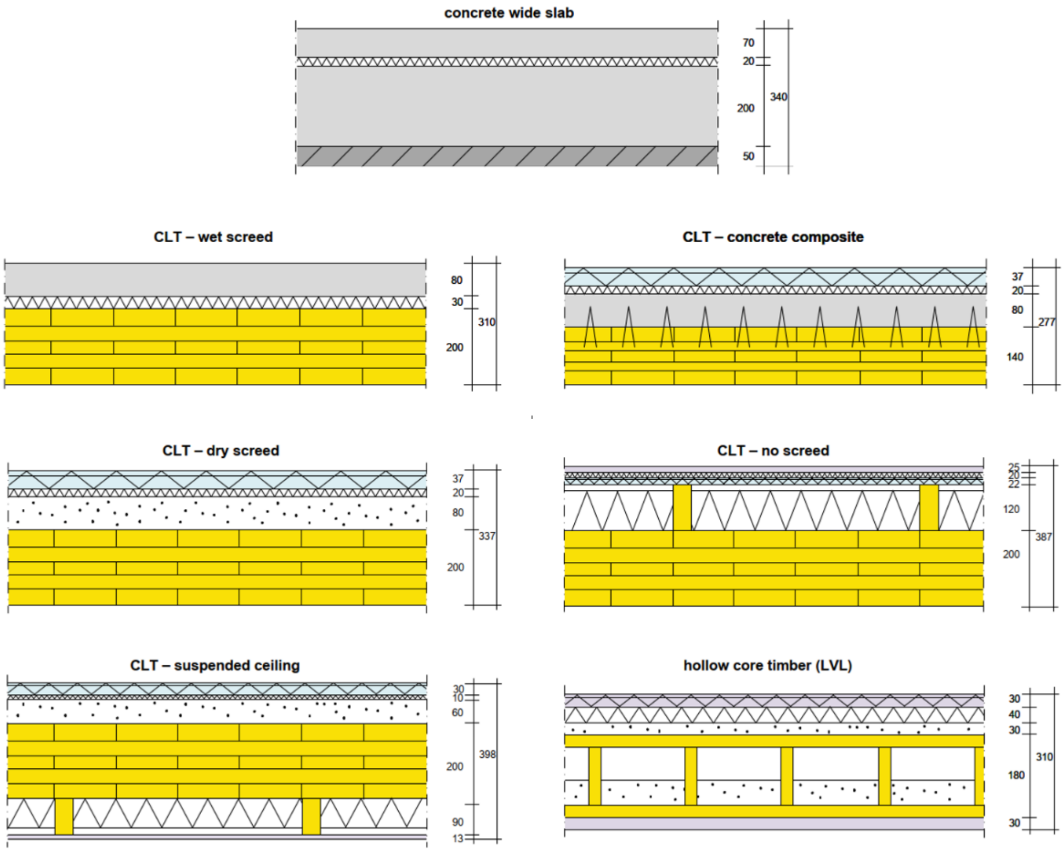


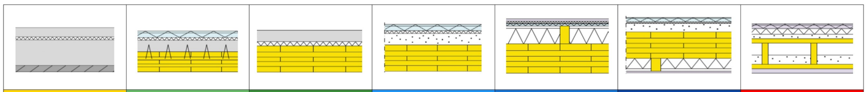
Figure 4.10: Overview of suitable floor cross-sections according to requirements discussed in Section 4.1, based on literature (INBO, 2022) (Binderholz, 2024).

Assessment

Similar to the assessment of walls, the assessment of floors is given in a quantitive and qualitative way in Figure 4.11. The quantitative indicators are equal, while the qualitative indicators are partially different, being:

- Demountability: the possibility of deconstructing the structure at the end of its life.
- Aesthetic benefits timber: the level of exposed timber is often seen as favourable by architects and users.
- Fire resilience: the level of fire resilience, as discussed in the previous sections.
- Complexity of build-up: the amount of (different) layers in the build-up, indicating a more difficult-to-construct section.
- Diaphragm behaviour: the potential to act as a diaphragm to distribute (lateral) loads
- Space for installations: the available space to include installations, such as MEP installations, within the cross-section of the floor.
- Moisture-related risks: the potential risk due to the combination of wet screeds or layers and timber.

Besides, in Figure 4.12, GWP-GHG and GWP-total are plotted against costs, to be able to compare the build-ups more easily.



	concrete wide slab	CLT-concrete composite	CLT wet screed	CLT dry screed	CLT no screed	CLT suspended ceiling	hollow core timber
thickness *[mm]*	340	277	310	337	387	398	370
weight *[kg/m2]*	599	232	227	241	112	208	186
GWP-GHG *[kg CO2-eq./m2]*	94	61	38	33	37	33	48
GWP-total *[kg CO2-eq./m2]*	94	-2	-36	-52	-56	-47	0
costs *[euro/m2]*	157	196	218	245	294	273	187
demountability	--	-	0	++	++	++	++
aesthetic benefits timber	-	+	+	+	+	-	-
fire resilience	+	+	+	-	-	-	-
complexity of build-up	+	-	++	0	--	--	--
diaphragm behaviour	++	++	+	+	+	+	-
space for installations	++	--	--	--	--	++	++
moisture related risks	-	-	-	+	+	+	+

Figure 4.11: Assessment of suitable floor sections on global warming potential, costs, weight and thickness.

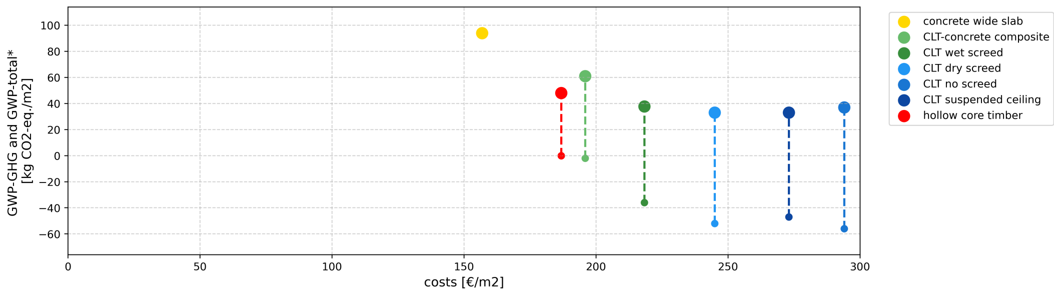


Figure 4.12: Visualisation of costs vs. GWP-GHG and GWP-total for floor types. Note that the large dots represent GWP-GHG, while the small dots represent GWP-total, which is defined as GWP-GHG + 50% GWP-biogenic.

Conclusions

Based on the analysis in the previous sections, the following conclusions can be drawn:

- Concrete wide slab floors are a relatively affordable solution. However, they have high levels of embodied carbon, roughly 2x as high as timber-based solutions.
- Achieving composite action between CLT and concrete (instead of a concrete screed) makes an element cheaper by 15%. However, higher levels of embodied carbon will be present due to the additional cladding needed, roughly 14%.
- CLT with a dry screed (for example, gravel) leads to a more affordable variant with a lower embodied carbon than variants without any screed (only studs, boarding and insulation).
- Hollow core timber floors provide a relatively affordable solution while having slightly higher levels of embodied carbon compared to other timber alternatives. Besides, this floor type has practical benefits, such as the possibility of including installations.

4.5. Conclusions

Some conclusions can be drawn to conclude this chapter. This will answer the sub-research question of this chapter, which aims to investigate how the design requirements are incorporated into the design of structural systems and elements.

Structural systems

- For mid-rise residential buildings, a complete timber structure on top of a concrete foundation is feasible, as the height does not require a concrete core.
- Due to the residential nature of the building, apartment-separating walls are very suitable, which could act as gravitational and lateral load-bearing systems.

- Panallised structures are more suitable for medium heights than timber frames. Depending on the layout of the apartments, column-beam grids could be a suitable addition to this.

Structural elements: walls

- Calcium silicate brick walls are preferable over prefab concrete walls due to lower levels of embodied carbon and slightly lower costs.
- Single-panel CLT walls are preferable over double-panel CLT walls, as the higher costs of double panels do not lead to large environmental benefits, as carbon storage by law cannot be currently included.
- Within single-panel CLT walls, all variants have similar values in terms of costs and environmental impact, with variant 3 having practical and aesthetic benefits over the other variants.

Structural elements: floors

- Only when low costs are the most critical design aspect, concrete wide slab floors are preferable.
- CLT-concrete composite floors, hollow core timber floors and CLT-dry screed floors all have their own benefits over the other variants. Which floor type is preferable depends on the design strategy: CLT-dry screed floors will have the lowest amount of embodied carbon, while the other two floors are less expensive and still have much lower values for embodied carbon than concrete wide slab floors.
- In general, the costs of timber floors are much closer to the conventional alternatives than is true for timber walls. This suggests a much higher effectiveness in lowering embodied carbon of changing floors than changing walls.

Part III

Case study

5
Case study introduction

In this chapter, the case study will be explained, and the case study building will be analysed. First, the case study building, location and characteristics will be described. After that, an in-depth analysis of the existing design, both structurally and environmentally, will be given, followed by the case study approach. Based on this, the following research question will be addressed:

"What are limiting structural, environmental and economic factors in the original design of the case study building, and which redesign strategies can be retrieved from this?"

5.1. Case study introduction

For the case study, an ongoing development project of a residential building in Zwijndrecht, the Netherlands, has been selected. As part of a larger development project, this building will host 27 apartments, four storage areas, and a separate entrance building.

The galleries leading to the apartments' entries are accessible via the entrance building. Apart from the galleries, all elevated apartments will have a balcony on the opposite side of the apartment, facing the street. The apartments will be 70-75m^2 and allocated for social housing. Three main rooms will be present within the apartments: two bedrooms and a combined living room and kitchen, which is common for these types of buildings.

The load-bearing structure of the five-storey-high building will be constructed in calcium silicate bricks and concrete, having a masonry facade. The project has been selected due to its common layout, simplicity, and high level of repetitiveness. Similar buildings are widely present throughout the country; therefore, the case study results are more likely to be valid for these building types in general.

Van Wijnen Projectontwikkeling West is the client of this project. Venster Architecten provides the architectural design, while Van Wijnen Engineering Dordrecht is responsible for the structuring engineering.

In Figure 5.1, a 3D visualisation of the building is given, in which the front and left-hand sides can be seen. In Figure 5.2, the back side is shown in a 2D view, showing the galleries and entrances to the apartments. The entrance building leading to the galleries is visible on the right-hand side, while the emergency stairs are displayed on the left-hand side. Figure 5.3 shows both the left-hand side and right-hand side of the building.

Figure 5.1: 3D visualisation of the building, showing the front and left-hand side of the building (Venster Architecten, 2024).

Figure 5.2: 2D visualisation of the back side of the building, showing the entrances of the apartments (Venster Architecten, 2024).

Figure 5.3: 2D visualisation of the right-hand side and left-hand side of the building, showing the separations between the main building and the entrance building (Venster Architecten, 2024).

5.2. Case study approach

In this section, the approach of the case study is given. The input and workflow for both redesigns within and beyond the existing grid are presented. An adapted version of the workflow from Chapter 2 is shown in Figure 5.4, detailing the steps for the case study chapters.

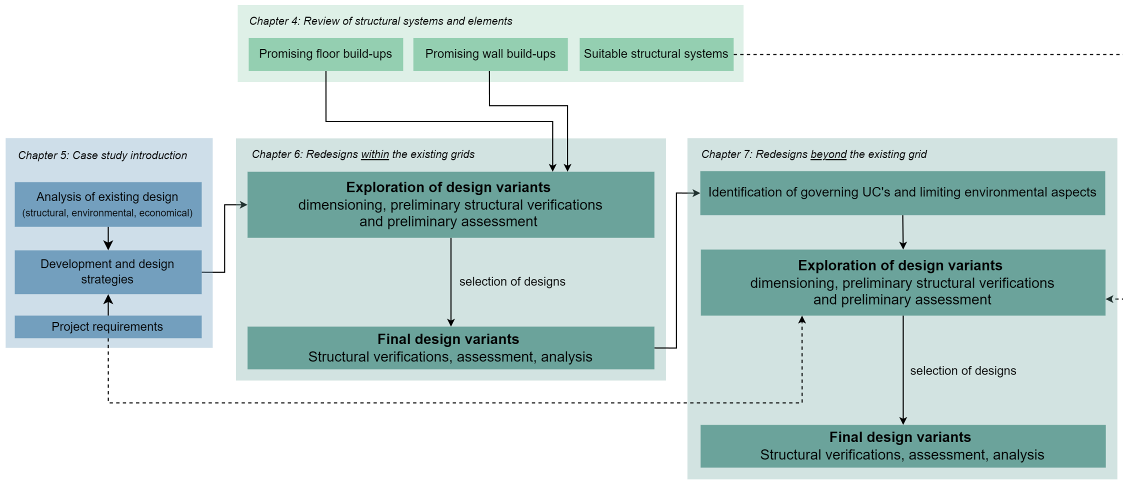


Figure 5.4: Workflow of the case study chapters, with input for each phase shown.

For the redesigns within the existing grid, combinations of promising floor and wall build-ups from the preliminary research will be combined in line with development and design strategies. Potential designs will be explored, and structural feasibility will be investigated by dimensioning elements and, for example, finding solutions to achieve lateral stability. The most promising designs will be selected, and these final designs will be assessed using the methods mentioned previously. For this chapter, the following design principles will be used:

- The existing grid sizes will be maintained, meaning the centre-to-centre distance between the apartment separating walls will be maintained, being 6.82m. When various wall sections have different thicknesses, this assumption could lead to minor changes in usable floor area. However, this will be neglected as the change is expected to be smaller than 1%, based on the dimensions of the previous chapter. Besides, the same depth of apartments will be maintained.
- The entrance building will remain a structurally separated building.

For the next chapter, where redesigns beyond the existing grid will be made, governing structural and limiting environmental aspects will first be identified. Partially based on this, new designs will be explored, again using several development and design strategies. Furthermore, the workflow is similar to the previous chapter, yet uses different design principles:

- The redesigns need to fit within the building site, with dimensions of 17.5m by 42.0m;
- A similar amount of apartments need to be created with the same floor space: 27 apartments with an average gross floor area of 73.6m^2;
- A similar area needs to be available for storage: total gross floor area of 274.4m^2;
- Common architectural layouts of apartments must be possible, with sufficient daylight entry.

5.3. Structural analysis of existing design

In this section, the structural design of the existing variants is explained in four parts: the superstructure of the main building, the superstructure of the entrance building, the foundations, and balconies and galleries.

5.3.1. Main building

Two main structural elements can be identified for the main building: calcium silicate brick walls and concrete wide slab floors. The apartment separating walls - in the transverse directions - are high-strength calcium silicate brick walls with a width of 250mm for the inner walls and 175mm for the outer walls. The concrete wide slab floors are placed directly on top of the walls, as can be seen in the right-hand side of Figure 5.8. For the ground floor, concrete hollow core floors are used, as shown in the right-hand side of Figure 5.9.

Stability in both directions is ensured by the dead load of walls and floors. In the transverse direction, all seven walls take up parts of the lateral forces. As the self-weight of the structure is large enough to counteract the tension forces resulting from a bending moment on the building, stability is ensured. In the longitudinal direction, the self-weight of the structure is again sufficient to ensure stability. For this, the connections between floors and walls are checked at each storey for moment capacity, which turned out to be sufficient. Note that the facades do not have a load-bearing function; hence, non-load-bearing calcium silicate brick walls of regular strength are used.

This all together leads to the design as shown in Figures 5.5 and 5.7. As shown in the figures, the span of the floors is 6820mm, with a centre-to-centre distance between the supporting walls. In the other direction, the inside length of the apartments is 9774mm. Furthermore, the floors have a thickness of 370mm, while the free height of a storey is 2630mm, leading to a combined 3000mm per storey. Besides, the total length of the building is 41.6 meters, while the building is 10.7 meters deep and just over 15.0 meters high.

The architectural layout of two apartments is shown on the left-hand side of Figure 5.9. The entrance - shown on the top side - leads to a hallway from which all rooms are accessible. The bedrooms are towards the gallery, while the living room is towards the street side, giving access to the balcony. The layouts of the apartments are not similar for all apartments but are mirrored in the transverse walls. Hence, the kitchen area in one apartment is next to the kitchen area in the other. Finally, the ground floor differs from the upper floors: only three apartments are present, while the other areas are used for storage.

5.3.2. Entrance building

The entrance building, as can be seen on the right-hand side of Figure 5.7, is structurally separated from the main building. This building acts as an entrance to the galleries, with an elevator and stairs. A different material is used for the load-bearing structure of the entrance building: both floors and walls are made from prefabricated concrete. The walls transfer both gravitational and lateral forces to the foundation. By making these elements in concrete, tension forces resulting from lateral loading can better be transferred to the foundations.

5.3.3. Foundation

The load-bearing walls of both buildings will transfer forces via prefab concrete beams to the foundation beams. These foundation beams are supported by 60 vibropiles, chosen based on the weight of the structure and the relatively unfavourable local soil conditions. A detail of the connection between the walls and foundation beams is given on the right-hand side of Figure 5.9, while Figure 5.6 gives an overview of the location of foundation piles.

The foundation beams are made from cast in situ concrete, with dimensions of 550x600mm for the transverse inner walls, 400x600mm for the longitudinal facade walls and 650x600 for all other walls. The vibro piles have a diameter of 456/515mm and a length of 35m. When placing a vibro-pile, a steel tube with a closed tip is driven into the ground by hammering its top. Once at the desired depth, reinforcement is placed inside, and the tube is filled with concrete. At the same time, the tube is lifted out by hammering or vibrating to ensure proper compaction and bond with the surrounding soil.

5.3.4. Balconies and galleries

As visible in Figure 5.5, balconies are located on the front side of the apartments, facing the street. The galleries are on the back side, facing parking places. The area of the balconies is 6.18m^2, each having a depth of 2.3m, while the galleries have a depth of 1.7m.

The balconies and galleries are connected to the floors and work as a cantilever. Connected via load-bearing thermal break elements, no load-bearing vertical supports are present. The connection between a gallery plate and a floor is shown on the left-hand side of Figure 5.8.

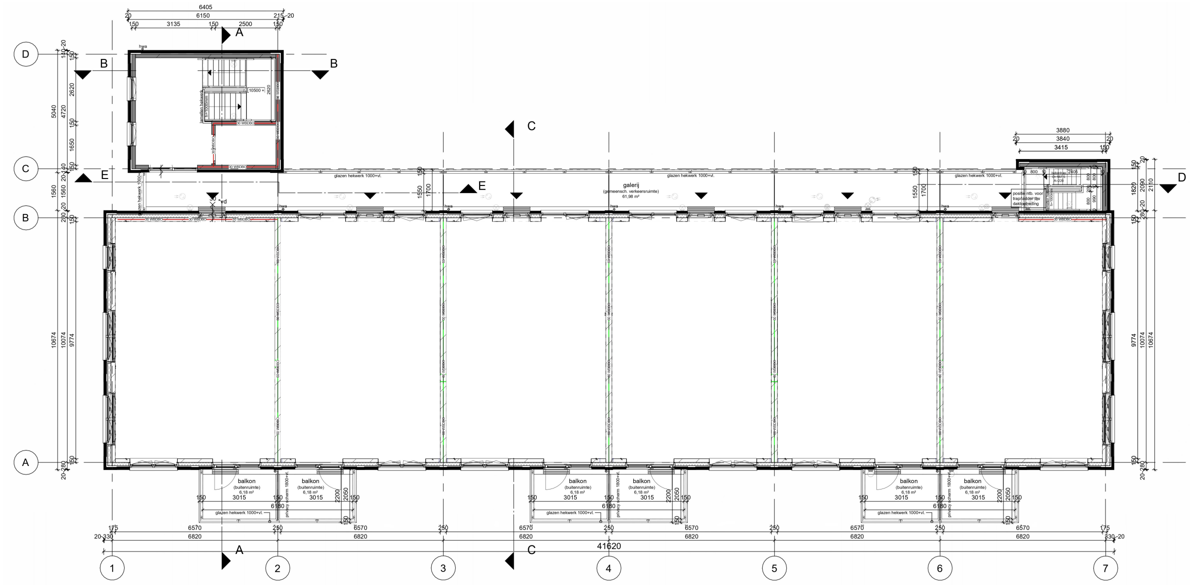


Figure 5.5: Horizontal section of the project: the main building, entrance building, gallery and balconies are shown for the fourth level (Venster Architecten, 2024).

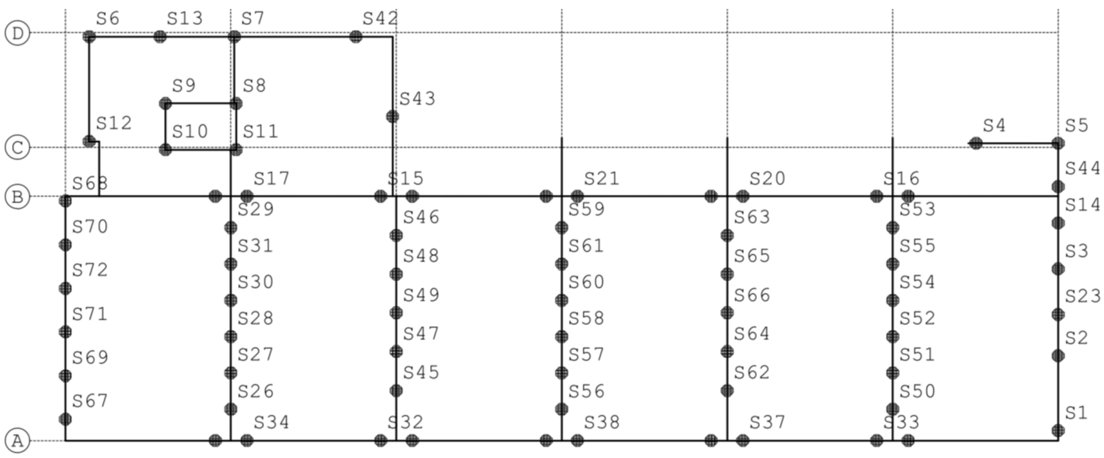


Figure 5.6: Overview of pile locations for the project, showing 60 foundation piles (Van Wijnen Engineering, 2024).

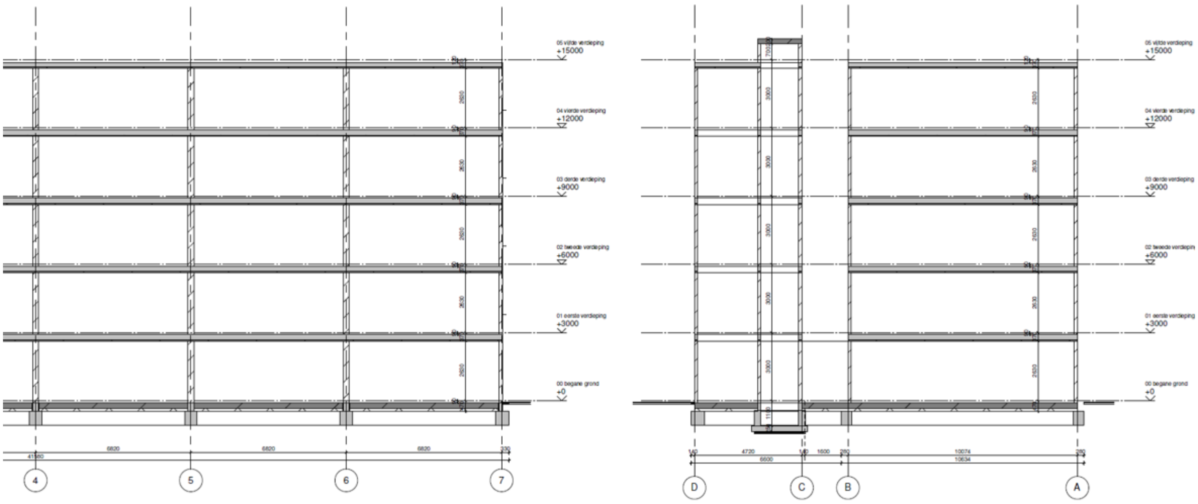


Figure 5.7: Longitudinal vertical section of the main building (left) and transverse vertical section of the main building and entrance building (right) (Venster Architecten, 2024).

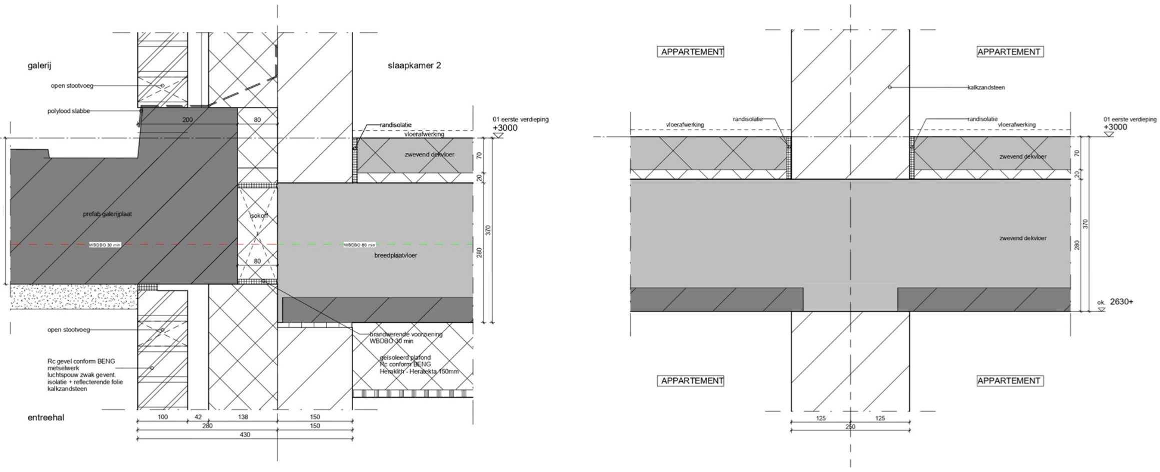


Figure 5.8: Details of a gallery connection via thermal break elements (left) and of the connection between the walls and floors of the main building (right) (Venster Architecten, 2024).

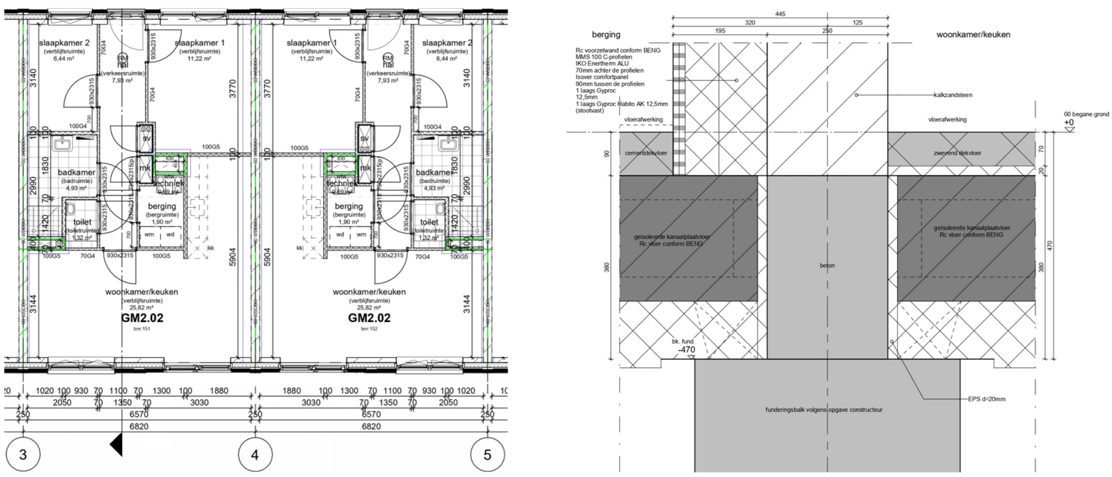


Figure 5.9: Architectural layout of the apartments (left) and detail of the connection between the load-bearing walls and the foundation (right) (Venster Architecten, 2024).

5.4. Assessment of existing design

In this section, the existing design will be assessed based on environmental and economic impact, similar to how the redesigns will be assessed in later chapters, allowing for a comparison. First, an overview of the assessment results will be given, after which the environmental and economic aspects will be discussed. In Appendix D.3, more details are provided.

Below, in Figure 5.10, an overview of the assessment results is given. Two groups of columns can be identified. The left column represents the values per square meter of gross floor area, an indicator that can be used to compare different designs and projects. The right column represents the value per meter or square meter of an element. By giving this information as well, the values of the left column are put in perspective, and the impact of an element can be more objectively analysed compared to other elements.

Variant 0		value per m2 of total GFA		value per m or m2 of element	
Calcium silicate brick walls and concrete wide slab floors		GWP-GHG	costs	GWP-GHG	costs
		[kg CO2-eq./m2]	[euro/m2]	[kg CO2-eq./m	[euro/m^x]
Floors, roofs					
Main building	**Roofs**	14,8	28,4	93,7	179,7
Main building	**Storey floors**	59,2	99,4	93,8	157,5
Main building	**Ground floors**	11,7	14,9	79,2	100,8
Entrance building	**Roofs**	1,0	2,0	93,7	179,7
Entrance building	**Storey floors**	4,1	6,9	93,8	157,5
Entrance building	**Ground floors**	0,4	0,5	79,2	100,8
Walls, facades					
Main building	**Transverse outer walls**	3,0	7,3	35,0	85,0
Main building	**Transverse inner walls**	13,5	24,8	50,0	91,6
Main building	**Longitudinal facades**	5,4	21,9	17,2	69,4
Entrance building	**Inner walls**	5,3	10,3	48,0	93,2
Foundation					
Main building	**Beam**	5,6	10,8	93,7	179,5
Main building	**Piles**	40,4	54,3	53,2	71,5
Entrance building	**Beam**	1,7	2,9	124,8	217,7
Entrance building	**Piles**	6,7	9,0	53,2	71,5
Others					
Main building	**Balconies**	4,8	14,0	89,6	234,1
Main building	**Galleries**	9,2	26,7	89,6	234,1
	TOTAL	**187,0**	**334,2**		

Figure 5.10: Overview of the results of the assessment of the original design.

Environmental aspects - element perspective

When looking at the category floors and roofs, the values per m^2 of an element are relatively close together. However, the concrete wide slab floors of the storey levels have a slightly larger value for GWP-GHG than the concrete hollow core slabs. In the category walls, the load-bearing walls contribute significantly more to the total embodied carbon, assessed in the indicator GWP-GHG, than the non-load-bearing elements. Concrete walls have a similar performance due to a combination of a higher environmental footprint and smaller dimensions.

The comparison of foundations is less straightforward, as values are given per meter of an element, not per square meter. Nevertheless, the impact is significant. Furthermore, balconies and galleries have similar values compared to floors.

Environmental aspects - building perspective

In Figure 5.11, a simplified visualisation of the results of the environmental part of the analysis is given. The results are separated into four categories, as shown before: floors, walls, foundation, and others. Values are given per square meter of gross floor area. As visible in the figures, floors contribute the most to the total amount of embodied carbon, with nearly 49%. Second is the foundation with 29%, while the walls and other elements have a significantly smaller contribution. The impact of floors can be related to the type of materials used and the size of the floors. The impact of the piles is partly due to the unfavourable soil conditions and partly due to the high self-weight of the structure. Note that the total value is equal to 187.0 kg CO_2-eq./m^2 of GFA, which far exceeds the target values for this, as discussed in Chapter 3.

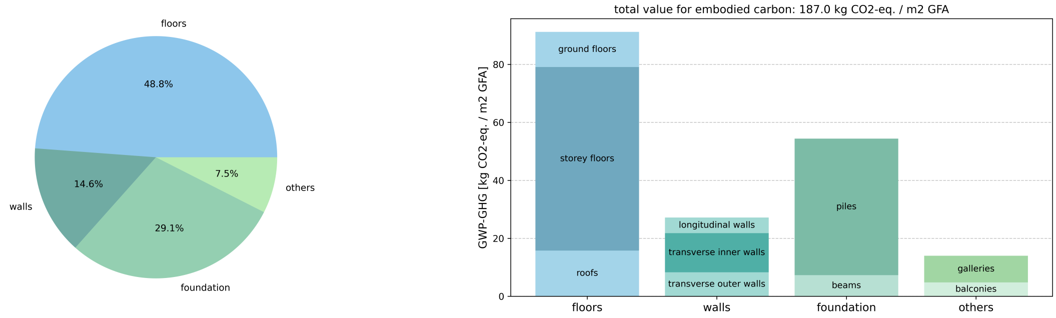


Figure 5.11: Contribution to total embodied carbon of various construction parts, given in GWP-GHG.

Economic aspects - element perspective

When looking at the economic impact per square meter of an element, a slightly different trend can be seen compared to environmental impact. Costs are highest for galleries, followed by roofs. Floors follow shortly after, while walls have a significantly lower share per square meter. Based on the values for elements given in meters, foundation beams contribute substantially more to costs than piles due to the larger cross-section and more labour-intensive construction process.

Economic aspects - building perspective

When looking at the whole building, and thus at cost values per m^2 of total GFA, floors and foundation piles can be identified as the two elements contributing the most to total costs: a combination of relatively high element costs and high presence throughout the building. Interestingly, the total cost of non-load-bearing calcium silicate brick walls is close to those of load-bearing outer walls, while environmental impact is only a third.

5.5. Conclusions

Based on the sections above, several conclusions can be drawn, which will help answer the sub-research question stated at the beginning of this chapter.

Conclusions on the structural analysis of the existing design

The following important aspects follow from the structural analysis, which could become a limiting factor in redesigning with timber:

- Large spans of 6.8m between the separating walls are present, larger than the advised spans for timber floors.
- Both galleries and balconies are cantilevers connected with moment-resisting connections to the floors, which is more challenging to create in timber. Especially the balconies, cantilevering 2.3 meters, will be challenging to redesign in timber.
- Stability is based on having sufficient self-weight only, preventing potential tension forces resulting from lateral loading. This principle is likely to be insufficient in timber design variants.
- Tension forces already occur in the entrance building when lateral forces are applied; these forces will be significantly larger when designing in timber due to lower self-weight.
- The local soil conditions are relatively unfavourable, leading to larger foundation piles than usual for these types of buildings.

Conclusions on the assessment of existing design

The following conclusions can be drawn from the assessment, identifying limiting factors and effective optimisation targets:

- All horizontal elements contribute significantly to the total value for GWP-GHG: ground floors, storey floors, roofs and even galleries.
- The foundation piles contribute significantly to the total value for GWP-GHG, while the foundation beams contribute significantly per meter of an element compared to other elements.
- The calcium silicate brick walls have a low contribution to total GWP-GHG, while costs are relatively low as well. Also, when looking at values per square meter of an element, this type of wall is effective in both categories.
- The impact of balconies and galleries on total GWP-GHG and costs is not significant. However, this is mostly due to the small area, as the values per square meter of an element are relatively unfavourable.

Design and development strategies

To conclude this chapter and to answer the sub-research question, the following redesign strategies have been selected based on the conclusions above:

- Changing floors seems inevitable for all redesigns, as the contribution to GWP-GHG of these elements alone is above the desirable values for the next decades. Based on this, changing only floors could be a first strategy to lower GWP-GHG in a relatively simple way.
- Next to changing floors, lowering the self-weight of the structure could lead to a reduction of foundation size, leading to lower values for GWP-GHG and costs. Based on this, changing both floors and walls could be seen as a second strategy, as the total weight will decrease further.

6
Redesigns within the existing grid

In this chapter, redesigns within the existing grid will be investigated. First, the design input will be given, after which redesigns for different components of the building will be explored individually. Final design variants will be provided, being combinations of individual components using various design strategies. Final designs will be assessed on environmental and economic impact, and the resulting data will be analysed. Finally, the chapter will be concluded by answering the following research question:

"How can the original design of the case study building be adjusted optimally into timber or hybrid timber variants, within the existing grid?"

6.1. Input for design exploration

The conclusions from the previous chapter will be used as input for this chapter, along with the design goals and boundaries, as described briefly below.

6.1.1. Design goals and boundaries

As stated in the research question of this chapter, the goal of this part of the research is to find optimally adjusted design variants using timber. However, optimal can be seen from various perspectives. Therefore, the following, more specific, sub-goals have been stated:

- Optimize GWP-GHG for costs $\leq$ costs of the original design;
- Optimize GWP-GHG for costs $\leq 1.10 \cdot$ costs of the original design;
- Find the lowest value for GWP-GHG within the given boundaries, independently from costs.

This approach will explore the possibilities of reducing embodied carbon levels while maintaining comparable costs, both currently and in the future. The value for costs increase of 10% compared to the original costs has been chosen, as this is an often used value within the industry (Van Wijnen Projectontwikkeling, 2024). Besides, research shows that industry improvements, such as industries of scale, could lower costs by up to 20% (McKinsey & Company, 2019). As a result, the design variants could have comparable costs in the future and are, therefore, interesting to pursue. Additionally, finding the lowest possible GWP-GHG values could provide new insights into the environmental limits of this concept.

To ensure that the redesigns of the building fulfil a similar function as the original design of the building, the following boundaries will be used:

- The existing grid sizes will be maintained, meaning the centre-to-centre distance of 6.82m between the apartment separating walls will be maintained;
- The entrance building will remain a structurally separated building with similar dimensions;
- The area of the balconies will be equal, being 6.18m^2 per apartment;
- The depth of the galleries will be equal, being 1.7m.

6.2. Exploration of design variants

In this section, various designs of building components are explored. The components that will be discussed are the main building, the entrance building, the balconies and galleries, and the foundation.

6.2.1. Main building

For the main building, a combination of design strategies and promising wall and floor elements lead to six possible combinations of walls and floors: three variants maintaining calcium silicate brick walls and three variants with CLT walls, being:

- Only changing floors: calcium silicate brick walls + CLT-dry screed floors
- Only changing floors: calcium silicate brick walls + CLT-concrete composite floors
- Only changing floors: calcium silicate brick walls + hollow core timber floors
- Changing floors and walls: singular CLT walls + CLT-dry screed floors
- Changing floors and walls: singular CLT walls + CLT-concrete composite floors
- Changing floors and walls: singular CLT walls + hollow core timber floors

However, simply stating combinations of elements is not a feasible structural design. Therefore, the dimensions of floor systems, wall systems, and stability systems are explored below. Based on that, preliminary design variants for the main building will be given.

Dimensioning of floor systems

To determine the dimensions of the three different variants for the storey floors and a timber version of the ground floor, the following assumptions have been made:

- Panels will have the length of two apartments: 2 x 6.82m. This reduces bending moments and deflections at mid-span while leading to panel sizes within the regular transportation sizes;
- Dead-load of 0.5 to 1.5kN/m^2 for additional mass and cladding, variable load of 2.55kN/m^2;
- Service class 2;
- Fire resistance of 90 minutes to fire from the bottom side only;
- Damping coefficient of 2.5% for CLT and 1.0% for other timber floors;
- Serviceability limits as stated in NEN regulations and local building codes.

Based on this, using the *Calculatis by Stora Enso* design tool and the LVL design guide by Metsä Wood, the following dimensions will be used for the storey floors:

- *CLT dry screed*: CLT 240 L7s, using C24 spruce;
- *CLT-concrete composite*: CLT 140 C5s, using C24 spruce and 100mm concrete C25/30;
- *Timber hollow core*: Kerto-Ripa Box 280, using Kerto LVL S-panels and Q-panels;

For the timber ground floors, an adjusted version of the timber hollow core floor will be used. Note that vibrations are governing for all floor types and that more extensive calculations will be needed for final verifications. More information will be provided during the verification of final design variants.

Dimensioning of wall systems

The dimensioning of wall systems is done based on different principles. The dimensions of calcium silicate brick walls are based on the minimum mass needed to fulfil acoustic requirements. For CLT walls, dimensions have been based on residual element size for fire resistance of 90 minutes, assuming fire on one side, as the other side is protected by cladding. This leads to the following sizes:

- Calcium silicate brick 250mm, using CS36;
- CLT 180L5s, using C24 spruce.

Dimensioning of stability systems

The dimensioning of stability systems is less straightforward than the dimensioning of wall and floor systems, as it is only discussed briefly in the previous chapters. Besides, a different system is likely to be needed compared to the original design. In Appendix B.1, an extensive overview of hand calculations is given, while a summary is provided below.

For lateral forces on the longitudinal facades, the apartment separating walls will act as shear walls to transfer lateral forces to the foundation, similar to the original design. No tension forces will occur in the variants with calcium silicate brick walls. Minor tension forces will occur in the variants with CLT walls, which can easily be transferred to the foundations. As a result, both wall variants are structurally feasible., as shown in Figure 6.1 below.

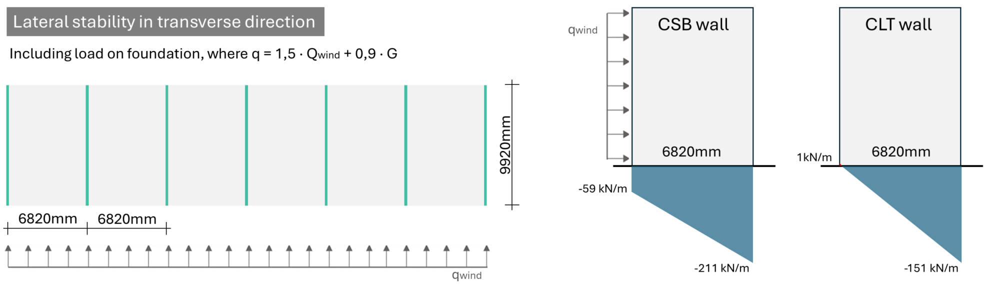


Figure 6.1: Overview of the stability system in the transverse direction, indicated in green, including resulting loads on the foundation.

For lateral forces on the transverse facades, no walls are present in the same direction to act as shear walls. Creating sufficient moment-resisting connections is not possible within the given height or is impractical. Three possibilities have been identified to achieve sufficient stability:

1. Reinforced concrete facade walls, with large openings for doors and windows, are used for all facades on both longitudinal sides. While leading to low forces per element, it uses large quantities of concrete, a material with high levels of embodied carbon.

   Due to the large openings in the facade elements, CLT and timber frame walls are not suitable for this system. As tension forces need to be transferred, calcium silicate brick walls are also not suitable.

2. Reinforced concrete stability walls in four specific locations in the facades of the outer apartments. Both apartments on the outer sides have windows in the transverse walls, so larger closed sections are possible in the outer longitudinal facades. While using far less concrete than the previous options, forces between stability elements on different levels are significant. Therefore, coupling between sections and to the foundation is important to ensure the resulting tension forces can be redirected to the foundation. Note that one of the windows of each outer apartment will need to be removed.

   Next to concrete, a steel frame could fulfil a similar function. A reinforced concrete stability wall, however, has been chosen due to its practical benefits. Due to the high forces within the elements, using CLT walls is unsuitable for this system: the tensile capacity of the material will be exceeded at the location of the connections.

3. Internal CLT walls in the longitudinal direction in all apartments. These walls need to be roughly 3 meters per apartment, perpendicular to the separating walls, in the location where partition walls are in the current design. Stability walls on both sides of the separating wall will be connected, working as one stability wall of 6 meters. In total, three of these 6-meter-long walls will be needed. This solution leads to slightly less flexibility in the layout of the apartments but uses a material with a significantly lower environmental footprint. This is the main reason why CLT walls are preferable over, for example, a steel frame fulfilling the same function. However, foundation beams need to be extended, and more piles are likely to be needed. Furthermore, minor tension forces will occur and will need to be redirected to the foundation, which can easily be done within the capacity of connectors, as will be explained in the next section.

Which of these stability systems is preferable depends on the aim of the design, the chosen floor system and the impact on the foundations. Below, a visualisation of the three variants has been provided.

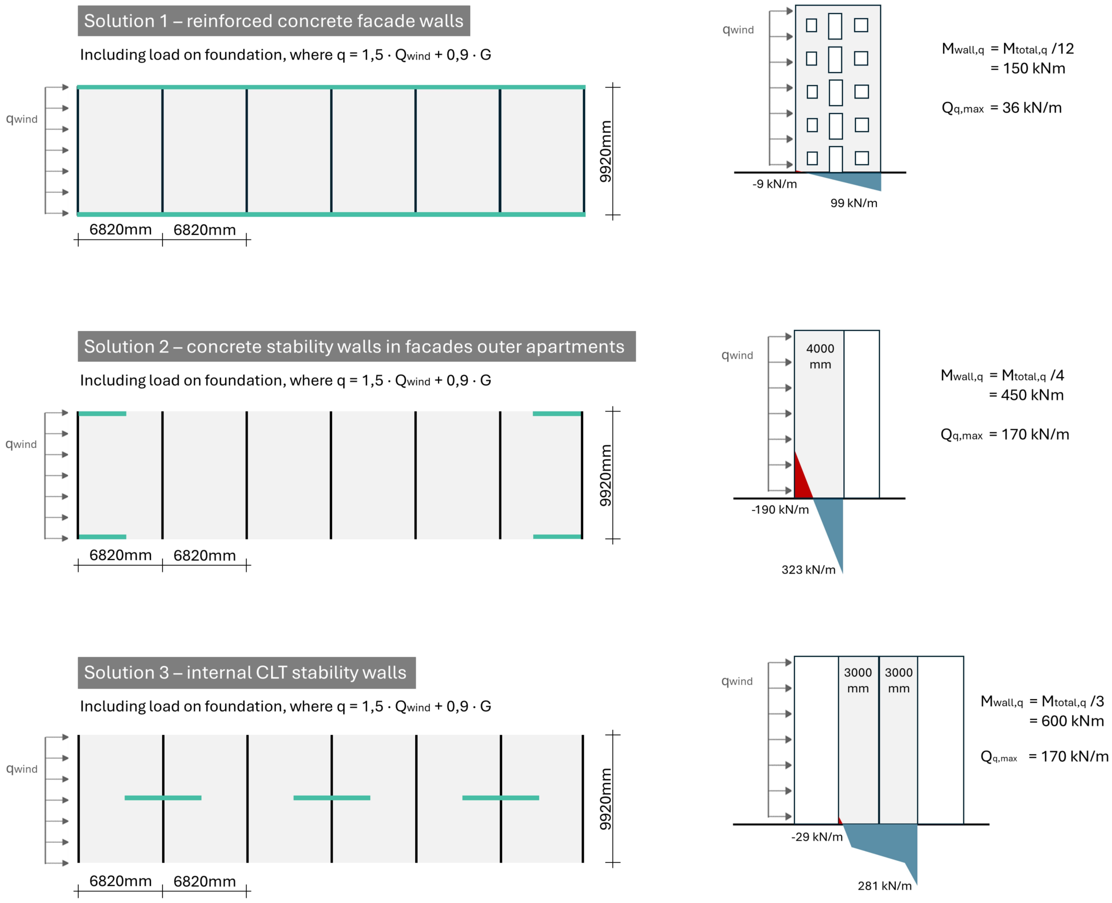


Figure 6.2: Overview of solutions for stability systems in the longitudinal direction, shown in green, including resulting loads on the foundation and occurring moments as a result of lateral forces (M).

Connections

In this subsection, more information is given about connections between or with CLT elements. This will show the reason why, for example, internal stability walls are feasible in CLT, while stability walls in four specific locations in the outer facades are not feasible in CLT. In Figure 6.3, standard and innovative connection methods to transfer the tension and shear forces are given based on a design guide by connection manufacturer Rothoblaas (Rothoblaas, 2024).

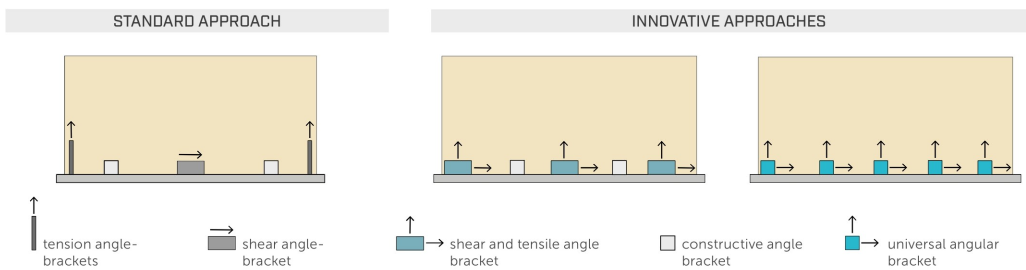


Figure 6.3: Overview of connection methods between CLT walls and floors (Rothoblaas, 2024).

As can be seen, a combination of angle brackets and hold-downs is the most efficient way to transfer tension forces. Angle brackets can best transfer shear forces. Besides, tension and shear forces can be transferred on the outside of walls, depending on the location of the walls. In Figure 6.4, the design capacities of the connections are given for the largest available connection size. In Appendix B.3, calculations are shown.

Based on the figures, the following conclusions can be drawn:

- For connections to the foundation, using hold downs and angle brackets is the most logical; they provide larger capacity and have practical benefits over plates, as alignment with foundation beams is not likely due to facades.
- For tensile forces in walls on the outer perimeter of the building, using tensile plates is logical; this provides a significantly larger capacity.
- For shear forces between timber elements and tensile forces on internal walls, using angle brackets will give the largest capacity.

The combined tensile capacity of one hold down and one angle bracket is assumed to be the maximum possible connection due to the limited length of elements transferring specific force, often only 2.0m. Forces are generally the largest at connections to the foundation, as summarised in Figure 6.2. For this location, a tensile design strength of 135kN will be the maximum allowable force. Using more connectors would lead to unknown interaction between connectors and the CLT and is therefore not considered. Next to this, the combined tensile strength of the CLT layers parallel to the grain has been verified to ensure the connections are governing and not the CLT itself.

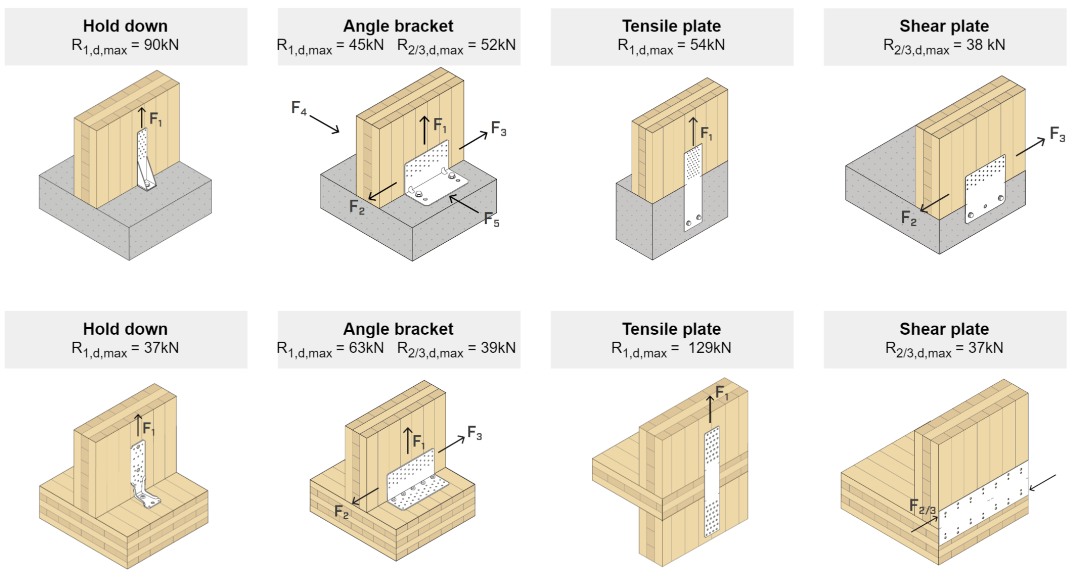


Figure 6.4: Overview of design capacities for tensile and shear connectors with largest capacities, for both timber-to-concrete and timber-to-timber connections (Rothoblaas, 2024).

Preliminary design variants

To create the preliminary design variants for the main building, floor and wall systems have to be combined with stability systems. Two stability systems are found most suitable: reinforced concrete stability walls in four specific locations and internal CLT stability walls. Reinforced concrete facade elements have not been selected, as they use more materials than the concrete stability walls in four specific locations, therefore having a larger environmental footprint and higher costs.

Achieving stability via reinforced concrete stability walls in outer apartments will be used in combination with calcium silicate brick walls and CLT walls, as shown earlier. Both CLT-dry screed floors and CLT-concrete composite floors can provide sufficient diaphragm action in the floor to transfer the lateral forces to the stability elements. Hollow core timber floors are assumed not suitable for this due to the location of the stability walls close to transverse facades. As hollow core floors can only span in two directions, the efficiency of transferring the lateral forces via the floors to the stability walls is far lower and, therefore, not considered. Overall, this stability system will lead to the first four variants, visualised in the top and middle schematisation in Figure 6.5.

Stability can be achieved via internal CLT walls in each apartment, independent of the wall type. However, in line with design strategies, only combining them with CLT walls has been chosen. Therefore, no combinations will be made with calcium silicate brick walls. CLT-dry screed floors and hollow core timber floors are most suitable, as only bio-based structural materials will be used, contrary to CLT-concrete composite floors. This stability system will lead to the fifth and sixth variants, visualised in the bottom schematisation in Figure 6.5. Below, the six preliminary design variants are given:

Achieving stability via reinforced concrete stability walls in the outer apartments:

1. Only changing floors: **Calcium silicate brick walls + CLT-dry screed floors**
2. Only changing floors: **Calcium silicate brick walls + CLT-concrete composite floors**
3. Changing floors and walls: **CLT walls + CLT-dry screed floors**
4. Changing floors and walls: **CLT walls + CLT-concrete composite floors**

Achieving stability via internal CLT walls in each apartment:

5. Changing floors and walls: **CLT walls + CLT-dry screed floors**
6. Changing floors and walls: **CLT walls + Hollow core timber floors**

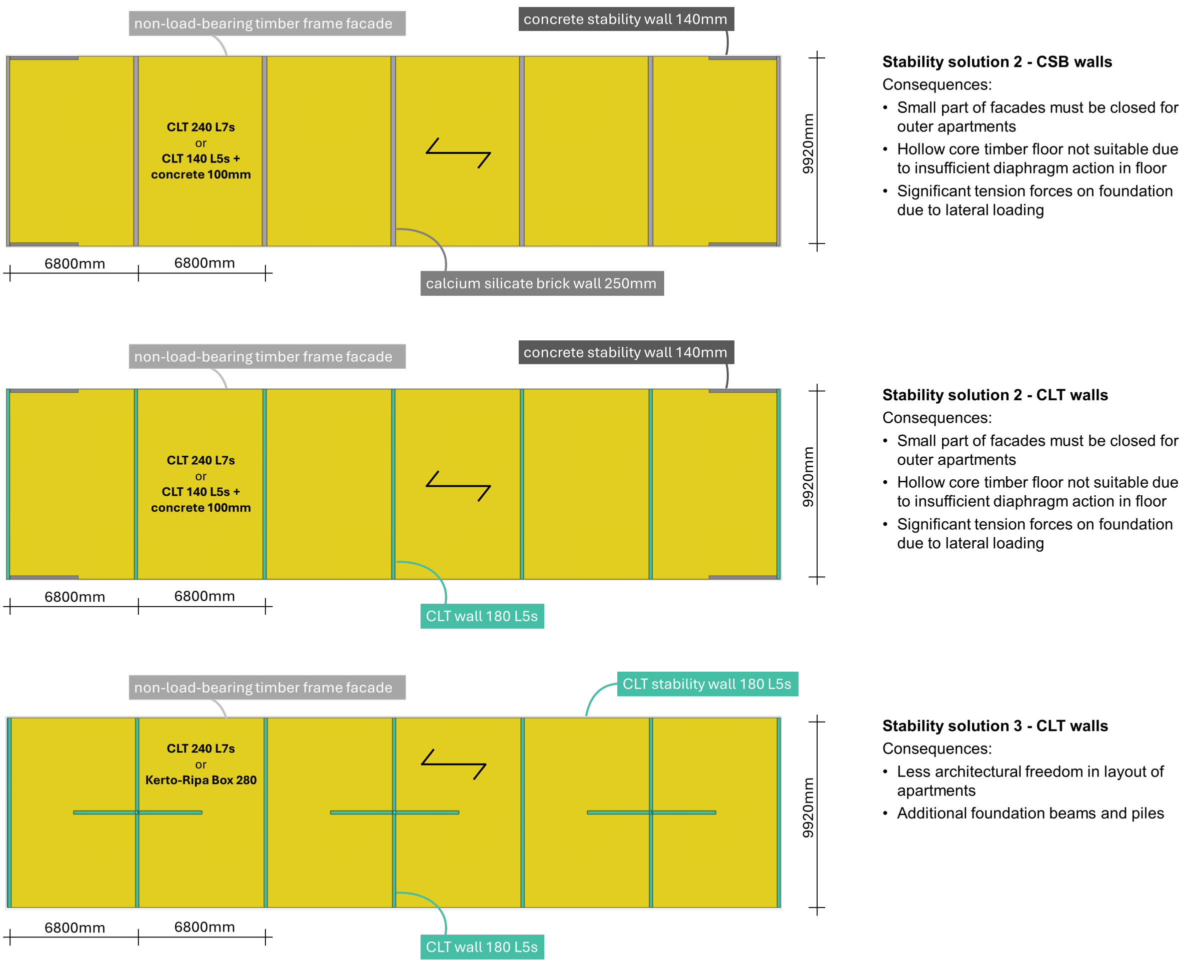


Figure 6.5: Visualisation of the preliminary design variants.

6.2.2. Entrance building

As the entrance building is structurally independent of the main building, separate redesigns need to be made. For the variants of the main building where only timber floors are included, it makes practical sense to do the same for the entrance building: keep the prefab concrete walls from the original design, combined with either of the CLT floor options. For the variants of the main building where CLT walls are used, again, it makes sense to do the same for the entrance building: change the walls to CLT walls, combined with either of the three floor options, as all three floor variants will be used in the main building in combination with CLT walls.

A structural feasibility check has been performed for lateral stability to ensure the mentioned strategies are possible. Details are given in Appendix B.2, while a summary is shown below in Figure 6.6. In this figure, the situation for the governing lateral load is given: wind load on the longer side, transferred to the foundation by the shorter walls. As can be seen, both the variants with prefab concrete walls and CLT walls will lead to significant tension forces. The tension forces that can arise in the variant with CLT walls are larger than the capacity of regular CLT connections, as discussed previously. Hence, the concrete variant will be used for all final design variants, along with the same floor as used in the main building.

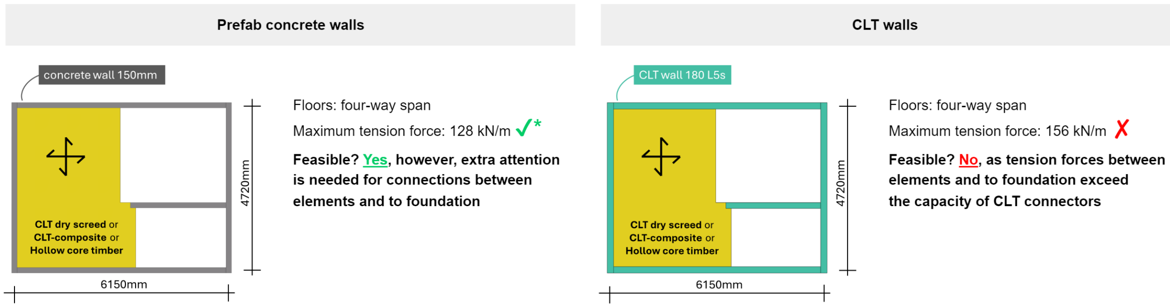


Figure 6.6: Summary of exploratory design of variants for the entrance building.

6.2.3. Galleries and balconies

Galleries

In the existing design of the building, the prefab concrete gallery plates are connected to the wide slab floor using moment-resisting connections, leading to a cantilever of 1.7m. As discussed earlier, achieving this purely by moment-resistant connections in timber is difficult. Besides, as timber is combustible and galleries are part of the emergency exit ways, this would likely not be sufficient.

The most straightforward solution to ensuring a 90-minute fire resistance pathway is to use non-combustible materials. For example, steel columns and beams could be a load-bearing structure with a lightweight, non-combustible floor. The structure could be fully independent of the main building or connected on one side, as shown in Figure 6.7. Besides, a solution with concrete slabs and columns can be used, eliminating the use of beams and lowering the use of materials.

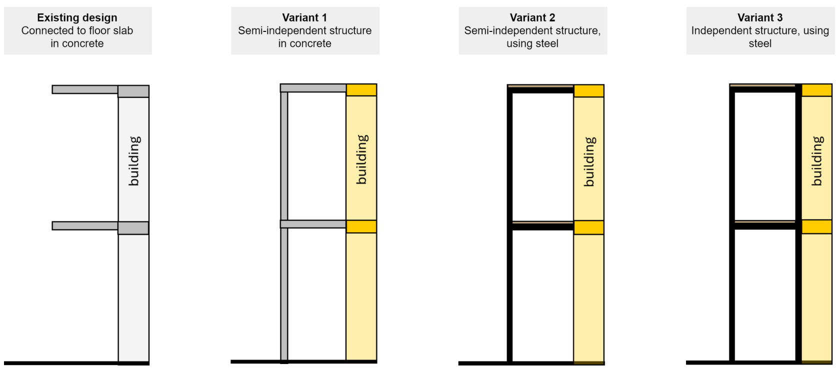


Figure 6.7: Summary of structural possibilities for the gallery structure.

All design variants of the main building will be combined with variant 2 for galleries. This variant has been chosen over variants 1 and 3, as it has the lowest amount of embodied carbon, as shown in Appendix B.4. However, extra attention is needed for the connections to the timber floors, ensuring thermal breaks and barriers against moisture. Note that a solution with only timber has not been considered, as this would likely not be sufficient in terms of fire resistance or would need a significant amount of treated hardwood, leading to the cost being too high.

Balconies

For balconies, there are two significant differences compared to galleries: the cantilever is larger, being 2.3m, and from an architectural point of view, columns are not preferable. As a result, a variant connected to the floor and supported by tie-backs is the most straightforward, which is visualised in the variants in Figure 6.8 below. Variant 2 is preferred, as the embodied carbon is lower, as shown in Appendix B.4.

Note that a solution where the balcony is party incorporated within the main structure, commonly known as a loggia, has not been considered. This is because the extra materials needed for walls will have far higher costs than those required for variant 2. As balconies are not part of the emergency exits, CLT or other lightweight timber floors can be used.

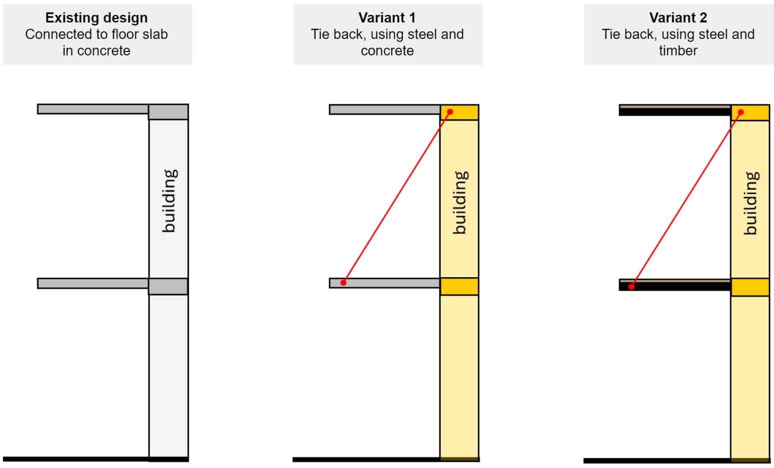


Figure 6.8: Summary of structural possibilities for the balcony structure.

6.2.4. Foundation

As mentioned before, the foundation piles in the current design have a length of 35m. As the redesigned structure is expected to be lighter, fewer or smaller foundation piles will likely suffice. Based on the geotechnical report, a suitable soil layer at 18m depth has been identified. In Figure 6.9, several variants of square prefab foundation piles to this depth have been given, along with their expected compression and tension design capacity.

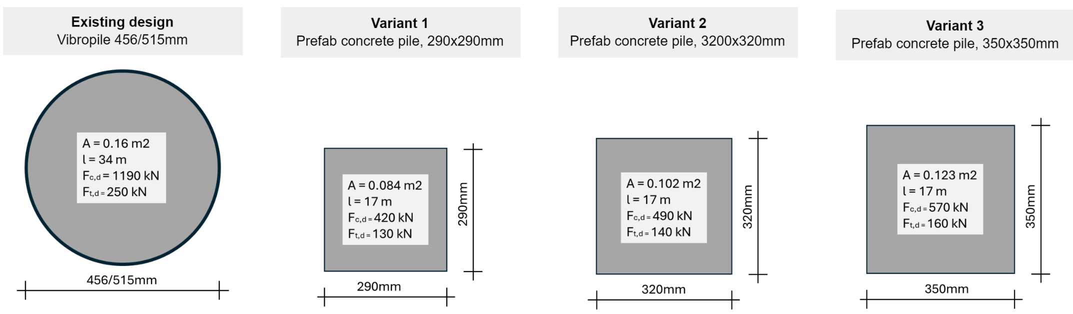


Figure 6.9: Schematisation of the original foundation piles and proposed alternatives.

In later stages, the foundation piles with size 320x320mm will be used as a starting point, while adjustments will be made later if necessary. Furthermore, the foundation beams are kept similar in size compared to the original design, as the dimensions are required for connections between the sub and superstructure.

6.3. Results: final design variants

As concluded in the previous section, six preliminary design variants for the main building have been created. In this section, these variants will be combined with redesigns for the entrance building, galleries, balconies and foundation.

All design variants for the main building will be combined with a design for the entrance building with prefab concrete walls and the same bio-based floor as in the main building. Galleries and balconies will be partly connected to the main building and partly supported by an external steel structure: columns for the galleries and ties for the balconies. Smaller foundation piles will be used: prefab concrete piles of 17 meters, being 320x320mm. More details will be given on the following pages, while final structural verifications are given in Appendix C.

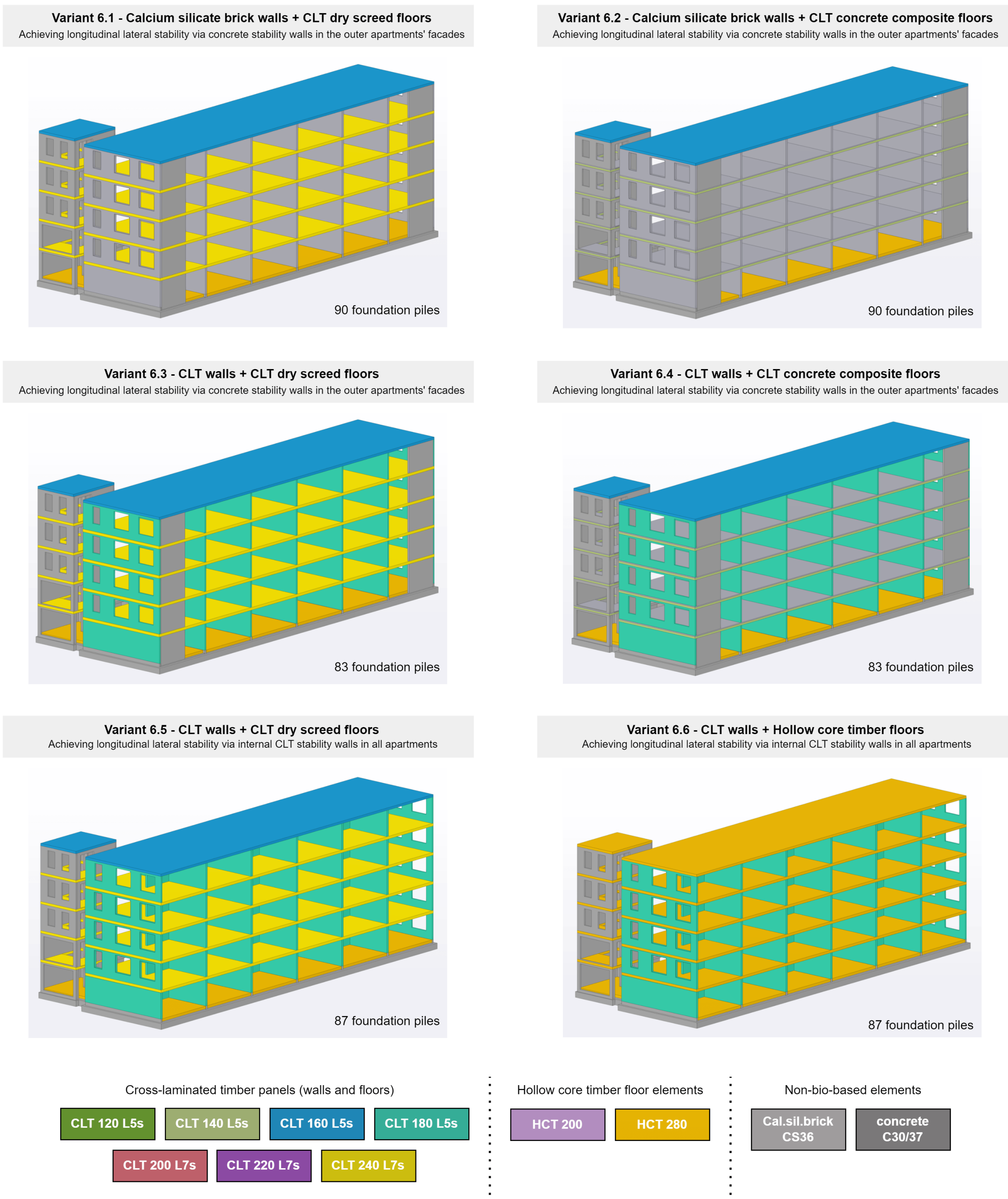


Figure 6.10: Overview of the final design variants of Chapter 6: Redesigns within the existing grid.

Variant 6.1 - Calcium silicate brick walls + CLT-dry screed floors

In this variant, the strategy of only changing floors is applied. Therefore, the separating walls are made of calcium silicate brick, similar to the original design. Floors are dry screed CLT floors, using CLT 240 L7s. Longitudinal lateral stability is achieved by concrete walls in the facades of the outer apartments, which transfer tension forces to the foundation. For the main building, 75 prefab foundation piles of 320x320mm are used with a length of 17m. Furthermore, the ground floors are hollow core timber floors, and the inner walls of the longitudinal facades are timber frame walls. Other elements, such as balconies, are as described in the previous section.

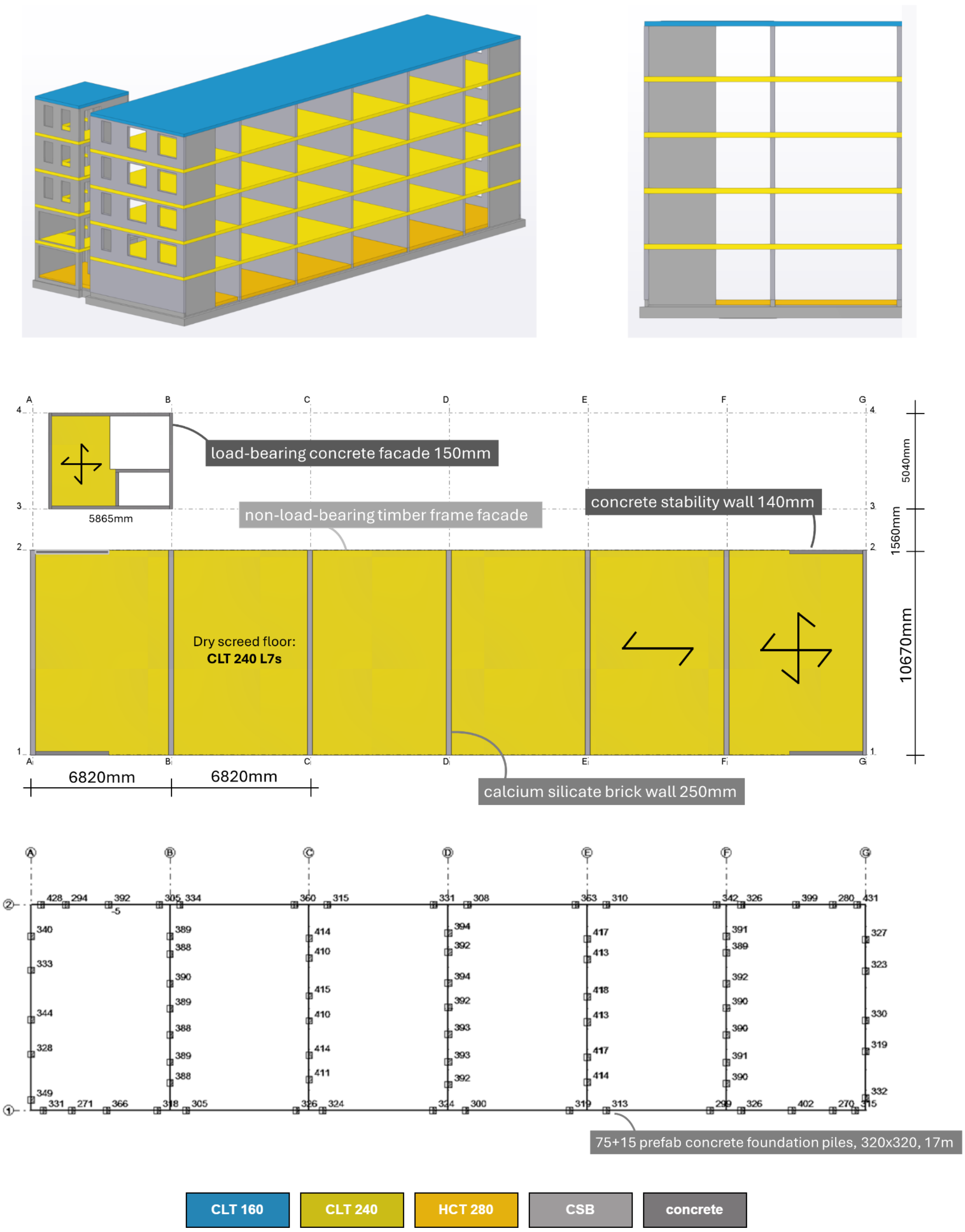


Figure 6.11: Details for final design variant 6.1. The top left image gives a 3D visualisation of the building, while in the top right image, a part of a section along axis 1 is given. Below, dimensions and materials are provided, including an overview of the location of foundation piles and complementary maximum loads per pile.

Variant 6.2 - Calcium silicate brick walls + CLT-concrete composite floors

In this variant, the strategy of only changing floors is applied again. Therefore, the separating walls are made of calcium silicate brick, similar to the original design. Contrary to the previous design, floors CLT-concrete composite floors, use CLT 140 L5s and 100mm of concrete. Longitudinal lateral stability is again achieved by concrete walls in the facades of the outer apartments, which transfer tension forces to the foundation. For the main building, 75 prefab foundation piles of 320x320mm are used with a length of 17m. Furthermore, the ground floors are hollow core timber floors, and the inner walls of the longitudinal facades are timber frame walls. Other elements, such as balconies, are as described in the previous section.

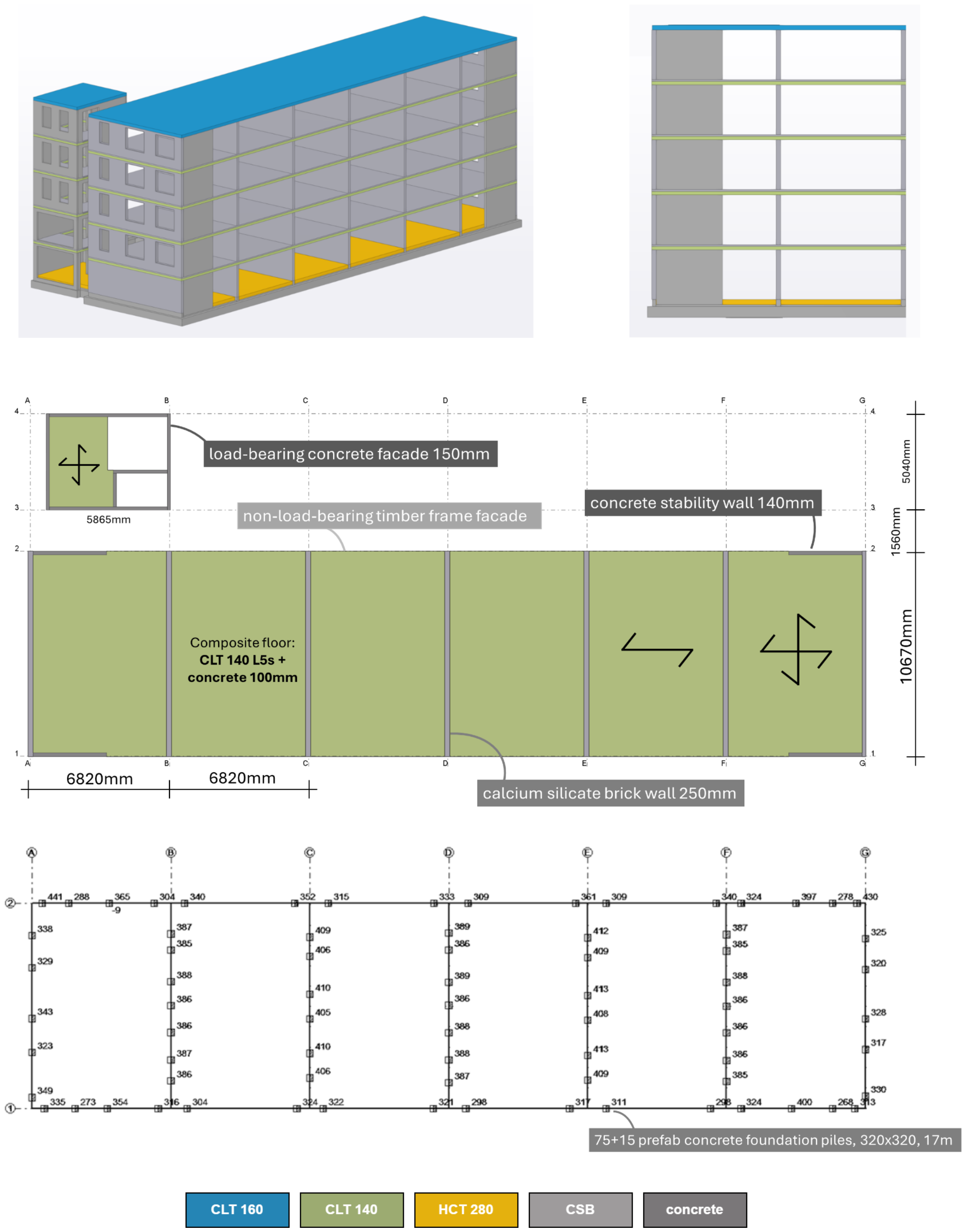


Figure 6.12: Details for final design variant 6.2. The top left image gives a 3D visualisation of the building, while in the top right image, a part of a section along axis 1 is given. Below, dimensions and materials are provided, including an overview of the location of foundation piles and complementary maximum loads per pile.

Variant 6.3 - CLT walls + CLT-dry screed floors

In this variant, the strategy of changing floors and walls is applied. Therefore, separating walls are CLT walls, using CLT 180 L5s. Floors are dry screed CLT floors, using CLT 240 L7s. Longitudinal lateral stability is achieved by stability walls in the facades of the outer apartments, which transfer tension forces to the foundation. As tension forces are beyond the capacity of CLT, concrete is used for these walls. For the main building, 68 prefab foundation piles of 320x320mm are used with a length of 17m. Furthermore, the ground floors are hollow core timber floors, and the inner walls of the longitudinal facades are timber frame walls. Other elements, such as balconies, are as described in the previous section.

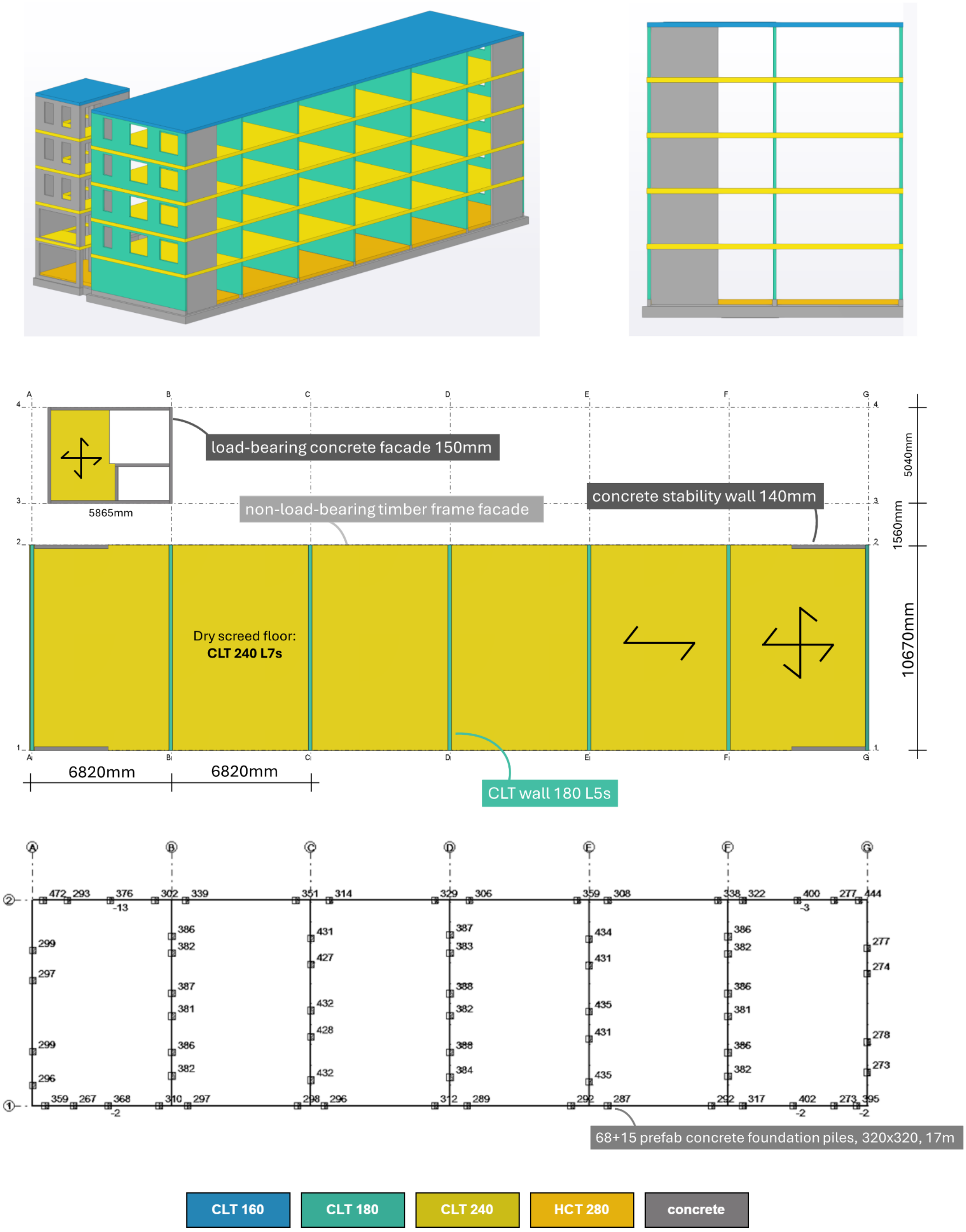


Figure 6.13: Details for final design variant 6.3. The top left image gives a 3D visualisation of the building, while in the top right image, a part of a section along axis 1 is given. Below, dimensions and materials are provided, including an overview of the location of foundation piles and complementary maximum loads per pile.

Variant 6.4 - CLT walls + CLT-concrete composite floors

In this variant, the strategy of changing floors and walls is applied again. Therefore, separating walls are CLT walls, using CLT 180 L5s. Contrary to the previous design, floors CLT-concrete composite floors, use CLT 140 L5s and 100mm of concrete. Longitudinal lateral stability is again achieved by concrete stability walls in the facades of the outer apartments, which transfer tension forces to the foundation. For the main building, 75 prefab foundation piles of 320x320mm are used with a length of 17m. Furthermore, the ground floors are hollow core timber floors, and the inner walls of the longitudinal facades are timber frame walls. Other elements, such as balconies, are as described in the previous section.

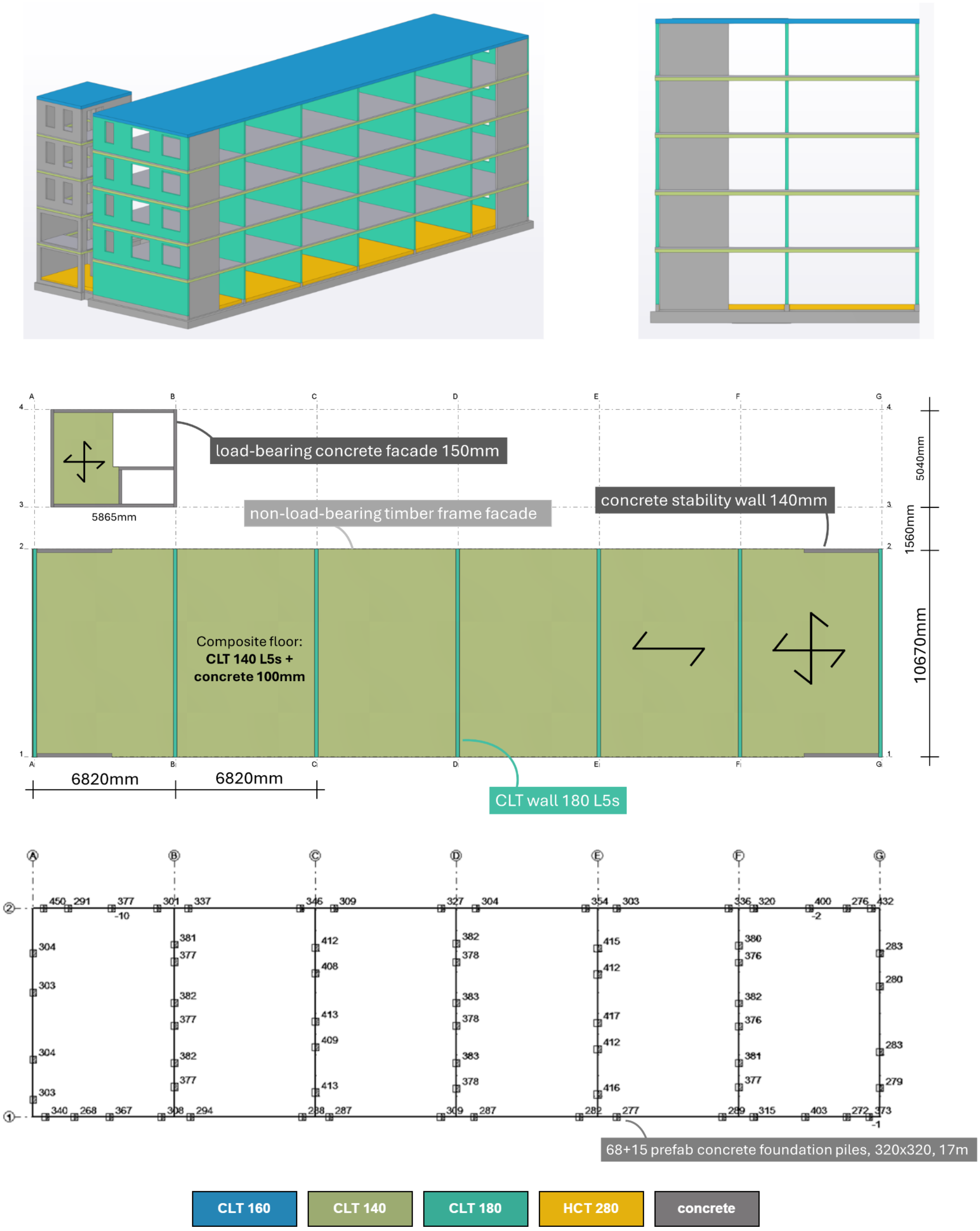


Figure 6.14: Details for final design variant 6.4. The top left image gives a 3D visualisation of the building, while in the top right image, a part of a section along axis 1 is given. Below, dimensions and materials are provided, including an overview of the location of foundation piles and complementary maximum loads per pile.

Variant 6.5 - CLT walls + CLT dry screed floor

This variant is similar to variant 6.3, however, longitudinal lateral stability is achieved differently. Contrary to the previous designs, stability walls will be made from concrete. However, the location is different, being in the middle of the apartments, in a location of non-load-bearing walls between rooms in the current design. Large dead loads on the outer sides of these walls prevent large tension forces. For the main building, 72 prefab foundation piles of 320x320mm are used with a length of 17m. Furthermore, the ground floors are hollow core timber floors, and the inner walls of the longitudinal facades are timber frame walls. Other elements, such as balconies, are as described in the previous section.

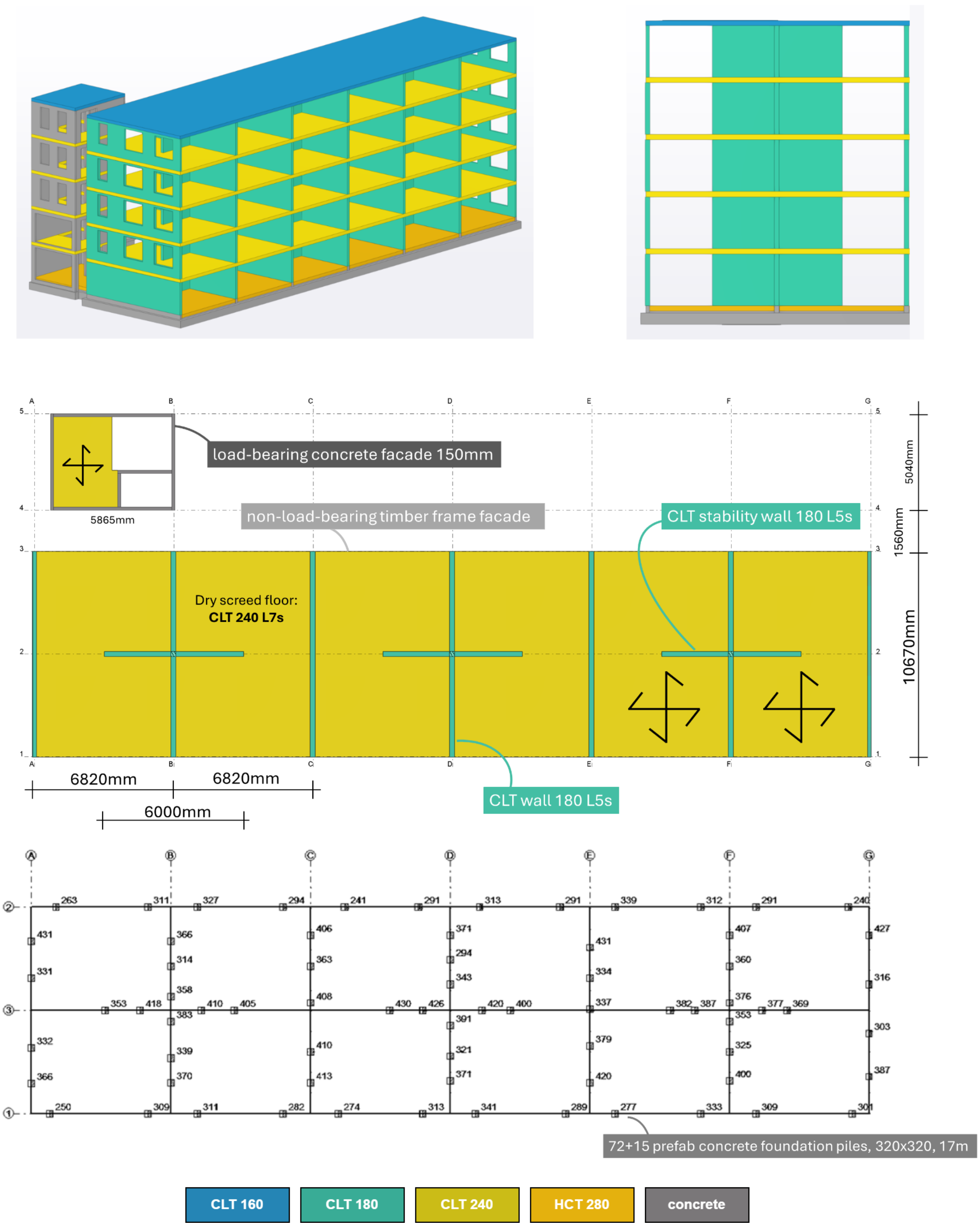


Figure 6.15: Details for final design variant 6.5. The top left image gives a 3D visualisation of the building, while in the top right image, a part of a section along axis 1 is given. Below, dimensions and materials are provided, including an overview of the location of foundation piles and complementary maximum loads per pile.

Variant 6.6 - CLT walls + Hollow core timber floors

This design variant is similar to variant 6.5, except for the floor type: Hollow core timber floors with a thickness of 280mm will be used. Note that in this design variant, contrary to the ones having stability walls in the outer apartments' facades, sufficient diaphragm action can be achieved to transfer lateral forces to the foundation via the floors and walls, which enables the use of timber hollow core floors. However, more attention is needed to detail stability walls and floors compared to CLT floors. Again, 72 prefab foundation piles of 320x320mm are used with a length of 17m. Furthermore, the ground floors are hollow core timber floors, and the inner walls of the longitudinal facades are timber frame walls. Other elements, such as balconies, are as described in the previous section.

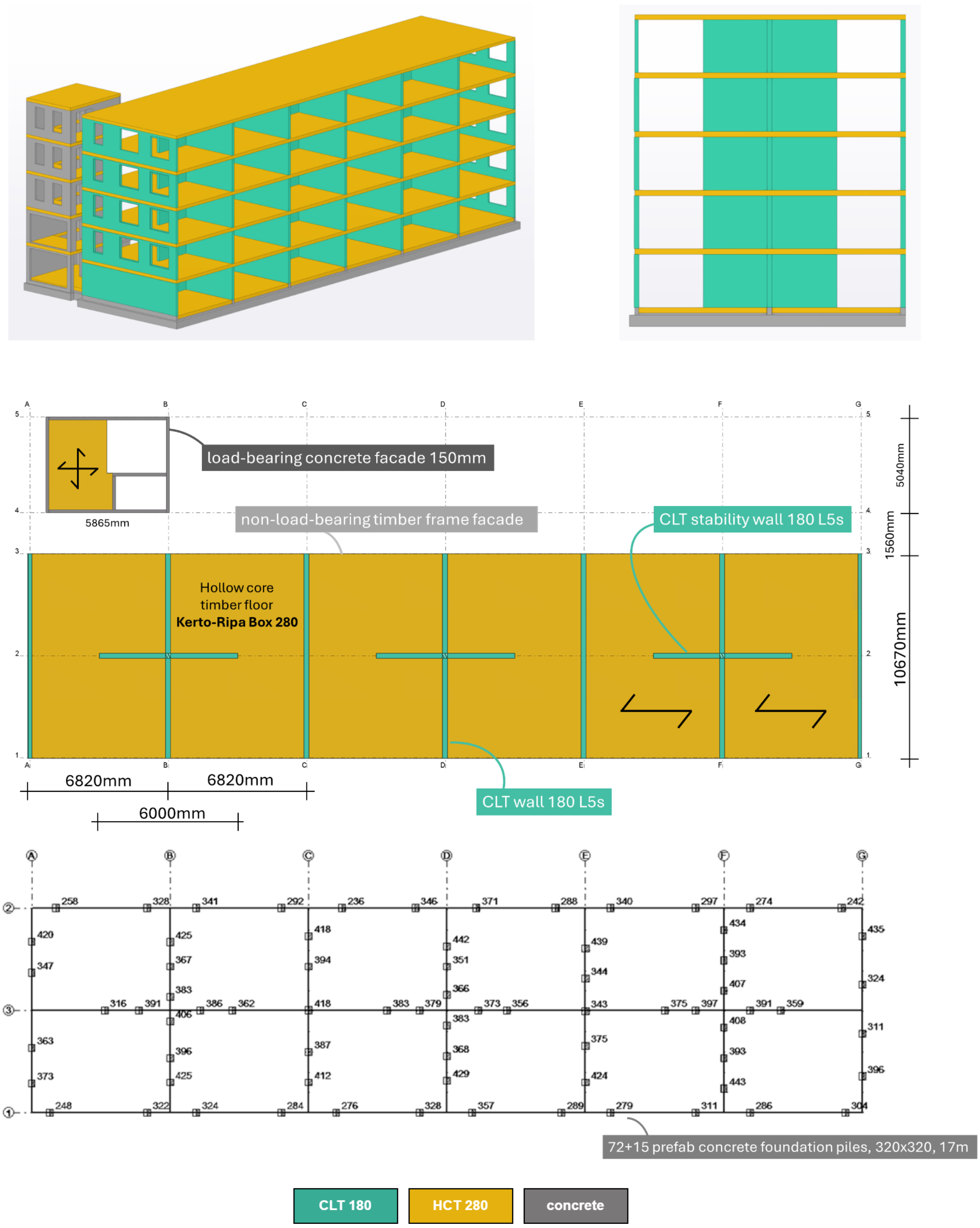


Figure 6.16: Details for final design variant 6.6. The top left image gives a 3D visualisation of the building, while in the top right image, a part of a section along axis 1 is given. Below, dimensions and materials are provided, including an overview of the location of foundation piles and complementary maximum loads per pile.

6.4. Results: assessment

In this section, the results of the assessment will be provided. First, an overview will be given, after which more details will be given per variant.

Overview of results

All designs of the previous section have been assessed to the criteria determined in Chapter 3: GWP-GHG, GWP-total, costs and volume of timber. Note that GWP-total has been defined as GWP-GHG plus 50% of the total sequestrated carbon defined in LCA module A. The results of the assessment are given in Figure 6.17 below. In this figure, the relative differences are given compared to the original design - which is sometimes labelled as variant 0.

	GWP-GHG	Δ	GWP-total	Δ	costs	Δ	volume timber
	[kg CO2-eq./m2]	riginal design	[kg CO2-eq./m2]	original design	[euro/m2]	vs. variant 0	[m3]
Existing design	187,0		187,0		334,2		0,0
Variant 6.1	98,2	-47%	-3,0	-102%	360,9	8%	626,4
Variant 6.2	114,1	-39%	37,9	-80%	319,4	-4%	451,7
Variant 6.3	91,6	-51%	-33,2	-118%	404,8	21%	796,2
Variant 6.4	107,6	-42%	7,7	-96%	363,3	9%	592,5
Variant 6.5	94,1	-50%	-37,6	-120%	430,6	29%	839,9
Variant 6.6	100,3	-46%	2,1	-99%	354,2	6%	501,9

Figure 6.17: Overview of results of the assessment for the redesigns of Chapter 6.

As can be seen in the figure above, significant reductions of GWP-GHG can be realised when timber is included in the structural system. The reductions for GWP-GHG have a range from 39% to 51%. For GHG-total, reductions between 80% and 120% have been realised, indicating net storage of carbon for several variants.

In terms of costs, most variants will have larger values compared to the original design, except for variant 6.2. Differences in cost values range from -4% to +29%. Finally, the amount of timber used is between 452 and 840 m^3 for the whole building.

Detailed results per design variant

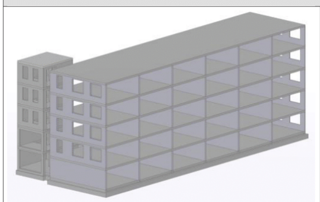
In the figures below and on the next page, a more detailed overview of the assessments is given, where the impact has been categorised:

- Horizontal elements: floors, roofs, beams
- Vertical elements: walls, facades, columns
- Foundation: beams and piles
- Others: galleries, balconies

For all these categories, the values for the mentioned categories are given, allowing for better comparisons of results. In Appendix D, an even more detailed overview is provided, given the single elements within a category.

Existing design

Calcium silicate brick walls + concrete wide slab floors - Achieving longitudinal lateral stability by having sufficient self-weight to prevent tension forces

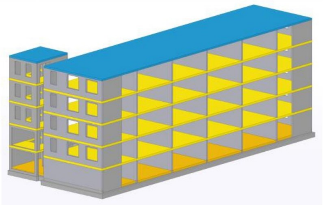


	GWP-GHG	GWP-total	costs	volume timber
	[kg CO2-eq./m2]	[kg CO2-eq./m2]	[euro/m2]	[m3]
Floors, roofs, beams	91,3	91,3	152,1	0,0
Walls, facades, columns	27,3	27,3	64,3	0,0
Foundation	54,4	54,4	77,1	0,0
Others	14,0	14,0	40,7	0,0
TOTAL	187,0	187,0	334,2	0,0

Figure 6.18: Detailed assessment of the existing designs.

Variant 6.1

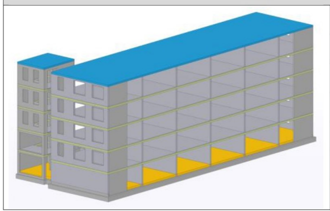
Calcium silicate brick walls + CLT dry screed floors - Achieving longitudinal lateral stability via concrete stability walls in the outer apartments' facades



	GWP-GHG	GWP-total	costs	volume timber
	[kg CO2-eq./m2]	[kg CO2-eq./m2]	[euro/m2]	[m3]
Floors, roofs, beams	37,1	-48,9	231,5	522,9
Walls, facades, columns	25,3	23,3	70,3	0,0
Foundation	25,0	25,0	33,9	0,0
Others	10,7	-2,4	25,2	103,5
TOTAL	98,2	-3,0	360,9	626,4

Variant 6.2

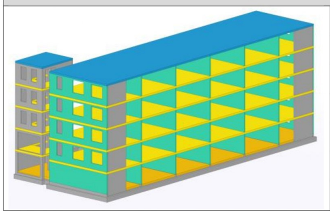
Calcium silicate brick walls + CLT-concrete composite floors - Achieving longitudinal lateral stability via concrete stability walls in the outer apartments' facades



	GWP-GHG	GWP-total	costs	volume timber
	[kg CO2-eq./m2]	[kg CO2-eq./m2]	[euro/m2]	[m3]
Floors, roofs, beams	52,9	-8,2	190,0	348,2
Walls, facades, columns	25,3	23,3	70,3	0,0
Foundation	25,0	25,0	33,9	0,0
Others	10,9	-2,3	25,2	103,5
TOTAL	114,1	37,9	319,4	451,7

Variant 6.3

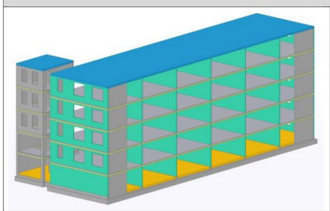
CLT walls + CLT dry screed floors - Achieving longitudinal lateral stability via concrete stability walls in the outer apartments' facades



	GWP-GHG	GWP-total	costs	volume timber
	[kg CO2-eq./m2]	[kg CO2-eq./m2]	[euro/m2]	[m3]
Floors, roofs, beams	37,1	-48,9	231,5	522,9
Walls, facades, columns	20,2	-5,5	115,8	169,8
Foundation	23,6	23,6	32,3	0,0
Others	10,7	-2,4	25,2	103,5
TOTAL	91,6	-33,2	404,8	796,2

Variant 6.4

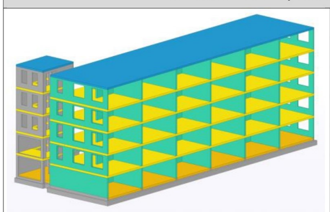
CLT walls + CLT-concrete composite floors - Achieving longitudinal lateral stability via concrete stability walls in the outer apartments' facades



	GWP-GHG	GWP-total	costs	volume timber
	[kg CO2-eq./m2]	[kg CO2-eq./m2]	[euro/m2]	[m3]
Floors, roofs, beams	52,9	-8,2	190,0	319,2
Walls, facades, columns	20,2	-5,5	115,8	169,8
Foundation	23,6	23,6	32,3	0,0
Others	10,9	-2,2	25,2	103,5
TOTAL	107,6	7,7	363,3	592,5

Variant 6.5

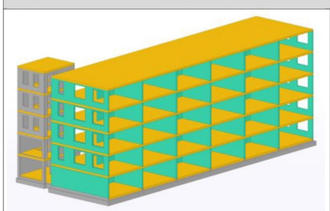
CLT walls + CLT dry screed floors - Achieving longitudinal lateral stability via internal CLT stability walls in all apartments



	GWP-GHG	GWP-total	costs	volume timber
	[kg CO2-eq./m2]	[kg CO2-eq./m2]	[euro/m2]	[m3]
Floors, roofs, beams	37,1	-48,9	231,5	522,9
Walls, facades, columns	20,7	-11,8	138,3	213,6
Foundation	25,6	25,6	35,6	0,0
Others	10,7	-2,4	25,2	103,5
TOTAL	94,1	-37,6	430,6	839,9

Variant 6.6

CLT walls + Hollow core timber floors - Achieving longitudinal lateral stability via internal CLT stability walls in all apartments



	GWP-GHG	GWP-total	costs	volume timber
	[kg CO2-eq./m2]	[kg CO2-eq./m2]	[euro/m2]	[m3]
Floors, roofs, beams	43,4	-9,2	155,0	184,9
Walls, facades, columns	20,7	-11,8	138,3	213,6
Foundation	25,6	25,6	35,6	0,0
Others	10,7	-2,4	25,2	103,5
TOTAL	100,3	2,1	354,2	501,9

Figure 6.19: Detailed assessment of the redesign variants 6.1 to 6.6.

6.5. Analysis of results

In this section, the results that were previously shown will be analysed in order to answer the research question stated at the beginning of the chapter. Relations between various elements and materials will be provided, and comparisons will be made to the original design.

Visualisations of results

Below, in Figure 6.20, costs are plotted against GWP-GHG and GWP-total for the redesigns and the original variant. In Figure 6.21, more zoomed-in plots are given for only the redesigns.

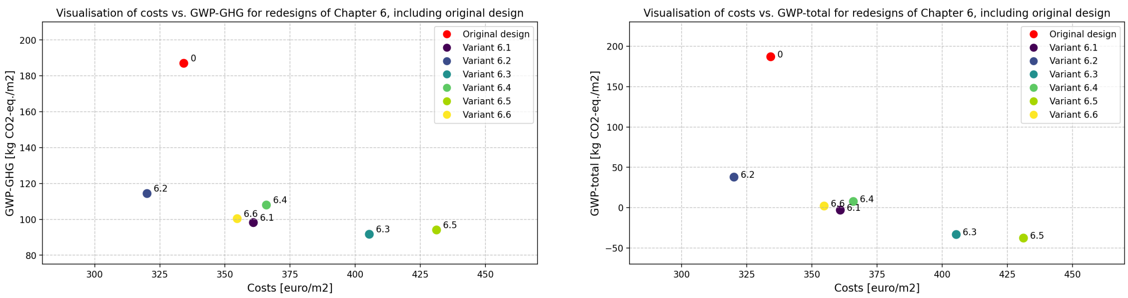


Figure 6.20: Visualisation of costs vs. GWP-GHG (left) and costs vs. GWP-total (right), for the redesigns of Chapter 6 and the original design.

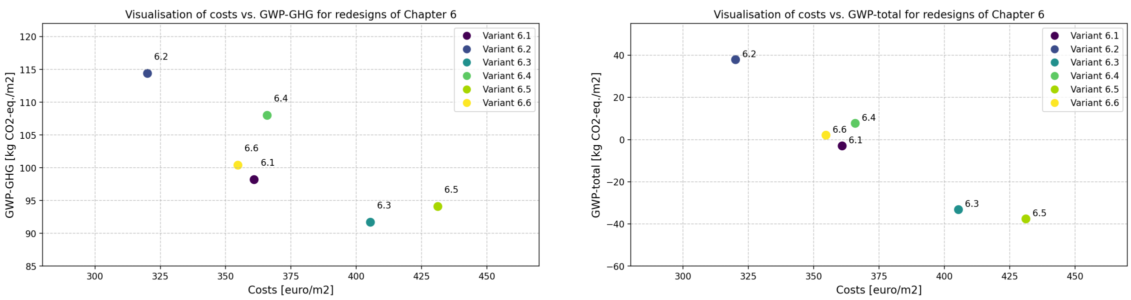


Figure 6.21: Visualisation of costs vs. GWP-GHG (left) and costs vs. GWP-total (right), for the redesigns of Chapter 6.

6.5.1. Comparison of redesigns of Chapter 6: element level

Below, the impact of different building elements and changes will be discussed for different wall systems, floor systems, stability systems and foundation systems.

Wall system

Within the redesigns, two different wall systems have been used: calcium silicate brick walls and CLT walls. When comparing the differences between similar variants where the wall system is the only different element - variant 6.1 vs. 6.3 and variant 6.2 vs. 6.4 - a small reduction of GWP-GHG and a large reduction in GWP-total can be identified. In terms of costs, a relatively large increase can be seen, as summarised below in Figure 6.22. When comparing the differences in global warming potential divided by costs, relatively low values resulted, indicating relatively low environmental benefits compared to costs. The reason for this is twofold: a relatively low difference in GWP-GHG, compared to, for example, the difference with concrete walls, and a more significant difference in costs.

Impact of wall system change	Δ GWP-GHG	Δ GWP-total	Δ costs	Δ GWP-GHG / costs	Δ GWP-total / costs
	[kg CO2-eq./m2]	[kg CO2-eq./m2]	[euro/m2]	[kg CO2-eq./euro]	[kg CO2-eq./euro]
Calcium silicate brick to CLT	-5,2	-28,8	45,5	-0,11	-0,63

Figure 6.22: Impact of changes in wall systems compared to the original design, given for the contribution of walls only.

Floor system

Within the redesigns, all floor systems are different compared to the original wide slab floors. Averaged values indicate significant reductions in GWP-GHG for all floor types. Reductions are largest when switching to CLT-dry screed floors and lowest for CLT-concrete composite floors, with hollow core timber floors in between. For GWP-total, significant reductions have been achieved as well, with reductions for CLT dry screed floor being the largest. In terms of costs, CLT-dry screed floors are significantly more expensive, while hollow core timber floors are similar to the original design, as shown in Figure 6.23. When comparing the differences in global warming potential divided by costs, the values are much higher compared to changes in wall systems, indicating a higher effectiveness of the changes. Hollow core timber floors have high values for this as a result of significantly lower GWP-GHG values for similar costs.

Impact of floor system change for spans of 6.8m	Δ GWP-GHG	Δ GWP-total	Δ costs	Δ GWP-GHG / costs	Δ GWP-total / costs
	[kg CO2-eq./m2]	[kg CO2-eq./m2]	[euro/m2]	[kg CO2-eq./euro]	[kg CO2-eq./euro]
Wide slab floor to CLT dry screed floor	-54,2	-140,2	79,3	-0,68	-1,77
Wide slab floor to CLT-concrete composite floor	-38,3	-99,5	37,8	-1,01	-2,63
Wide slab floor to Hollow core timber floor	-47,9	-100,5	2,9	-16,55	-34,73

Figure 6.23: Impact of changes in floor systems compared to the original design, given for the contribution of floors only.

Stability system

Within the redesigns, two different stability systems can be identified, as shown in the top two rows below in Figure 6.24. Note that all values for GWP-GHG are positive, as stability elements needed to be added compared to the original design, as longitudinal lateral stability was achieved without additional elements in that design. While GWP values between the two elements are similar, differences in costs are significant. In the bottom row of the figure below, the differences between the top two rows, and thus the two stability systems, have been given. Interestingly, a net increase in GWP-GHG will be realised when changing to CLT walls instead of concrete walls: due to the location of the walls, extra foundation beams are needed to realise the change, leading to the increased values. Therefore, switching to CLT for these design variants is not preferable.

Impact of stability system change	Δ GWP-GHG	Δ GWP-total	Δ costs	Δ GWP-GHG / costs	Δ GWP-total / costs
	[kg CO2-eq./m2]	[kg CO2-eq./m2]	[euro/m2]	[kg CO2-eq./euro]	[kg CO2-eq./euro]
Inclusion of concrete stability walls in outer apartments longitudinal facades	4,3	4,3	7,7	0,56	0,56
Inclusion of LT stability walls internally	5,7	-0,7	27,1	0,21	-0,03
Concrete stability walls outer facades to internal CLT stability walls	1,4	-4,9	19,4	0,07	-0,25

Figure 6.24: Impact of changes in stability systems compared to the original design, given for the contribution of all additionally needed elements, such as walls and foundation beams.

Foundation system

Within the redesigns, three different combinations of wall and stability systems can be identified: variants 6.1 and 6.2, variants 6.3 and 6.4, and variants 6.5 and 6.6. While different floor types have been used, this did not lead to significant differences in weight; hence, there was no significant difference in foundation size. In Figure 6.25, it can be seen that for GWP-GHG, GWP-total as well as for costs significant, yet similar reductions have been achieved. The possibility of switching to smaller piles is the main reason for the reductions in GWP and costs. When comparing the differences in global warming potential divided by costs, the impact is similar to switching to CLT-dry screed floors.

Impact on foundation	Δ GWP-GHG	Δ GWP-total	Δ costs	Δ GWP-GHG / costs	Δ GWP-total / costs
	[kg CO2-eq./m2]	[kg CO2-eq./m2]	[euro/m2]	[kg CO2-eq./euro]	[kg CO2-eq./euro]
Calcium silicate brick walls (concrete stability walls outer facades)	-25,3	-25,3	-36,9	0,69	0,69
CLT walls (concrete stability walls outer facades)	-26,8	-26,8	-38,5	0,69	0,69
CLT walls (CLT stability walls internally)	-24,8	-24,8	-35,2	0,70	0,70

Figure 6.25: Impact of changes in foundation systems compared to the original design, given for the contribution of all foundation elements.

6.5.2. Comparison of redesigns of Chapter 6: building level

The various impacts on an element level all have different impacts on a building level, as the relative contribution of elements is different. Therefore, in this section, the impact on building level is discussed for each indicator, based on the element level analysis and data provided in Figure 6.17.

Comparison of GWP-GHG

Across all variants, significant reductions in GWP-GHG have been achieved, ranging from 39% to 51%. While having a small range, it indicates a high overall effectiveness of the redesigns. Compared to the original design, the largest savings in GWP-GHG can be found in floors and foundations, both decreasing over 50% for all variants. In contrast, changing wall systems has proven to be significantly less efficient in reducing GWP-GHG.

Among the variants, 6.3 and 6.5, both featuring CLT floors and walls, achieve the lowest GWP-GHG values. Contrary to this, variants 6.2 and 6.4, both featuring CLT-concrete composite floors, have the highest GWP-GHG values. Despite all improvements, none of the variants aligns with the governmental goals for GWP-GHG reductions for the coming decades.

Comparison of GWP-total

Except for variant 6.2, the reductions in GWP-total were so significant that they resulted in values below the established thresholds for the Paris Proof Indicator. Some values are even negative, indicating net carbon storage. The reductions range between 8% and 120%. Compared to the original design, all building elements contributed to reductions in GWP-total, with floors contributing the most to these reductions.

Among the variants, variants 6.3 and 6.5, both featuring CLT walls and floors, achieve far lower GWP-total values than all other variants, a different trend than can be recognised for GWP-GHG. Variants 6.1, 6.4 and 6.6 achieve similar values, around zero. Note that the highest value of GWP-total is still over two times lower than the lowest GWP-GHG value.

Comparison of costs

When considering costs, the measured values differ from -4% to +29% compared to the original design, generally reflecting higher costs. The main reason for this is the price of CLT, which is significantly higher than any other floor or wall type. This is also the cause for CLT-concrete composite floors having far lower costs: the amount of CLT is simply much lower. The reason for the relatively limited increase in price up to 29% is the reduction in costs for the foundation, as discussed earlier.

Variants 6.3 and 6.5, both having CLT floors and walls, have a significantly higher cost increase compared to the other redesigns. In contrast, variants 6.1, 6.4, and 6.6 have comparable costs despite their conceptual differences. However, all have in common that they do not use both CLT floors and walls. This is similar to the trend for GWP-total values. Interestingly, variant 6.2 shows lower costs compared to the original design. The reason for this is that the decrease in costs for foundations outweighs the increase in costs for floors. Notably, four out of six variants have cost increases of less than 10%, in line with the goals.

Comparison of volume of timber

The total amount of used volume of timber differs significantly between the variants. This, of course, can be related directly to the type of walls and floors used. However, it is interesting to mention that solutions with CLT walls combined with CLT-concrete composite floors or hollow core timber floors consist of less timber than variants with calcium silicate brick walls and Dry screed CLT floors. In other words, the floor contributes significantly more to the total volume.

6.6. Conclusions

In this section, conclusions will be drawn that will help answer the research question stated at the beginning of the chapter. The aim is to find optimally adjusted designs, including timber.

Conclusions on element level

On an element level, the following can be concluded for design choices:

- Switching from calcium silicate brick walls to CLT walls results in a slight reduction in GWP-GHG but a significant reduction in GWP-total. On the contrary, the increase in costs is relatively high, making wall changes less economically efficient compared to other changes.
- The impact of changing the floor system is largest compared to other elements. For this, CLT-dry screed floors provide the largest reductions in GWP-GHG and GWP-total but lead to significantly higher costs. Including hollow core timber floors will lead to a lower decrease in GWP-GHG and GWP-total while having comparable costs to the original design. CLT-concrete composite floors deliver the smallest GWP reductions, being between the other variants in terms of costs. This leads to hollow core timber floors being preferable over the others.
- Most of the other reductions in GWP and in costs are related to the foundation: due to the lower weight of the floors, the size of the foundation can be significantly smaller.
- Achieving longitudinal lateral stability will always lead to higher GWP-GHG and cost values as additional materials are needed. The switch from concrete to CLT stability walls is not beneficial when additional foundation beams are needed to achieve this.

Furthermore, the following areas have been identified for further improvement:

- Material strength limits for floors are far from utilised, as vibrations are the governing criteria. As spans are inverted quadratically proportionate to this, creating smaller spans could lead to smaller floor sections, lowering both GWP and cost
- Material use of super and substructure for the entrance building is disproportionately large; combining the main building and entrance building could lower both GWP and costs.
- Finding ways to combine stability- and apartment-separating walls could lower material use.

Conclusions on building level

On a building level, the following can be concluded for design choices:

- Variants with both CLT walls and floors have the highest reductions in GWP-GHG while still being significantly higher than the governmental targets. Costs for these variants, however, are well above the design goal of a maximum increase of 10%. This indicates that either walls or floors should be non-CLT for the variant to be economically attractive.
- For all other variants, having combinations of different floor and wall types, costs are below the design goal of a maximum increase of 10% relative to the original design. When combining calcium silicate brick walls with CLT-concrete composite floors, costs can even be below the costs of the original design.
- For all variants, values for GWP-GHG are well above the governmental targets, while for GWP-total, most variants have values below the targets. The range between GWP-GHG values is relatively small, while the range of costs is significantly larger.
- Design strategies focussing on changing only floors can achieve the set goals, for a significant part achieved by the reductions in foundation size, and therefore values for GWP-GHG, GWP-total and costs. This indicates a higher suitability of timber design variants for locations with specific soil configurations that allow for these changes in the foundation.
- When selecting CLT walls, it is not efficient to include CLT-concrete composite floors. A more cost-effective design with similar GWP values can be found when CLT-dry screed floors and calcium silicate brick walls are combined.
- In general, any combination of wall system and floor system not being both CLT could achieve the set goals economically. While environmental savings are significant, they will always be well below the governmental goals.

7

Redesigns beyond the existing grid

In this chapter, redesigns beyond the existing grid will be investigated. A similar approach will be taken to the one in the previous chapter. However, different boundary conditions will be fulfilled. The following research question is aimed to be answered:

"How can the original design of the case study building be adjusted optimally into timber or hybrid timber variants, beyond the existing grid?"

7.1. Input for design exploration

7.1.1. Design goals and boundaries

As stated above, this part of the research aims to find optimal redesigns. A similar approach will be taken to the one in the previous chapter, aiming to find designs optimal for GWP-GHG at certain cost thresholds. Another aim is to find the lowest possible GWP-GHG value within the boundaries.

To ensure the redesigned buildings fulfil a similar function to the building of the original design, the following boundaries will be ensured:

- The area of the existing building site will be maintained;
- The amount of apartments is 27, having an average GFA of 73.6m^2 per apartment;
- Apartments with three rooms need to be created, having sufficient daylight entry;
- The amount of storage needs to be equal to the original design, being 274.4m^2;
- The area of the balconies will be equal, being 6.18m^2 per apartment;
- The depth of the galleries will be equal, being 1.7m.

7.1.2. Conclusions of previous design stage

Some of the conclusions of the previous design stage will be taken into account for this stage. However, as variants that were unfavourable in the previous chapter might become favourable after the changes in this chapter, these or similar variants are not disregarded. For example, when a design variant has unfavourably high costs due to CLT floor panels with a large cross-section, this could change when a thinner floor panel is possible due to the redesigns of this chapter.

The following targets have been identified for potential improvement:

- Ensure thinner floor sections can be used by creating smaller spans;
- Combine the entry building and the main building structurally;
- Ensure timber stability elements can be used without using extra foundation;
- Adjust the CLT wall type for different strategies.

7.2. Exploration of design variants

In this section, the aim is to find optimal ways to include the targets as described in the previous section, which will be investigated in three subsections.

7.2.1. Decreasing floor spans by placing walls closer together

The first way to achieve the first target of decreasing floor spans is simply placing walls closer together. As a result of the common sizes of floor elements, spans of 6.0m, 5.4m and 4.8m are the most logical. However, as the building concept consists of six apartments next to each other, sharing the longest walls, the amount of daylight entry is limited. As three two bedrooms and one combined kitchen-living room all need sufficient daylight, changes to the architectural layout are needed.

In Figure 7.1, the architectural layout of apartments with spans of 6.8m and 6.0m is given, based on input from practice (Venster Architecten, 2024). As can be seen, due to the limited width of the apartments, one of the bedrooms needs to be transferred to the front side of the building, leading to a more narrow layout. When the spans decrease further, no sufficient amount of daylight can be present in all rooms. Different configurations will be needed, which will be pursued in the next section.

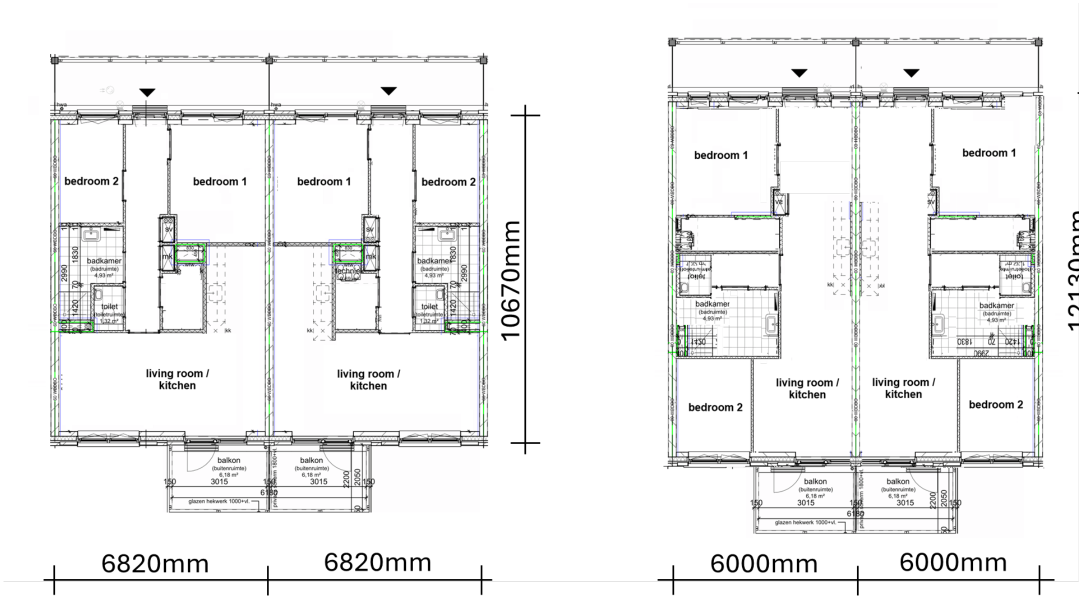


Figure 7.1: Different architectural layouts of apartments for spans of 6.8m (left) and 6.0m (right).

As a result of the change, the thickness of floor size can be reduced, leading to, for example, CLT 200 L5s for dry screed floors instead of L7s 240. While this is a significant reduction, there will be an increase in wall length; therefore, more materials will be used on that part. In the assessment later in the chapter, the impact of both changes will be shown, revealing if this strategy leads to more optimal designs. More details on the exploratory calculations can be found in Appendix B.6.

As decreasing floor spans by placing walls closer together is a realistic solution, this strategy will be pursued, with the inclusion of entrance buildings and different wall and floor types according to the strategies. In Figure 7.2, the first two schematisations show an overview of this target, with various wall types used.

7.2.2. Decreasing floor spans by including beams

A second way to achieve smaller floor spans is by including beams in the design. The beams, spanning from wall to wall, could reduce the span of floors and, therefore, reduce the thickness of floors.

Based on preliminary calculations, however, for beams with a 6.0m span, creating a floor span of 3.6m, glulam GL24h beams would need to be 440mm in height. This, including floor height, would lead to a significant increase in building height and, therefore, would need more additional materials than would be saved. For beams creating a floor span of 4.8m, Glulam beams would need to be 520mm in height, leading to even more additional material use. Therefore, the use of glulam beams will not be investigated further. More details can be found in B.6.

The inclusion of steel beams has also been investigated. Also based on preliminary calculations, steel S355 beams spanning 6.0m, creating a floor span of 3.6m, would need a HEA200 profile. For beams creating a floor span of 4.8m, HEA220 would be needed, leading to GWP-GHG values between 20-25 kg CO_2-eq./m^2, assuming at least three beams per apartment. The additional GWP-GHG is far more than the potential savings by smaller floors, even when floor thickness is twice as small.

As both glulam and steel beams would not lead to designs with a lower environmental footprint in their most simple appearance, this strategy will not be pursued further. Note that the inclusion of beams for a span of 6.8 meters would lead to even larger elements. The combination of using only beams and columns instead of a panellised system with walls could potentially lead to reduced GWP-GHG values. However, as concluded earlier, this conceptual typology is not suited for residential buildings but rather for office buildings.

7.2.3. Combining apartment-separating walls and stability walls

Another strategy to decrease material use or impact is by combining apartment-separating walls and stability walls. By doing so, CLT stability walls can be created without needing extra foundation beams and piles, contrary to variants 6.5 and 6.6 in the previous chapter.

An example of rotation (and translation) of the outer two apartments is shown in Figure 7.2, in the step from the second to the third sub-figure. Instead of three separate stability walls of 6 meters, one single stability wall of 11 to 12 meters will be realised. Due to the fact that this wall is one large element instead of several single elements, the total lateral load will be spread more evenly and have a lower peek value. Consequently, the total length of stability walls is smaller, and only a third of the length of the building needs to have an additional foundation beam. This leads to lower material use and lower GWP-GHG and cost values.

Many other possibilities which have been investigated will lead to additional walls or facades compared to the existing redesigns. The existing redesigns simply use more apartment-separating walls than outer walls, which is relatively efficient. Hence, other redesigns do not lead to more optimised designs regarding global warming potential.

This strategy will be pursued, as preliminary calculations have shown potential for the reduction of materials. These redesigns will only be done for variants with CLT walls, as tension forces need to be transferred, and calcium silicate bricks are less suitable for this. The entrance building will be included in all redesign variants, and both CLT and HCT floors will be used according to design strategies.

7.2.4. Preliminary design variants

As a result of the design process above, six variants are concluded to be promising. All include the entry building and have similar galleries and balconies as the designs of Chapter 6. This leads to the following variants:

Achieving stability via internal concrete stability walls in each apartment

1. Only changing floors: **Calcium silicate brick walls + CLT-dry screed floors**
2. Only changing floors: **Calcium silicate brick walls + CLT-concrete composite floors**

Achieving stability via internal CLT stability walls in each apartment

3. Changing floors and walls: **CLT walls + CLT-dry screed floors**
4. Changing floors and walls: **CLT walls + Hollow core timber**

Achieving stability via one internal CLT stability walls of the rotated apartment:

5. Changing floors and walls: **CLT walls + CLT-dry screed floors**
6. Changing floors and walls: **CLT walls + Hollow core timber floors**

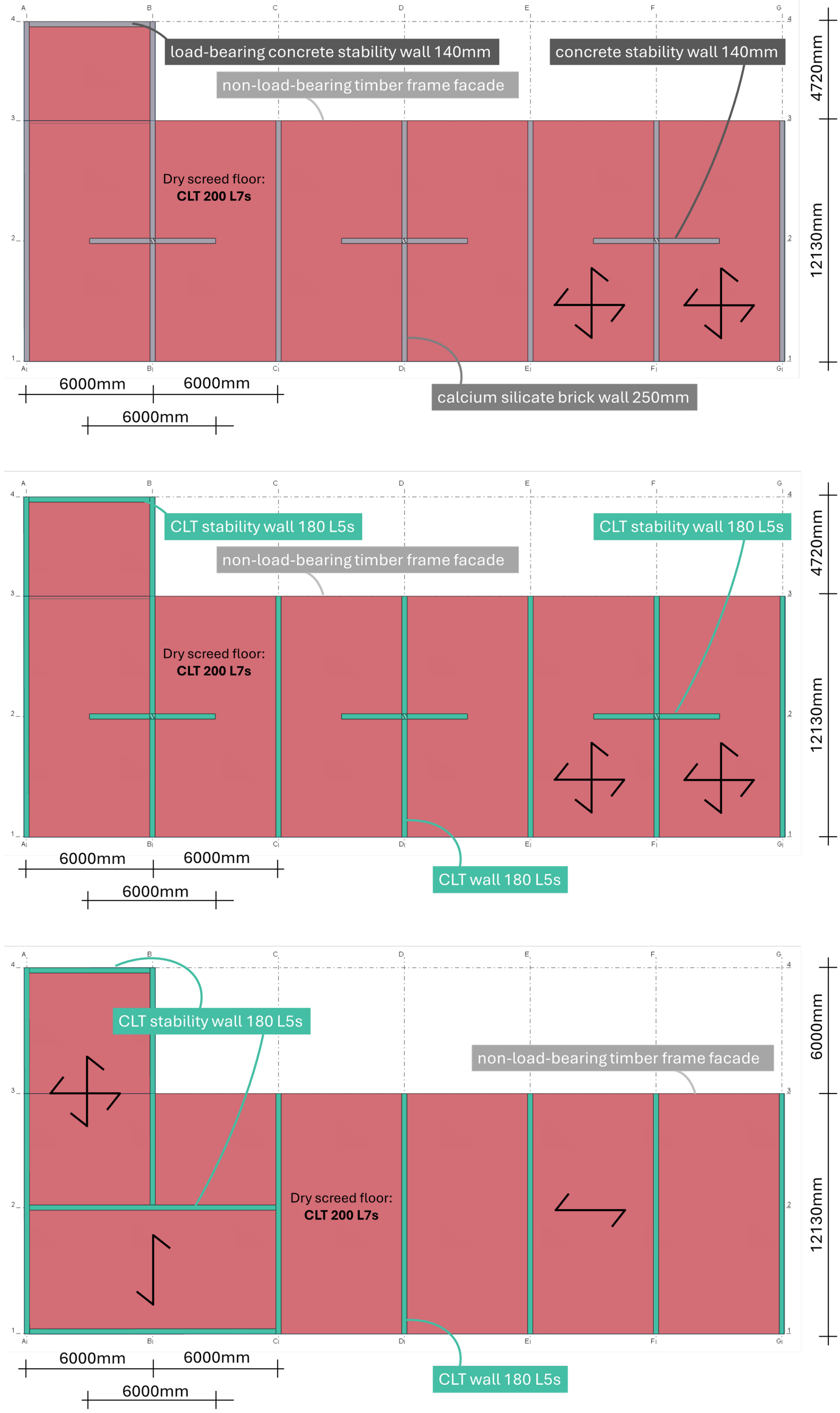


Figure 7.2: Overview of the design variants following from the exploration process. The top two visitations show the variants where only the floor span has decreased from 6.8m to 6.0m, with different wall types. The bottom visualisation shows the variants with the rotated outer apartments, having a floor span of 6.0m

7.3. Results: final design variants

As shown in the previous section, six preliminary design variants for the main building have been created. In this section, these final variants will be explained in more detail, and their impact on the foundation will be discussed.

All design variants will include the entrance building, which will consist of the same material as the rest of the building. This is in contrast to the redesigns of the previous chapter. Galleries and balconies will again be partly connected to the main building and partly supported by an external steel structure: columns for the galleries and ties for the balconies. Smaller foundation piles will be used: prefab concrete piles of 17 meters, being 320x320mm. More details will be given on the following pages, while final structural verifications are given in Appendix C.

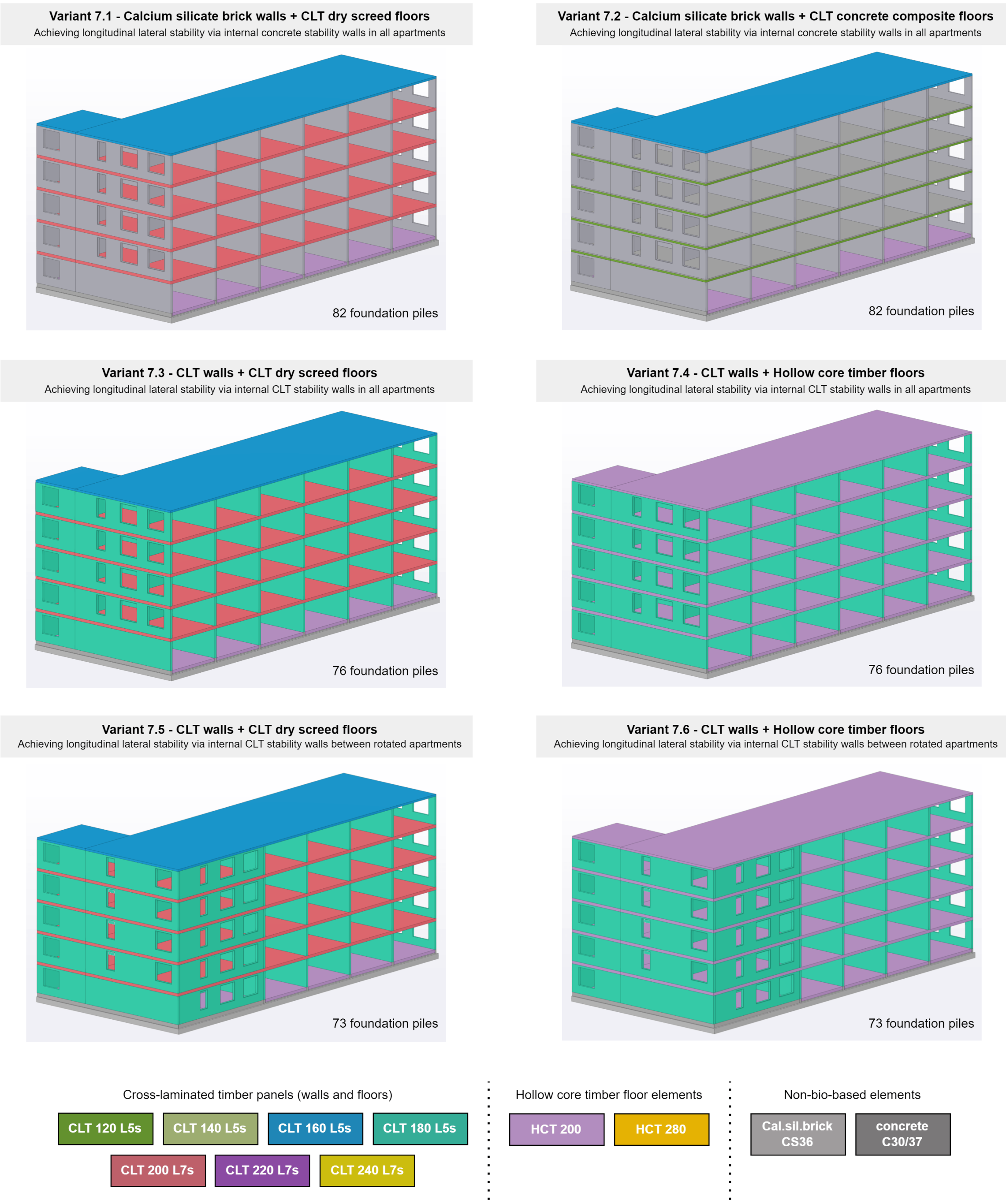


Figure 7.3: Overview of the final design variants of Chapter 7: Redesigns beyond the existing grid.

Variant 7.1 - Calcium silicate brick walls + CLT-dry screed floors

In this variant, the strategy of only changing floors is applied. Therefore, the separating walls are made of calcium silicate brick, similar to the original design. Floors are dry screed CLT floors, using CLT 200 L5s. Longitudinal, lateral stability is achieved by concrete walls within the apartments, which are a solution that uses less material than achieving stability via concrete facades. Creating closed sections in the facades of the outer apartments is not possible due to the smaller floor span. In total, 82 prefab foundation piles of 320x320mm are used with a length of 17m. Furthermore, the ground floors are hollow core timber floors, and the inner walls of the longitudinal facades are timber frame walls. Other elements, such as balconies, are as described in the previous chapter.

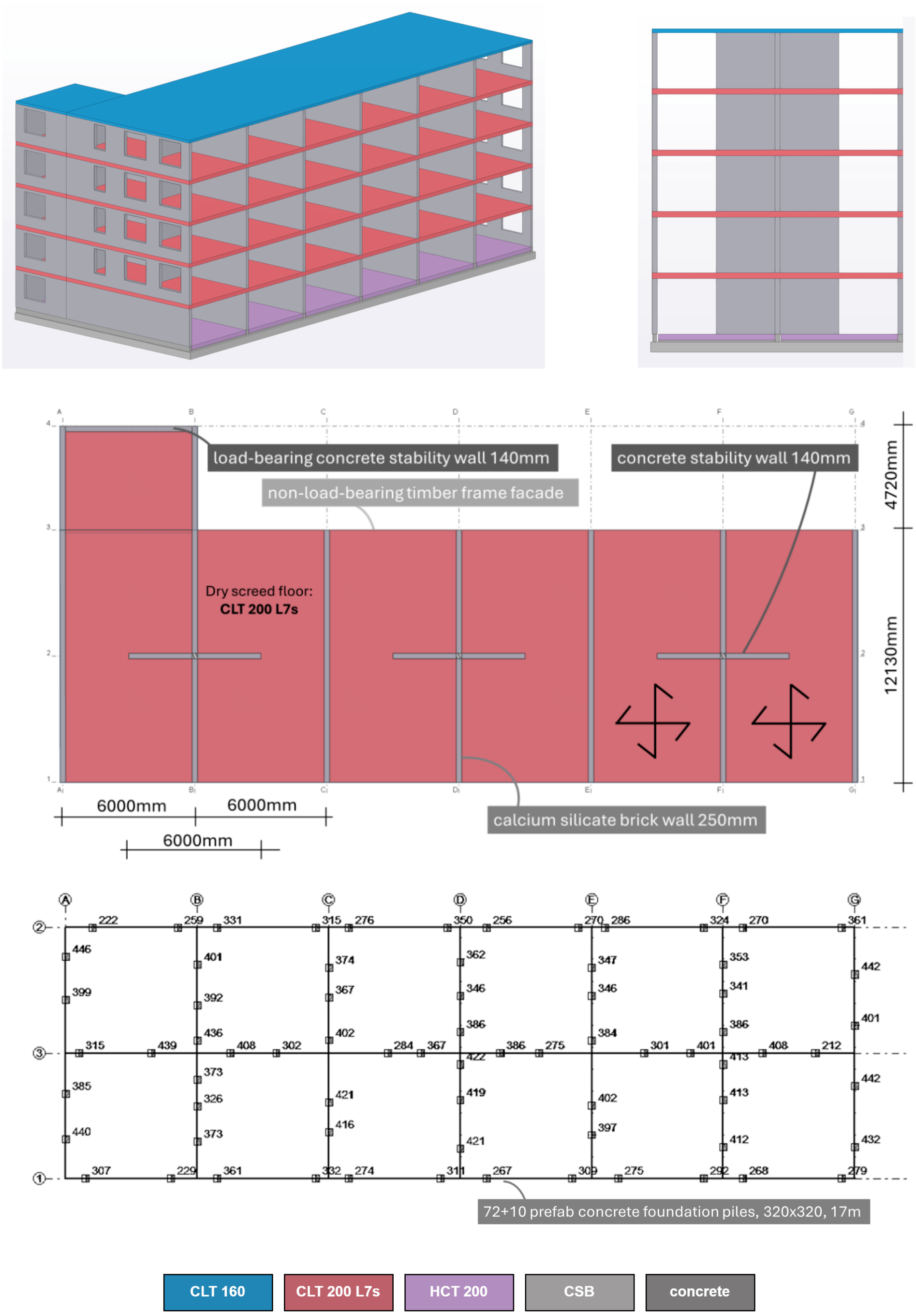


Figure 7.4: Details for final design variant 7.1. The top left image gives a 3D visualisation of the building, while in the top right image, a part of a section along axis 1 is given. Below, dimensions and materials are provided, including an overview of the location of foundation piles and complementary maximum loads per pile.

Variant 7.2 - Calcium silicate brick walls + CLT-concrete composite floors

In this variant, the strategy of only changing floors is applied again. Similar to the previous variant, separating walls are calcium silicate brick walls. Floors, however, are CLT-concrete composite floors, using CLT 120 L5s and 100mm of concrete. Longitudinal, lateral stability is achieved by concrete walls within the apartments, similar to the previous variant. In total, 82 prefab foundation piles of 320x320mm are used with a length of 17m. Furthermore, the ground floors are hollow core timber floors, and the inner walls of the longitudinal facades are timber frame walls. Other elements, such as balconies, are as described in the previous chapter.

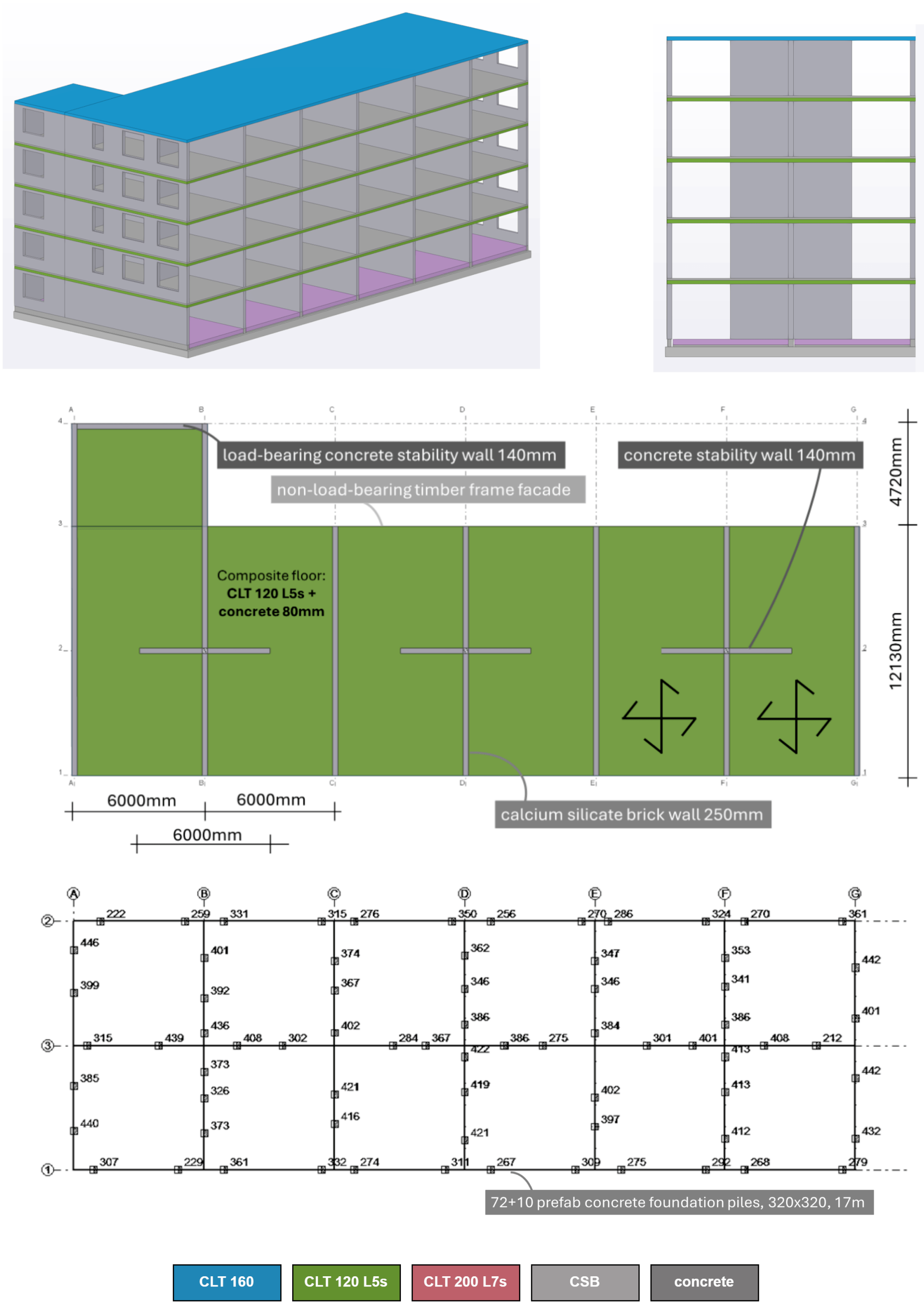


Figure 7.5: Details for final design variant 7.2. The top left image gives a 3D visualisation of the building, while in the top right image, a part of a section along axis 1 is given. Below, dimensions and materials are provided, including an overview of the location of foundation piles and complementary maximum loads per pile.

Variant 7.3 - CLT walls + CLT-dry screed floors

In this variant, the strategy of changing floors and walls is applied. Therefore, separating walls are CLT walls, using CLT 180 L5s. Floors are dry screed CLT floors, using CLT 200 L7s. In line with the strategy, longitudinal lateral stability is achieved by CLT stability walls within the apartments. In total, 76 prefab foundation piles of 320x320mm are used with a length of 17m. Furthermore, the ground floors are hollow core timber floors, and the inner walls of the longitudinal facades are timber frame walls. Other elements, such as balconies, are as described in the previous chapter.

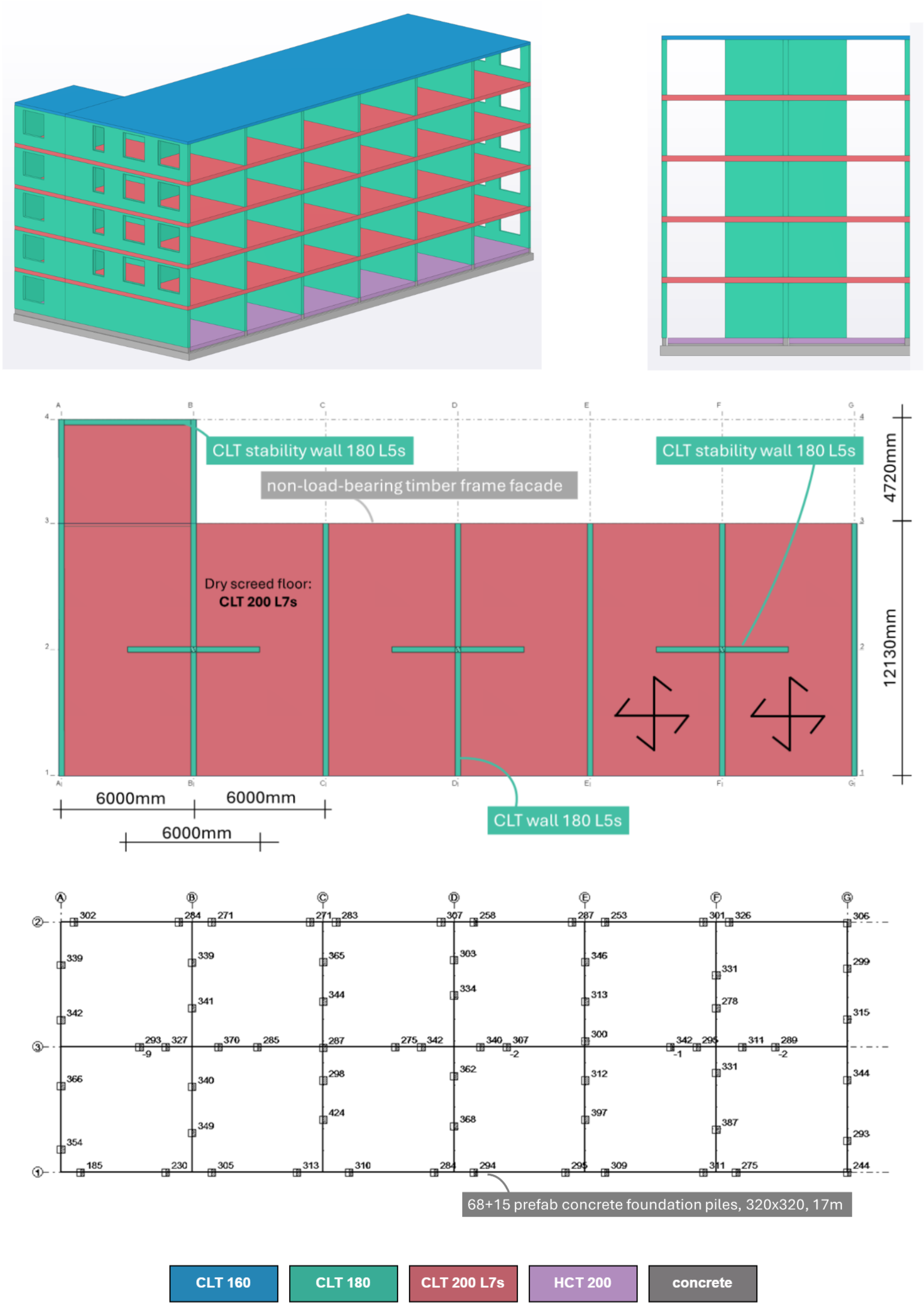


Figure 7.6: Details for final design variant 7.3. The top left image gives a 3D visualisation of the building, while in the top right image, a part of a section along axis 1 is given. Below, dimensions and materials are provided, including an overview of the location of foundation piles and complementary maximum loads per pile.

Variant 7.4 - CLT walls + hollow core timber floors

In this variant, the strategy of changing floors and walls is applied again. Therefore, separating walls are CLT walls, using CLT 180 L5s. Floors, however, are hollow core timber floors. In line with the strategy, longitudinal lateral stability is again achieved by CLT stability walls within the apartments. In total, 76 prefab foundation piles of 320x320mm are used with a length of 17m. Furthermore, the ground floors are hollow core timber floors, and the inner walls of the longitudinal facades are timber frame walls. Other elements, such as balconies, are as described in the previous chapter.

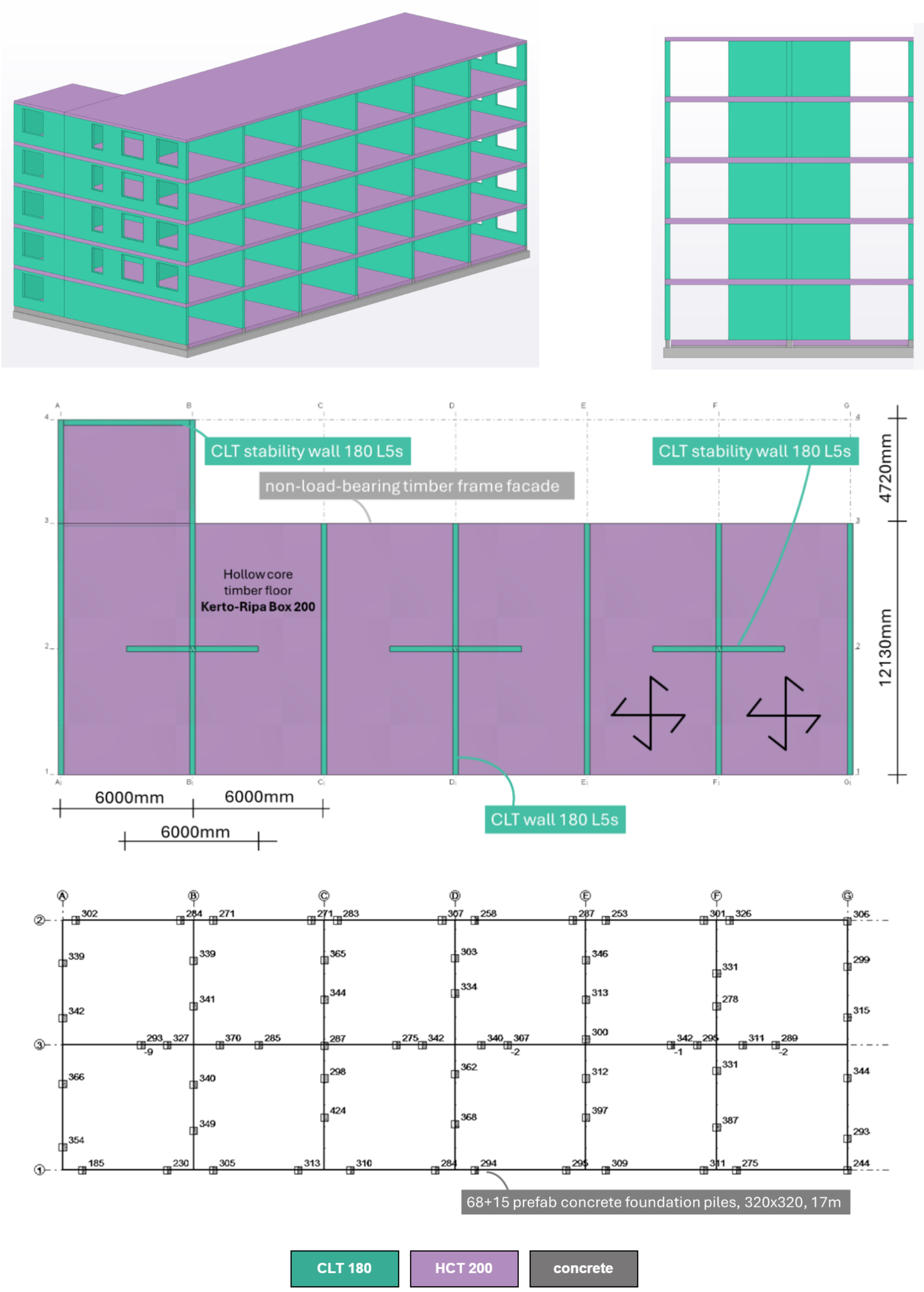


Figure 7.7: Details for final design variant 7.4. The top left image gives a 3D visualisation of the building, while in the top right image, a part of a section along axis 1 is given. Below, dimensions and materials are provided, including an overview of the location of foundation piles and complementary maximum loads per pile.

Variant 7.5 - CLT walls + CLT-dry screed floors (rotated)

This variant is similar to variant 7.3; however, the outer two apartments are rotated and translated, as shown below. Complementary to the strategy of changing floors and walls, separating walls are CLT walls, using CLT 180 L5s. Floors are dry screed CLT floors, using CLT 200 L7s. Contrary to the previous variants, longitudinal lateral stability is achieved by one large stability-separating wall. In total, 73 prefab foundation piles of 320x320mm are used with a length of 17m. Furthermore, the ground floors are hollow core timber floors, and the inner walls of the longitudinal facades are timber frame walls. Other elements, such as balconies, are as described in the previous chapter.

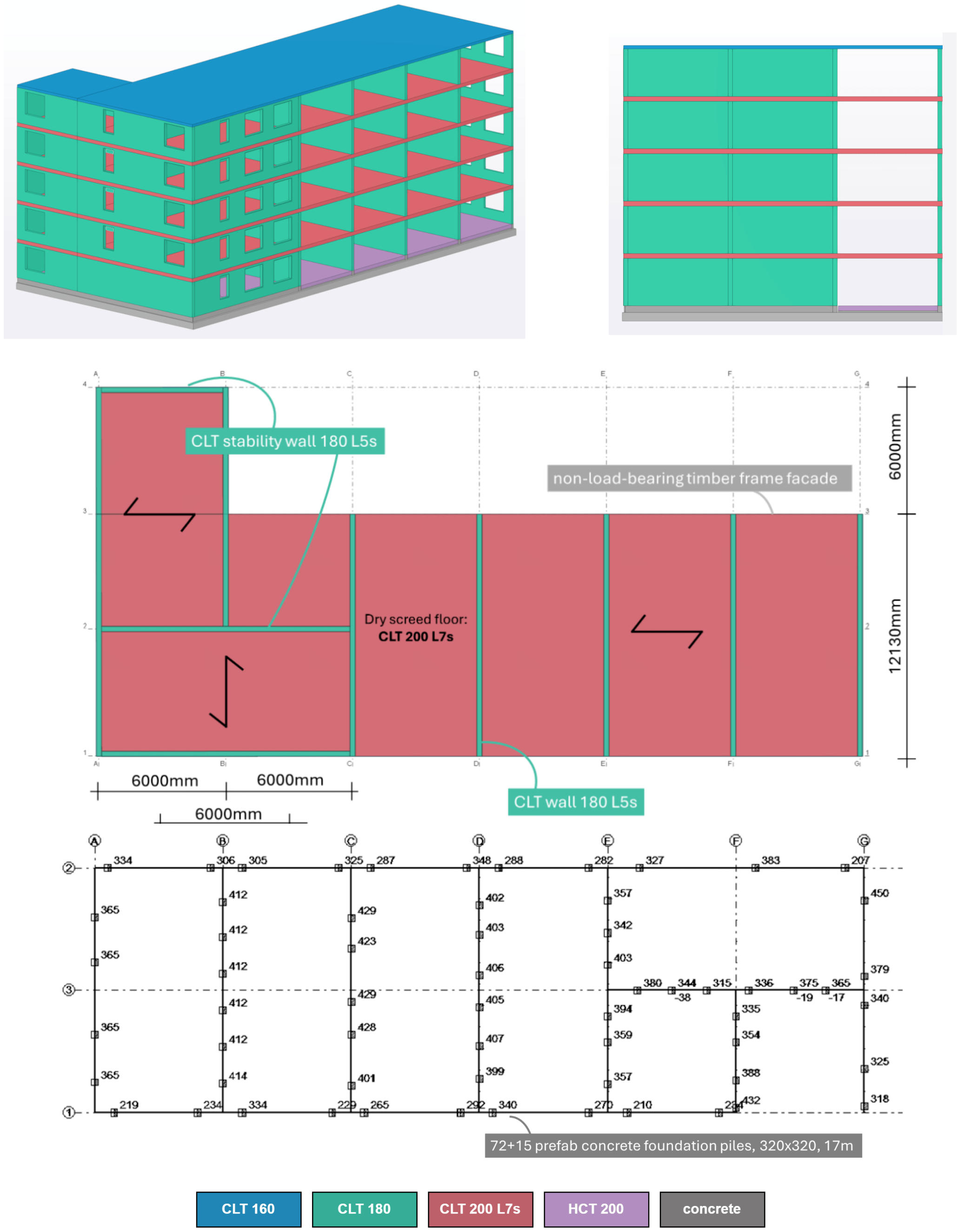


Figure 7.8: Details for final design variant 7.5. The top left image gives a 3D visualisation of the building, while in the top right image, a part of a section along axis 1 is given. Below, dimensions and materials are provided, including an overview of the location of foundation piles and complementary maximum loads per pile.

Variant 7.6 - CLT walls + hollow core timber floors (rotated)

This variant is similar to variant 7.4; however, the outer two apartments are rotated and translated, similar to the previous variant. Complementary to the strategy of changing floors and walls, separating walls are CLT walls, using CLT 180 L5s. Floors are hollow core timber floors with a height of 200mm. Longitudinal lateral stability is achieved by one large stability-separating wall. In total, 73 prefab foundation piles of 320x320mm are used with a length of 17m. Furthermore, the ground floors are hollow core timber floors, and the inner walls of the longitudinal facades are timber frame walls. Other elements, such as balconies, are as described in the previous

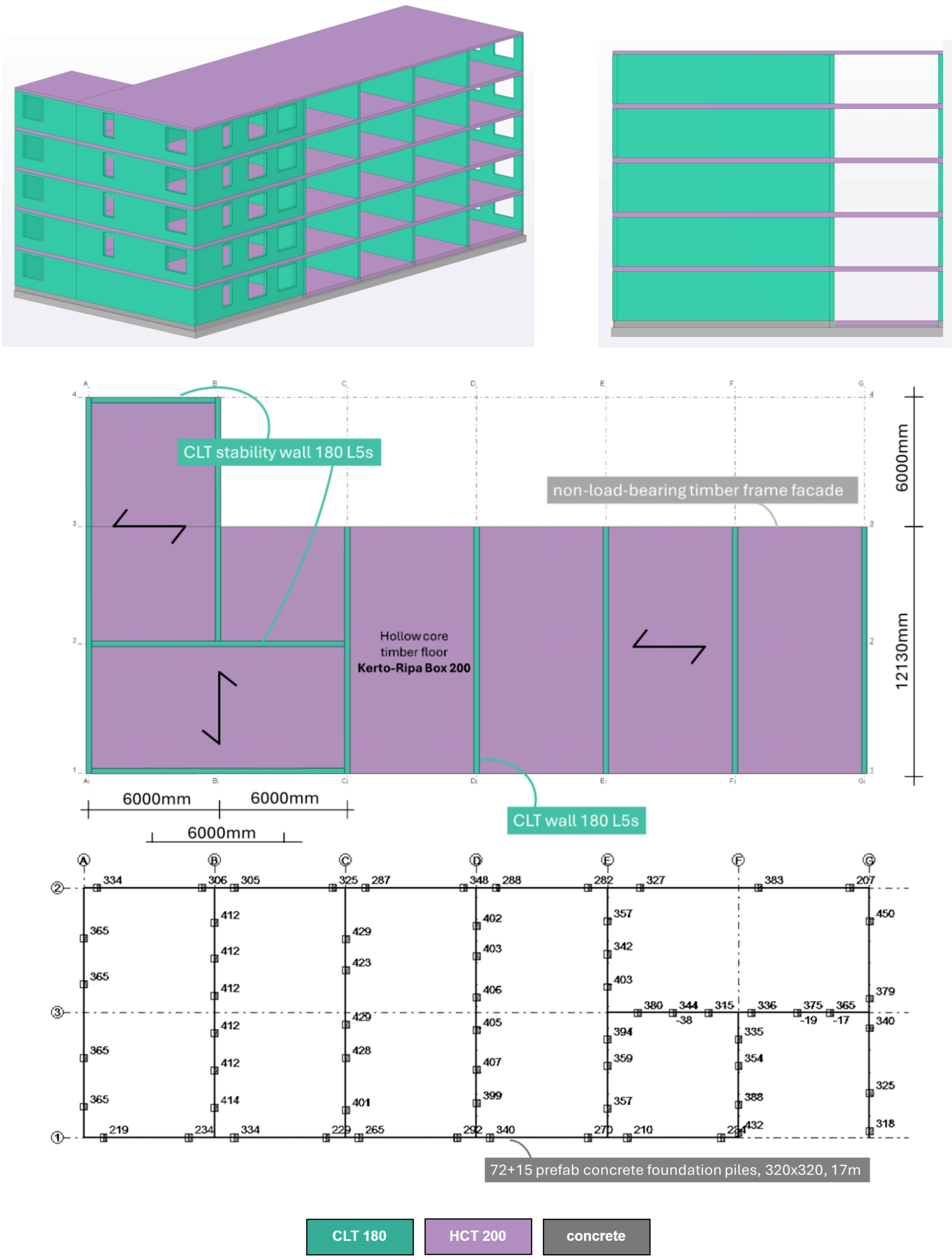


Figure 7.9: Details for final design variant 7.6. The top left image gives a 3D visualisation of the building, while in the top right image, a part of a section along axis 1 is given. Below, dimensions and materials are provided, including an overview of the location of foundation piles and complementary maximum loads per pile.

7.4. Results: assessment

In this section, the results of the assessment will be provided. First, an overview will be given, after which more details will be given per variant.

Overview of results

All designs in the previous section have been assessed according to the criteria determined in Chapter 3: GWP-GHG, GWP-total, costs, and volume of timber. This is similar to the process of the previous chapter. Note that GWP-total has been defined as GWP-GHG plus 50% of the total sequestrated carbon defined in LCA module A. The assessment results are given in Figure 7.10 below, including the assessment of the original design. In this figure, the relative differences are given compared to the original design - which is sometimes labelled as variant 0.

	GWP-GHG	Δ	GWP-total	Δ	costs	Δ	volume timber
	[kg CO2-eq./m2]	vs. variant 0	[kg CO2-eq./m2]	vs. variant 0	[euro/m2]	vs. variant 0	[m3]
Existing design	187,0		187,0		334,2		0,0
Variant 7.1	94,9	-49%	6,1	-97%	341,1	+2%	531,0
Variant 7.2	108,5	-42%	40,2	-78%	310,2	-7%	387,4
Variant 7.3	86,5	-54%	-41,4	-122%	419,1	+25%	800,9
Variant 7.4	88,9	-52%	-3,9	-102%	341,1	+2%	661,4
Variant 7.5	82,5	-56%	-42,6	-123%	401,1	+20%	801,2
Variant 7.6	85,0	-55%	-5,0	-103%	322,9	-3%	487,5

Figure 7.10: Overview of results of the assessment for the redesigns of Chapter 7.

As can be seen in the figure above, again, significant reductions of GWP-GHG and GWP-total, as well as, for some designs, even costs can be achieved when including timber in the structural system. The reductions for GWP-GHG range from 42% to 56%. For GHG-total, negative values were realised for most variants, except for the variants using calcium silicate brick walls instead of CLT walls.

In terms of costs, the relative change to the original design is between -7% and +25%. The volume of timber used is between 387 and 801m^3.

Detailed results per design variant

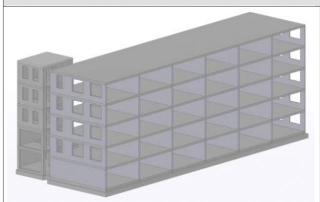
In the figures below and on the next page, a more detailed overview of the assessments is given, similar to the previous chapter. Again, the following categories have been used:

- Horizontal elements: floors, roofs, beams
- Vertical elements: walls, facades, columns
- Foundation: beams and piles
- Others: galleries, balconies

For all these categories, the values for the mentioned indicators are given, which allows for a better comparison between results. In Appendix D, an even more detailed overview is provided, given values for the single elements within each category.

Existing design

Calcium silicate brick walls + concrete wide slab floors - Achieving longitudinal lateral stability by having sufficient self-weight to prevent tension forces

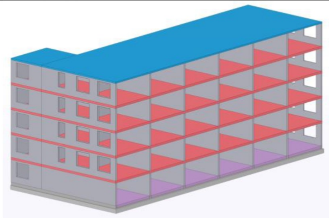


	GWP-GHG	GWP-total	costs	volume timber
	[kg CO2-eq./m2]	[kg CO2-eq./m2]	[euro/m2]	[m3]
Floors, roofs, beams	91,3	91,3	152,1	0,0
Walls, facades, columns	27,3	27,3	64,3	0,0
Foundation	54,4	54,4	77,1	0,0
Others	14,0	14,0	40,7	0,0
TOTAL	187,0	187,0	334,2	0,0

Figure 7.11: Detailed assessment of the existing design.

Variant 7.1

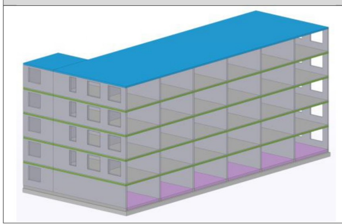
Calcium silicate brick walls + CLT dry screed floors - Achieving longitudinal lateral stability via internal concrete stability walls in all apartments



	GWP-GHG	GWP-total	costs	volume timber
	[kg CO2-eq./m2]	[kg CO2-eq./m2]	[euro/m2]	[m3]
Floors, roofs, beams	33,5	-42,2	209,3	446,4
Walls, facades, columns	26,8	24,6	75,5	0,0
Foundation	24,8	24,8	34,5	0,0
Others	9,8	-1,1	21,9	84,6
TOTAL	94,9	6,1	341,1	531,0

Variant 7.2

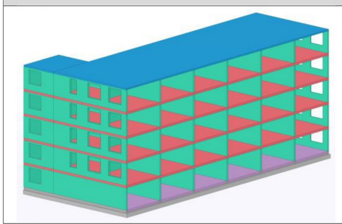
Calcium silicate brick walls + CLT-concrete composite floors - Achieving longitudinal lateral stability via internal concrete stability walls in all apartments



	GWP-GHG	GWP-total	costs	volume timber
	[kg CO2-eq./m2]	[kg CO2-eq./m2]	[euro/m2]	[m3]
Floors, roofs, beams	47,0	-8,2	178,3	302,8
Walls, facades, columns	26,8	24,6	75,5	0,0
Foundation	24,8	24,8	34,5	0,0
Others	9,9	-0,9	21,9	84,6
TOTAL	108,5	40,2	310,2	387,4

Variant 7.3

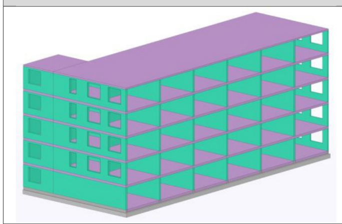
CLT walls + CLT dry screed floors - Achieving longitudinal lateral stability via internal CLT stability walls in all apartments



	GWP-GHG	GWP-total	costs	volume timber
	[kg CO2-eq./m2]	[kg CO2-eq./m2]	[euro/m2]	[m3]
Floors, roofs, beams	33,5	-42,2	209,3	446,4
Walls, facades, columns	19,6	-21,8	154,8	269,9
Foundation	23,6	23,6	33,2	0,0
Others	9,8	-1,1	21,9	84,6
TOTAL	86,5	-41,4	419,1	800,9

Variant 7.4

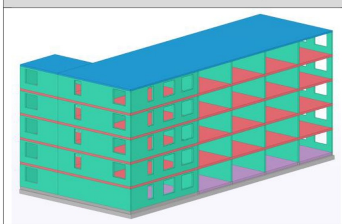
CLT walls + Hollow core timber floors - Achieving longitudinal lateral stability via internal CLT stability walls in all apartments



	GWP-GHG	GWP-total	costs	volume timber
	[kg CO2-eq./m2]	[kg CO2-eq./m2]	[euro/m2]	[m3]
Floors, roofs, beams	36,1	-4,5	131,6	306,9
Walls, facades, columns	19,6	-21,8	154,8	269,9
Foundation	23,4	23,4	32,8	0,0
Others	9,8	-1,1	21,9	84,6
TOTAL	88,9	-3,9	341,1	661,4

Variant 7.5

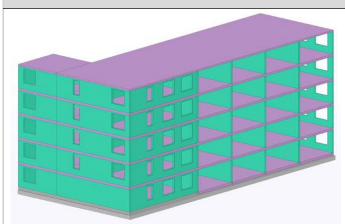
CLT walls + CLT dry screed floors - Achieving longitudinal lateral stability via internal CLT stability walls between rotated apartments



	GWP-GHG	GWP-total	costs	volume timber
	[kg CO2-eq./m2]	[kg CO2-eq./m2]	[euro/m2]	[m3]
Floors, roofs, beams	33,5	-42,3	209,7	456,3
Walls, facades, columns	18,3	-20,4	140,8	260,4
Foundation	21,1	21,1	29,1	0,0
Others	9,6	-1,1	21,5	84,6
TOTAL	82,5	-42,6	401,1	801,2

Variant 7.6

CLT walls + Hollow core timber floors - Achieving longitudinal lateral stability via internal CLT stability walls between rotated apartments



	GWP-GHG	GWP-total	costs	volume timber
	[kg CO2-eq./m2]	[kg CO2-eq./m2]	[euro/m2]	[m3]
Floors, roofs, beams	36,2	-4,5	131,8	142,6
Walls, facades, columns	18,3	-20,4	140,8	260,4
Foundation	20,9	20,9	28,7	0,0
Others	9,6	-1,1	21,5	84,6
TOTAL	85,0	-5,0	322,9	487,5

Figure 7.12: Detailed assessment of the redesign variants 7.1 to 7.6.

7.5. Analysis of results

In this section, the results that were previously shown will be analysed in order to address the research question stated at the beginning of the chapter. Relations between various elements and materials will be provided, and comparisons will be made to the original design.

Visualisation of results of Chapter 7

In Figure 7.13, costs are plotted against GWP-GHG and GWP-total for the redesigns of Chapter 7 compared to the original design. In Figure 7.14, more zoomed-in plots are given for only the redesigns. A comparison of the results of this chapter to the original design can be seen in the next chapter.

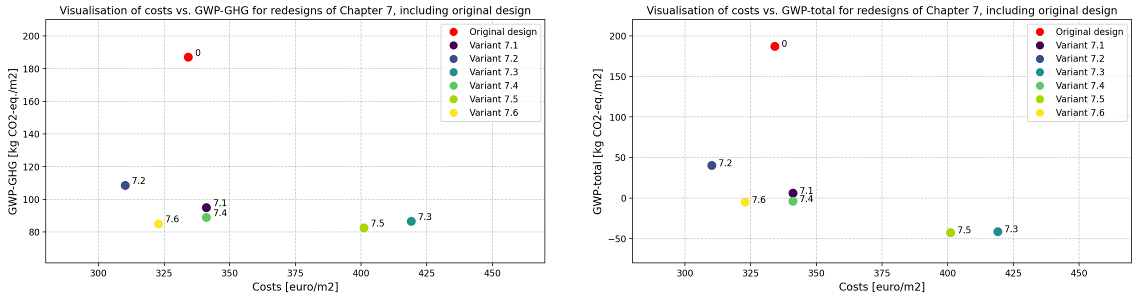


Figure 7.13: Visualisation of costs vs. GWP-GHG (left) and costs vs. GWP-total (right), for the redesigns of Chapter 7 and the original design.

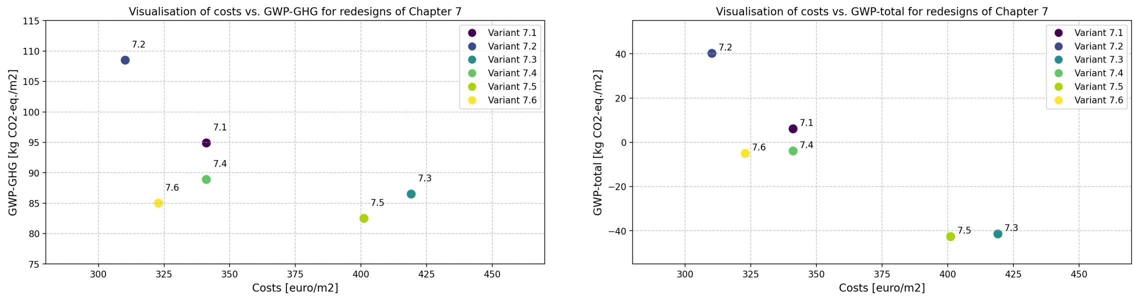


Figure 7.14: Visualisation of costs vs. GWP-GHG (left) and costs vs. GWP-total (right), for the redesigns of Chapter 7.

Combined visualisations of results of Chapters 6 and 7

Below, in Figure 7.15, costs are plotted against GWP-GHG for all redesigns, both of Chapter 6 and Chapter 7. In Figure 7.16, more detailed assessment data is provided, which is a summary of the figures shown before.

Figure 7.15: Visualisation of costs vs. GWP-GHG for the redesigns of Chapter 6, Chapter 7 and the original design.

	GWP-GHG	Δ	GWP-total	Δ	costs	Δ	volume timber
	[kg CO2-eq./m2]	vs. variant 0	[kg CO2-eq./m2]	vs. variant 0	[euro/m2]	vs. variant 0	[m3]
Existing design	187,0		187,0		334,2		0
Variant 6.1	98,2	-47%	-3,0	-102%	360,9	8%	626
Variant 6.2	114,1	-39%	37,9	-80%	319,4	-4%	452
Variant 6.3	91,6	-51%	-33,2	-118%	404,8	21%	796
Variant 6.4	107,6	-42%	7,7	-96%	363,3	9%	593
Variant 6.5	94,1	-50%	-37,6	-120%	430,6	29%	840
Variant 6.6	100,3	-46%	2,1	-99%	354,2	6%	502
Variant 7.1	94,9	-49%	6,1	-97%	341,1	2%	531
Variant 7.2	108,5	-42%	40,2	-78%	310,2	-7%	387
Variant 7.3	86,5	-54%	-41,4	-122%	419,1	25%	801
Variant 7.4	88,9	-52%	-3,9	-102%	341,1	2%	661
Variant 7.5	82,5	-56%	-42,6	-123%	401,1	20%	801
Variant 7.6	85,0	-55%	-5,0	-103%	322,9	-3%	488

Figure 7.16: Combined overview of results of the assessment for the redesigns of Chapters 6 and 7.

In Figure 7.17, the same results are plotted, this time sorted by various characteristics, such as floor type, wall type and overall typology.

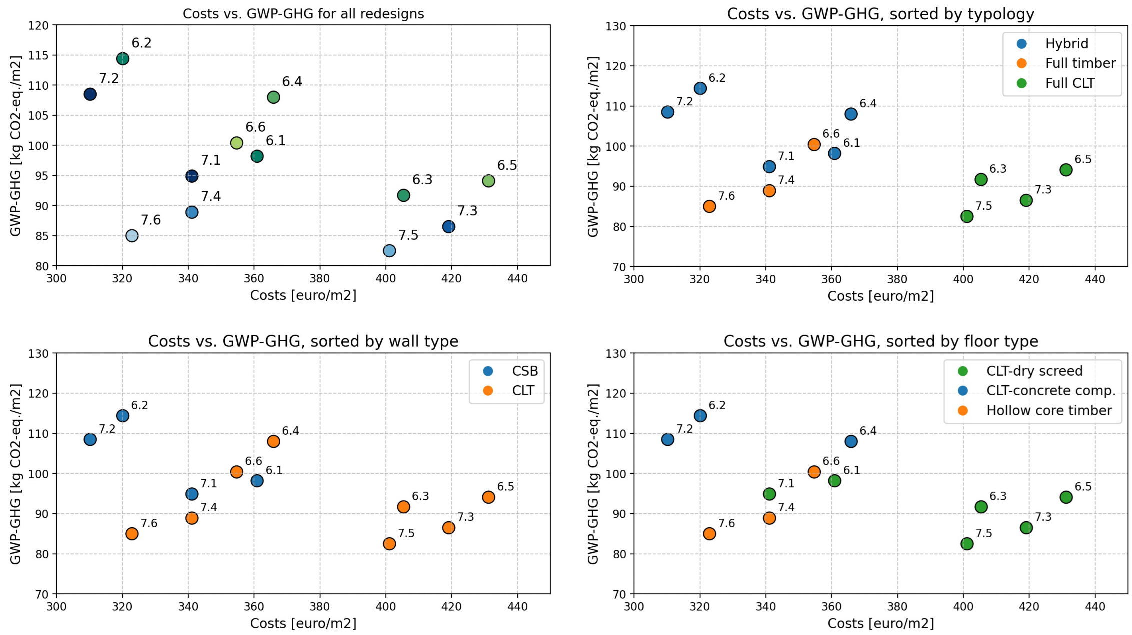


Figure 7.17: Costs vs. GWP-GHG for all redesigns, sorted by typology, wall type and floor type.

7.5.1. Comparisons of redesigns of Chapters 6 and 7: element level

In this subsection, an overview of the impact of separate elements will be given. This will be done for the variants of Chapter 7. However, values will also be compared to values of Chapter 6 to a certain extent.

Wall system

Within the redesigns, the same two wall systems have been used as in the previous chapter. When comparing average values of elements with similar wall configurations yet different floor types, a small reduction of GWP-GHG can be seen, as visible in Figure 7.18. Furthermore, an increase in costs will follow. Compared to the previous chapter, the values for the redesigns of this chapter are slightly lower for GWP-GHG and slightly higher for costs. This is a result of switching to CLT for the entrance building.

When comparing the differences in global warming potential divided by costs, results with a lower value than in the previous chapter indicate a lower reduction of GWP-GHG for a certain cost level. As visible in Figure 7.17, using CLT walls often leads to higher costs and lower GWP-GHG. However, no distinct trend can be identified.

Impact of wall system change	Δ GWP-GHG [kg CO2-eq./m2]	Δ GWP-total [kg CO2-eq./m2]	Δ costs [euro/m2]	Δ GWP-GHG / costs [kg CO2-eq./euro]	Δ GWP-total / costs [kg CO2-eq./euro]
Calcium silicate brick to CLT	-6,7	-43,7	75,3	-0,09	-0,58

Figure 7.18: Impact of changes in wall systems compared to the original design, given for the contribution of walls only.

Floor system

Within the redesigns of this chapter, having a span of 6.0m, all floor systems are different compared to the original wide slab floors. Averaged values indicate significant reductions in GWP-GHG for all floor types. Compared to the previous chapter, GWP-GHG differences are much closer for CLT-dry screed floors and hollow core timber floors. Costs for all changes are between 10-20 euro/m^2 lower due to the smaller floor sizes.

For hollow core timber floors, this will lead to a floor with lower costs than the floor of the original design. Comparisons with the floors of the previous chapter will be discussed on the building level in a later section.

Impact of floor system change	Δ GWP-GHG [kg CO2-eq./m2]	Δ GWP-total [kg CO2-eq./m2]	Δ costs [euro/m2]	Δ GWP-GHG / costs [kg CO2-eq./euro]	Δ GWP-total / costs [kg CO2-eq./euro]
Wide slab floor to CLT dry screed floor	-57,8	-133,5	57,3	-1,01	-2,33
Wide slab floor to CLT-concrete composite floor	-44,3	-99,5	26,2	-1,69	-3,80
Wide slab floor to Hollow core timber floor	-55,1	-95,8	-20,4	2,70	4,69

Figure 7.19: Impact of changes in floor systems of Chapter 7, compared to the original design, given for the contribution of floors only.

Stability system

Within the redesigns of this chapter, two changes in the stability system can be identified: a switch from concrete internal stability walls to CLT internal stability walls and the change of location of CLT stability wall(s), introduced by rotating the outer apartments. The changes are shown below in Figure 7.20.

Both changes lead to (slightly) lower values for GWP, while only switching to CLT stability walls will lead to higher costs. When rotating stability walls, a similar cost decrease can be seen, meaning that the most efficient CLT stability system has similar costs to the regular concrete stability system for these redesigns. Again, a comparison to the stability systems of the previous chapter will be made on a building level in a later section.

Impact of stability system change	Δ GWP-GHG [kg CO2-eq./m2]	Δ GWP-total [kg CO2-eq./m2]	Δ costs [euro/m2]	Δ GWP-GHG / costs [kg CO2-eq./euro]	Δ GWP-total / costs [kg CO2-eq./euro]
Concrete stability walls to CLT stability walls	-0,1	-6,7	16,7	-0,01	-0,40
CLT stability walls to combined CLT stability-separating wall	-3,8	-1,1	-18,0	0,21	0,06

Figure 7.20: Impact of changes in stability systems within the chapter, given for the contribution of all additional elements, such as walls and foundation beams.

Foundation system

Finally, for foundation systems, a similar trend to the previous chapter can be seen in Figure 7.21. Significant savings in GWP-GHG and GWP-total can be realised, both slightly larger compared to those in Chapter 6. Cost savings are also significant and larger than in the previous chapter. When comparing the differences in global warming potential divided by costs, values are very similar to those of the previous chapter, indicating a linear dependency between costs and GWP-GHG.

Impact on foundation	Δ GWP-GHG [kg CO2-eq./m2]	Δ GWP-total [kg CO2-eq./m2]	Δ costs [euro/m2]	Δ GWP-GHG / costs [kg CO2-eq./euro]	Δ GWP-total / costs [kg CO2-eq./euro]
Calcium silicate brick walls (and concrete stability walls)	-29,7	-29,7	-42,6	0,70	0,70
CLT walls (and CLT stability walls)	-30,9	-30,9	-44,1	0,70	0,70
CLT walls (combined with CLT stability wall)	-33,4	-33,4	-48,2	0,69	0,69

Figure 7.21: Impact of changes in foundation systems compared to the original design, given for the contribution of all foundation elements.

7.5.2. Comparisons of redesigns of Chapters 6 and 7: building level

The various impacts on an element level all have a different impact on a building level. Therefore, in this section, the impact on a building level is discussed. This will be discussed per major design change and for each indicator, based on the element level analysis and data provided in Figures 7.16, 7.15 and 7.17.

Impact of decreasing floor span

One of the major targets of the redesigns in this chapter is decreasing the floor spans. In Figure 7.22, averaged values for decreasing floor spans are given per floor type. Notably, the changes do not achieve reductions in GWP-GHG for CLT-dry screed floors and CLT-concrete composite floors. For the latter, it will not even lead to lower costs. For hollow core timber floors, a small net decrease in both GWP-GHG and costs can be seen. Overall, the main reason that no significant decrease has been achieved is the increased size of walls and, thus, the contribution of walls to GWP-GHG.

When looking at the impact on building level for various floors with various spans, as shown in Figure 7.17, different trends can be recognised. First of all, CLT-dry screed floors have significantly higher costs for most designs. CLT-concrete composite floors and hollow core timber core floors have lower costs with different GWP-GHG impact: hollow core timber floors are in the same range compared to CLT-dry screed floors. In contrast, CLT-concrete composite floors show significantly higher GWP-GHG values.

Impact of decreasing floor span	Δ GWP-GHG	Δ GWP-total	Δ costs	Δ GWP-GHG / costs	Δ GWP-total / costs
	[kg CO2-eq./m2]	[kg CO2-eq./m2]	[euro/m2]	[kg CO2-eq./euro]	[kg CO2-eq./euro]
Average for CLT-dry screed floor	0,9	6,9	-3,4	-0,27	-2,02
Average for CLT-concrete composite floor	0,6	5,8	7,7	0,08	0,75
Average for hollow core timber floor	-4,5	-0,2	-3,1	1,48	0,05

Figure 7.22: Impact on building level for the reduction of floor span from 6.8m to 6.0m, given for all elements of the main building only.

Impact of combining apartment-separating walls and stability walls

The other major target of the redesigns in this chapter is combining apartment-separating walls and stability walls. In Figure 7.23, the averaged values for the inclusion of all different stability systems have been given. While absolute values for GWP-GHG and GWP-total are relatively low, several trends can be identified. For example, the difference between the inclusion of stability walls in concrete and CLT does not necessarily indicate CLT is favourable. On average, similar GWP-GHG values are achieved, while costs are significantly higher for CLT elements. Only when CLT stability walls are combined with apartment-separating walls are slightly lower GWP-GHG and similar cost values achieved compared to concrete.

Impact of changing stability system	Δ GWP-GHG	Δ GWP-total	Δ costs	Δ GWP-GHG / costs	Δ GWP-total / costs
	[kg CO2-eq./m2]	[kg CO2-eq./m2]	[euro/m2]	[kg CO2-eq./euro]	[kg CO2-eq./euro]
Inclusion of concrete stability walls in outer apartments longitudinal facades	3,8	3,8	7,2	0,53	0,53
Inclusion of concrete stability walls internally	4,3	3,0	5,6	0,77	0,53
Inclusion of CLT stability walls internally	4,2	-2,3	24,7	0,17	-0,09
Inclusion of combined CLT stability-separating wall	2,6	-0,5	9,5	0,27	-0,06

Figure 7.23: Impact on building level for the inclusion of different stability systems, given for all relevant items to stability, for the contribution of all additional elements, such as walls and foundation beams.

Comparison of GWP-GHG

Comparing the values for GWP-GHG of the redesigns of this chapter, first of all, significant reductions can be seen, ranging from 42% to 56%: an even smaller range than before. Improvements have been made compared to the previous chapter, however, the improvements are relatively small. Notably, all variants have lower values compared to similar variants of the previous chapter, which indicates a net gain by the combination of including the entrance building and taking other measures, such as making smaller floor spans.

Variant 7.5 has the lowest value for GWP-GHG, with 82.5 kg CO_2-eq./m^2. Variant 7.6 is close to this value, having a GWP-GHG value of 85.0 kg CO_2-eq./m^2. Again, despite all improvements, none of the variants align with the governmental targets for GWP-GHG reductions in the coming decades.

Comparison of GWP-total

Comparing the GWP-total values of the redesigns of this chapter with the redesign of the previous chapter, small changes can be identified compared to those of the previous chapter. The reason for this is that the decrease in floor volume counters the increase in wall volume. The inclusion of the entrance building in CLT. The lowest value for GWP-total is -42.6 kg CO_2-eq./m^2, achieved by variant 7.5. All variants with CLT walls have negative values, while those with calcium silicate brick walls have positive values. Except for variant 7.2, all variants are again in line with the governmental targets for the next decades.

Comparison of costs

Comparing costs for the redesigns of this chapter, more beneficial values can be identified compared to the previous chapter. The variants with only CLT, variants 7.3 and 7.5, have an increase in costs of respectively 25% and 20%. All other variants of this chapter have costs which are no more than a 2% increase compared to the original design. In other words, comparable costs to the original design can be achieved for a range of designs: calcium silicate brick walls with any floors, as well as CLT walls with hollow core timber floors. Savings are mostly related to savings in foundations and a limited increase in costs for other elements. Compared to the previous chapter, for conceptually similar designs, costs are generally between 5 and 10 percentage points lower, reflecting the optimisations of this chapter.

Comparison of volume of timber

The total amount of used volume of timber differs significantly between the variants. This, of course, can be related directly to the type of walls and floors used, similar to the previous chapter. Mentionable is that savings in the volume of floors outweigh the additional timber used as a result of the inclusion of the entrance building.

7.6. Conclusions

This section will draw conclusions that will help address the research question stated at the beginning of the chapter. The aim is to find optimally adjusted designs, including timber.

Conclusions of element level

On an element level, the following can be concluded for design choices:

- Switching from calcium silicate brick walls to CLT walls results in slight reductions in GWP-GHG and more significant reductions in GWP-total. However, the increase in costs is significant, even more so than in the previous chapter, as there are relatively more walls due to decreased spans. This makes wall changes less economically efficient compared to other changes.
- The impact of changing the floor system is, again, largest compared to other elements. Compared to the previous chapter, savings in GWP-GHG and GWP-total are more significant, while costs are generally lower. This indicated the suitability of changing only floors as an efficient redesign strategy. As a result, especially hollow core timber floors have become more beneficial, with even slightly lower costs than the original design.
- Similar to the previous chapter, simply changing concrete stability walls to CLT stability walls is not beneficial. However, when changing layouts and combining apartment-separating walls and stability walls, using CLT can be beneficial, minimising the impact of needing additional stability elements.
- Most of the additional reductions in GWP and in costs are again related to the foundation, which is even more optimised compared to the redesigns of the previous chapter.

Conclusions of building level

On a building level, the following can be concluded for design choices:

- All designs with calcium silicate brick walls, as well as designs with CLT walls and hollow core timber floors, lead to variants with significant savings in GWP with comparable costs to the original design. The increase in costs is no higher than 2%, which is well below the aimed 10%.

- GWP-GHG values for the above-mentioned variants are between 85.0 and 108.5 kg CO_2-eq./m^2, generally lower for the variants with CLT walls. While all reductions in GWP-GHG are significant compared to the original design, none are in line with the goals of the Paris Agreement. When potentially including the benefits of sequestrated carbon, measured by the indicator GWP-total, most variants would be in line with these goals.
- For all redesigns of both chapters with CLT walls and floors, the cost increase is over 20% compared to the original, favouring designs which are hybrid or include hollow core timber floors.
- The reduction of floor spans from 6.8m to 6.0m did not lead to more optimised designs for variants with CLT-dry screed floors and CLT-concrete composite floors. Only for hollow core timber floors have slight improvements have been found.
- Changing the building layout to combine apartment-separating walls and stability walls in CLT did reduce GWP-GHG and cost values, therefore being desirable.

8

Sensitivity analysis

In this chapter, uncertainty in input variables will be investigated. First, the sensitivity of small changes in input values used for the assessment will be investigated: global warming potential and costs. Secondly, the sensitivity of small changes in dimensions will be investigated. Based on this, the following research questions will be addressed:

"Which input parameters are most likely to affect the case study results, and to what extent do they influence the ability to extrapolate these results to mid-rise residential buildings in general?"

8.1. Sensitivity of input values for GWP and costs

8.1.1. Sensitivity of input values for GWP

One of the most important input values is the environmental data retrieved from the environmental product declarations. While the average values of several EPDs have been taken for all elements, there is still an uncertainty in the input values. Based on recent research by the British Committee on Developing and Commenting on the ISO regulations, "the minimum uncertainty in any A1-A3 carbon footprint (GWP-total) is probably ±10%, although a few producer-specific values from basic material manufacturers will have lower uncertainty" (Foster and Anderson, 2024). The scope of this research is slightly larger, leading to increased uncertainty. As many data sheets directly retrieved from manufacturers have been used, leading to lower uncertainty, both lower and higher uncertainties are present. As a result, the uncertainty value of ±10% will be investigated. This will be done for GWP-GHG rather than for GWP-total, as this is the main environmental indicator used in this research.

The impact of changes in GWP-GHG values has been investigated based on 1000 runs with different input values: GWP-GHG = original value ± 10%. The value in the uncertainty range ± 10% is chosen randomly for each run, assumed uniformly distributed, and is different for each group of construction materials.

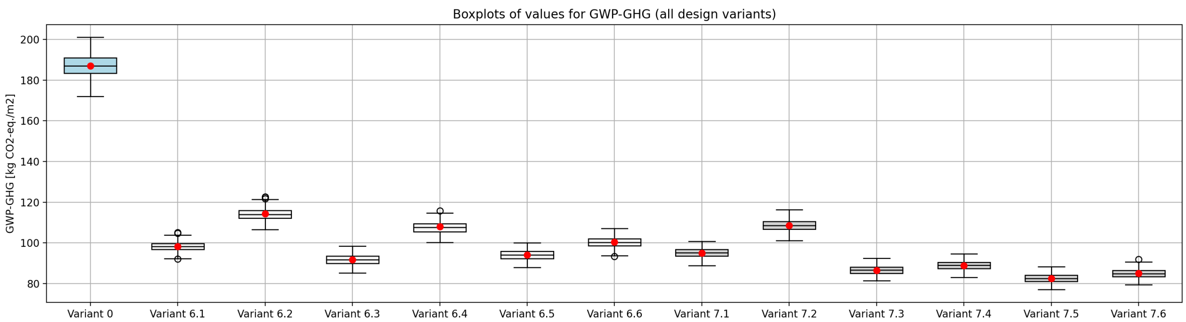


Figure 8.1: Boxplots for GWP-values of the original design and all redesigns, based on 1000 runs with different input values for GWP, having an uncertainty of ± 10%. In red, the measure values from the previous chapters have been plotted.

In Figure 8.1, the uncertainty is plotted for all design variants compared to the original design. Noteworthy is a difference in the uncertainty range of the original design compared to all others. More detailed uncertainties are given in a boxplot in Figure 8.2. Based on this, an average standard deviation of 2.4 kg CO_2-eq./m^2 can be found. This value is relatively low. However, the range of measured values in the previous chapter is also relatively small. Therefore, some of the interquartile ranges overlap.

This overlap is especially true in Chapter 6, for variants 6.1 and 6.5, with variants 6.3 and 6.5 having values within the uncertainty values of the aforementioned variants. Besides, the interquartile ranges of the GWP-values for variants 6.3 and 6.5 themself overlap. For Chapter 7, the measured GWP-values for variants 7.3 to 7.6 are all within 6.4 kg CO_2-eq./m^2 of each other, leading to many overlaps in the boxplot indicators. The median of the simulated values almost always coincides with the measured values, as shown with the red dots in the visualisation.

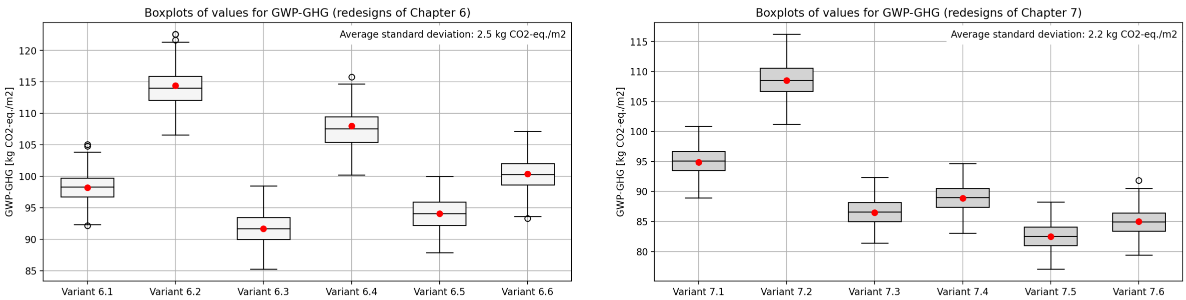


Figure 8.2: Boxplots for GWP-values of the redesigns, based on 1000 runs with different input values for GWP, having an uncertainty of ± 10%. In red, the measure values from the previous chapters have been plotted.

8.1.2. Sensitivity of input values for costs

Next to an uncertainty of input values for environmental data, there is an uncertainty of the input data for costs. Similar to the previous section, the impact of changes in cost values has been investigated based on 1000 runs with different input values: costs = original value ± 10%. This value has been chosen as such, as it reflects medium-term changes in costs due to material and labour price variation. The value in the uncertainty range ± 10% has been chosen randomly for each run, assumed uniformly distributed, and is different for each group of construction materials.

In Figure 8.3, the simulation results have been plotted, leading to an average standard deviation of 11.1 euro/m^2. This value is much larger compared to the uncertainty in GWP-GHG. Many interquartile ranges have overlaps, while the medians are similar to the measured values for most variants, except for variants 6.2 and 6.4. For both these variants, having CLT-concrete composite floors, the median is lower than the measured values, indicating a high likelihood of a small overestimation of costs in the previous chapter.

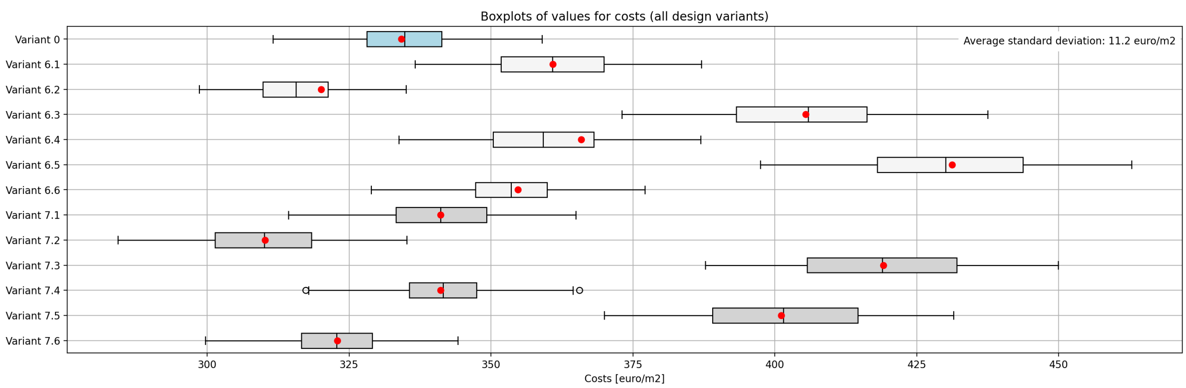


Figure 8.3: Boxplots for cost values of the original design and all redesigns, based on 1000 runs with different input values for GWP, having an uncertainty of ± 10%. In red, the measure values from the previous chapters have been plotted.

Furthermore, as many of the interquartile values overlap, measured values with minor differences between them should be treated as reasonably equal in formulating conclusions. This is especially true for the differences below 11.1 euro/m^2.

Uncertainty in costs price for timber

Over the last years, the price of wood and timber has changed significantly over the last years, well over the assumed 10%. While this price is fairly stable at the time of this research, potential changes should be considered.

The price increase of timber elements, however, is linearly dependent on one of the indicators used throughout this research: the volume of timber. Therefore, this indicator can be used to indicate the sensitivity to changes in timber prices. Costs for variants with both CLT walls and floors - which already have the highest values for cost - will increase the most. As a result, variants 6.3, 6.5, 7.3 and 7.5 are the least resilient against a timber price increase. The last column of Figure 7.16 can be used to indicate the sensitivity of other variants.

8.1.3. Combined sensitivity of input values for GWP and costs

Next to uncertainty in input values for GWP and costs separately, looking at combined uncertainty is important. In Figures 8.4 and 8.5, the uncertainty of costs and GWP-GHG are plotted against each other. Measured values are given in solid dots, while each uncertainty run discussed before is plotted in the same colour but opaque. As a result, the darker the colour, the more that specific combination of measured values did occur in the simulation. These graphs confirm the findings of the previous subsections and highlight the difference in uncertainty between global warming potential and costs.

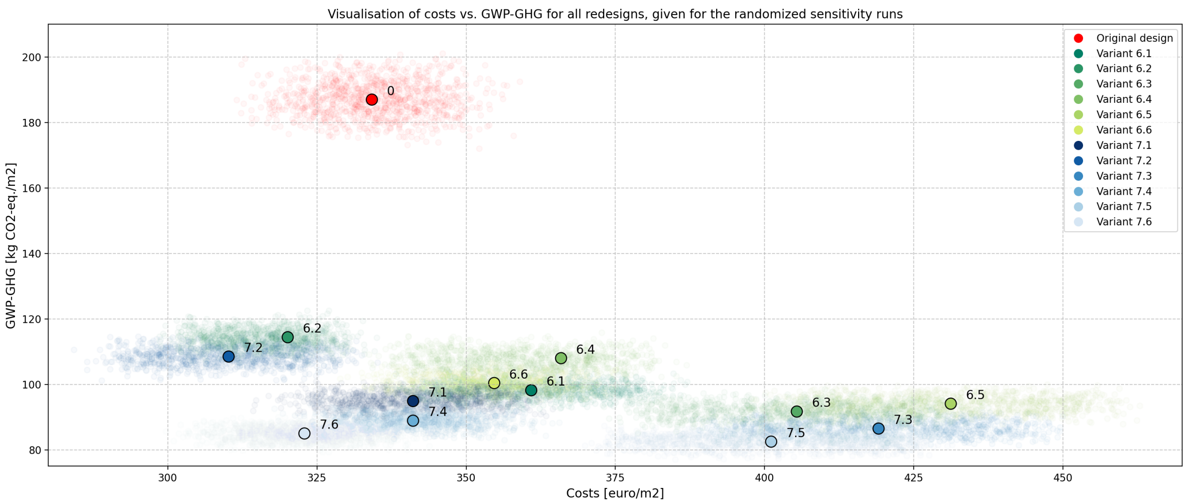


Figure 8.4: Costs vs. GWP-GHG for Chapters 6 and 7 measurements, including uncertainty in GWP and costs values and the values for the original design

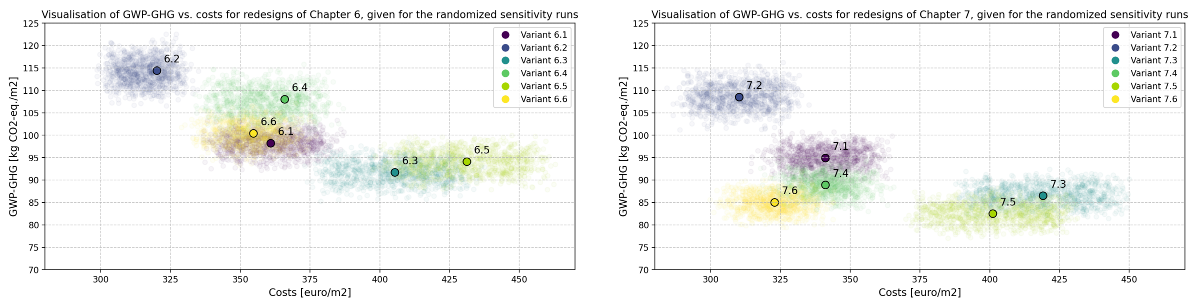


Figure 8.5: Costs vs. GWP-GHG for Chapters 6 and 7 measurements, including uncertainty in GWP and costs values.

8.2. Sensitivity of dimensional input values

Next to sensitivity to small changes in input values of GWP and costs, sensitivity to small changes in dimensional input values is important. Dimensional input values are values used in the calculations of sizes, such as length, width and height of elements. Minor changes in these values should not significantly impact the results. Minor changes in this section are assumed to be changes with a range of ±5% compared to the original values, reflecting minor design tweaks. Note that changes in floor area due to, for example, a change to larger apartments are not part of this section.

Below, in Figure 8.6, the impact of the changes described above are plotted for the results of the previous chapters. Again, uniformly distributed randomness is assumed for each group of elements, and results are given for 1000 runs. Compared to Figure 8.5, a significant difference can be seen: the range of values is smaller for all variants, indicating a smaller sensitivity. This trend can also be seen in the values for average standard deviation. Being 1.2 kg CO_2-eq./m^2 and 4.3 euro/m^2, these values are significantly lower. As almost no overlap in any value can be seen, the impact of minor changes in dimensional input variables is assumed to be minimal compared to minor changes in GWP-GHG and costs.

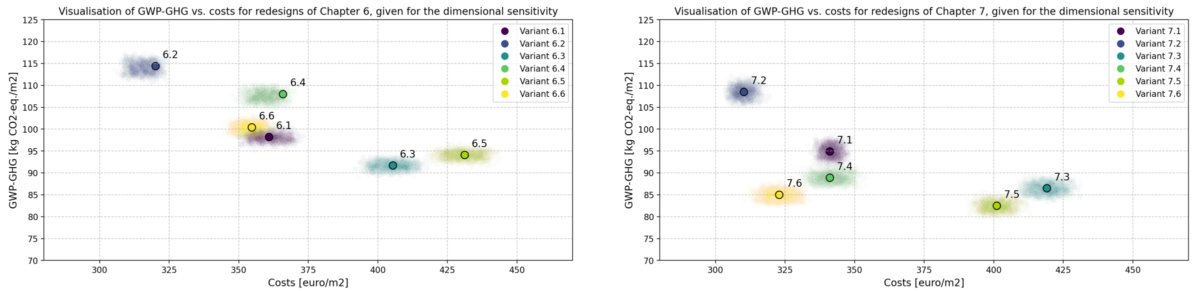


Figure 8.6: Costs vs. GWP-GHG for Chapters 6 and 7 measurements, including uncertainty of dimensional input values.

8.3. Conclusions

In this section, conclusions will be drawn, which will help to address the research question stated at the beginning of the chapter, aiming to find the impact of changes to input parameters.

Based on the previous section, the following can be concluded:

- Sensitivity to changes of input values of GWP is of relevant size compared to some differences in measured values, impacting how comparisons should be made. Variants with measured values within the averaged standard deviation range of each other, being 2.5 kg CO_2-eq./m^2, should be assumed to have similar levels of global warming potential.
- Sensitivity to changes of cost input values is of relevant size compared to most differences in measured values, impacting how comparisons should be made. Variants with measured values within the averaged standard deviation range of each other, being 11.2 kg CO_2-eq./m^2, should be assumed to have similar cost levels.
- The impact of minor changes in dimensional input values should be assumed minimal due to the low values for averaged standard deviation compared to the previously mentioned ones.

Part IV

Research outcome

9
Discussion

In this chapter, assumptions and limitations relevant to the research will be discussed. Along with a critical reflection on the design choices, this discussion will contribute to answering the main research question in the next chapter.

9.1. Discussion on assumptions

In this section, several assumptions made during the research will be discussed, along with their impact on the research outcome.

Assumptions on embodied carbon

Based on existing research, the assumption has been made that for a typical medium-scale residential building, roughly 67% of the embodied carbon can be related to the load-bearing structure. This percentage has been used to place the case study results in perspective relative to the targeted values of the Paris Agreements. However, assuming this division of embodied carbon will decrease proportionate with the overall needed decrease in embodied carbon simplifies the issue. Other elements, such as internal finishes, facades, and installations, are also subject to change. By not considering this, the established thresholds for embodied carbon of the load-bearing structure can be either underestimated or overestimated. Note that this does not affect the comparison between the variants, only the comparison to the targeted values.

Furthermore, the established threshold values are calculated based on the available carbon budgets for the sector, based on research by the Dutch Green Building Council. Due to a lack of other available research, these values have only been compared to the targeted reduction goals relative to the emissions of 1990 and are found to be roughly similar. Using no other sources leads to relatively high uncertainty in these threshold values, which could again lead to either underestimated or overestimated values.

Assumptions on generalisability and approach of the case study

The primary research method used is a case study. While a building has been selected with general characteristics, many buildings in practice are — to a certain extent — different from this case study building. Many aspects can be different, such as building height, length and depth. Therefore, the outcome of the case study only reflects a typical mid-rise residential building to a certain extent. For example, when the number of storeys changes, the demands for fire resistance change. From six storeys onwards, the resistance needs to be 120 minutes. This would lead to thicker wall elements and/or more encapsulation. Above eight storeys, the use of sprinklers would become more favourable (Qvist, 2022). Contrary to this, a similar approach to the five-storey building can be taken for a four-storey building, while lower buildings are outside the research scope.

When the dimensions of apartments change, minor changes in GWP and cost values are expected. This is because the capacity of elements next to each other can be utilised slightly more or less efficiently. Changing the layout of apartments more severely would lead to different design changes not investigated by this research. Next to this, the changes within this case study related to the foundation are very situation-specific, having a more significant uncertainty than the rest of the building. Generalising this part of the findings is difficult, as soil conditions vary significantly throughout the country.

Furthermore, during this research, the assumption that using a case study rather than designing from scratch is more suitable is assumed indirectly. By doing so, it is likely that characteristics or dimensions more favourable for non-bio-based elements have been used. This leads to designs which are likely not to utilise bio-based materials optimally, leaving room for optimisation unexploited.

Assumptions on carbon sequestration

Within the current life cycle assessment framework, the benefits of temporary carbon storage cannot be accounted for. Therefore, the indicator GWP-GHG has been used as the main environmental impact indicator. Within this research, GWP-total has been defined as an additional indicator which accounts for the benefits of temporary carbon storage, considering it for 50%. This percentage reflects a time-equivalent part of carbon sequestration for a product, not considering any end-of-life scenario. A simplification of the dynamic calculation method has been used to determine the level of inclusion for biogenic carbon. The method assumes sustainable forestry, a first life span of 50 years and a rotation period of 100 years. These assumptions do not consider the type of bio-based material and, therefore, have a certain uncertainty.

9.2. Discussion on limitations

In this section, several limitations of the research will be discussed, along with their impact on the validity of the research outcome.

Limitations on definition of environmental footprint

Within this research, the environmental impact is measured by the Paris Proof Indicator: the value for GWP of the LCA module A. Two indicators have been used: GWP-GHG and GWP-total. Using only GWP-values for these stages as representatives of environmental footprint highlights the priority of addressing climate change. However, it limits the scope of the research, as other indicators, such as water use or acidification, are not investigated. Besides, material depletion has been addressed in a limited way. As the environmental footprint is more than climate change, this gives an incomplete overview.

Limitations on scope: cradle-to-practical completion

The chosen scope, cradle to practical completion, provides a clear understanding of the impact up to the point of practical completion, which aligns closely with decision-making in practice. However, this leads to an incomplete picture of the total life cycle performance, as it could shift environmental burdens to other life cycle stages. For example, more maintenance could be needed during the use stage, or different energy levels are required at the end-of-life stage.

There is a risk of neglecting long-term sustainability goals, such as circularity. Considering the complete life cycle could shift the balance of which design is more favourable. For example, demountability and reusability will become more important and particularly relevant as redesigns with many different construction methods have been investigated. For example, significant differences in end-of-life scenarios are present between floors with and without a concrete screed. In this research, this has only been considered in a minor way when selecting suitable wall and floor types.

Furthermore, not using end-of-life scenarios is a simplification in relation to carbon storage and the amount of time carbon is kept from the atmosphere. In reality, end-of-life scenarios and storage levels depend on the designs and construction methods. For example, the higher the level of demountability, the larger the possibility for reuse, and the longer carbon will be stored. This favours demountable construction methods but is not considered in this research. Depending on the end-of-life scenario of each variant, this could lead to different underestimations or overestimations. However, as this research does not consider any end-of-life scenario, this approach could be seen as conservative. At the same time, it neglects important aspects of decision-making in reality.

Limitations on scope: load-bearing elements, structural systems and level of detail

Within this research, solely load-bearing elements and building physics elements directly related to this have been considered. While leading to most of the embodied carbon, more elements contribute to this. For example, the environmental and economic impact of generic elements, such as building site equipment or facades, have not been considered. As a result, the measured values only reflect a part of the total impact. When including other items next to the load-bearing structure, the relative differences in measured values compared to the original design would be smaller.

The scope of this research is further limited to structural systems composed of panellised or post-and-beam structures. By not considering other systems, such as modular or timber frame systems, potentially more beneficial systems have been left out of the scope. Conceptual changes in the foundation system have not been investigated; only size adjustments have been made. While considering the benefits of lighter construction methods, this leaves room for further improvement unexploited.

Besides, the chosen level of detail could underestimate the difficulties of designing and constructing in a later phase. Another limitation is the extent to which concrete has been part of this research. Concrete, especially a low-carbon optimised variant of concrete, could provide benefits over calcium silicate brick walls due to the levels of prefabrication and, thus, demountability. Not including this leads to an incomplete overview and disregards valuable information for comparison.

Increased adoption of timber

This research considers values for global warming potential and costs valid in 2024. Due to the increased adoption of timber, these values can change over the years and decades due to optimisation or changes in workflows, supply chains, and construction methods. While this could lead to a shift favouring variants consisting of more bio-based materials, it has not been considered.

9.3. Discussion on design process

Finally, decisions made during the design process and their impact on the outcome of the research will be discussed.

Simplifications

Several assumptions have been made regarding whether or not to pursue design variants or elements during the design process. First of all, a simplification of balconies and galleries has been chosen. By doing so, room for optimisation has been left unexploited. Furthermore, the assumption has been made that hollow core timber floors are unsuitable for transferring lateral forces from the short side of the building directly to parallel stability elements in the longitudinal facades due to the tight path the forces need to follow. With more focus on details, this could potentially be possible. Given the beneficial characteristics of hollow core timber floors, this leaves potentially more optimal design variants not considered. A similar principle is valid for combining calcium silicate brick walls and hollow core timber floors for the redesigns of Chapter 7.

Besides, hollow core timber floors have been used for the ground floor, leading to lower GWP values but leaving practical challenges unsolved. Next to this, wall and floor cladding could have been adjusted more optimally for various strategies, optimising for either GWP or costs. Overall, room for further optimisation has been left unexploited, providing an incomplete overview.

Inclusion of concrete wall elements

During this research, calcium silicate brick walls have generally been used over prefab concrete walls. This is based on the preliminary assessment, favouring calcium silicate bricks in GWP-GHG emissions and costs for the selected scope. However, when the whole life cycle would have been considered and practical aspects accounted for, there are several reasons to prefer concrete over calcium silicate bricks.

Exploratory calculations have been made for the environmental and economic impact of four variants in which calcium silicate brick walls have been changed for prefab concrete walls. In these adjusted variants, the calcium silicate brick walls are changed to prefab concrete walls of similar weight. Based on estimations, an indication can be given that GWP values would increase by 4%, while costs would increase by 2%. While slightly less favourable, all these adjusted variants would still provide significantly lower GWP values than the original design, while costs would be in a similar range. More details can be found in Appendix D.

Inclusion of temporary carbon storage

During the design process, GWP-GHG has been used as the leading indicator on which to base environmental decisions and conclusions. This led to redesigns providing significant reductions in GWP, yet all far above PPI targets for 2050. When GWP-total values would have been used for this, values around or below the targeted Paris Proof values would have been achieved far more easily. As a result, a more distinct division between variants with GWP-total values above and below the threshold would have occurred.

Both variants with calcium silicate brick walls and CLT-concrete composite floors, variants 6.2 and 7.2, have GWP-total values above the thresholds. The same is true for the estimations for variants using concrete instead of calcium silicate brick walls. Consequently, these variants could have been targeted for further reductions in GWP-total values.

All other variants have values below the threshold values for 2050. Hence, they could have been targeted for cost reduction, as no further incentive to lower environmental impact would be present after achieving the needed values for GWP-total. Conclusively, many aspects of decision-making would have been different if this indicator had been used.

10 Conclusions

In this chapter, the research will be concluded by answering the main research question.

10.1. Answers to the main research question

Throughout the various chapters of this research, each of the sub-research questions has been addressed. After evaluating the case study results, performing a sensitivity analysis, and discussing the assumptions, limitations and design choices of this research, the main research question can now be addressed:

"To what extent can a change in structural system towards timber lead to a reduction of the environmental footprint of a typical mid-rise residential building in the Netherlands, while ensuring economic feasibility?"

This question will be addressed from multiple perspectives. First, the extent to which redesigns can reduce the environmental footprint compared to the established environmental targets will be given. Subsequently, insights will be provided on which building concepts can be realised within various thresholds of economic feasibility.

Reduction of environmental footprint compared to environmental targets

Compared to the original design of the case-study building, the redesigns with timber and hybrid timber structural systems can achieve reductions in value for the Paris Proof Indicator (measured in GWP-GHG) between 39% and 56%. These reductions are significant and, for several redesigns, achievable within the limits of economic feasibility. The resulting GWP-GHG values are between 82 and 114 kg CO_2-eq./m^2, depending on the specific building concept. When considering designs of mid-rise residential buildings in general, taking into account the uncertainty in input values and thresholds, and leaving a margin for potential optimisation of designs, the researched building concepts can be in line with the targets of the Paris Agreement up to 2035.

However, these targets are roughly twice as high as the targets for 2050. Hence, achieving the targets for 2050 within the researched design strategies is unlikely. The potential inclusion of biogenic carbon, equal to a representative amount of sequestration which would happen during the lifespan of a building, can significantly impact the outcome of the research. Reductions in value for the Paris Proof Indicator (measured in GWP-total) would range between 78% and 123%. This partial inclusion would lead to all researched building concepts being in line with the targets for 2045, with most in line with targets beyond 2050. Whether or not this approach is possible in the future depends on political decisions.

To achieve these targets without the inclusion of biogenic carbon, different design strategies will need to be applied. For example, using recycled or reused construction materials could further reduce the environmental footprint. Without this, the cradle-to-practical completion scope for the Paris Proof Indicator likely results in a lower bound that exceeds the target value for mid-rise residential buildings.

Building concepts within various thresholds of economic feasibility

When interpreting economically feasible as having costs not being higher compared to non-bio-based mid-rise residential buildings, two conceptually different types of buildings are promising using timber. The first building concept is a hybrid construction between calcium silicate brick walls and CLT-concrete composite floors. Over a range of floor spans and stability systems, PPI values around 110 kg CO_2-eq./m^2 of GFA are achievable. The second building concept combines CLT walls and hollow core timber floors. This concept can only provide costs within the set limit for specific configurations. Values for PPI are significantly lower compared to the first concept, with around 85 kg CO_2-eq./m^2 of GFA. Besides these concepts, the combination of calcium silicate brick walls and hollow core timber floors showed potential for suitability when optimised further.

When interpreting economically feasible as having costs no higher than +10% compared to non-bio-based buildings, a wider range of building concepts is promising. Calcium silicate brick walls combined with any bio-based floor type can significantly reduce environmental footprint within the cost limit, with PPI values down to roughly 95 kg CO_2-eq./m^2 of GFA. When considering various variants with CLT walls and either hollow core timber or CLT-concrete composite floors, these values range again from 85-110 kg CO_2-eq./m^2 of GFA, indicating similar values compared to variants with lower costs.

Variants with both CLT walls and CLT floors are likely to exceed the economic feasibility thresholds of +10% significantly. Besides, no significant reductions in PPI values are likely compared to concepts with CLT walls and hollow core timber floors. Finally, for all variants using calcium silicate brick walls, estimations show that a change to prefab concrete walls would lead to a GWP-GHG increase of roughly 4%, while costs are in the same threshold range for economic feasibility.

Note that all PPI values are given for the load-bearing structure only, and are compared to established thresholds adjusted for this.

11
Recommendations

In this chapter, recommendations will be made for practical applications of the lessons learned from this research. Besides, recommendations for further research will be provided.

11.1. Recommendations for practical application

In this section, recommendations for the practical application of the lessons learned from this research are given for several relevant professions.

Recommendations for project developers

For project developers, the following recommendations can be given based on this research:

- Using bio-based materials for the load-bearing structures of mid-rise residential buildings can significantly reduce their environmental footprint while remaining competitive in costs. As economic considerations are often more important than environmental ones in decision-making, creating more awareness about this competitiveness is crucial. Structural concepts with PPI values down to 85 kg CO_2-eq./m² of GFA can be achieved at costs within +10% of those of non-bio-based systems. Moreover, design optimisation can further reduce costs, making these systems even more competitive. The PPI values align with the 2035 governmental goals, providing medium-term solutions.
- In situations where soil conditions are relatively unfavourable, using bio-based structural systems can be especially suitable, as savings in total weight are significant. This can lead to smaller foundations and savings in costs up to 50%. Awareness of this should be enlarged.

Recommendations for structural engineers and architects

For structural engineers, architects and other people involved in the design or development process of residential buildings, the following recommendations can be given based on this research:

- In selecting suitable wall systems, single CLT wall systems are favourable over double CLT wall systems. The amount of fire-proof cladding needed significantly impacts the environmental footprint and is relevant to architectural appearance and fire design strategy. Therefore, this should be considered in early design stages. Calcium silicate brick walls provide a useful alternative to CLT, often leading to a slightly higher environmental impact for significantly lower costs.
- In selecting floor systems, CLT-concrete composite floors, hollow core timber floors and CLT-dry screed floors all have their benefits. Which floor type is preferable depends on the design strategy and needed dimensions. The focus in design should lay on changing floor systems, as this will lead to far more significant environmental benefits and cost reductions than changing other elements, such as wall systems.
- Designs combining calcium silicate brick walls with any of the mentioned floor types will significantly reduce environmental footprint for comparable costs. The same applies to designs com-

bining CLT walls with CLT-concrete composite or hollow core timber floors. Designs combining CLT walls and CLT floors are likely outside the range for comparable costs. Knowledge about this should be spread and used in decision-making.

- The subsequent savings in total building weight are significant, which can lead to major reductions in foundation size. In several situations, the decrease in foundation costs can be larger than the increase in costs for the superstructure, leading to overall more affordable designs. Knowledge about this should be spread, and the impact of changes in foundation size should be considered to a larger extent in early design stages.
- In realising a feasible design, lateral stability is an important aspect to address. Depending on the configuration of a building, the resulting tension forces on the foundations are likely. Using apartment-separating walls in the transverse direction, as well as other stability elements in the longitudinal direction to transfer these forces to the foundation, is likely and necessary. The latter is challenging to achieve in bio-based materials. Connections between the stability elements on the ground floor and the foundation are generally governing. Ensuring the stability elements are bio-based is of lower importance compared to other elements. Only when no additional foundation beams and piles are needed can a switch from concrete to CLT stability walls lead to slight reductions in environmental footprint.

  Often, due to strength limitations, the possibility of achieving longitudinal lateral stability in the outer facade is limited in bio-based materials. As a result, it is advised to create a layout with at least one apartment rotated 90 degrees to combine apartment-separating and stability walls.
- Reductions in floor span do not necessarily lead to reductions in environmental footprint or costs, as the extra wall length needed to realise the same floor area counteracts the reduction in floor thickness.

Recommendations for policymakers

For policymakers, the following recommendations can be given based on this research:

- Within the current system of assessing the environmental impact of buildings, no specific targets exist for embodied carbon. Establishing targets for this, for example, by introducing thresholds for the Paris Proof Indicator, could create the incentive to focus on reducing embodied carbon. This is important, as embodied carbon is expected to become dominant over operational carbon.
- Within the current regulations, achieving PPI values close to the targeted values for 2050 is unlikely without the extensive use of reused materials, even when a building is primarily made from bio-based materials. Accounting for the benefits of carbon sequestration is not possible within the current regulations, as the storage is seen as temporary. Therefore, some of the benefits of bio-based materials are neglected. Allowing for this to be accounted for to a certain extent can be argued as reasonable, something which could promote the use of bio-based materials.

  However, an unintended consequence could be that designs with a relatively small amount of bio-based materials could already align with the governmental goals of 2050. Consequently, an incentive to further optimise will no longer be present. Besides, it could even lead to using materials with a worse environmental footprint, as cost optimisation becomes of higher importance. All this should be considered in further policy development in this area.

11.2. Recommendations for further research

Next to recommendations for practical application, there are recommendations for further research:

- Different building layouts and sizes could be investigated to verify the results of this research and widen the range of applicability. Most of the findings are based on case study results. While a general type of building has been selected, and the impact of small changes in input values has been investigated, the influence of building size could change results to a certain extent. Important parameters to change are apartment size, number of apartments and building height.
- The scope of the life cycle analysis could be enlarged: investigate cradle-to-cradle instead of cradle-to-practical completion. By doing so, the long-term sustainability aspects are reflected better. Knowing the impact of different end-of-life scenarios on the overall environmental footprint

and knowing the effect this has on design choices could lead to more well-based decisions. In reality, different end-of-life scenarios are related differently to various construction methods. For example, wet and dry screed floors have different effects on end-of-life scenarios. Therefore, there will be differences in decision-making between them, which should be considered. Furthermore, other environmental indicators should be included next to global warming potential.

- Designs could be optimised in general, and different structural systems could be investigated to provide a more complete overview. Areas to exploit could be modular buildings, buildings constructed with timber frame structures and other foundation systems suitable for lightweight construction. Furthermore, the inclusion of reused construction materials, optimisation of gallery and balcony structures and more innovative stability systems could be investigated. Besides, including low-carbon concrete - both as screed floor and prefab elements - in the comparison could provide more insights into the effectiveness of bio-based materials compared to this.
- The impact of different floor spans on overall environmental impact could be investigated, as this research suggests no optimum has been identified yet. Contrary to existing research, the effect of changes in span to wall and foundation sizes should be considered in detail for various floor types.
- The long-term impact of increased adaptation of timber could be investigated, as changes in supply chain and construction workflows could lead to a lowering of the environmental footprint and costs.

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A

Additional information to preliminary research

A.1. Background information on fire resistance approach

Over-dimensioning and charring rates

When over-dimensioning timber, the effective cross-section that can be accounted for in calculations for the load-bearing resistance needs to be determined. This can be done according to the following formula 4.1. In the figure below, an overview is given.

$$h_{\text{ef}} = h_{\text{CLT}} - d_0 - \beta_{\text{char},0} \cdot t$$

where:

- h_{ef} is the effective height for load-bearing calculations
- h_{CLT} is the height of the CLT element before charring
- d_0 is the non-load-bearing layer
- $\beta_{\text{char},0}$ is 0,65 mm/min and is a one-dimensional charring rate in a standard fire (when CLT is used)
- t is the fire exposure time

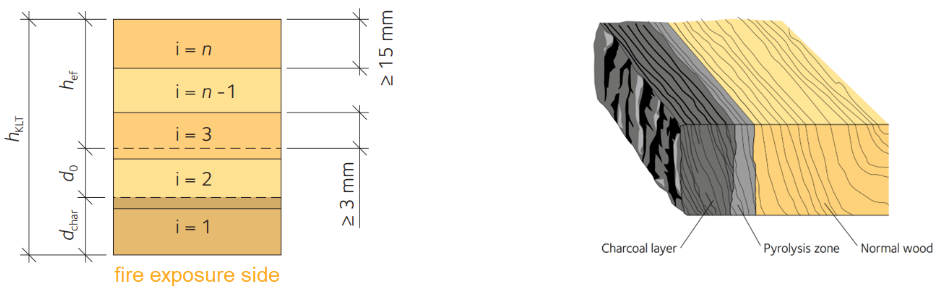


Figure A.1: For single-sided fire exposure, the residual cross-section is denoted by h_{ef}, the char layer is represented by d_{char}, and the non-load-bearing layer is given by d_0 (left). This is closely related to the charring layers within normal wood (right) (Skogsindustrier, 2019).

Gypsum plasterboards and failure times

When adding gypsum plasterboards to a (structural) element, the time before that element starts burning is delayed. There are many types of gypsum plasterboard that comply with the codes, most commonly, types A and F are used:

- Type A, regular common boards with porous gypsum core and no reinforcement except the paper laminated surface. The abbreviation GtA is often used, and its common thickness is 12,5mm.
- Type F, fire protection board with improved core cohesion at high temperatures. The abbreviation GtF is often used, and a common thickness is 15,0mm.

Studies have shown at what time after the start of a fire, various combinations of gypsum boards will fail. An overview of failure times for the most common element thicknesses is given below (Just, Schmid, and König, 2011).

Cladding	Thickness in mm	Failure times of gypsum boards in minutes		Equivalent decrease in effective height of CLT without cladding		Difference between thickness of cladding and equivalent decrease in effective height	
		Walls	Floors	Walls	Floors	Walls	Floors
Type F, one layer	15,0	44	25	45,6	37,25	-30,6	-22,3
Type F, two layers	30,0	80	57	69	58,05	-39,0	-28,1
Type F + Type A	27,5	81	50	69,65	53,5	-42,2	-26,0
Type A, one layer	12,5	17	16	28,05	31,4	-15,6	-18,9
Type A, two layers	25,0	39	-	42,35	-	-17,4	-
Type A, three layers	37,5	55	-	52,75	-	-15,3	-

Figure A.2: Overview of failure times in minutes for different configurations of gypsum boards Type A 12,5mm and Type F 15,0mm, combined with equivalent decrease and effective height and potential savings in thickness(Just, Schmid, and König, 2011)

A.2. Analysis of environmental product declarations

In the following figures, an overview is given of the data used to determine values for global warming potential based on EPDs. Note that the definition for GWP-total as defined in EN 15804+A2 has been used.

Element	Description	Unit	Density (kg/unit)	Year	RSL (years)	Geographical scope	A4-distance (km)	GWP	A1-3	A4	A5	A1-5
CLT	CLT by Stora Enso, moisture content 12%	m3	470	2023	50	Sweden - Europe	634	GWP-fossil	5,25E+01	2,59E+01	5,38E+00	8,38E+01
								GWP-bio	-7,62E+02	1,03E-02	1,00E-03	-7,62E+02
								GWP-luluc	8,78E-01	9,72E-03	4,06E-04	8,88E-01
								GWP-total	-7,08E+02	2,59E+01	5,38E+00	-6,77E+02
								GWP-GHG	5,34E+01	2,59E+01	5,38E+00	8,47E+01
	Derix X-LAM (Cross laminated timber) , mc 10%	m3	474	2023	75	Germany - Europe	170	GWP-fossil	1,20E+02	7,05E+00	7,41E+00	1,35E+02
								GWP-bio	-5,66E+02	5,34E-03	3,93E-01	-5,66E+02
								GWP-luluc	8,61E-01	5,34E-03	3,93E-01	1,26E+00
								GWP-total	-4,45E+02	7,06E+00	8,20E+00	-4,30E+02
								GWP-GHG	1,21E+02	7,06E+00	7,80E+00	1,36E+02
	Setra KL Trä (Cross-laminated timber), mc 12%	m3	436	2022	50	Italy - Europe	248	GWP-fossil	5,80E+01	7,50E+00	8,00E-01	6,63E+01
								GWP-bio	-8,40E+02	-4,90E+00	-1,60E+01	-8,61E+02
								GWP-luluc	3,50E-01	2,70E-03	3,00E-02	3,83E-01
								GWP-total	-7,82E+02	2,60E+00	-1,52E+01	-7,94E+02
								GWP-GHG	5,84E+01	7,50E+00	8,30E-01	6,67E+01
	KLH® - CLT (Cross Laminated Timber), mc12%	m3	470	2023	100	Austria - Europe	582	GWP-fossil	8,53E+01	4,55E+01	1,30E+01	1,44E+02
								GWP-bio	-7,62E+02	0,00E+00	0,00E+00	-7,62E+02
								GWP-luluc	2,09E+00	1,79E-02	9,46E-04	2,11E+00
								GWP-total	-6,75E+02	4,55E+01	1,30E+01	-6,16E+02
								GWP-GHG	8,74E+01	4,55E+01	1,30E+01	1,46E+02
CLT	**Average** of all the above	m3	462				409	GWP-fossil	7,90E+01	2,15E+01	6,65E+00	1,07E+02
								GWP-bio	-7,33E+02	-1,22E+00	-3,90E+00	-7,38E+02
								GWP-luluc	1,04E+00	8,92E-03	1,06E-01	1,16E+00
								GWP-total	-6,52E+02	2,03E+01	2,85E+00	-6,29E+02
								GWP-GHG	8,00E+01	2,15E+01	6,75E+00	1,08E+02
Glulam	Glulam construction wood products of spruce	m3	430	2023		Denmark - Europe	0	GWP-fossil	1,22E+02			
								GWP-bio	-6,78E+02			
								GWP-luluc	5,27E-01			
								GWP-total	-5,55E+02			
								GWP-GHG	1,23E+02			
	Glued laminated timber - Studiengemeinschaft Holzleimbau	m3	450	2018	100	Germany - Europe		GWP	-6,15E+02	0,00E+00	4,52E+00	-6,10E+02
	Glued Laminated Timber Beams - GLULAM from Moretti S.p.A.	m3	466	2024	50	Italy - Europe		GWP-fossil	2,85E+02			
								GWP-bio	-5,03E+02			
								GWP-luluc	1,11E+00			
								GWP-total	-2,17E+02			
								GWP-GHG	2,86E+02			
Glulam	**Average** of no1 and no3	m3						GWP-fossil	2,04E+02			
								GWP-bio	-5,91E+02			
								GWP-luluc	8,19E-01			
								GWP-total	-3,86E+02			
								GWP-GHG	2,04E+02			
LVL	Kerto LVL (various types)	m3	468	2021	100	Finland - Europe	Eu average	GWP-fossil	2,80E+02	1,98E+01	3,75E+01	3,37E+02
								GWP-bio	-6,63E+02	5,14E-02	1,71E+01	-6,46E+02
								GWP-luluc	3,53E-01	1,14E-01	1,78E-02	4,85E-01
								GWP-total	-3,83E+02	2,00E+01	5,46E+01	-3,08E+02
								GWP-GHG	2,80E+02	1,99E+01	3,75E+01	3,38E+02
	LVL (Laminated Veneer Lumber) by Stora Enso	m3	510	2023	50	Finland - Europe	614	GWP-fossil	1,21E+02	2,72E+01	6,08E+00	1,54E+02
								GWP-bio	-8,15E+02	1,08E-02	7,50E-04	-8,15E+02
								GWP-luluc	4,43E+00	1,02E-02	4,11E-04	4,44E+00
								GWP-total	-6,90E+02	2,72E+01	6,08E+00	-6,56E+02
								GWP-GHG	1,25E+02	2,72E+01	6,08E+00	1,59E+02
LVL	**Average** of all the above	m3	489					GWP-fossil	2,01E+02	2,35E+01	2,18E+01	2,46E+02
								GWP-bio	-7,39E+02	3,11E-02	8,55E+00	-7,30E+02
								GWP-luluc	2,39E+00	6,21E-02	9,13E-03	2,46E+00
								GWP-total	-5,36E+02	2,36E+01	3,03E+01	-4,82E+02
								GWP-GHG	2,03E+02	2,36E+01	2,18E+01	2,48E+02
Sawn timber	Svenskt Tra - Swedish sawn dried timber of spruce or pine	m3	489	2021	100	Sweden		GWP-fossil	2,87E+01			2,87E+01
								GWP-bio	-7,73E+02			-7,73E+02
								GWP-luluc	1,99E-01			1,99E-01
								GWP-total	-7,44E+02	0,00E+00	0,00E+00	-7,44E+02
								GWP-GHG	2,89E+01	0,00E+00	0,00E+00	2,89E+01
	Standard and special sawn timber from UPM Timber	m3	523	2022	-	Finland - Global	359 + 7007	GWP-fossil	3,41E+01	1,08E+01	1,70E+00	4,66E+01
								GWP-bio	-7,86E+02	1,93E-02	9,68E-05	-7,86E+02
								GWP-luluc	5,29E-01	2,08E-02	5,33E-05	5,50E-01
								GWP-total	-7,51E+02	1,08E+01	1,70E+00	-7,39E+02
								GWP-GHG	3,46E+01	1,08E+01	1,70E+00	4,71E+01
Sawn timber	**Average** of all the above	m3	506					GWP-fossil	3,14E+01	1,08E+01	1,70E+00	3,76E+01
								GWP-bio	-7,80E+02	1,93E-02	9,68E-05	-7,79E+02
								GWP-luluc	3,64E-01	2,08E-02	5,33E-05	3,74E-01
								GWP-total	-7,48E+02	5,40E+00	8,50E-01	-7,41E+02
								GWP-GHG	3,18E+01	5,39E+00	8,50E-01	3,80E+01

Figure A.3: Data used for determination of GWP values - part 1

Gypsum type F	Knauf - Gypsum Board - FR-DF 15.0mm	m2	12,5	2024	60	Global	-	GWP-fossil	3,37E+00	1,59E-01	3,45E-01	3,87E+00
								GWP-bio	-3,93E-02	-2,01E-03	1,92E-02	-2,21E-02
								GWP-luluc	5,49E-03	1,27E-03	2,09E-04	6,97E-03
								GWP-total	3,34E+00	1,58E-01	3,64E-01	3,86E+00
								GWP-GHG	3,38E+00	1,60E-01	3,45E-01	3,88E+00
	British Gypsum Saint Gobain - Gyproc FireLine 15 mm	m2	12,6	2024	60	UK > global	171	GWP-fossil	2,45E+00	1,73E-01	5,11E-01	3,13E+00
								GWP-bio	-8,66E-01	-2,58E-03	3,20E-01	-5,49E-01
								GWP-luluc	7,29E-03	1,61E-03	1,18E-03	1,01E-02
								GWP-total	1,59E+00	1,72E-01	8,32E-01	2,60E+00
								GWP-GHG	2,46E+00	1,75E-01	5,12E-01	3,14E+00
	Rigips Saint Gobain - Gyproc FireLine 15 mm	m2	12,65	2023	50	Greece	287+262	GWP-fossil	3,12E+00	3,13E-01	2,43E-01	3,68E+00
								GWP-bio	-1,03E+00	-3,96E-04	3,54E-01	-6,76E-01
								GWP-luluc	2,13E-03	2,17E-03	3,24E-04	4,62E-03
								GWP-total	2,09E+00	3,15E-01	5,97E-01	3,00E+00
								GWP-GHG	3,12E+00	3,15E-01	2,43E-01	3,68E+00
Gypsum type F	**Average** of all the above	m2	12,6					GWP-fossil	2,98E+00	2,15E-01	3,66E-01	3,56E+00
								GWP-bio	-6,45E-01	-1,66E-03	2,31E-01	-4,16E-01
								GWP-luluc	4,97E-03	1,68E-03	5,71E-04	7,22E-03
								GWP-total	2,34E+00	2,15E-01	5,98E-01	3,15E+00
								GWP-GHG	2,98E+00	2,17E-01	3,67E-01	3,57E+00
Mineral wool	Ravatherm Bio Mineral Wool from RBS Ravago	kg		2023	50	Turkey - Global	500	GWP-fossil	6,58E+00	5,00E-02	1,25E-02	6,64E+00
								GWP-bio	3,75E-02	8,00E-05	1,75E+00	1,79E+00
								GWP-luluc	2,50E-02	1,38E-05	3,25E-06	2,50E-02
								GWP-total	6,64E+00	5,01E-02	1,76E+00	8,45E+00
								GWP-GHG	6,60E+00	5,00E-02	1,25E-02	6,66E+00
		kg		2021		Turkey - Global	200+2000	GWP-fossil	5,02E-01	1,65E-02	5,67E-01	1,09E+00
								GWP-bio	3,96E-03	2,90E-06	1,98E-03	5,94E-03
								GWP-luluc	1,98E-03	7,52E-07	4,07E-07	1,98E-03
								GWP-total	5,08E-01	1,65E-02	5,69E-01	1,09E+00
								GWP-GHG	5,04E-01	1,65E-02	5,67E-01	1,09E+00
	Others	kg						GWP-total	1,05E+00	1,69E-02	3,31E-02	1,10E+00
		kg							1,76E+00	2,57E-01	3,17E-01	2,33E+00
Mineral wool	**Average** of first two, likely to be an overestimation based on the two other results, however , assumed so to be on the safe side due to high variation	kg						GWP-fossil	3,54E+00	3,33E-02	2,90E-01	3,86E+00
								GWP-bio	2,07E-02	4,14E-05	8,76E-01	8,97E-01
								GWP-luluc	1,35E-02	7,25E-06	1,83E-06	1,35E-02
								GWP-total	3,57E+00	3,33E-02	1,17E+00	4,77E+00
								GWP-GHG	3,55E+00	3,33E-02	2,90E-01	3,87E+00
calcium silicate brick	Calduran - Calcium silicate high-rise elements 175mm	m2	376	2022	75	Netherlands	?	GWP-fossil	3,49E+01	7,62E+00	2,72E+00	4,52E+01
								GWP-bio	5,73E-02	3,52E-03	2,39E-01	3,00E-01
								GWP-luluc	4,98E-03	2,79E-03	5,20E-04	8,29E-03
								GWP-total	3,50E+01	7,63E+00	2,96E+00	4,55E+01
								GWP-GHG	3,49E+01	7,62E+00	4,52E+01	4,52E+01
calcium silicate brick	Calduran - Calcium silicate high-rise elements, same as used in original variant, not much other data available	m3	2150	2022	75	Netherlands	?	GWP-fossil	1,99E+02	4,35E+01	1,55E+01	2,59E+02
								GWP-bio	3,27E-01	2,01E-02	1,37E+00	1,71E+00
								GWP-luluc	2,85E-02	1,59E-02	2,97E-03	4,74E-02
								GWP-total	2,00E+02	4,36E+01	1,69E+01	2,60E+02
								GWP-GHG	1,99E+02	4,36E+01	2,59E+02	2,59E+02
Concrete precast wall	Deelproduct: Constructies in kg , **Betonmortel** C30/37	m3	2400	2020	1000	Netherlands	?	GWP-total	2,31E+02		3,16E-01	2,31E+02
	Precast solid concrete walls and floors from Skandinaviska Bygg el	tonne		2019	100	Sweden	250	GWP-total	1,60E+02			1,74E+02
		m3	2500	2019	100	Sweden	250	GWP-total	4,00E+02			4,35E+02
	Precast concrete products - **Solid walls** from Perdanga, UAB	m3	2500	2021	100	Lithuania - Europe	158	GWP-fossil	5,55E+02	4,60E+01		6,01E+02
								GWP-bio	6,13E+00	3,15E-02		6,16E+00
								GWP-luluc	2,29E-01	3,15E-02		2,61E-01
								GWP-total	5,61E+02	4,61E+01		6,07E+02
								GWP-GHG	5,55E+02	4,60E+01		6,01E+02
	Solid concrete **wall** from Gunnar Prefab AB	m3	2500	2023	50	Sweden		GWP-fossil	3,98E+02	2,63E+01		4,24E+02
								GWP-bio	8,43E+00	8,18E-02		8,51E+00
								GWP-luluc	2,60E-01	1,47E-01		4,07E-01
								GWP-total	4,06E+02	2,65E+01		4,33E+02
								GWP-GHG	3,98E+02	2,64E+01		4,24E+02
Concrete precast wall	**Average** of the bottom prefab wall elements, as most complete and valid (per m3, however, based on sections of 200mm thickness)	m3	2500					GWP-fossil	4,76E+02	3,61E+01		5,12E+02
								GWP-bio	7,28E+00	5,66E-02		7,33E+00
								GWP-luluc	2,45E-01	8,91E-02		3,34E-01
								GWP-total	4,84E+02	3,63E+01		5,20E+02
								GWP-GHG	4,76E+02	3,62E+01		5,13E+02

Figure A.4: Data used for determination of GWP values - part 2

Aggregates / washed gravel	Aggregates from Vilniaus karjerai, JSC - crushed gravel/stone	tonne				Baltics - Europe		GWP-fossil	3,63E+00			
								GWP-bio	1,42E-02			
								GWP-luluc	1,48E-03			
								GWP-total	3,65E+00			
								GWP-GHG	3,63E+00			
	Aggregates from Vilniaus karjerai, JSC - crushed gravel/stone	m3	1700			Baltics - Europe		GWP-fossil	6,17E+00			
								GWP-bio	2,41E-02			
								GWP-luluc	2,52E-03			
								GWP-total	6,20E+00			
								GWP-GHG	6,17E+00			
	Aggregates & Granular Fill (Belgard Quarry) from Roadstone	tonne				Ireland - Europe		GWP-fossil	6,88E+00	1,85E+00		8,73E+00
								GWP-bio	0,00E+00	0,00E+00		0,00E+00
								GWP-luluc	1,40E-02	1,76E-03		1,57E-02
								GWP-total	6,89E+00	1,85E+00		8,74E+00
								GWP-GHG	6,89E+00	1,85E+00		8,74E+00
	Aggregates & Granular Fill (Belgard Quarry) from Roadstone	m3	1700			Baltics - Europe		GWP-fossil	1,17E+01	3,15E+00	0,00E+00	1,48E+01
								GWP-bio	0,00E+00	0,00E+00	0,00E+00	0,00E+00
								GWP-luluc	2,38E-02	2,99E-03	0,00E+00	2,68E-02
								GWP-total	1,17E+01	3,15E+00	0,00E+00	1,49E+01
								GWP-GHG	1,17E+01	3,15E+00	0,00E+00	1,49E+01
	Land-won aggregates from Žvyro karjerai, JSC	tonne				Baltics - Europe		GWP-fossil	1,38E+00			
								GWP-bio	9,19E-03			
								GWP-luluc	8,92E-04			
								GWP-total	1,39E+00			
								GWP-GHG	1,38E+00			
	Land-won aggregates from Žvyro karjerai, JSC	m3	1700			Baltics - Europe		GWP-fossil	2,35E+00			
								GWP-bio	1,56E-02			
								GWP-luluc	1,52E-03			
								GWP-total	2,36E+00			
								GWP-GHG	2,35E+00			
Aggregates / washed gravel	**Average of all the above**, in m3, with a4 from roadstone							GWP-fossil	6,73E+00	3,15E+00		9,88E+00
								GWP-bio	1,33E-02	0,00E+00		1,33E-02
								GWP-luluc	9,27E-03	2,99E-03		1,23E-02
								GWP-total	6,76E+00	3,15E+00		9,91E+00
		m3	1700					GWP-GHG	6,74E+00	3,15E+00		9,89E+00
insulation impact EPS	1m2 of Expanded Polystyrene (EPS) insulation boards from Kauno š	m3		2023	20	Lithuania - Europe		GWP-fossil	8,40E+01	3,28E-01		8,43E+01
								GWP-bio	1,76E-01	-1,36E-04		1,76E-01
								GWP-luluc	8,80E-03	2,68E-06		8,80E-03
								GWP-total	8,80E-03	2,68E-06		8,45E+01
								GWP-GHG	8,40E+01	3,28E-01		8,43E+01
	PLASTOPOR EPS 100-035, EPS 100-037 and EPS 150 from Plastforn	m3	18,0	2023	70	Croatia - Europe	100	GWP-fossil	4,67E+01	2,06E-01		4,69E+01
								GWP-bio	2,45E-01	-2,62E-04		2,45E-01
								GWP-luluc	3,12E-02	1,69E-03		3,29E-02
								GWP-total	4,70E+01	2,07E-01		4,72E+01
								GWP-GHG	4,67E+01	2,08E-01		4,69E+01
insulation impact EPS	**Average of all the above**, in m3, with a4 from roadstone							GWP-fossil	6,53E+01	2,67E-01		6,56E+01
								GWP-bio	2,10E-01	-1,99E-04		2,10E-01
								GWP-luluc	2,00E-02	8,45E-04		2,08E-02
								GWP-total	2,35E+01	1,04E-01		6,58E+01
			18,04					GWP-GHG	6,54E+01	2,68E-01		6,56E+01
Fibreboard gypsum	Rigidur® H - Gipsfaserplatten based on 12.5mm	m3				Europe		GWP-fossil	2,83E+02	6,77E+00	1,17E+01	3,02E+02
								GWP-bio	-2,88E+02	-1,16E-02	1,34E+00	-2,87E+02
								GWP-luluc	1,31E-01	5,51E-02	1,00E-02	1,96E-01
								GWP-total	-4,67E+00	6,81E+00		1,52E+01
								GWP-GHG	2,83E+02	6,82E+00		3,02E+02
Medium dense fibreboard	Medium Density Fibreboard, MDF	m3	650			UK - Europe		GWP-fossil	2,51E+02	2,32E+01	7,05E-01	2,75E+02
								GWP-bio	-1,03E+03	5,96E-01	8,80E+00	-1,02E+03
								GWP-luluc	9,92E-02	3,39E-03	2,14E-05	1,03E-01
								GWP-total	-7,79E+02	2,38E+01		-7,46E+02
								GWP-GHG	2,51E+02	2,32E+01		2,75E+02
Concrete C37 pressure layer		m3	NMD Deelproduct: Vrijdragende Vloeren, Beton,in het werk gestort, C30/37; incl.wapening					GWP-total	2,31E+02	5,68E+00		2,36E+02
		m2	NMD Deelproduct: Vrijdragende Vloeren, Druklaag breedplaatvloer; betonmortel C30/37; incl. wapening						5,84E+01	1,07E+00		5,95E+01
									4,61E+01	1,14E+00	0,00E+00	4,73E+01
									5,22E+01	1,10E+00	0,00E+00	5,34E+01
Wide slab floor	Dycore breedplaatvloer 60							GWP-fossil	1,86E+01	6,54E-02	1,89E-04	1,87E+01
								GWP-bio	-2,82E-02	4,75E-05	-3,04E-07	-2,81E-02
								GWP-luluc	8,91E-03	1,91E-05	8,78E-08	8,93E-03
								GWP-total	1,86E+01	6,55E-02		1,86E+01
								GWP-GHG	1,86E+01	6,54E-02		1,87E+01
Wide slab floor	Dycore breedplaatvloer - correction for 50mm of 10%							GWP-fossil	1,67E+01	5,89E-02	1,70E-04	1,68E+01
								GWP-bio	-2,53E-02	4,28E-05	-2,74E-07	-2,53E-02
								GWP-luluc	8,02E-03	1,72E-05	7,90E-08	8,04E-03
								GWP-total	1,67E+01	5,89E-02		1,68E+01
								GWP-GHG	1,67E+01	5,89E-02		1,68E+01
Concrete screed	zandcement NMD	m2	assumed 70mm						1,19E+01	5,06E-01		1,24E+01

Figure A.5: Data used for determination of GWP values - part 3

A.3. Analysis of quotes for cost determination of CLT elements

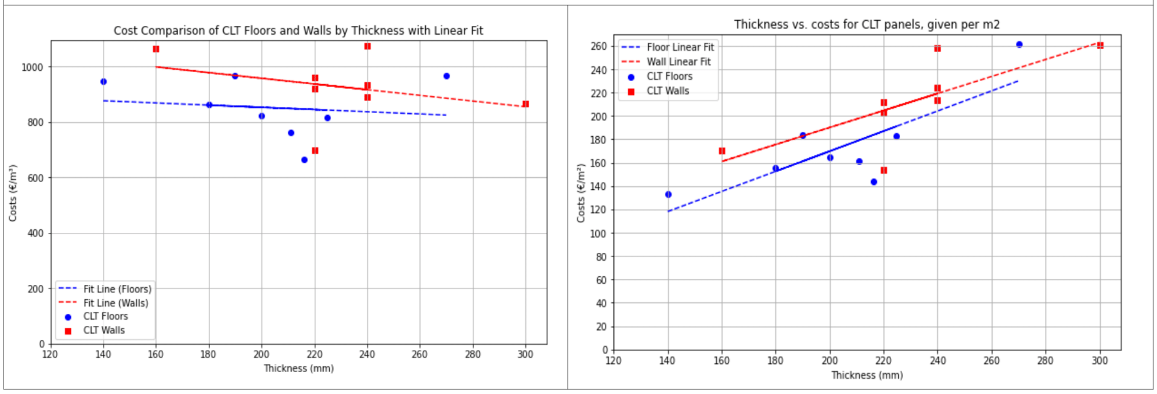
Underneath, in Figure A.6, an overview of the used cost values for CLT is provided, based on an analysis of existing quotes. Values have been retrieved as shown in the process below, verified by cost experts from practice. A more detailed overview in Figure A.7.

1. **Data Collection:** Existing quotes were analysed, and cost values (in €/m^3) were recorded for various thicknesses of CLT walls and floors.
2. **Data Correction:** The gathered values were adjusted to account for both the timber's value at the time of analysis and inflation.
3. **Trend Identification:** The corrected values were plotted, and a linear fit was applied to establish a trend line.
4. **Value Retrieval:** Based on the trend line, the cost values for different thicknesses of CLT walls and floors were extracted.

Values retrieved from quotes

CLT walls	*thickness (mm)*	*costs (euro/m3)*	*CLT floors*	*thickness (mm)*	*costs (euro/m3)*
	240	1076		140	1.108,00
	220	699		224,8	815,00
	240	891		216,2	664,00
	220	961		211	763,00
	160	1066		180	863,00
	220	922		200	822,00
	240	934		190	967,00
	300	868		270	969,00

Linear fit



Values based on linear fit

CLT walls	*thickness (mm)*	*costs (euro/m2)*	*CLT floors*	*thickness (mm)*	*costs (euro/m2)*
	90	109,98		140	118,13
	100	117,26		160	135,34
	120	131,82		180	152,55
	140	146,38		200	169,77
	160	160,94		220	186,99
	180	175,5		240	204,2
	200	190,06		260	221,42

Figure A.6: Overview of average prices for CLT panels, based on linear fit data from existing quotes.

Correction factors: total value, contribution of value of timber, contribution of inflation			
Quote 1	**0,95**	0,81	1,17
Quote 2	**0,93**	0,79	1,17
Quote 3	**0,93**	0,79	1,17
Quote 4	**1,18**	0,99	1,19
Quote 5	**1,22**	1,00	1,22
Quote 6	**0,94**	0,91	1,04
Quote 7	**0,88**	0,88	1,00
Quote 8	**1,04**	1,00	1,04

Quote information for CLT elements									
quote 1	*product*			*price quote*			*corrected price*		
Quote 1	walls	240	mm	€	272	/m2	€	258	/m2
				€	1.133	/m3	€	1.076	/m3
	floors	140	mm	€	140	/m2	€	133	/m2
				€	1.000	/m3	€	949	/m3
	floors	224,8	mm*	€	193	/m2	€	183	/m2
				€	859	/m3	€	815	/m3
Quote 2	floors	unknown		€	126	/m2	€	117	/m2
	walls	unknown		€	141	/m2	€	130	/m2
Quote 3	floors	216,2	mm*	€	155	/m2	€	144	/m2
				€	717	/m3	€	664	/m3
	walls	220	mm	€	166	/m2	€	154	/m2
				€	755	/m3	€	699	/m3
Quote 4	walls	240	mm	€	182	/m2	€	214	/m2
				€	758	/m3	€	891	/m3
	floors	211,0	mm*	€	137	/m2	€	161	/m2
				€	649	/m3	€	763	/m3
Quote 5	floors	180	mm	€	128	/m2	€	155	/m2
				€	708	/m3	€	863	/m3
	floors	200	mm	€	135	/m2	€	164	/m2
				€	675	/m3	€	822	/m3
	walls	220	mm	€	174	/m2	€	211	/m2
				€	789	/m3	€	961	/m3
	walls	160	mm	€	140	/m2	€	171	/m2
				€	875	/m3	€	1.066	/m3
	walls	220	mm	€	167	/m2	€	203	/m2
				€	757	/m3	€	922	/m3
	walls	240	mm	€	184	/m2	€	224	/m2
				€	767	/m3	€	934	/m3
Quote 6	mix walls en floors			€	239	/m2	€	226	/m2
Quote 7	mix walls en floors			€	305	/m2	€	268	/m2
Quote 8	walls	300	mm	€	251	/m2	€	261	/m2
				€	837	/m3	€	868	/m3
	floors	190	mm	€	177	/m2	€	184	/m2
				€	932	/m3	€	967	/m3
	floors	270	mm	€	252	/m2	€	262	/m2
				€	933	/m3	€	969	/m3

Figure A.7: Overview of data used for linear fit, including correction factors in relation to 2024.

A.4. Assessment data of vertical load-bearing elements: walls

Underneath, in Figure A.8, an overview is given of the build-up of wall sections, combined with an assessment of GWP and costs.

general data				embodied carbon / m2					costs
thickness [mm]	**calcium silicate brick**	**density [kg/m3]**	**weight [kg/m2]**	**GWP-fossil/m2**	**GWP-bio/m2**	**GWP-luluc/m2**	**GWP-total/m2**	**GWP-GHG/m2**	**euro/m2**
250	calcium silicate brick HS36	2150	537,5	49,97	0,06	0,01	50,02	49,98	91,64
250			**537,5**	49,97	0,06	0,01	**50,02**	**49,98**	**91,64**

thickness [mm]	prefab concrete	density [kg/m3]	weight [kg/m2]	GWP-fossil/m2	GWP-bio/m2	GWP-luluc/m2	GWP-total/m2	GWP-GHG/m2	euro/m2
220	concrete C30/37	2500	550,0	70,40	0,00	0,07	70,47	70,47	106,70
220			**550,0**	70,40	0,00	0,07	**70,47**	**70,47**	**106,70**

thickness [mm]	CLT - singular 1 - not exposed	density [kg/m3]	weight [kg/m2]	GWP-fossil/m2	GWP-bio/m2	GWP-luluc/m2	GWP-total/m2	GWP-GHG/m2	euro/m2
30	gypsum board type F	800	24,0	7,11	-0,83	0,01	6,71	7,12	24,60
50	insulation (hemp)	24	1,2	0,59	-3,64	0,04	-1,19	0,63	13,49
70	timber studs (10%)	475	3,3	0,26	-5,46	0,00	-2,46	0,27	10,00
90	CLT 90-3layers	450	40,5	9,64	-66,39	0,10	-23,45	9,75	109,98
70	timber studs	475	3,3	0,26	-5,46	0,00	-2,46	0,27	10,00
50	insulation (hemp)	24	1,2	0,59	-3,64	0,04	-1,19	0,63	13,49
30	gypsum board type F	800	24,0	7,11	-0,83	0,01	6,71	7,12	24,60
290			**97,6**	25,58	-86,24	0,21	**-17,34**	**25,78**	**206,16**

thickness [mm]	CLT - singular 2 - not exposed	density [kg/m3]	weight [kg/m2]	GWP-fossil/m2	GWP-bio/m2	GWP-luluc/m2	GWP-total/m2	GWP-GHG/m2	euro/m2
25	gypsum board type F	800	20,0	5,93	-0,69	0,01	5,59	5,94	18,46
60	insulation (hemp)	24	1,4	0,71	-4,37	0,04	-1,43	0,75	16,23
85	timber studs (10%)	475	4,0	0,32	-6,63	0,00	-2,99	0,32	12,20
100	CLT 100-5layers	450	45,0	10,71	-73,76	0,12	-26,05	10,83	117,26
85	timber studs	475	4,0	0,32	-6,63	0,00	-2,99	0,32	12,20
60	insulation (hemp)	24	1,4	0,71	-4,37	0,04	-1,43	0,75	16,23
25	gypsum board type F	800	20,0	5,93	-0,69	0,01	5,59	5,94	18,46
320			**96,0**	24,63	-97,14	0,23	**-23,71**	**24,86**	**211,04**

thickness [mm]	CLT - singular 3 - semi exposed	density [kg/m3]	weight [kg/m2]	GWP-fossil/m2	GWP-bio/m2	GWP-luluc/m2	GWP-total/m2	GWP-GHG/m2	euro/m2
25	gypsum board type F	800	20,0	5,93	-0,69	0,01	5,59	5,94	18,46
60	insulation (hemp)	24	1,4	0,71	-4,37	0,04	-1,43	0,75	16,23
85	timber studs (10%)	475	4,0	0,32	-6,63	0,00	-2,99	0,32	12,20
180	CLT 180-5layers	450	81,0	19,28	-132,77	0,21	-46,89	19,49	175,50
290			**106,5**	26,24	-144,46	0,27	**-45,72**	**26,51**	**222,39**

thickness [mm]	CLT - double 1 - not exposed	density [kg/m3]	weight [kg/m2]	GWP-fossil/m2	GWP-bio/m2	GWP-luluc/m2	GWP-total/m2	GWP-GHG/m2	euro/m2
25	gypsum board type F	800	20,0	5,93	-0,69	0,01	5,59	5,94	18,46
90	CLT 90-3layers	450	40,5	9,64	-66,39	0,10	-23,45	9,75	109,98
50	insulation (hemp)	24	1,2	0,59	-3,64	0,04	-1,19	0,63	13,49
10	air layers	0	0,0	0,00	0,00	0,00	0,00	0,00	0,00
90	CLT 90-3layers	450	40,5	9,64	-66,39	0,10	-23,45	9,75	109,98
25	gypsum board type F	800	20,0	5,93	-0,69	0,01	5,59	5,94	18,46
290			**122,2**	31,73	-137,80	0,27	**-36,90**	**32,00**	**270,37**

thickness [mm]	CLT - double 2 - not exposed	density [kg/m3]	weight [kg/m2]	GWP-fossil/m2	GWP-bio/m2	GWP-luluc/m2	GWP-total/m2	GWP-GHG/m2	euro/m2
12,5	gypsum board type F	800	10,0	2,96	-0,35	0,01	2,80	2,97	18,46
100	CLT 100-3layers	450	45,0	10,71	-73,76	0,12	-26,05	10,83	117,26
50	insulation (hemp)	24	1,2	0,59	-3,64	0,04	-1,19	0,63	13,49
10	air layers	0	0,0	0,00	0,00	0,00	0,00	0,00	0,00
100	CLT 100-3layers	450	45,0	10,71	-73,76	0,12	-26,05	10,83	117,26
12,5	gypsum board type F	800	10,0	2,96	-0,35	0,01	2,80	2,97	18,46
285			**111,2**	27,95	-151,86	0,28	**-47,70**	**28,22**	**284,93**

thickness [mm]	CLT - double 3 - semi exposed	density [kg/m3]	weight [kg/m2]	GWP-fossil/m2	GWP-bio/m2	GWP-luluc/m2	GWP-total/m2	GWP-GHG/m2	euro/m2
12,5	gypsum board type F	800	10,0	2,96	-0,35	0,01	2,80	2,97	18,46
100	CLT 100-3layers	450	45,0	10,71	-73,76	0,12	-26,05	10,83	117,26
50	insulation (hemp)	24	1,2	0,59	-3,64	0,04	-1,19	0,63	13,49
10	air layers	0	0,0	0,00	0,00	0,00	0,00	0,00	0,00
160	CLT 100-3layers	450	72,0	17,14	-118,02	0,19	-41,68	17,33	160,94
332,5			**128,2**	31,41	-195,77	0,34	**-66,13**	**31,75**	**310,15**

thickness [mm]	CLT - double 4 - exposed	density [kg/m3]	weight [kg/m2]	GWP-fossil/m2	GWP-bio/m2	GWP-luluc/m2	GWP-total/m2	GWP-GHG/m2	euro/m2
160	CLT 160-3layers	450	72,0	17,14	-118,02	0,19	-41,68	17,33	160,94
50	insulation (hemp)	24	1,2	0,59	-3,64	0,04	-1,19	0,63	13,49
10	air layers	0	0,0	0,00	0,00	0,00	0,00	0,00	0,00
160	CLT 160-3layers	450	72,0	17,14	-118,02	0,19	-41,68	17,33	160,94
380			**145,2**	34,88	-239,68	0,41	**-84,56**	**35,28**	**335,37**

Figure A.8: Build-up and assessment of wall sections.

A.5. Assessment data of horizontal load-bearing elements: floors

Underneath, in Figure A.9, an overview is given of the build-up of floor sections, combined with an assessment of GWP and costs. Note that orange values are measured per kg, not per m^3.

general data				embodied carbon / m2					costs
thickness [mm]	concrete wide slab floor	density [kg/m3]	weight [kg/m2]	GWP-fossil/m2	GWP-bio/m2	GWP-luluc/m2	GWP-total/m2	GWP-GHG/m2	euro/m2
70	concrete screed	1700	119				12,44	12,44	17,62
20	insulation EPS	17,3	0,346	1,31	0,00	0,00	1,31	1,31	10,95
200	pressure layer wide slab C30/37	2400	480	64,00	0,00	0,00	64,00	64,00	128,29
50	prefab wide slab			16,00	0,00	0,00	16,00	16,00	0,00
340			**599,35**				**93,75**	**93,75**	**156,86**
thickness [mm]	CLT + concrete screed	density [kg/m3]	weight [kg/m2]	GWP-fossil/m2	GWP-bio/m2	GWP-luluc/m2	GWP-total/m2	GWP-GHG/m2	euro/m2
80	concrete screed	1700	136				14,22	14,22	19,05
30	insulation impact EPS	17,3	0,519	1,97	0,01	0,00	1,97	1,97	12,27
200	CLT 200 L5s	450	90,0	21,43	-147,53	0,23	-52,10	21,66	186,99
310			**226,52**				**-35,92**	**37,84**	**218,31**
thickness [mm]	CLT + concrete composite	density [kg/m3]	weight [kg/m2]	GWP-fossil/m2	GWP-bio/m2	GWP-luluc/m2	GWP-total/m2	GWP-GHG/m2	euro/m2
15	flooring/fibre board (15 gypsum)	800	12,0	3,56	-0,42	0,01	3,35	3,56	12,30
22	flooring/fibre board	650	14,3	6,05	-22,66	0,00	-5,28	6,05	27,52
20	insulation impact EPS	17,3	0,346	1,31	0,00	0,00	1,31	1,31	10,95
0	steel connectors 1% volume		6,28	3,22	0,04	0,01	3,25	3,23	7,91
100	concrete floor	1700	170	32,00	0,00	0,00	32,00	32,00	19,05
140	CLT 140 L5s	450	63,0	15,00	-103,27	0,16	-36,47	15,16	118,13
297			**265,93**				**-1,84**	**61,31**	**195,86**
thickness [mm]	CLT + dry screed	density [kg/m3]	weight [kg/m2]	GWP-fossil/m2	GWP-bio/m2	GWP-luluc/m2	GWP-total/m2	GWP-GHG/m2	euro/m2
15	flooring/fibre board (15 gypsum)	800	12,0	3,56	-0,42	0,01	3,35	3,56	12,30
22	flooring/fibre board	650	14,3	6,05	-22,66	0,00	-5,28	6,05	27,52
20	insulation impact EPS	17,3	0,346	1,31	0,00	0,00	1,31	1,31	10,95
80	washed gravel	1700	136	0,79	0,00	0,00	0,79	0,79	7,20
200	CLT 200 L5s	450	90,0	21,43	-147,53	0,23	-52,10	21,66	186,99
337			**240,65**				**-51,92**	**33,38**	**244,96**
thickness [mm]	CLT + no screed	density [kg/m3]	weight [kg/m2]	GWP-fossil/m2	GWP-bio/m2	GWP-luluc/m2	GWP-total/m2	GWP-GHG/m2	euro/m2
25	flooring/fibre board (gypsum 2*12,5)	800	20,0	5,93	-0,69	0,01	5,59	5,94	24,60
20	insulation impact EPS	17,3	0,346	1,31	0,00	0,00	1,31	1,31	10,95
22	flooring/fibre board	650	14,3	6,05	-22,66	0,00	-5,28	6,05	27,52
95	insulation (hennep)	24	2,3	1,13	-6,92	0,07	-2,26	1,19	25,68
120	floor joists + sylodyn (only timber calc, 10%)	475	5,7	0,45	-9,35	0,00	-4,22	0,46	18,00
200	CLT 200 L5s	450	90,0	21,43	-147,53	0,23	-52,10	21,66	186,99
387			**112,28**				**-56,96**	**36,61**	**293,74**
thickness [mm]	CLT + suspended ceiling	density [kg/m3]	weight [kg/m2]	GWP-fossil/m2	GWP-bio/m2	GWP-luluc/m2	GWP-total/m2	GWP-GHG/m2	euro/m2
25	flooring/fibre board (gypsum 2*12,5)	800	20,0	5,93	-0,69	0,01	5,59	5,94	24,60
10	insulation impact EPS	17,3	0,173	0,66	0,00	0,00	0,66	0,66	10,95
60	washed gravel	1700	102	0,59	0,00	0,00	0,59	0,59	5,40
200	CLT 200 L5s	450	90,0	21,43	-147,53	0,23	-52,10	21,66	186,99
90	floor joists (calc, 10%)	475	4,3	0,34	-7,02	0,00	-3,17	0,34	14,00
70	insulation (hennep)	24	1,7	0,83	-5,10	0,05	-1,67	0,88	18,92
13	flooring/fibre board (gypsum 2*12,5)	800	10,4	3,08	-0,36	0,01	2,91	3,09	12,30
398			**208,36**				**-47,19**	**33,15**	**273,16**
thickness [mm]	Timber hollow core - LVL	density [kg/m3]	weight [kg/m2]	GWP-fossil/m2	GWP-bio/m2	GWP-luluc/m2	GWP-total/m2	GWP-GHG/m2	euro/m2
30	flooring/fibre board (2x15 gypsum)	800	24,0	7,11	-0,83	0,01	6,71	7,12	24,60
40	insulation impact EPS	17,3	0,692	2,62	0,01	0,00	2,63	2,62	16,69
30	washed gravel	1700	51	0,30	0,00	0,00	0,30	0,30	2,70
30	gravel inside box	1700	51	0,30	0,00	0,00	0,30	0,30	2,70
240	LVL box 30-180-30, weight based on kg of LVL, not mm	489	70	35,21	-104,50	0,35	-16,68	35,57	115,50
30	gypsum board type F	800	24,0	7,11	-0,83	0,01	6,71	7,12	24,60
370			**196,00**				**-0,05**	**53,03**	**186,79**

Figure A.9: Build-up and assessment of floor sections.

B

Details on exploratory calculations of redesigns

B.1. Exploratory calculations for lateral stability of main building

Calcium silicate brick walls and CLT walls

As can be seen below and on the next page, the moment distribution to various walls as a result of lateral forces and the effect on the foundation has been determined for both calcium silicate brick walls and CLT walls. Below, an indicatory visualisation has been provided, after which calculations are shown.

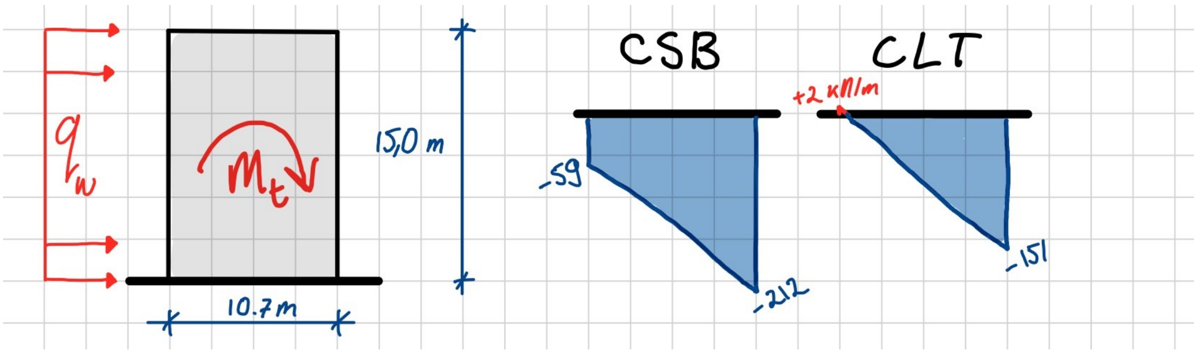


Figure B.1: Visualisation of wind load perpendicular to the longitudinal facade and resulting forces on governing transverse wall.

First, the total bending moment induced by wind forces has been calculated:

$$
\begin{aligned}
q_{w,\text{tot}} &= q_p(z) \cdot c_\text{s}c_\text{d} \cdot 0.85 \cdot c_{pE,\text{tot}} \cdot b \\
&= 0.98 \cdot 0.85 \cdot 0.85 \cdot 1.32 \cdot 41.6 \\
&= 39.0\,\text{kN/m}
\end{aligned}
$$

$$
\begin{aligned}
M_\text{tot} &= 1.1 \cdot 1.1 \cdot 0.5 \cdot q \cdot h^2 \\
&= 1.1 \cdot 1.1 \cdot 0.5 \cdot 39.0 \cdot 15.0^2 \\
&= 5310\,\text{kNm}
\end{aligned}
$$

Based on this total moment, the division of moments between walls has been calculated using Technosoft Balkrooster, leading to the following distribution:

- Wall 1, 7: 6.7% = 356 kNm
- Wall 2, 6: 18.3% = 972 kNm
- Wall 3, 4, 5: 16.6% = 881 kNm

Based on this, for the governing wall, the forces on the foundation have been calculated:

$$Q = \frac{M}{\frac{1}{6} \cdot d^2} = \frac{972 \cdot 10^6}{\frac{1}{6} \cdot 10700^2} = 50.9 \text{ kN/m}$$

When applying load factors, the maximum forces are as shown below. Left indicates the wind pressure side; right indicates the wind suction side:

$$\begin{aligned} Q_{\text{,CSB,left}} &= -0.9 \cdot Q_G + 1.5 \cdot Q_{\text{wind}} \\ &= -0.9 \cdot (15 \cdot 5.5 + 5 \cdot 6.8 \cdot 2.0) + 1.5 \cdot 50.9 \\ &= -59.1 \text{ kN/m} \end{aligned}$$

$$\begin{aligned} Q_{\text{,CSB,right}} &= 0.9 \cdot Q_G - 1.5 \cdot Q_{\text{wind}} \\ &= -0.9 \cdot (15 \cdot 5.5 + 5 \cdot 6.8 \cdot 2.0) - 1.5 \cdot 50.9 \\ &= -211.8 \text{ kN/m} \end{aligned}$$

$$\begin{aligned} Q_{\text{,CLT,left}} &= -0.9 \cdot Q_G + 1.5 \cdot Q_{\text{wind}} \\ &= -0.9 \cdot (15 \cdot 1.0 + 5 \cdot 6.8 \cdot 2.0) + 1.5 \cdot 50.9 \\ &= +1.6 \text{ kN/m} \end{aligned}$$

$$\begin{aligned} Q_{\text{,CLT,right}} &= 0.9 \cdot Q_G - 1.5 \cdot Q_{\text{wind}} \\ &= -0.9 \cdot (15 \cdot 1.0 + 5 \cdot 6.8 \cdot 2.0) - 1.5 \cdot 50.9 \\ &= -151.1 \text{ kN/m} \end{aligned}$$

As can be seen, only minor tension forces arise in the variant with CLT walls, as visualised in the figure below. Therefore, both variants are feasible.

B.1.1. Lateral stability in longitudinal direction

Determination of forces

Similar to the previous loading direction, first, the total bending moment induced by wind forces has been calculated. Below, a visualisation of the loading direction is provided and calculations are shown.

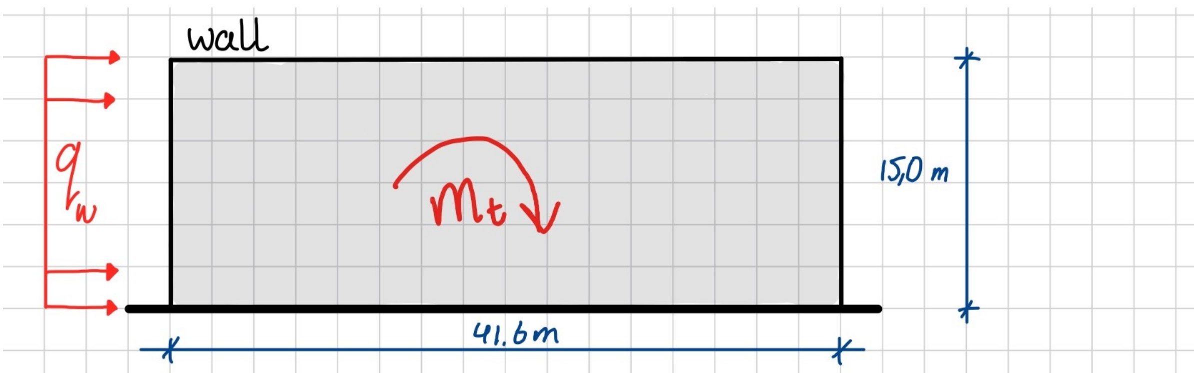


Figure B.2: Visualisation of wind load perpendicular to the transverse facade.

$$q_{w,\text{tot}} = q_p(z) \cdot c_\text{s}c_\text{d} \cdot 0.85 \cdot c_{pE,\text{tot}} \cdot b$$
$$= 0.98 \cdot 0.85 \cdot 0.85 \cdot 1.32 \cdot 41.6$$
$$= 39.0\,\text{kN/m}$$

$$F_{w,\text{wr}} = 0.98 \cdot 0.04 \cdot 10.7 \cdot 20.3 = 8.5\,\text{kN}$$

$$M_\text{tot} = 1.1 \cdot 1.1 \left(0.5 \cdot q_w \cdot h^2 + F_{w,\text{wr}} \cdot h\right)$$
$$= 1801\,\text{kNm}$$

On the following pages, maximum loads are provided according to several solution to achieve longitudinal lateral stability

Solution 1: reinforced concrete facade walls

When using reinforced concrete panels for the longitudinal facade, only minor tension forces can arise, which can easily be redirected to the foundation. For this variant, the use of CLT is not suitable, as due to the large openings, forces on the timber would lead to failure. Below, a visualisation of the solution is provided and the total wind force for an element is given.

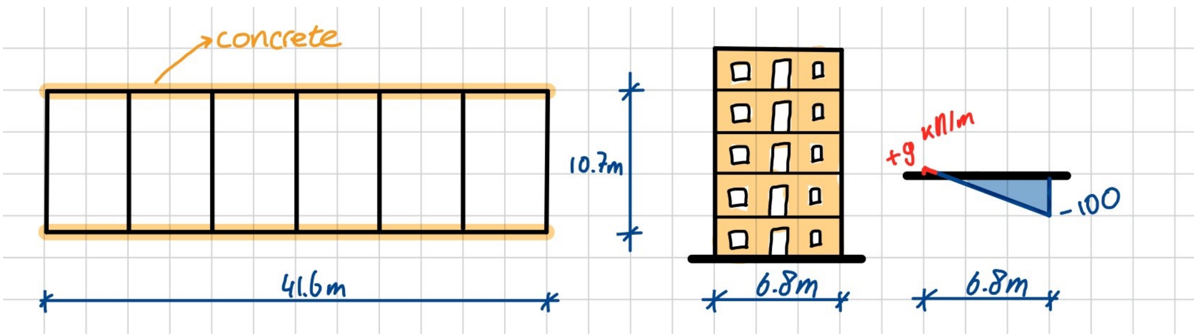


Figure B.3: Visualisation of solution 1 for longitudinal lateral stability and resulting forces on each stability element.

$$M_\text{tot} = 1801\,\text{kNm}$$

$$M_\text{element} = \frac{1}{12} \cdot M_\text{tot} = \frac{1}{12} \cdot 1801 = 150\,\text{kNm}$$
$$Q_w = \frac{M_\text{element}}{W \cdot b} = \frac{150 \cdot 10^6}{4.16 \cdot 10^6} = 36\,\text{kN/m}$$

When applying load factors, the maximum forces are as shown below. Left indicates the wind pressure side; right indicates the wind suction side:

$$Q_\text{solution1,left} = -0.9 \cdot Q_G + 1.5 \cdot Q_\text{wind}$$
$$= -0.9 \cdot \left(0.75 \cdot 15\text{m} \cdot 0.14\text{m} \cdot 25\text{kN/m}^3 + 5 \cdot 1.0\text{m} \cdot 2.0\text{kN/m}^2\right) + 1.5 \cdot 36$$
$$= -44.5 + 54 = +9.5\,\text{kN/m}$$

$$Q_\text{solution1,right} = -0.9 \cdot Q_G - 1.5 \cdot Q_\text{wind}$$
$$= -0.9 \cdot \left(0.75 \cdot 15\text{m} \cdot 0.14\text{m} \cdot 25\text{kN/m}^3 + 5 \cdot 1.0\text{m} \cdot 2.0\text{kN/m}^2\right) - 1.5 \cdot 36$$
$$= -44.5 - 54 = -99.5\,\text{kN/m}$$

Solution 2: reinforced concrete facade element in outer apartments

When using reinforced concrete panels only on the outer apartments' facades, high forces can arise. However, these forces can be redirected to the foundation by coupling the elements. Not that using a steel frame could be an alternative. However, due to practical reasons, this variant is preferred. Due to the high forces, CLT panels are not sufficient. Below, a visualisation of the solution is provided and the total wind force for an element is given.

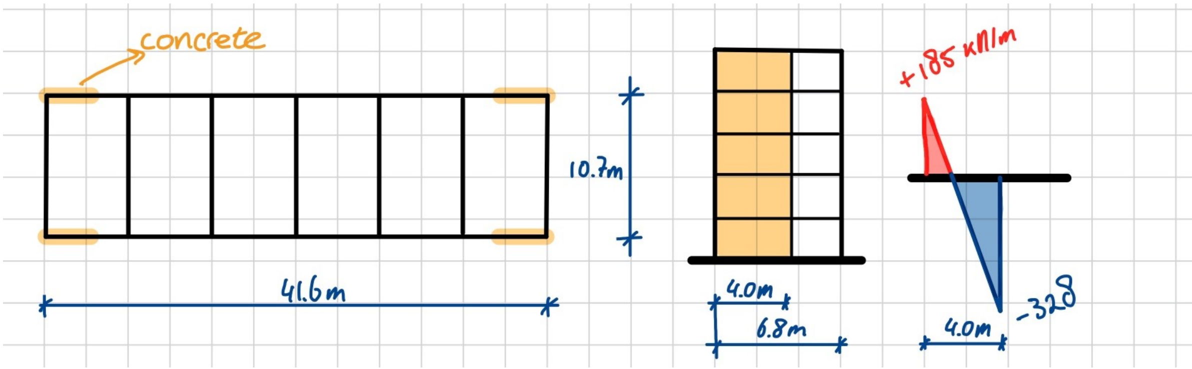


Figure B.4: Visualisation of solution 2 for longitudinal lateral stability and resulting forces on each stability element.

$$M_{\text{tot}} = 1801\,\text{kNm}$$

$$M_{\text{element}} = \frac{1}{4} \cdot M_{\text{tot}} = \frac{1}{4} \cdot 1801 = 450\,\text{kNm}$$

$$Q_w = \frac{M_{\text{element}}}{\frac{1}{6} \cdot d^2} = \frac{450 \cdot 10^6}{\frac{1}{6} \cdot 4000^2} = 170\,\text{kN/m}$$

$$F_w = \frac{M_{\text{element}}}{a} = \frac{450 \cdot 10^6}{4000} = 113\,\text{kN}$$

When applying load factors, the maximum forces are as shown below. Left indicates the wind pressure side; right indicates the wind suction side:

$$\begin{aligned} Q_{\text{solution1,left}} &= -0.9 \cdot Q_G + 1.5 \cdot Q_{\text{wind}} \\ &= -0.9 \cdot \left(15\text{m} \cdot 0.18\text{m} \cdot 25\text{kN/m}^3 + 5 \cdot 1.0\text{m} \cdot 2.0\text{kN/m}^2\right) + 1.5 \cdot 170 \\ &= -69.8 + 255 = +185.3\,\text{kN/m} \end{aligned}$$

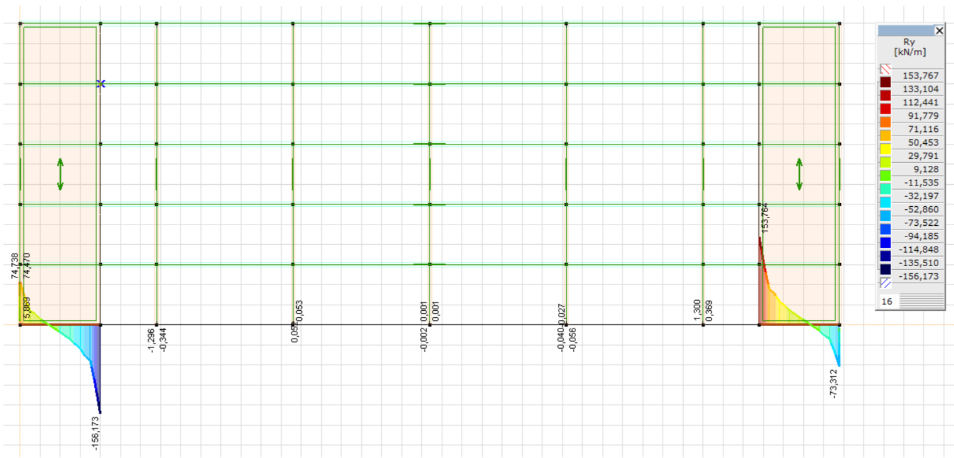
$$\begin{aligned} Q_{\text{solution1,right}} &= -0.9 \cdot Q_G - 1.5 \cdot Q_{\text{wind}} \\ &= -0.9 \cdot \left(15\text{m} \cdot 0.18\text{m} \cdot 25\text{kN/m}^3 + 5 \cdot 1.0\text{m} \cdot 2.0\text{kN/m}^2\right) - 1.5 \cdot 170 \\ &= -69.8 - 255 = -328.8\,\text{kN/m} \end{aligned}$$

Below, the forces in the coupling elements are shown, assuming steel rebars with a diameter of 25mm. Used tension force is the similar to the area in tension as shown above. As the stress in the steel is below the capacity, coupling is easily possible.

$$\sigma_{t,d} = \frac{134000}{0.25\pi(0.25)^2} = \frac{134000}{491} = 272\,\text{N/mm}^2$$

As the wind forces on the short facades need to be redirected to the stability elements close to this facade, sufficient diaphragm action is needed. To verify whether or not this is possible, a simple FEM model has been used, leading to the reaction forces below. Note that wind forces are from left to right.

The distribution of forces is as expected, with comparable, but different values. In the model, not all safety factors have been taken into account, hence the lower values. However, it can be seen that the wall closest to the wind pressure side takes up more compression than tension, and the wall closest to the wind suction side takes up more tension than compression. All values however, are within the limits.



Solution 3: internal CLT walls

When using internal CLT walls, a larger self-weight of the floor above is present on the outer sides, as the walls are load-bearing. As a result, the peek tension forces will be reduced, leading to values that can easily be transferred to the foundation. Below, a visualisation of the solution is provided and the total wind force for an element is given.

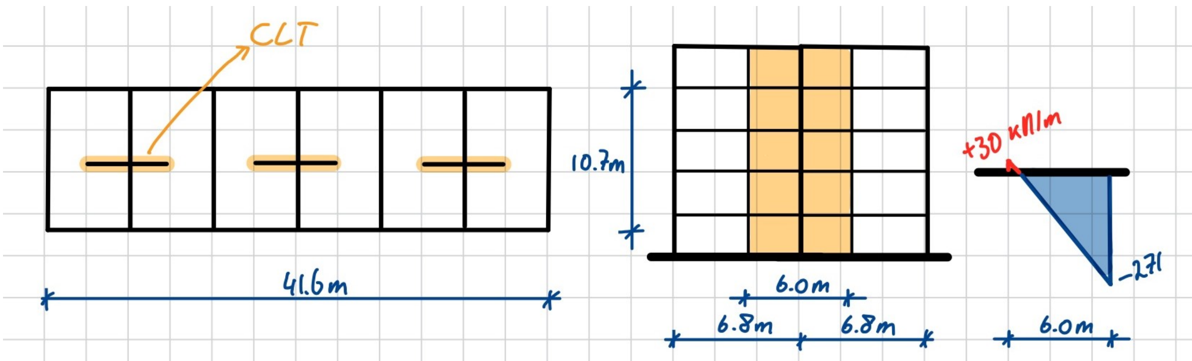


Figure B.5: Visualisation of solution 3 for longitudinal lateral stability and resulting forces on each stability element.

$$M_{\text{tot}} = 1801 \,\text{kNm}$$

$$M_{\text{element}} = \frac{1}{3} \cdot M_{\text{tot}} = \frac{1}{3} \cdot 1801 = 600 \,\text{kNm}$$

$$Q_w = \frac{M_{\text{element}}}{\frac{1}{6} \cdot d^2} = \frac{600 \cdot 10^6}{\frac{1}{6} \cdot 6000^2} = 100 \,\text{kN/m}$$

When applying load factors, the maximum forces are as shown below. Left indicates the wind pressure side; right indicates the wind suction side:

$$\begin{aligned} Q_{\text{solution1,left}} &= -0.9 \cdot Q_G + 1.5 \cdot Q_{\text{wind}} \\ &= -0.9 \cdot \left(15\text{m} \cdot 1.0\text{kN/m}^2 + 5 \cdot 12\text{m}^2/m \cdot 2.0\text{kN/m}^2\right) + 1.5 \cdot 100 \\ &= -121.5 + 150 = +28.5\,\text{kN/m} \end{aligned}$$

$$\begin{aligned} Q_{\text{solution1,right}} &= -0.9 \cdot Q_G - 1.5 \cdot Q_{\text{wind}} \\ &= -0.9 \cdot \left(15\text{m} \cdot 0.18\text{m} \cdot 25\text{kN/m}^3 + 5 \cdot 1.0\text{m} \cdot 2.0\text{kN/m}^2\right) - 1.5 \cdot 100 \\ &= -121.5 - 150 = -271.5\,\text{kN/m} \end{aligned}$$

B.2. Exploratory calculations for lateral stability of entrance building

Wind forces on the long side of the entrance building are governing. Due to the large opening in the front side facade, it was assumed that all lateral forces on the long side are taken up by the wall on the back side, being 4.72m. As this assumption from the original design does not lead to an efficient design, two walls will be assumed for the recalculations. Hence, changes to the facade need to be made. For both concrete and CLT, loads will be determined to check feasibility of either of the variants.

Below, a visualisation of the loading direction is provided, and calculations are shown to determine the maximum moment for the governing stability element.

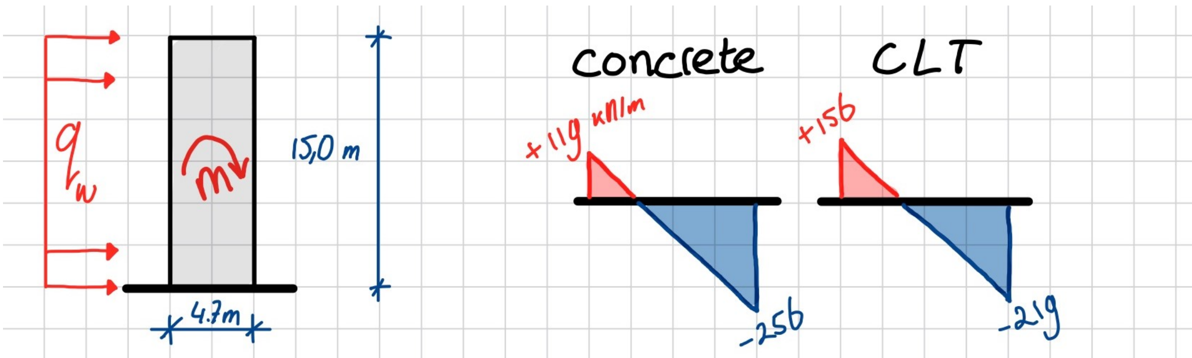


Figure B.6: Visualisation of wind load perpendicular to the longitudinal facade of the entrance building and resulting forces on each transverse wall.

$$\begin{aligned} q_{w,\text{tot}} &= q_p(z) \cdot c_{\text{s}}c_{\text{d}} \cdot 0.85 \cdot c_{pE,\text{tot}} \cdot b \\ &= 0.98 \cdot 0.95 \cdot 0.85 \cdot 1.4 \cdot 6.15 \\ &= 6.8\,\text{kN/m} \end{aligned}$$

$$M_{\text{tot}} = 1.1 \cdot 1.1 \cdot 0.5 \cdot q_w \cdot h^2 = 925\,\text{kNm}$$
$$M_{\text{element}} = 0.5 \cdot M_{\text{tot}} = 925\,\text{kNm}$$
$$Q_w = \frac{M_{\text{element}}}{\frac{1}{6} \cdot d^2} = \frac{462.5 \cdot 10^6}{\frac{1}{6} \cdot 4720^2} = 125.0\,\text{kN/m}$$

When applying load factors, the maximum forces are as shown below. Left indicates the wind pressure side; right indicates the wind suction side:

$$\begin{aligned} Q_{,\text{concrete,left}} &= -0.9 \cdot Q_G + 1.5 \cdot Q_{\text{wind}} \\ &= -0.9 \cdot \left(15m \cdot 0.15m * 25kN/m^3 + 5 \cdot 2\text{m}^2/m \cdot 2.0\text{kN/m}^2\right) + 1.5 \cdot 125.0 \\ &= -68.6 + 187.5 = +118.9\,\text{kN/m} \end{aligned}$$

$$\begin{aligned} Q_{\text{,concrete,right}} &= 0.9 \cdot Q_G - 1.5 \cdot Q_{\text{wind}} \\ &= -0.9 \cdot \left(15m \cdot 0.15m * 25kN/m^3 + 5 \cdot 2\text{m}^2/m \cdot 2.0\text{kN/m}^2\right) - 1.5 \cdot 125.0 \\ &= -68.6 - 187.5 = -256.1\,\text{kN/m} \end{aligned}$$

$$\begin{aligned} Q_{\text{,CLT,left}} &= -0.9 \cdot Q_G + 1.5 \cdot Q_{\text{wind}} \\ &= -0.9 \cdot \left(15m \cdot 1.0kN/m^2 + 5 \cdot 2\text{m}^2/m \cdot 2.0\text{kN/m}^2\right) + 1.5 \cdot 125.0 \\ &= -31.5 + 187.5 = +156\,\text{kN/m} \end{aligned}$$

$$\begin{aligned} Q_{\text{,CLT,right}} &= 0.9 \cdot Q_G - 1.5 \cdot Q_{\text{wind}} \\ &= -0.9 \cdot \left(15m \cdot 1.0kN/m^2 + 5 \cdot 2\text{m}^2/m \cdot 2.0\text{kN/m}^2\right) - 1.5 \cdot 125.0 \\ &= -31.5 - 187.5 = -219.0\,\text{kN/m} \end{aligned}$$

As can be concluded, tension forces are too large for connections in the CLT wall. For concrete walls, forces will be significant yet possible to transfer.

B.3. Exploratory calculations for connections

For exploratory calculations for connections, the maximum capacity of the largest element per type has been determined, based on the following formula:

$$R_{1,d} = \min\left(\frac{R_{k,\text{timber}} \cdot k_{\text{mod}}}{\gamma_M}, \frac{R_{k,\text{steel}}}{\gamma_{M0}}, R_{d,\text{concrete}}\right)$$

For each connection, the elements below have been chosen. Elements are based on a design guide by Rothoblaas, and capacity is calculated based on values from this guide.

Timber-to-concrete connections:

$$\begin{aligned} \text{Hold down: WHT55} \quad & R_{1,d} = \min\left(\frac{141.5 \cdot 0.8}{1.25}, \frac{120}{1.00}, 107\right) = 90.5\,\text{kN} \\ \text{Angle bracket: TTN240} \quad & R_{1,d} = \frac{71.4 \cdot 0.8}{1.25} = 45.7\,\text{kN}, \quad R_{2/3,d} = \frac{81.7 \cdot 0.8}{1.25} = 52.3\,\text{kN} \\ \text{Tensile plate: WHT plate 540} \quad & R_{1,d} = \frac{84.9 \cdot 0.8}{1.25} = 54.4\,\text{kN} \\ \text{Shear plate: TCP300} \quad & R_{2/3,d} = \frac{59.4 \cdot 0.8}{1.25} = 38\,\text{kN} \end{aligned}$$

Timber-to-timber connections:

$$\begin{aligned} \text{Hold down: WKR285} \quad & R_{1,d} = \frac{57.6 \cdot 0.8}{1.25} = 36.9\,\text{kN} \\ \text{Angle bracket: TTV240} \quad & R_{1,d} = \frac{99 \cdot 0.8}{1.25} = 63\,\text{kN}, \quad R_{2/3,d} = \frac{61 \cdot 0.8}{1.25} = 39\,\text{kN} \\ \text{Tensile plate: WHTPT820} \quad & R_{1,d} = \frac{202.7 \cdot 0.8}{1.25} = 129\,\text{kN} \\ \text{Shear plate: TTP300} \quad & R_{2/3,d} = \frac{59.2 \cdot 0.8}{1.25} = 37\,\text{kN} \end{aligned}$$

Besides, the tensile capacity of CLT L7s 180 panels with strength C24 has been calculated, based on a connection with a width of 100mm. Note that only 120mm of the CLT layers have an orientation parallel to the grain, for the check is performed.

$$\frac{\sigma_{t,d}}{f_{t,0,x,d}} = \frac{10.8}{10.7} = 1.01 > 1$$
$$\sigma_{t,d} = \frac{129000}{120 \cdot 100} = 10.8\,\text{N/mm}^2$$
$$f_{t,0,x,d} = \frac{k_{\text{sys}} \cdot k_{\text{mod}} \cdot f_{t,0,x,k}}{\gamma_M} = \frac{1.15 \cdot 0.8 \cdot 14.5}{1.25} = 10.7\,\text{N/mm}^2$$

While this value is not sufficient, when the impact of layers perpendicular to the grain is accounted for, sufficient capacity is present.

B.4. Exploratory calculations for galleries and balconies

Below, exploratory calculations for GWP or costs are performed for several gallery and balcony variants.

Gallaries

Below, exploratory calculations for the total volume of three variants of galleries are shown.

Variant 1 - Concrete - semi-separate structure:

$$\text{Volume of concrete slab} = 1.7\text{m} \cdot 6.8\text{m} \cdot 0.25\text{m} = 2.89\,\text{m}^3$$
$$\text{Volume of concrete columns} = 3.0\text{m} \cdot 0.2\text{m} \cdot 0.2\text{m} = 0.12\,\text{m}^3$$
$$\text{Total concrete volume} = 2.89 + 0.12 = 3.01\,\text{m}^3/\text{apartment}$$
$$\text{GWP} = 960\,\text{kg CO}_2\text{-eq.}$$

Variant 2 - Steel - semi-separate structure:

$$\text{Length of beams} = 6.8\,\text{m} + 2 \cdot 1.7\,\text{m} = 10.2\,\text{m}$$
$$\text{Assuming HEA140, mass of beams} = 256\,\text{kg}$$
$$\text{Length of columns} = 3.0\,\text{m}$$
$$\text{Assuming RHS200x100, mass of beams} = 105\,\text{kg}$$
$$\text{Total mass of steel} = 256 + 105 = 360\,\text{kg}/\text{apartment}$$
$$\text{GWP} = 670\,\text{kg CO}_2\text{-eq.}$$

Variant 3 - Steel - separate structure:

$$\text{Length of beams} = 2 \cdot 6.8\,\text{m} + 2 \cdot 1.7\,\text{m} = 17.0\,\text{m}$$
$$\text{Assuming HEA140, mass of beams} = 427\,\text{kg}$$
$$\text{Length of columns} = 2 \cdot 3.0\text{m} = 6.0\,\text{m}$$
$$\text{Assuming RHS200x100, mass of beams} = 210\,\text{kg}$$
$$\text{Total mass of steel} = 427 + 210 = 637\,\text{kg}/\text{apartment}$$
$$\text{GWP} = 1178\,\text{kg CO}_2\text{-eq.}$$

As a result, variant 2 is preferable. Note that light/timber floors have not been included, but are assumed to have minimum impact.

Balconies

Below, exploratory calculations for the total volume of two variants of balconies are shown.

Variant 1 - Concrete - semi-separate structure:

$$\text{Volume of concrete slab} = 6.18\text{m}^3 \cdot 0.28\text{m} = 1.7\,\text{m}^3$$
$$\text{GWP} = 553\,\text{kg CO}_2\text{-eq.}$$

Variant 2 - Steel - semi-separate structure:

$$\begin{aligned}\text{Length of beams} &= 2 \cdot 2.3\,\text{m} + 1 \cdot 3.0\,\text{m} = 7.3\,\text{m}\\ \text{Assuming HEA140, mass of beams} &= 184\,\text{kg}\\ \text{GWP} &= 338\,\text{kg CO}_2\text{-eq.}\end{aligned}$$

As a result, variant 2 is preferable. Note that light/timber floors have not been included, but are assumed to have minimum impact.

Loggia vs. balcony

The decision not to include a loggia, aninternally integrated balcony, has been made due to the significantly higher costs associated with the additional walls required for its construction in comparison to a relatively simpler steel supporting structure.

B.5. Exploratory calculations for pile capacity

Below, the compression and tension capacity have been determined for a square prefab pile in concrete to a depth of NAP -18m. The calculations are based on base and shaft resistance, following from the soil investigation report shown on the next pages.

$$\begin{aligned}Q_{\text{compression}} &= Q_s + Q_b = \alpha_s \cdot q_c \cdot A_s + \alpha_p \cdot q_c \cdot A_b\\ &= 0.010 \cdot 4000 \cdot (4.0 \cdot 4.0 \cdot 0.32) + 0.7 \cdot 4000 \cdot 0.32^2\\ &= 205 + 286 = 491\,\text{kN}\end{aligned}$$

$$\begin{aligned}Q_{\text{tension}} &= Q_s = \alpha_t \cdot q_c \cdot A_s\\ &= 0.007 \cdot 4000 \cdot (4.0 \cdot 4.0 \cdot 0.32) = 143\,\text{kN}\end{aligned}$$

Note that due to measurement inconsistency, $q_c = 4000kPa$ will be assumed for the layer NAP-14m to NAP-18m. Only this layer will be accounted for in the calculation of the shaft resistance. The following capacities have been calculated for prefab concrete piles with other dimensions, also placed to a depth of NAP-18m:

For piles square 290mm:

$$\begin{aligned}Q_{\text{compression}} &= Q_s + Q_b = 186 + 235 = 421\,\text{kN}\\ Q_{\text{tension}} &= Q_s = 129\,\text{kN}\end{aligned}$$

For piles square 350mm:

$$\begin{aligned}Q_{\text{compression}} &= Q_s + Q_b = 224 + 343 = 567\,\text{kN}\\ Q_{\text{tension}} &= Q_s = 157\,\text{kN}\end{aligned}$$

Below, two pages of the soil investigation report have been shown. These figures have been used to determine the capacity of the foundation piles on the previous page.

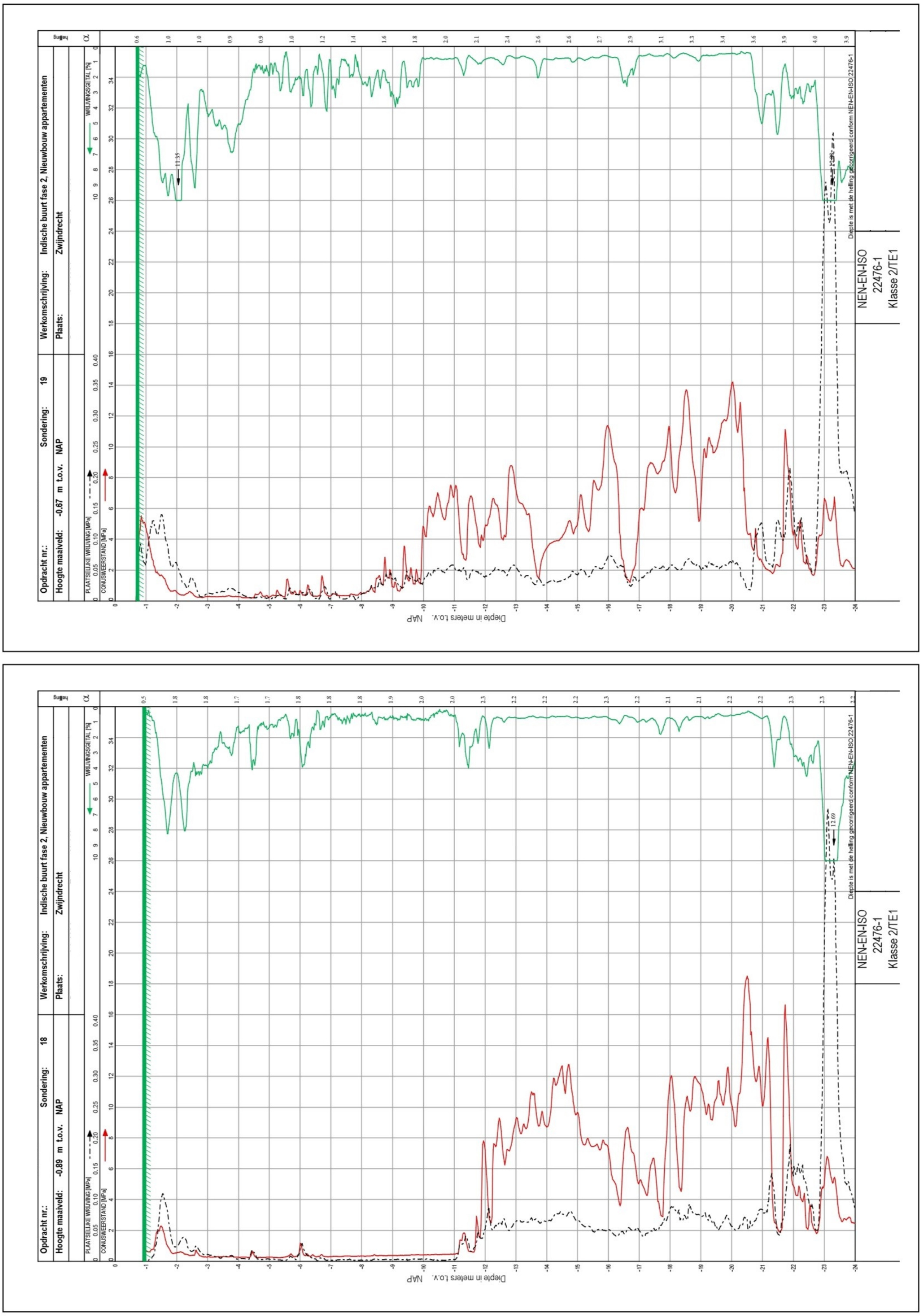
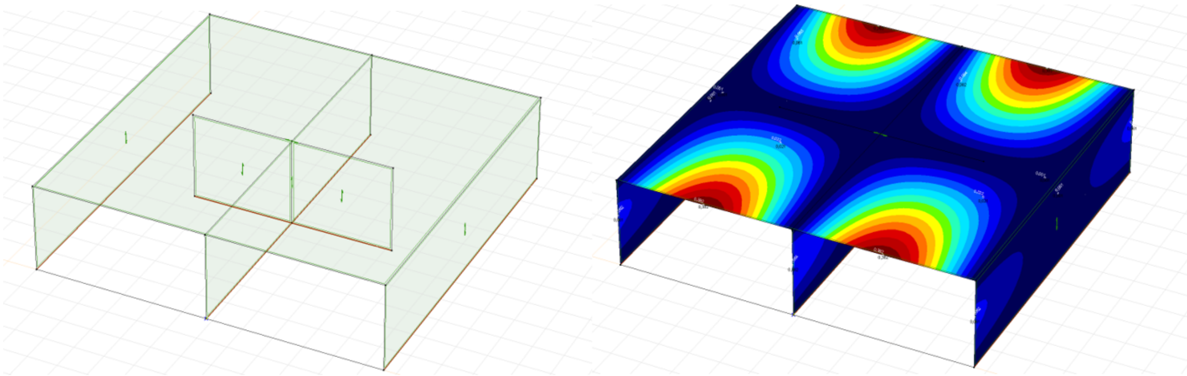


Figure B.7: Section of the soil investigation report.

B.6. Exploratory calculations for reducing floor spans

Based on preliminary calculations, the floor size for a CLT-dry screed floor has been selected as CLT 200 L7s for a span of 6.0m. This selection was made by evaluating the lowest fundamental frequencies for various floor thicknesses and determining the minimum required thickness to achieve a frequency above 8.0 Hz. This approach was chosen because it proved to be governing in earlier calculations for a span of 6.8m. Internal CLT stability walls are assumed, with a length of 3.0m per apartment. The following values for the lowest fundamental frequencies have been found:



CLT 220 L7s	CLT 200 L7s	CLT 180 L5s
Modus 1 (8,83 Hz)	Modus 1 (8,47 Hz)	Modus 1 (7,97 Hz)
Modus 2 (8,97 Hz)	Modus 2 (8,54 Hz)	Modus 2 (8,02 Hz)
Modus 3 (10,18 Hz)	Modus 3 (10,22 Hz)	Modus 3 (9,76 Hz)
Modus 4 (10,98 Hz)	Modus 4 (10,46 Hz)	Modus 4 (9,80 Hz)
Modus 5 (11,11 Hz)	Modus 5 (10,53 Hz)	Modus 5 (10,24 Hz)
Modus 6 (12,97 Hz)	Modus 6 (11,54 Hz)	Modus 6 (10,38 Hz)
Modus 7 (14,08 Hz)	Modus 7 (12,23 Hz)	Modus 7 (10,82 Hz)
Modus 8 (14,42 Hz)	Modus 8 (12,98 Hz)	Modus 8 (11,73 Hz)
Modus 9 (15,39 Hz)	Modus 9 (13,60 Hz)	Modus 9 (12,14 Hz)

Figure B.8: Overview of finite element model and resulting fundamental frequencies for various floor sizes.

Note that CLT 200 L7s has not been checked on other ULS and SLS capacities or other stability systems. However, relevant checks will be performed in the final calculations. CLT-concrete composite floors are assumed more stiff for similar dimensions, hence CLT-dry screed floors are governing.

C

Details on structural verifications of redesigns

In this Appendix, all structural verifications will be shown. Note that verifications are sorted by element, not by variants. This approach has been chosen as many elements are similar for various variants. When relevant, governing elements and loads will be selected and choices will be explained.

C.1. Structural verifications of floors

Introduction

In this section, the three floor types that will be used for the storey floors will be verified, being:

- CLT-dry screed: CLT 240 L7s, using C24 spruce;
- CLT-concrete composite: CLT 140 C5s, using C24 spruce and 100mm concrete C25/30;
- Timber hollow core: Kerto-Ripa Box 280, using Kerto LVL S-panels and Q-panels;

Note that several variants will use the same floor, hence the combined verification. The following assumptions will be made

- Panels will be have the length of two apartments: 2 x 6.82m, leading to a span over three supports
- Dead-load of 1.5kN/m^2 for CLT-dry screed floors and hollow core timber floors, a dead-load of 0.5kN/m^2 for the CLT-concrete composite floors, additional to the self-weight of the element.
- Variable load of 2.55kN/m^2;
- Service class 2;
- Fire resistance of 90 minutes to fire from the bottom side only;
- Damping coefficient of 2.5% for CLT and 1.0% for other timber floors;
- Serviceability limits as stated in NEN regulations and local building codes.

In this research, static structural verifications will be performed using the design tool Calculatis by Stora Enso. Dynamic structural verifications - namely SLS limits for vibrations - will be performed using AxisVM. The results of both tools will be verified by hand calculations to verify the tools.

On the following pages, the load and material factors will be given, and an overview of the applied loads and their resulting forces will be provided. Afterwards, structural verifications will be given per floor type.

Load factors

γ-factors (assuming CC2, so K_{FI}=1,0)

Design situation	Permanent loads		Variable loads	
	Unfavourable	Favourable	Leading	Other
ULS 1	1.35	0.9	-	$1.5 \cdot \Psi_{0,i}$
ULS 2	1.2	0.9	1.5	$1.5 \cdot \Psi_{0,i}$
ULS fire	1.0	0.9	$1 \cdot \Psi_{1,i}$	-
SLS	1	-	1	$1 \cdot \Psi_{0,i}$
SLS vibrations	1	-	0.1	-

Ψ-factors

Category	Ψ_0	Ψ_1	Ψ_2
	factor for combination value of a variable action	factor for frequent value of a variable action	factor for quasi-permanent value of a variable action
A – residential	0.4	0.5	0.3

Figure C.1: Overview of load factors used in further calculations

Material factors

Use class 1 is sufficient (Situations in which the wood or wood-based product is inside a construction, not exposed to the weather and wetting.

Service class 1 or 2 is assumed (RH in construction lower than 12% / 20%)

Modification factors (k_{mod})

Load duration class	Permanent	Long-term	Medium-term	Short-term	instantaneous
	Self-weight	Storage	Imposed floor load	Snow, wind	Wind, accidental load
Service class 1/2	0.6	0.7	0.8	0.9	1.1

Creep factors (k_{def})

Service class	**1**	**2**
Solid timber, glulam (QR)	0.6	0.8
CLT (handbook)	0.85	1.1

system strength factor (k_{sys})

k_{sys} is assumed to be 1.15, assuming an effective width larger than 1.5m

γ-factors

Glulam, CLT	1.25
Solid timber/connection	1.30

Figure C.2: Overview of material factors for timber used in further calculations

Applied loads and force distribution

For the detailed calculations, the force distributions, as shown below, will be used, based on distributed load Q and a span between two supports of L.

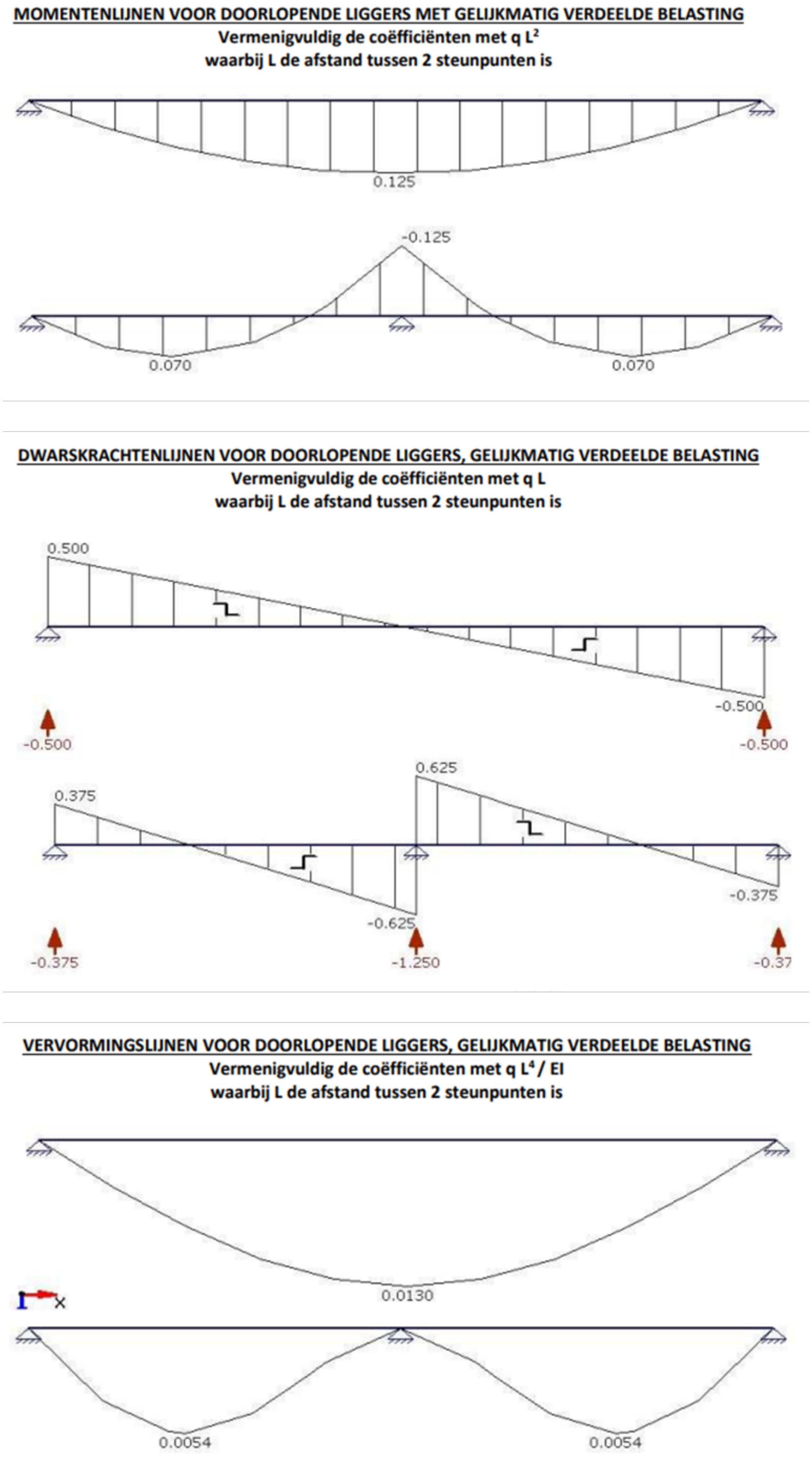
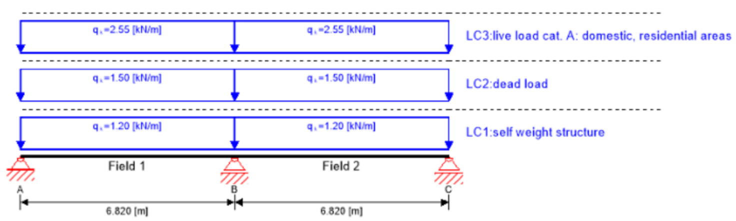


Figure C.3: Overview of force distributions for continuous elements.

C.1.1. CLT-dry screed floors, span 6.8m

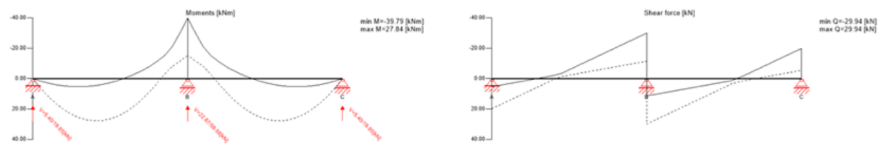
As can be seen below, all static verifications have unity checks well below 100%. While also true for vibrations, the minimum calculated frequency is not below 8.0 Hz, as a result of different limits in the design tool. As support reactions are simplified in this variant, it is likely that the lowest frequency is above the threshold when these support reactions are taken into account more accurately

System



Section: CLT 240 L7s; **Material**: C24 spruce ETA (2022); **Service class**: service class 2; **Fire resistance class**: R 90

Utilization 67%



w_{inst} = w[char] ✓					
Field	K_{def}	Limit [-]	w_{limit} [mm]	$w_{calc.}$ [mm]	Ratio
1	1	L/250	27.3	11.4	42%
2	1	L/250	27.3	11.5	42%

w_{fin} = w[char] + w[q.p.]*kdef ✓					
Field	K_{def}	Limit [-]	w_{limit} [mm]	$w_{calc.}$ [mm]	Ratio
1	1	L/250	27.3	18.2	67%
2	1	L/250	27.3	18.3	67%

$w_{net,fin}$ = w[frq] - w[D.L] + w[q.p.]*kdef ✓					
Field	K_{def}	Limit [-]	w_{limit} [mm]	$w_{calc.}$ [mm]	Ratio
1	1	L/333	20.5	10.1	49%
2	1	L/333	20.5	10.1	50%

Flexural stress analysis							38%
$M_{y,d}$ =	-39.79	kNm		$f_{m,k}$ =	24.00	N/mm²	
$M_{z,d}$ =	0.00	kNm		$f_{m,k,z}$ =	24.00	N/mm²	
$N_{t,d}$ =	0.00	kN		$f_{t,0,k}$ =	0.00	N/mm²	
$\sigma_{t,d}$ =	0.00	N/mm²		$f_{t,0,d}$ =	8.96	N/mm²	
$\sigma_{m,y,d}$ =	-6.42	N/mm²		$f_{m,y,d}$ =	16.90	N/mm²	
$\sigma_{m,z,d}$ =	0.00	N/mm²	<	$f_{m,z,d}$ =	0.00	N/mm²	✓
Shear stress analysis							7%
V_d =	-29.94	kN		$f_{v,k}$ =	4.00	N/mm²	
$\tau_{v,d}$ =	0.17	N/mm²	<	$f_{v,d}$ =	2.56	N/mm²	✓
Rolling shear analysis							25%
V_d =	-29.94	kN		$f_{r,k}$ =	1.05	N/mm²	
$\tau_{r,d}$ =	0.17	N/mm²	<	$f_{r,d}$ =	0.67	N/mm²	✓

Flexural stress analysis Fire							24%
$M_{y,d}$ =	-19.83	kNm		$f_{m,k}$ =	24.00	N/mm²	
$M_{z,d}$ =	0.00	kNm		$f_{m,k,z}$ =	24.00	N/mm²	
$N_{t,d}$ =	0.00	kN		$f_{t,0,k}$ =	0.00	N/mm²	
$\sigma_{t,d}$ =	0.00	N/mm²		$f_{t,0,d}$ =	16.10	N/mm²	
$\sigma_{m,y,d}$ =	-7.14	N/mm²		$f_{m,y,d}$ =	30.36	N/mm²	
$\sigma_{m,z,d}$ =	0.00	N/mm²	<	$f_{m,z,d}$ =	0.00	N/mm²	✓
Shear stress analysis Fire							3%
V_d =	-14.72	kN		$f_{v,k}$ =	4.00	N/mm²	
$\tau_{v,d}$ =	0.12	N/mm²	<	$f_{v,d}$ =	4.60	N/mm²	✓
Rolling shear analysis Fire							9%
V_d =	-14.72	kN		$f_{r,k}$ =	1.05	N/mm²	
$\tau_{r,d}$ =	0.11	N/mm²	<	$f_{r,d}$ =	1.21	N/mm²	✓

Vibration analysis					98%
Criterion	Calc.	Cl. I	Cl. II	Cl. I	Cl. II
Frequency min	6.084	4.5	4.5	✓	✓
Frequency	6.084	8.0	6.0	-	✓
Acceleration	0.049	0.05	0.1	✓	✓
Stiffness	0.139	0.25	0.5	✓	✓

Figure C.4: Summary of static and dynamic structural verifications for CLT-dry screed floors, span 6.8m

When modelling a part of the building in a finite element model, as shown below, more extensive calculations can be made. When including the stability walls in the facades, the lowest fundamental frequencies are much higher than the above values; at 12.96 Hz, serviceability limits are fulfilled.

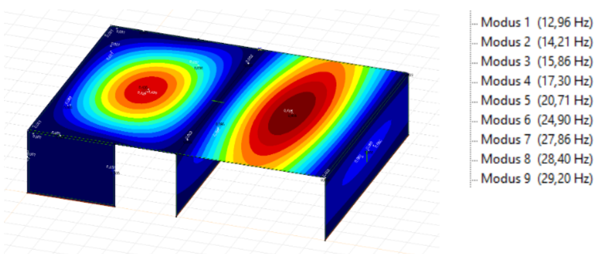


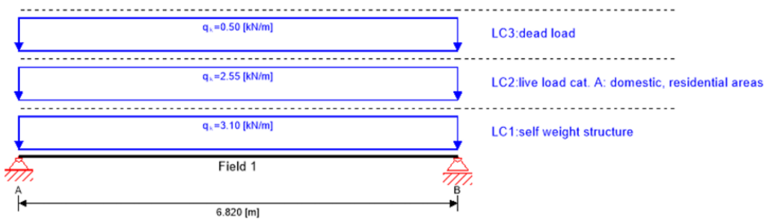
Figure C.5: Summary of vibration analaysis for CLT-dry screed floors, span 6.8m

C.1.2. CLT-concrete composite floors, span 6.8m

As shown below, the design tool does not support continuous spans. However, since forces are higher when verifying the structural integrity of single-floor spans, it is assumed that continuous spans will also meet the strength requirements. As can be seen below, all static verifications have unity checks well below 100%.

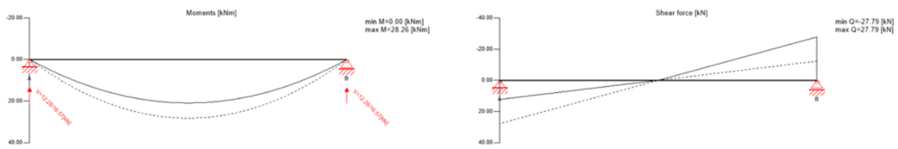
However, the lowest fundamental frequency is not above 8.0 Hz. As the stiffness of this floor is much higher compared to the variant in CLT with a dry screed floor, and the weight is roughly similar, no finite element model is created to verify the gain in the lowest fundamental frequency by improved support conditions and continuous span over multiple supports.

System



Section: Timber-concrete composite floor: 10 - CLT 140 L5s; **Material**: C24 spruce ETA (2022); **Service class**: service class 2; **Fire resistance class**: R 0

Utilization 58%



Flexural stress analysis							34%
$M_{y,d}$ =	34.00	kNm		$f_{m,k}$ =	30.00	N/mm²	
$\sigma_{m,y,d}$ =	-6.84	N/mm²	<	$f_{m,y,d}$ =	20.00	N/mm²	✓
Shear stress analysis							6%
V_d =	-27.79	kN		$f_{v,k}$ =	4.00	N/mm²	
$\tau_{v,d}$ =	0.16	N/mm²	<	$f_{v,d}$ =	2.56	N/mm²	✓
Rolling shear analysis							17%
V_d =	-27.79	kN		$f_{r,k}$ =	1.25	N/mm²	
$\tau_{r,d}$ =	0.13	N/mm²	<	$f_{r,d}$ =	0.80	N/mm²	✓

w_{inst} = w[char] ✓

Field	K_{def}	Limit	w_{limit}	$w_{calc.}$	Ratio
		[-]	[mm]	[mm]	
1	1	L/250	27.3	10.2	37%

$w_{net,fin}$ = w[frq] - w[D.L] + w[q.p.]*kdef ✓

Field	K_{def}	Limit	w_{limit}	$w_{calc.}$	Ratio
		[-]	[mm]	[mm]	
1	1	L/333	20.5	9.3	46%

Vibration analysis 95%

Criterion	Calc.	Cl. I	Cl. II	Cl. I	Cl. II
Frequency min	7.273	4.5	4.5	✓	✓
Frequency	7.273	8.0	6.0	-	✓
Acceleration	0.047	0.05	0.1	✓	✓
Stiffness	0.09	0.25	0.5	✓	✓

Figure C.6: Summary of static structural verifications for CLT-concrete composite floors, span 6.8m

C.1.3. Hollow core timber floors, span 6.8m

Contrary to the elements mentioned in the main part of this research, Kerto-Ripa Box 280, the dimensioning of elements in earlier design stages has been performed using the same design tool as for CLT floors: Calculatis by Stora Enso. As both elements consist of various LVL elements with roughly the same characteristics, and can have similar dimensions, the verifications of earlier design stages are assumed to be valid for the final design.

Again, the design tool is not suitable to check for continuous spans. However, the same assumption is made as has been done for CLT-concrete composite floors. As can be seen below, all static requirements for the chosen configuration are fulfilled. For vibrations, the acceleration and stiffness criteria are not sufficient. More attention will be needed for this in later hand verifications, and conclusions will be drawn based on that.

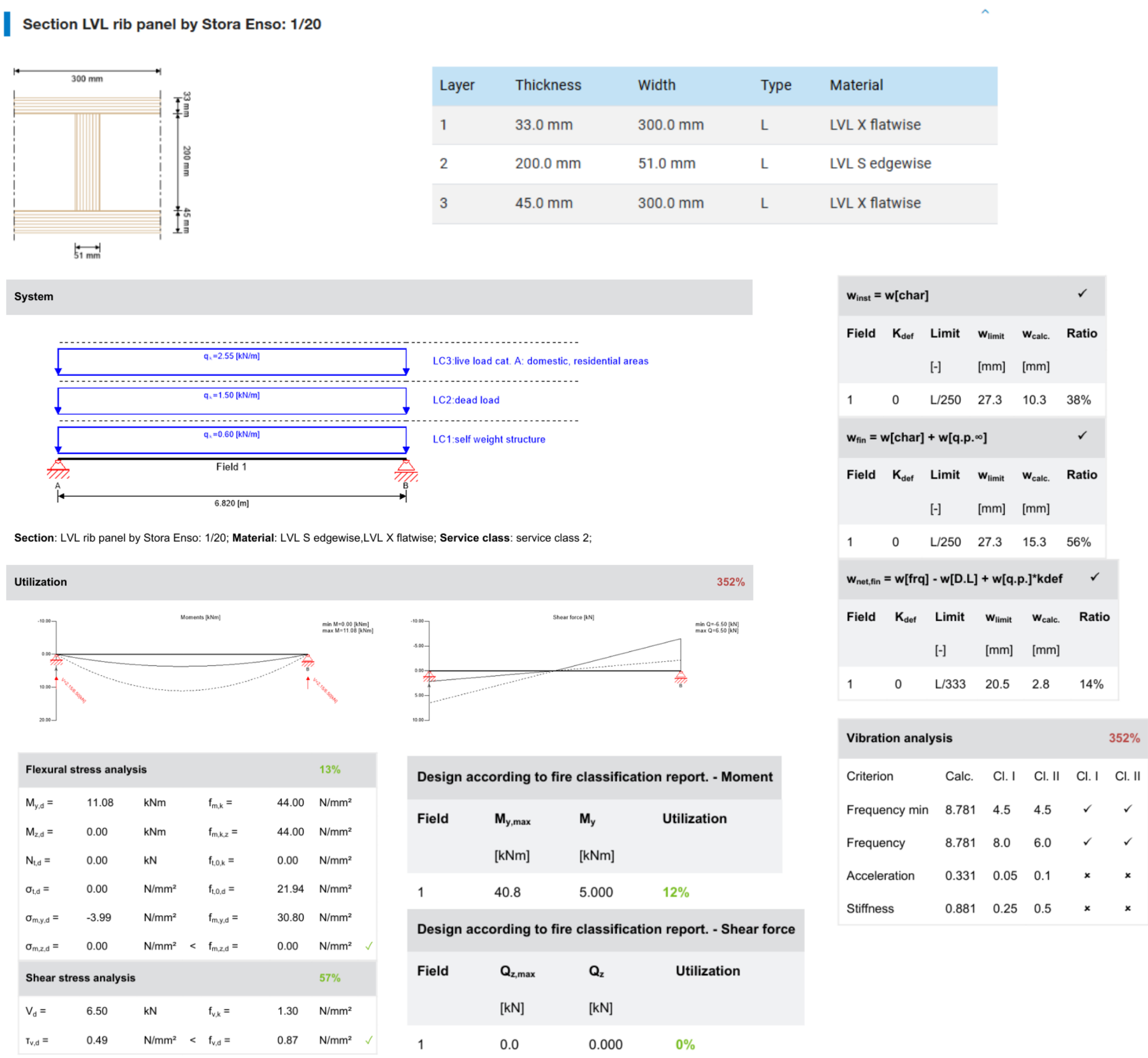
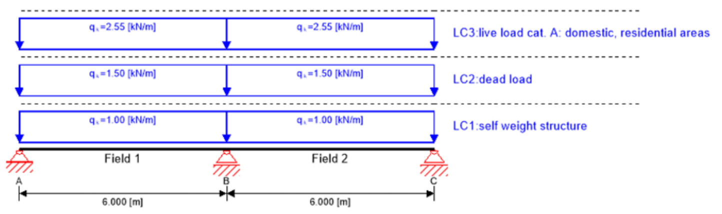


Figure C.7: Summary of static structural verifications for hollow core timber floors, span 6.8m

C.1.4. CLT-dry screed floors, span 6.0m

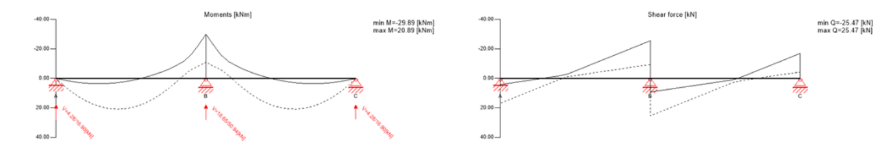
As can be seen below, all static verifications have unity checks well below 100%. For vibrations, verifications are not sufficient. However, as this floor type will be combined with internal stability walls, the influence of this will lead to sufficient verifications, as will be shown below.

System



Section: CLT 200 L7s; **Material**: C24 spruce ETA (2022); **Service class**: service class 2; **Fire resistance class**: R 90

Utilization 87%



w_{inst} = w[char] ✓

Field	K_{def}	Limit	w_{limit}	$w_{calc.}$	Ratio
		[-]	[mm]	[mm]	
1	1	L/250	24.0	13.2	55%
2	1	L/250	24.0	13.3	55%

w_{fin} = w[char] + w[q.p.]*kdef ✓

Field	K_{def}	Limit	w_{limit}	$w_{calc.}$	Ratio
		[-]	[mm]	[mm]	
1	1	L/250	24.0	20.8	87%
2	1	L/250	24.0	20.9	87%

$w_{net,fin}$ = w[frq] - w[D.L] + w[q.p.]*kdef ✓

Field	K_{def}	Limit	w_{limit}	$w_{calc.}$	Ratio
		[-]	[mm]	[mm]	
1	1	L/333	18.0	11.6	64%
2	1	L/333	18.0	11.7	65%

Flexural stress analysis							49%
$M_{y,d}$ =	-29.89	kNm		$f_{m,k}$ =	24.00	N/mm²	
$M_{z,d}$ =	0.00	kNm		$f_{m,k,z}$ =	24.00	N/mm²	
$N_{t,d}$ =	0.00	kN		$f_{t,0,k}$ =	0.00	N/mm²	
$\sigma_{t,d}$ =	0.00	N/mm²		$f_{t,0,d}$ =	8.96	N/mm²	
$\sigma_{m,y,d}$ =	-8.24	N/mm²		$f_{m,y,d}$ =	16.90	N/mm²	
$\sigma_{m,z,d}$ =	0.00	N/mm²	<	$f_{m,z,d}$ =	0.00	N/mm²	✓
Shear stress analysis							7%
V_d =	-25.47	kN		$f_{v,k}$ =	4.00	N/mm²	
$\tau_{v,d}$ =	0.17	N/mm²	<	$f_{v,d}$ =	2.56	N/mm²	✓
Rolling shear analysis							25%
V_d =	-25.47	kN		$f_{r,k}$ =	1.05	N/mm²	
$\tau_{r,d}$ =	0.17	N/mm²	<	$f_{r,d}$ =	0.67	N/mm²	✓

Flexural stress analysis Fire							51%
$M_{y,d}$ =	-14.58	kNm		$f_{m,k}$ =	24.00	N/mm²	
$M_{z,d}$ =	0.00	kNm		$f_{m,k,z}$ =	24.00	N/mm²	
$N_{t,d}$ =	0.00	kN		$f_{t,0,k}$ =	0.00	N/mm²	
$\sigma_{t,d}$ =	0.00	N/mm²		$f_{t,0,d}$ =	16.10	N/mm²	
$\sigma_{m,y,d}$ =	15.62	N/mm²		$f_{m,y,d}$ =	30.36	N/mm²	
$\sigma_{m,z,d}$ =	0.00	N/mm²	<	$f_{m,z,d}$ =	0.00	N/mm²	✓
Shear stress analysis Fire							4%
V_d =	-12.22	kN		$f_{v,k}$ =	4.00	N/mm²	
$\tau_{v,d}$ =	0.20	N/mm²	<	$f_{v,d}$ =	4.60	N/mm²	✓
Rolling shear analysis Fire							16%
V_d =	-12.22	kN		$f_{r,k}$ =	1.05	N/mm²	
$\tau_{r,d}$ =	0.20	N/mm²	<	$f_{r,d}$ =	1.21	N/mm²	✓

Vibration analysis 144%

Criterion	Calc.	Cl. I	Cl. II	Cl. I	Cl. II
Frequency min	5.703	4.5	4.5	✓	✓
Frequency	5.703	8.0	6.0	×	-
Acceleration	0.072	0.05	0.1	×	✓
Stiffness	0.198	0.25	0.5	✓	✓

Figure C.8: Summary of static structural verifications for CLT-dry screed floors, span 6.0m

When modelling a part of the building in a finite element model, as shown below, more extensive calculations can be made. When including the stability walls in the centre of the apartments, the lowest fundamental frequencies are higher than the above values. As the lowest value is 8.47 Hz, serviceability limits are fulfilled. Note that verifications by hand for other criteria will be performed later on.

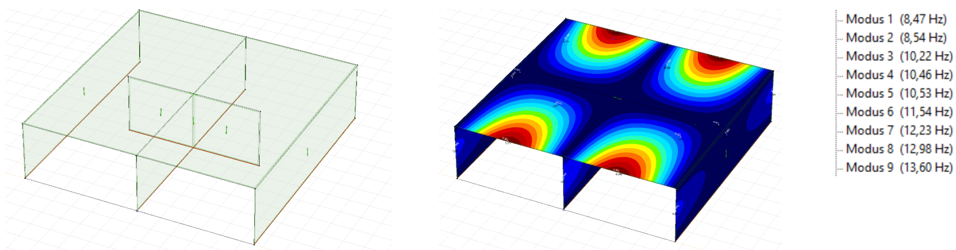


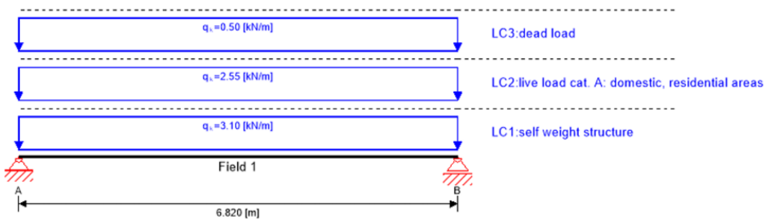
Figure C.9: Summary of vibration analaysis for CLT-dry screed floors, span 6.0m

C.1.5. CLT-concrete composite floors, span 6.0m

As shown below, the design tool does not support continuous spans. However, since forces are higher when verifying the structural integrity of single-floor spans, it is assumed that continuous spans will also meet the strength requirements. As can be seen below, all static verifications have unity checks well below 100%.

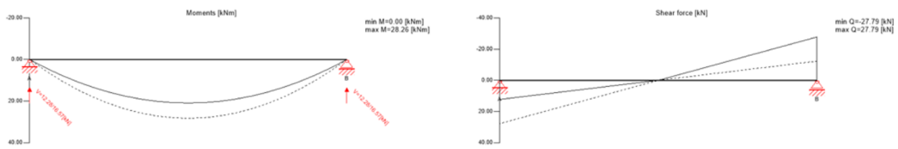
However, the lowest fundamental frequency is not above 8.0 Hz. As the stiffness of this floor is much higher compared to the variant in CLT with a dry screed floor, and the weight is roughly similar, no finite element model is created to verify the gain in the lowest fundamental frequency by improved support conditions and continuous span over multiple supports.

System



Section: Timber-concrete composite floor: 10 - CLT 140 L5s; **Material**: C24 spruce ETA (2022); **Service class**: service class 2; **Fire resistance class**: R 0

Utilization 58%



Flexural stress analysis							34%
$M_{y,d}$ =	34.00	kNm		$f_{m,k}$ =	30.00	N/mm²	
$\sigma_{m,y,d}$ =	-6.84	N/mm²	<	$f_{m,y,d}$ =	20.00	N/mm²	✓
Shear stress analysis							6%
V_d =	-27.79	kN		$f_{v,k}$ =	4.00	N/mm²	
$\tau_{v,d}$ =	0.16	N/mm²	<	$f_{v,d}$ =	2.56	N/mm²	✓
Rolling shear analysis							17%
V_d =	-27.79	kN		$f_{r,k}$ =	1.25	N/mm²	
$\tau_{r,d}$ =	0.13	N/mm²	<	$f_{r,d}$ =	0.80	N/mm²	✓

w_{inst} = w[char] ✓

Field	K_{def}	Limit	w_{limit}	$w_{calc.}$	Ratio
		[-]	[mm]	[mm]	
1	1	L/250	27.3	10.2	37%

$w_{net,fin}$ = w[frq] - w[D.L] + w[q.p.]*kdef ✓

Field	K_{def}	Limit	w_{limit}	$w_{calc.}$	Ratio
		[-]	[mm]	[mm]	
1	1	L/333	20.5	9.3	46%

Vibration analysis 95%

Criterion	Calc.	Cl. I	Cl. II	Cl. I	Cl. II
Frequency min	7.273	4.5	4.5	✓	✓
Frequency	7.273	8.0	6.0	-	✓
Acceleration	0.047	0.05	0.1	✓	✓
Stiffness	0.09	0.25	0.5	✓	✓

Figure C.10: Summary of static structural verifications for CLT-concrete composite floors, span 6.0m

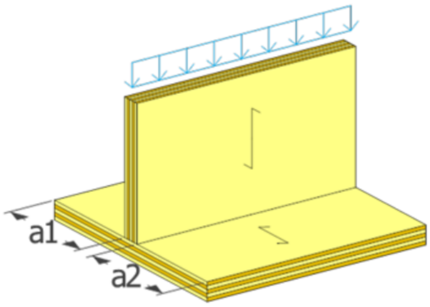
C.1.6. Hollow core timber floors, span 6.0m

The hollow core timber floor selected in this research is a Kerto-Ripa Box of 200mm. These dimensions have been based on ULS and SLS dimensioning tables in the manufacturer's design guides. The previously used design tool Calculatis by Stora Enso does not allow for verifications of elements of this size. Therefore, only hand calculations will be made. CLT floors with a span of 6.8m, hand calculations have been performed to verify the results of the design tools. Below, an overview has been given.

C.1.7. Verifications of connections and supports

Next to the checks for bending, shear and rolling shear capacity, it is important to check the forces at the supports. Compression perpendicular to the grain is governing for this, being highest for the floor on top of the ground floor wall. For both CLT L7s 240 and CLT L7s 200mm, this check will be performed. Maximum loads will be retrieved from the excel sheets used in calculation of loads on the foundation. Note that the values will be verified in the next section, where hand calculations will be made

Support



Support reaction	257	kN/m
Support reaction fire design	202	kN/m
K_{mod}	0.8	-
Material upper element	C24 spruce ETA (2022)	
Material lower element	C24 spruce ETA (2022)	
Upper CLT panel	CLT 180 L5s	
Lower CLT panel	CLT 240 L7s	
a1	3.3	m
a2	3.3	m
Fire resistance class	R 90	
Fire protection system	no fire protection	
Fire protection layering	no additional fire protection	

Lower element

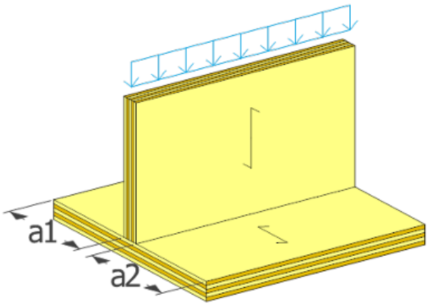
Name	Width	Length	Extension	Area	k_{mod}	γ_m	$k_{c,90}$	$f_{c,k}$	$f_{c,d}$	V_{max}	$\sigma_{c,90,d}$	Ratio
	[mm]	[mm]	[mm]	[cm²]	[-]	[-]	[-]	[N/mm²]	[N/mm²]	[kN]	[N/mm²]	
CLT 240 L7s	180	1000	60	2400.00	0.80	1.25	1.80	2.50	2.88	257.00	1.07	37%

Lower element Fire

Name	Width	Length	Extension	Area	k_{mod}	γ_m	$k_{c,90}$	$f_{c,k}$	$f_{c,d}$	V_{max}	$\sigma_{c,90,d}$	Ratio
	[mm]	[mm]	[mm]	[cm²]	[-]	[-]	[-]	[N/mm²]	[N/mm²]	[kN]	[N/mm²]	
CLT 240 L7s	110	1000	60	1700.00	1.00	1.00	1.80	2.50	5.18	202.00	1.19	23%

Figure C.11: Summary of compression of floors at the supports: compression perpendicular to the grain, for CLT-dry screed floors, span 6.8m

Support



Support reaction	179	kN/m
Support reaction fire design	142	kN/m
K_{mod}	0.8	-
Material upper element	C24 spruce ETA (2022)	
Material lower element	C24 spruce ETA (2022)	
Upper CLT panel	CLT 180 L5s	
Lower CLT panel	CLT 200 L7s	
a1	2.9	m
a2	2.9	m
Fire resistance class	R 90	
Fire protection system	no fire protection	
Fire protection layering	no additional fire protection	

Lower element

Name	Width	Length	Extension	Area	k_{mod}	γ_m	$k_{c,90}$	$f_{c,k}$	$f_{c,d}$	V_{max}	$\sigma_{c,90,d}$	Ratio
	[mm]	[mm]	[mm]	[cm²]	[-]	[-]	[-]	[N/mm²]	[N/mm²]	[kN]	[N/mm²]	
CLT 200 L7s	180	1000	60	2400.00	0.80	1.25	1.80	2.50	2.88	179.00	0.75	26%

Lower element Fire

Name	Width	Length	Extension	Area	k_{mod}	γ_m	$k_{c,90}$	$f_{c,k}$	$f_{c,d}$	V_{max}	$\sigma_{c,90,d}$	Ratio
	[mm]	[mm]	[mm]	[cm²]	[-]	[-]	[-]	[N/mm²]	[N/mm²]	[kN]	[N/mm²]	
CLT 200 L7s	110	1000	60	1700.00	1.00	1.00	1.80	2.50	5.18	142.00	0.84	16%

Figure C.12: Summary of compression of floors at the supports: compression perpendicular to the grain, for CLT-dry screed floors, span 6.0m

C.1.8. Verifications by hand calculations

In this section, structural verification tools will be verified by hand calculations. This will only be done for CLT dry-screed floors with a span of 6.8m. This has been chosen to limit calculations; vibrations are likely to be most influential in dry-screed floors of this size, compared to, for example, CLT-composite floors or smaller spans.

The following verifications will be performed for ULS

- Bending capacity
- Shear capacity
- Rolling shear capacity
- Reaction force capacity at support

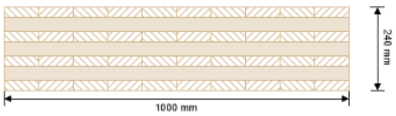
The following verifications will be performed for SLS

- Deflections - instant
- Deflections - final
- Vibrations - lowest fundamental frequency
- Vibrations - stiffness
- Vibrations - impulse velocity response

CLT dry-screed floors, using CLT L7s 240, with a span 6.8m

As retrieved from documentation of the manufacturer, the following cross-sectional quantities are used:

Section CLT 240 L7s



Layer	Thickness	Type	Material
1	30.0 mm	L	C24 spruce ETA (2022)
2	40.0 mm	C	C24 spruce ETA (2022)
3	30.0 mm	L	C24 spruce ETA (2022)
4	40.0 mm	C	C24 spruce ETA (2022)
5	30.0 mm	L	C24 spruce ETA (2022)
6	40.0 mm	C	C24 spruce ETA (2022)
7	30.0 mm	L	C24 spruce ETA (2022)

	Area	Moment of inertia	Section modulus
	[mm²]	[mm⁴]	[mm³]
Net	120,000	744,000,100	6,200,000
Total	240,000	1,152,000,000	9,600,000

Z	Static moment
[mm]	[mm³]
-120	0
-90	3,150,000
-50	3,150,000
-20	4,200,000
0	4,200,000
20	4,200,000
50	3,150,000
90	3,150,000
120	0

Figure C.13: Cross-sectional quantities for Stora Enso CLT L7s 240

The following material values will be used, assuming C24 spruce:

Material values

Material	$f_{m,k}$	$f_{t,0,k}$	$f_{t,90,k}$	$f_{c,0,k}$	$f_{c,90,k}$	$f_{v,k}$	$f_{r,k\,min}$	$E_{0,mean}$	G_{mean}	$G_{r,mean}$
	[N/mm²]	[N/mm²]	[N/mm²]	[N/mm²]	[N/mm²]	[N/mm²]	[N/mm²]	[N/mm²]	[N/mm²]	[N/mm²]
C24 spruce ETA (2022)	24.00	14.00	0.12	21.00	2.50	4.00	1.25	12,000.00	690.00	50.00

Figure C.14: Material values for C24 spruce

Bending moment capacity - Using the values above, the bending moment check is as shown below. Note that the value for the distributed load, $q = 1.2 \cdot 2.5 + 1.5 \cdot 2.55 = 6.83$ kN/m has been used. As can be seen, the values are very similar to those of the design tool. Minor differences are related to small variations in the maximum bending moment and system strength value.

$$\frac{\sigma_{m,y,d}}{f_{m,x\text{lay},d}} = \frac{6.4}{19.4} = 0.33 < 1 \text{, where}$$

$$\sigma_{m,y,d} = \frac{M_{y,d}}{W_{x,\text{net}}} = \frac{\frac{1}{8}ql^2}{W_{x,\text{net}}} = \frac{39.7 \cdot 10^6}{6.2 \cdot 10^6} = 6.4\,\text{N/mm}^2$$

$$f_{m,x\text{lay},d} = k_{\text{sys}} \cdot k_{\text{mod}} \cdot \left(\frac{f_{m,x\text{lay},k}}{\gamma_M}\right) = 1.15 \cdot 0.8 \cdot \frac{24}{1.25} = 19.43\,\text{N/mm}^2$$

Shear force capacity - Below, the shear force capacity check is performed. The values are nearly identical to those of the design tool.

$$\frac{\tau_{V,d}}{f_{V,d}} = \frac{0.16}{2.56} = 0.06 < 1\text{, where}$$

$$\tau_{V,d} = \frac{V_{0,d} \cdot S_{0,V,\text{net}}}{I_{0,\text{net}} \cdot b} = \frac{0.625qL \cdot S_{0,V,\text{net}}}{I_{0,\text{net}} \cdot b} = \frac{29.1 \cdot 10^3 \cdot 4.2 \cdot 10^6}{7.44 \cdot 10^8 \cdot 10^3} = 0.164\,\text{N/mm}^2$$

$$f_{V,d} = k_{\text{mod}} \cdot \frac{f_{V,k}}{\gamma_M} = 0.8 \cdot \frac{4}{1.25} = 2.56\,\text{N/mm}^2$$

Rolling shear force capacity - Below, the rolling shear force capacity check is performed. The values are, again nearly identical to those of the design tool.

$$\frac{\tau_{V,R,d}}{f_{V,R,d}} = \frac{0.123}{0.70} = 0.18 < 1\text{, where}$$

$$\tau_{V,R,d} = \frac{V_{0,d} \cdot S_{0,V,\text{net}}}{I_{0,\text{net}} \cdot b} = \frac{0.625qL \cdot S_{0,V,\text{net}}}{I_{0,\text{net}} \cdot b} = \frac{29.1 \cdot 10^3 \cdot 3.15 \cdot 10^6}{7.44 \cdot 10^8 \cdot 10^3} = 0.123\,\text{N/mm}^2$$

$$f_{V,R,d} = k_{\text{mod}} \cdot \frac{f_{V,R,k}}{\gamma_M} = 0.8 \cdot \frac{1.10}{1.25} = 0.70\,\text{N/mm}^2$$

Reaction force capacity at support - Below, the reaction force capacity at supports will be checked, namely the compression perpendicular to the grain. The values are, again nearly identical to those of the design tool, assuming an influence area of 30mm on both sides.

$$\frac{\sigma_{c,90,d}}{f_{c,90,d}} = \frac{1.07}{2.88} = 0.37 < 1\text{, where}$$

$$\sigma_{c,90,d} = \frac{257000}{240000} = 1.07\,N/mm^2$$

$$\frac{N_{90,d}}{f_{c,90,d}} = \frac{k_{c,90} \cdot f_{c,90,d}}{\gamma_M} = \frac{1.8 \cdot 2.5}{1.25} = 2.88\,N/mm^2$$

Deflection - instant - The instant deflection due to self-weight and variable load will be determined below, using $q_G = 1.0 \cdot 2.5$ and $q_Q = 1.0 \cdot 2.55$. Deflections differ reasonably compared to the design tool used, which can be explained by the difference in deflection limits used. However, all values are well within the limit.

$$\frac{w_{inst,d}}{w_{inst,max}} = \frac{6.35}{\frac{6820}{300}} = \frac{6.35}{22.7} = 0.28 < 1\text{, where}$$

$$w_{inst,G} = \frac{0.0054 \cdot ql^4}{EI} = \frac{0.0054 \cdot 2.5 \cdot 6820^4}{12000 \cdot 744000000} = 3.14\,mm$$

$$w_{inst,Q} = \frac{0.0054 \cdot ql^4}{EI} = \frac{0.0054 \cdot 2.55 \cdot 6820^4}{12000 \cdot 744000000} = 3.21\,mm$$

$$w_{inst,d} = 3.14 + 3.21 = 6.35\,mm$$

Deflection - final - The final deflection, a combination of instant deflection and deflection due to creep, is calculated below. Deflections differ slightly compared to the design tool used, which can be explained by the difference in deflection limits used. However, all values are well within the limit.

$$\frac{w_{\texttt{final,d}}}{w_{final,max}} = \frac{10.86}{\frac{6820}{200}} = \frac{10.86}{34.1} = 0.32 < 1 \text{, where}$$

$$w_{final,G} = (1 + k_{def}) \cdot w_{inst,G} = 2.1 \cdot 3.14 = 6.59\,mm$$

$$w_{final,Q} = (1 + k_{def} \cdot \Psi_2) \cdot w_{inst,Q} = (1 + 1.1 \cdot 0.3) \cdot 3.21 = 4.27\,mm$$

$$w_{final,d} = 6.59 + 4.27 = 10.86\,mm$$

Vibrations - lowest fundamental frequency -The lowest frequency has been checked below. While values align with those of the design tool, they are not within the limits. However, as explained before, FEM has been used to calculate the influence of different support conditions, leading to sufficient values.

$$\frac{8\,Hz}{f_1} = \frac{8}{5.5} = 1.46 > 1 \text{, where}$$

$$f_1 = \frac{\pi}{2l^2} \cdot \sqrt{\frac{EI_{x,eff}}{m}} = \frac{\pi}{2 \cdot 6820^2} \cdot \sqrt{\frac{12000 \cdot 74400000}{250 + 0.3 \cdot 255}} = 5.5\,Hz$$

Vibrations - stiffness - Due to the beam being not simply supported, calculating the deflection as a result of a point load op 1kN is slightly more complex. Using the earlier mentioned FEM model, a maximum deflection of 0.24mm was found for a point load in the centre of one span. Based on this, and using the value of $a = 1\,mm/kN$, sufficient stiffness has been ensured, as shown below.

$$\frac{w_1kN}{1\,kN} = \frac{0.24}{1.0} = 0.24 < a = 1.0$$

Vibrations - impulse velocity response - Using the value of $b = 120\,m/Ns^2$, the impuls velocity has been checken. Note that a relative damping of 2.5% has been assumed, and an initial fundamental frequency of 8 Hz. Values are significantly different to earlier calculations by the design tools, most likely as a result of the assumed width of a slab being 10m.

$$\frac{v}{b^{(f_1 \cdot \xi - 1)}} = \frac{0.000483}{0.0217} = 0.022 < 1 \text{, where}$$

$$v = \frac{(4 \cdot 0.4 + 0.6 \cdot n_{40})}{(mBL + 200)} = \frac{(4 \cdot 0.4 + 0.6 \cdot 3.84)}{((250 + 0.3 \cdot 255) \cdot 10 \cdot 6.82 + 200)} = 0.000483\,m/Ns^2$$

$$b^{(f_1 \cdot \xi - 1)} = 120^{(8 \cdot 0.025 - 1)} = 0.0217\,m/Ns^2$$

As all verifications are either in line with those of the design tool or will be verified using a finite element model for vibrations, the design tool is assumed sufficiently correct for the level of detail of this research.

C.2. Structural verifications of walls

Hand calculations will perform structural verifications of walls for the most governing CLT walls. Depending on whether self-weight will act favourable or unfavourable, different floor loads will be selected.

The following checks will be performed for ULS:

- Bending and compression capacity in plane
- Bending and compression capacity out of plane
- Shear force capacity

The following check will be performed for SLS:

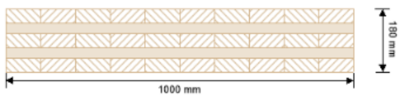
- Deformation

Note that potential tension forces on the foundation have already been calculated in the preliminary design stage and are found within acceptable limits. In some situations, minor tension forces can occur. As connections will not be designed, no final verifications for tension forces will be performed. Note that the acting loads have been retrieved from the weight calculations, shown in the section where foundations will be verified.

CLT transverse wall, using CLT L5s 180, with dimensions of 10.8m by 2.7m

As retrieved from the documentation of the manufacturer, the cross-sectional quantities are used, as shown below. Furthermore, the same material values will be used as for floors, assuming C24 spruce.

Section CLT 180 L5s



Layer	Thickness	Type	Material
1	40.0 mm	L	C24 spruce ETA (2022)
2	30.0 mm	C	C24 spruce ETA (2022)
3	40.0 mm	L	C24 spruce ETA (2022)
4	30.0 mm	C	C24 spruce ETA (2022)
5	40.0 mm	L	C24 spruce ETA (2022)

Thickness	$Thickness_h$	$Thickness_v$	EI_h	EI_v	$Area_h$	$Area_v$	EA_h	EA_v	Shear strength	f	n_x	n_y	n_{xy}
[m]	[m]	[m]	[kN*m²]	[kN*m²]	[m²]	[m²]	[kN]	[kN]	[kN/m]	[-]	[kN/m]	[kN/m]	[kN/m]
0.180	0.060	0.120	202.5	405	0.0090	0.0180	108000	216000	81200	0.1691667	1440.000	2880.000	240.000

Figure C.15: Cross-sectional quantities for CLT transverse walls, given for 1.0 meter of CLT L5s 180

Bending and compression capacity in plane - As can be seen below, strength is sufficient for bending and compression forces in plane, with stresses due to bending being minimal compared to compression. Note that $k_{c,y}$ has been assumed 1. For the governing wall, an internal transverse wall on axis B of variant 6.1:

$$\frac{\sigma_{c,0,d}}{k_{c,y} \cdot f_{c,0,d}} + \frac{\sigma_{m,0,d}}{f_{m,0,d}} = \frac{2.16}{10.08} + \frac{0.64}{15.36} = 0.26 < 1$$

$$\sigma_{c,0,d} = \frac{N_{0,d}}{A_{0,\text{net}}} = \frac{260000}{120000} = 2.16\,\text{N/mm}^2$$

$$\sigma_{m,0,d} = \frac{M_{0,d}}{W_{0,\text{net}}} = \frac{1458000000}{2.29 \cdot 10^9} = 0.64\,\text{N/mm}^2$$

$$f_{c,0,d} = \frac{k_{\text{sys}} \cdot k_{\text{mod}} \cdot f_{c,0,k}}{\gamma_M} = \frac{1 \cdot 0.6 \cdot 21}{1.25} = 10.08\,\text{N/mm}^2$$

$$f_{m,d} = \frac{k_{\text{sys}} \cdot k_{\text{mod}} \cdot f_{m,k}}{\gamma_M} = \frac{1 \cdot 0.8 \cdot 24}{1.25} = 15.36 \, \text{N/mm}^2$$

$$W_{0,\text{net}} = \frac{1}{6} \cdot t \cdot h^2 = \frac{1}{6} \cdot 120 \cdot 10700^2 = 22.9 \cdot 10^9 \, \text{mm}^3$$

Bending and compression capacity out of plane - For bending and compression out of plane, an outer wall has been chosen, as bending moments will be largest. Note that, indeed, the contribution of bending moments is larger than for in plane. Note that$k_{c,y} = 0.42$ has been calculated. For the governing wall, an outer transverse wall on axis A of variant 6.1:

$$\frac{\sigma_{c,0,d}}{k_{c,y} \cdot f_{c,0,d}} + \frac{\sigma_{m,0,d}}{f_{m,0,d}} = \frac{0.88}{5.64} + \frac{0.20}{15.36} = 0.17 < 1$$

$$\sigma_{c,0,d} = \frac{N_{0,d}}{A_{0,\text{net}}} = \frac{105000}{120000} = 0.875 \, \text{N/mm}^2$$

$$\sigma_{m,0,d} = \frac{M_{0,d}}{W_{0,\text{net}}} = \frac{1/8 \cdot q \cdot l^2}{2 \cdot I_{0,\text{net}}/h} = \frac{1300000}{6.49 \cdot 10^6} = 0.20 \, \text{N/mm}^2$$

$$f_{c,0,d} = \frac{k_{\text{sys}} \cdot k_{\text{mod}} \cdot f_{c,0,k}}{\gamma_M} = \frac{1 \cdot 0.8 \cdot 21}{1.25} = 13.44 \, \text{N/mm}^2$$

$$f_{m,d} = \frac{k_{\text{sys}} \cdot k_{\text{mod}} \cdot f_{m,k}}{\gamma_M} = \frac{1 \cdot 0.8 \cdot 24}{1.25} = 15.36 \, \text{N/mm}^2$$

$$I_{0,\text{net}} = 3ht^3 + 2a^2ht = 3 \cdot 1000 \cdot 40^3 + 2 \cdot 70 \cdot 1000 \cdot 40 = 5.84 \cdot 10^8 mm^3$$

Shear force capacity - As can be seen below, strength is sufficient for both failure mechanisms for shear capacity. Value for distributed load is determined based on the total bending moment, calculated in the exploratory calculations.

Mechanism 1:

$$\frac{\tau_{V,S,d}}{f_{V,S,d}} = \frac{0.30}{2.56} = 0.12 < 1$$

$$\tau_{V,S,d} = \frac{T}{A_{S,\text{net}}} = \frac{q \cdot l}{\min(A_{0,\text{net}}, A_{90,\text{net}})} = \frac{1.5 \cdot 8.64 \cdot 15000}{60 \cdot 10700} = 0.30 \, \text{N/mm}^2$$

$$f_{V,S,d} = \frac{k_{\text{mod}} \cdot f_{V,S,k}}{\gamma_M} = \frac{0.8 \cdot 4}{1.25} = 2.56 \, \text{N/mm}^2$$

Mechanism 2:

$$\frac{\tau_{V,d}}{f_{V,d}} = \frac{0.10}{0.70} = 0.14 < 1$$

$$\tau_{V,d} = \frac{T}{A_{S,\text{net}}} = \frac{q \cdot l}{A_{\text{tot}}} = \frac{1.5 \cdot 8.64 \cdot 15000}{180 \cdot 10700} = 0.10 \, \text{N/mm}^2$$

$$f_{V,d} = \frac{k_{\text{mod}} \cdot f_{V,S,k}}{\gamma_M} = \frac{0.8 \cdot 1.1}{1.25} = 0.70 \, \text{N/mm}^2$$

Deformation - The total deformation has been calculated based on the contribution of shear forces and bending moments. Deformations due to connections have not been assumed. Note that the maximum deflection limit is divided by 2, as the foundation is assumed to cause half the deformation.

$$\frac{\delta_{\text{total}}}{0.5 \cdot \delta_{\text{max}}} = \frac{5.78}{15} = 0.39 < 1$$

$$\delta_{\text{total}} = \delta_{\text{shear}} + \delta_{\text{bending}} = \frac{q_k \cdot h^2}{2 \cdot GA_s} + \frac{q_k \cdot h^4}{8 \cdot E_{\text{mean}} \cdot I_{\text{eff}}}$$

$$= \frac{8.64 \cdot (15 \cdot 10^3)^2}{2 \cdot 1.798 \cdot 10^8} + \frac{8.64 \cdot (15 \cdot 10^3)^4}{8 \cdot 1.2 \cdot 10^4 \cdot 1.225 \cdot 10^{13}} = 5.41 + 0.37 = 5.78\, mm$$

$$\delta_{\text{max}} = \frac{15000}{500} = 30\, mm$$

$$GA_s = \kappa \sum (G_i \cdot b_i \cdot t_i) = 0.203 \cdot 3 \cdot 690 \cdot 40 \cdot 10700 = 1.798 \cdot 10^8 N$$

$$I_{\text{eff}} = \frac{1}{12} \cdot 120 \cdot (10.7 \cdot 10^3)^3 = 1.225 \cdot 10^{13}\, mm^4$$

CLT stability wall, using CLT L5s 180, with dimensions of 6.0 by 2.7m

For this wall, the same dimensions are used as the transverse walls. Loading similar as axis 2 of variant 6.5 will be used

Bending and compression capacity in plane - As can be seen below, strength is sufficient for bending and compression forces in plane, with stresses due to bending being minimal compared to compression

$$\frac{\sigma_{c,0,d}}{k_{c,y} \cdot f_{c,0,d}} + \frac{\sigma_{m,0,d}}{k_{c,y} \cdot f_{m,0,d}} = \frac{1.44}{10.08} + \frac{1.25}{15.36} = 0.22 < 1$$

$$\sigma_{c,0,d} = \frac{N_{0,d}}{A_{0,\text{net}}} = \frac{173000}{120000} = 1.44\,\text{N/mm}^2$$

$$\sigma_{m,0,d} = \frac{M_{0,d}}{W_{0,\text{net}}} = \frac{900000000}{7.20 \cdot 10^8} = 1.25\,\text{N/mm}^2$$

$$f_{c,0,d} = \frac{k_{\text{sys}} \cdot k_{\text{mod}} \cdot f_{c,0,k}}{\gamma_M} = \frac{1 \cdot 0.6 \cdot 21}{1.25} = 10.08\,\text{N/mm}^2$$

$$f_{m,d} = \frac{k_{\text{sys}} \cdot k_{\text{mod}} \cdot f_{m,k}}{\gamma_M} = \frac{1 \cdot 0.8 \cdot 24}{1.25} = 15.36\,\text{N/mm}^2$$

$$W_{0,\text{net}} = \frac{1}{6} \cdot t \cdot h^2 = \frac{1}{6} \cdot 120 \cdot 6000^2 = 7.20 \cdot 10^8\,\text{mm}^3$$

Bending and compression capacity out of plane - As no wind load is directly applied on stability walls, no check is performed.

Shear force capacity - As can be seen below, strength is sufficient for both failure mechanisms for shear capacity in the internal stability walls. Value for distributed load is determined based on the total bending moment, calculated in the exploratory calculations.

Mechanism 1:

$$\frac{\tau_{V,S,d}}{f_{V,S,d}} = \frac{0.33}{2.56} = 0.13 < 1$$

$$\tau_{V,S,d} = \frac{T}{A_{S,\text{net}}} = \frac{q \cdot l}{\min(A_{0,\text{net}}, A_{90,\text{net}})} = \frac{1.5 \cdot 5.33 \cdot 15000}{60 \cdot 6000} = 0.33\,\text{N/mm}^2$$

$$f_{V,S,d} = \frac{k_{\text{mod}} \cdot f_{V,S,k}}{\gamma_M} = \frac{0.8 \cdot 4}{1.25} = 2.56\,\text{N/mm}^2$$

Mechanism 2:

$$\frac{\tau_{V,d}}{f_{V,d}} = \frac{0.11}{0.70} = 0.16 < 1$$

$$\tau_{V,d} = \frac{T}{A_{S,\text{net}}} = \frac{q \cdot l}{A_{\text{tot}}} = \frac{1.5 \cdot 5.33 \cdot 15000}{180 \cdot 6000} = 0.11\,\text{N/mm}^2$$

$$f_{V,d} = \frac{k_{\text{mod}} \cdot f_{V,S,k}}{\gamma_M} = \frac{0.8 \cdot 1.1}{1.25} = 0.70\,\text{N/mm}^2$$

Deformation - The total deformation has been calculated based on the contribution of shear forces and bending moments. Deformations due to connections have not been assumed. Note that the maximum deflection limit is divided by 2, as the foundation is assumed to cause half the deformation. Three stability walls of 6m have been considered, leading to higher values of GA_s and I_{eff}.

$$\frac{\delta_{\text{total}}}{0.5 \cdot \delta_{\text{max}}} = \frac{5.78}{15} = 0.39 < 1$$

$$\delta_{\text{total}} = \delta_{\text{shear}} + \delta_{\text{bending}} = \frac{q_k \cdot h^2}{2 \cdot 3 \cdot GA_s} + \frac{q_k \cdot h^4}{8 \cdot 3 \cdot E_{\text{mean}} \cdot I_{\text{eff}}}$$

$$= \frac{8.64 \cdot (15 \cdot 10^3)^2}{2 \cdot 3 \cdot 1.00 \cdot 10^8} + \frac{8.64 \cdot (15 \cdot 10^3)^4}{8 \cdot 1.2 \cdot 10^4 \cdot 2.16 \cdot 10^{12}} = 3.24 + 0.70 = 3.94\,mm$$

$$\delta_{\text{max}} = \frac{15000}{500} = 30\,mm$$

$$GA_s = \kappa \sum (G_i \cdot b_i \cdot t_i) = 0.203 \cdot 3 \cdot 690 \cdot 40 \cdot 6000 = 1.00 \cdot 10^8 N$$

$$I_{\text{eff}} = \frac{1}{12} \cdot 120 \cdot (6.0 \cdot 10^3)^3 = 2.16 \cdot 10^{12}\,mm^4$$

C.3. Structural verifications of foundations

For each variant, calculations have been made to determine the total loads on the foundations, which are used to calculate foundation size with the design tool Technosoft Balkrooster. A summary of the loads on the foundation will be shown on the following pages. Besides, for variant 6.1, an extensive overview of the calculation process for this will be shown. For each variant, the maximum load on each pile is given according to the loading combinations, as shown in the figure below.

1		Fundamer	1:Permanent	1.35	0:Geen.		0:Geen.		0:Geen.	
2		Fundamer	1:Permanent	1.35	2:Veranderlijk 2 extr	1.50M0	3:Veranderlijk rest extr.	1.50M0	0:Geen.	
3		Fundamer	1:Permanent	1.20	2:Veranderlijk 2 extr	1.50	3:Veranderlijk rest extr.	1.50M0	4:Toevallige	1.20
4		Fundamer	1:Permanent	1.20	2:Veranderlijk 2 extr	1.50M0	3:Veranderlijk rest extr.	1.50M0	5:Wind // Letter-Assen LINKS	1.50
5		Fundamer	1:Permanent	1.20	2:Veranderlijk 2 extr	1.50M0	3:Veranderlijk rest extr.	1.50M0	6:Wind // Letter-Assen Rechts	1.50
6		Fundamer	1:Permanent	1.20	2:Veranderlijk 2 extr	1.50M0	3:Veranderlijk rest extr.	1.50M0	7:Wind // Cijfer-Assen VOOR	1.50
7		Fundamer	1:Permanent	1.20	2:Veranderlijk 2 extr	1.50M0	3:Veranderlijk rest extr.	1.50M0	8:Wind // Cijfer-Assen Achter	1.50
8		Fundamer	1:Permanent	0.90	5:Wind // Letter-Assen LINKS	1.50	0:Geen.		0:Geen.	
9		Fundamer	1:Permanent	0.90	6:Wind // Letter-Assen Rechts	1.50	0:Geen.		0:Geen.	
10		Fundamer	1:Permanent	0.90	7:Wind // Cijfer-Assen VOOR	1.50	0:Geen.		0:Geen.	
11		Fundamer	1:Permanent	0.90	8:Wind // Cijfer-Assen Achter	1.50	0:Geen.		0:Geen.	

Figure C.16: Overview of load combinations used in calculations of foundation.

Effective length

Stability walls significantly influence the amount of floor area that is bearing on a certain load-bearing wall. Generally speaking, including a stability wall reduces the loads on the transverse walls, potentially leading to more tension forces. To calculate the correct values, finite element models have been used. For a load of 1kN/m2, the reaction forces have been calculated. These values reflect the effective length used in calculation. Below, for various stability systems, effective lengths have been given, assuming a CLT floor of 240mm.

Below, the effective length is given for variants with no stability walls. Note that this is not equal to simple assigning half the floor load to either of the walls.

Values for Q-loads (averaged) = values for F-loads

For middle wall: l = 7,6 m

For single outer wall: l = 3,0 m

For double outer wall: l = 6,0 m

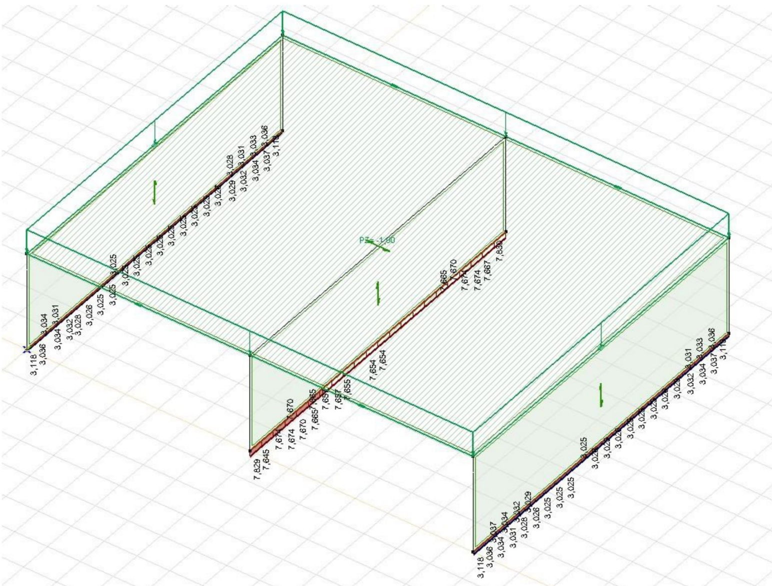


Figure C.17: Effective length is given for variant with no stability walls.

Below, the effective length is given for variants with stability walls in the outer facades.

Values for q-loads (averaged)

For middle wall: l = 7,0 m

For stability wall: l = 3,0 m

For single outer wall: l = 1,8 m

For double outer wall: l = 6,1 m

Values for F-loads

For middle wall: l = 6,2 m

For single outer wall: l = 0 m

For double outer wall: l = 6,4 m

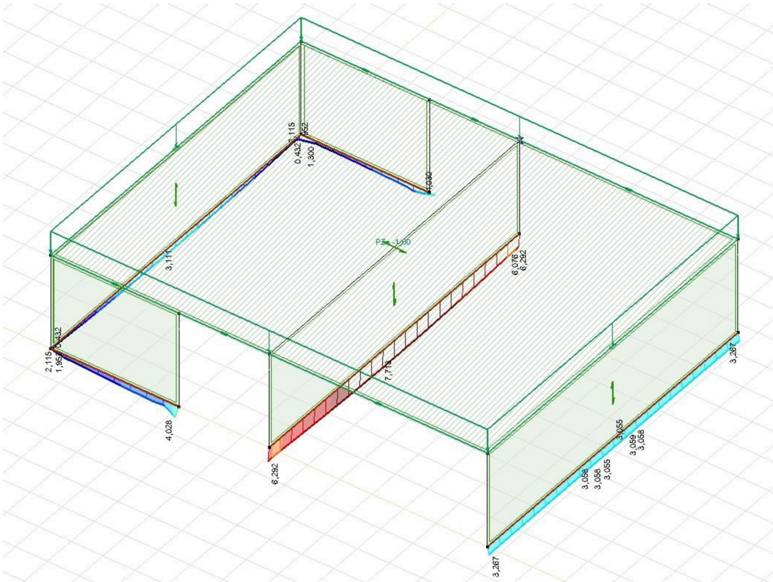


Figure C.18: Effective length is given for variants with stability wall in the outer facades.

Below, the effective length is given for variants with internal stability walls.

Values for q-loads (averaged)

For middle wall: l = 4,6 m

For stability wall: l= 4,3 m

For single outer wall: l = 2,5 m

For double outer wall: l = 5,0 m

Values for F-loads

For middle wall: l = 8,0 m

For single outer wall: l = 3,1 m

For double outer wall: l = 6,2 m

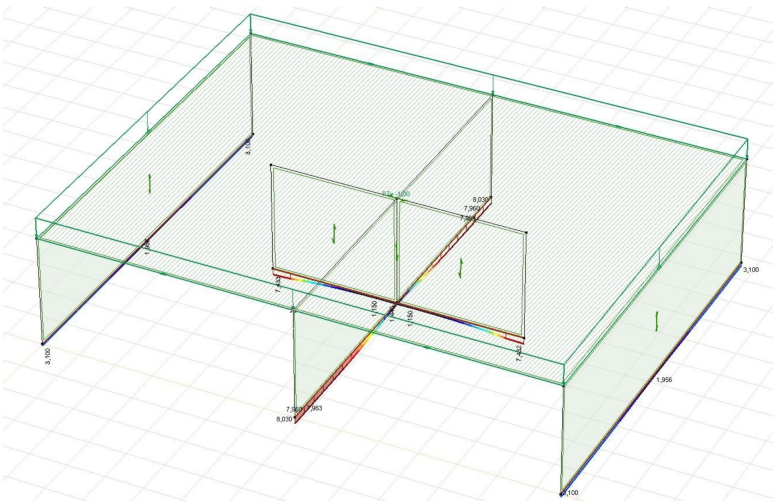
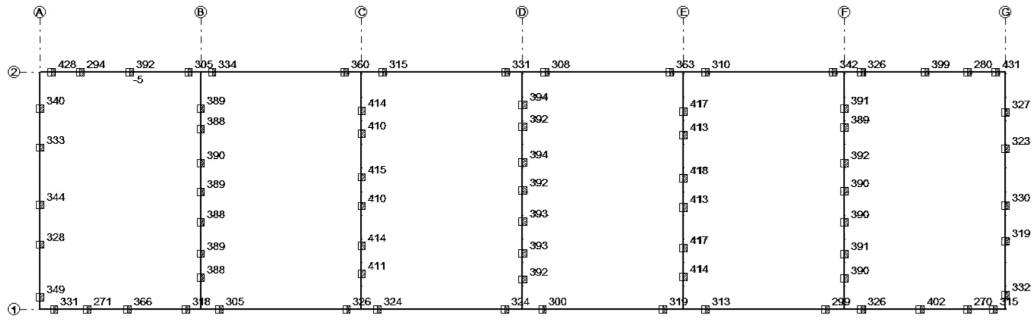


Figure C.19: Effective length is given for variants with internal stability walls.

Variant 6.1

Below, an overview of foundation piles is provided for variant 6.1, along with the used loads during calculation. Calculations have been performed using Technosoft Balkrooster, optimised for forces in foundation piles. Besides, the bending moment capacity of foundation beams has been checked.

75 piles (+15) – concrete prefab square 320x320 – length 17m – *loads on piles:*



Based on the following loads:

Kopgevelbalk as A / G	Q-last - permanent	Q,g	=	**99,6**	kN/m	
	Q-last - variabele extreem	Q,var1	=	**9,2**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**19,7**	kN/m	
	F-last - permanent	F,g	=	**0,0**	kN	langstgevel lasten worden door stabiliteitsmuur afgedragen
	F-last - variabele extreem	F,var1	=	**0,0**	kN	
	F-last - variabele niet extreem	F,var2	=	**0,0**	kN	
Bouwmuurbalk as B / D / F	Q-last - permanent	Q,g	=	**169,3**	kN/m	
	Q-last - variabele extreem	Q,var1	=	**35,7**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**60,1**	kN/m	
	F-last - permanent	F,g	=	**262,1**	kN	puntenlasten vanuit gevels en balkon/gallerij op uiteinde dwarsmuren
	F-last - variabele extreem	F,var1	=	**37,2**	kN	
	F-last - variabele niet extreem	F,var2	=	**37,2**	kN	
Bouwmuurbalk as C / E	Q-last - permanent	Q,g	=	**156,2**	kN/m	
	Q-last - variabele extreem	Q,var1	=	**31,1**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**54,6**	kN/m	
	F-last - permanent	F,g	=	**270,6**	kN	puntenlasten vanuit gevels en balkon/gallerij op uiteinde dwarsmuren
	F-last - variabele extreem	F,var1	=	**38,4**	kN	
	F-last - variabele niet extreem	F,var2	=	**38,4**	kN	
Stabiliteitsmuur	Q-last - permanent	Q,g	=	**118,1**	kN/m	bevat ook deel van vloerbelasting, vandaar reductie bij kopgevelbalk A / G
	Q-last - variabele extreem	Q,var1	=	**15,3**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**18,3**	kN/m	

Figure C.20: Overview of foundations piles and used loads during calculation for variant 6.1.

BELASTINGEN Waarde voor L aangepast naar CLT krachtsafdracht volgens FEM model

OMSCHRIJVING	AFMETINGEN			opp.	PERMANENTE LAST		VERANDERLIJKE LAST				REKENWAARDEN TOT.	
Kopgevelbalk as A	L	B	H	totaal	g_{rep}	G_{rep}	q_{rep}	Q_{rep}	ψ_0	$\psi_0 * Q_{rep}$	1,2G+1,5Q	1,35G+1,5Q[M]
	[m]	[m]	[m]	[m²]	[kN/m²]	[kN]	[kN/m²]	[kN]		[kN]	[kN]	[kN]
q-lasten												
Dak	1,80	1,00		1,8	3,82	6,9	1,00	1,8	0,00	0,0		
Kopgevels woningen KZS 75%		1,00	3,00	3,0	4,39	13,2						
Verd extreem?	NEE	0				*20,0*		*1,8*		*0,0*		
druk net boven 4e verd.						*20,0*		*0,0*		*0,0*	*24,0*	**27,1**
Verdiepingsvloer CLT	1,80	1,00		1,8	2,70	4,9	2,55	4,6	0,40	1,8		
Kopgevels woningen KZS 75%		1,00	3,00	3,0	4,39	13,2						
Verd extreem?	JA	1				*18,0*		*4,6*		*1,8*		
druk net boven 3e verd.						*38,1*		*4,6*		*1,8*	*52,6*	**54,1**
Verdiepingsvloer CLT	1,80	1,00		1,8	2,70	4,9	2,55	4,6	0,40	1,8		
Kopgevels woningen KZS 75%		1,00	3,00	3,0	4,39	13,2						
Verd extreem?	JA	1				*18,0*		*4,6*		*1,8*		
druk net boven 2e verd.						*56,1*		*9,2*		*3,7*	*81,1*	**81,2**
Verdiepingsvloer CLT	1,80	1,00		1,8	2,70	4,9	2,55	4,6	0,40	1,8		
Kopgevels woningen KZS 75%		1,00	3,00	3,0	4,39	13,2						
Verd extreem?	NEE	0				*18,0*		*4,6*		*1,8*		
druk net boven 1e verd.						*74,1*		*11,0*		*5,5*	*105,5*	**108,3**
Verdiepingsvloer CLT	1,80	1,00		1,8	2,70	4,9	2,55	4,6	0,40	1,8		
Kopgevels woningen KZS 75%		1,00	3,00	3,0	4,39	13,2						
Verd extreem?	NEE					*18,0*		*4,6*		*1,8*		
druk net boven b.g.						*92,1*		*12,9*		*7,3*	*129,8*	**135,4**
Kanaalplaatvloer hout BG	3,41	1,00		3,4	2,20	7,5	2,55	8,7	0,40	3,5		
Lege regel		0,00	0,00	0,0	0,00	0,0	0,00	0,0	0,00	0,0		
Verd extreem?	NEE	0				*7,5*		*8,7*		*3,5*		
druk op de palen						*99,6*		*16,3*		*10,8*	*144,1*	**150,7**

Verandelijke belasting tbv invoer in TS balkrooster	2 *Verdiepingen extreem:*	9,2	kN/m
	Resterende verdiepingen extreem:	19,7	kN/m

Figure C.21: Overview of load determination for wall A.

BELASTINGEN Waarde voor L aangepast naar CLT krachtsafdracht volgens FEM model

OMSCHRIJVING	AFMETINGEN			opp.	PERMANENTE LAST		VERANDERLIJKE LAST				REKENWAARDEN TOT.	
Bouwmuur As B	L	B	H	totaal	g_{rep}	G_{rep}	q_{rep}	Q_{rep}	ψ_0	$\psi_0 * Q_{rep}$	1,2G+1,5Q	1,35G+1,5Q[M]
	[m]	[m]	[m]	[m²]	[kN/m²]	[kN]	[kN/m²]	[kN]		[kN]	[kN]	[kN]
q-lasten												
Dak	7,00	1,00		7,0	3,82	26,7	1,00	7,0	0,00	0,0		
Woningscheidende wand KZS		1,00	2,70	2,7	3,85	10,4						
Verd extreem?	NEE	0				*37,1*		*7,0*		*0,0*		
druk net boven 4e verd.						*37,1*		*0,0*		*0,0*	*44,6*	**50,1**
Verdiepingsvloer CLT	7,00	1,00		7,0	2,70	18,9	2,55	17,9	0,40	7,1		
Woningscheidende wand KZS		1,00	2,70	2,7	3,85	10,4						
Verd extreem?	JA	1				*29,3*		*17,9*		*7,1*		
druk net boven 3e verd.						*66,4*		*17,9*		*7,1*	**106,5**	*100,4*
Verdiepingsvloer CLT	7,00	1,00		7,0	2,70	18,9	2,55	17,9	0,40	7,1		
Woningscheidende wand KZS		1,00	2,70	2,7	3,85	10,4						
Verd extreem?	JA	1				*29,3*		*17,9*		*7,1*		
druk net boven 2e verd.						*95,7*		*35,7*		*14,3*	**168,4**	*150,6*
Verdiepingsvloer CLT	7,00	1,00		7,0	2,70	18,9	2,55	17,9	0,40	7,1		
Woningscheidende wand KZS		1,00	2,70	2,7	3,85	10,4						
Verd extreem?	NEE	0				*29,3*		*17,9*		*7,1*		
druk net boven 1e verd.						*125,0*		*42,8*		*21,4*	**214,3**	*200,9*
Verdiepingsvloer CLT	7,00	1,00		7,0	2,70	18,9	2,55	17,9	0,40	7,1		
Woningscheidende wand KZS		1,00	2,70	2,7	3,85	10,4						
Verd extreem?	NEE					*29,3*		*17,9*		*7,1*		
druk net boven b.g.						*154,3*		*50,0*		*28,6*	**260,1**	*251,2*
Kanaalplaatvloer hout BG	6,82	1,00		6,8	2,20	15,0	2,55	17,4	0,40	7,0		
Lege regel		1,00	2,70	2,7	0,00	0,0	0,00	0,0	0,00	0,0		
Verd extreem?	NEE	0				*15,0*		*17,4*		*7,0*		
druk op de palen						*169,3*		*56,9*		*35,5*	**288,6**	*281,9*

Verandelijke belasting tbv invoer in TS balkrooster	2 *Verdiepingen extreem:*	35,7	kN/m
	Resterende verdiepingen extreem:	60,1	kN/m

Figure C.22: Overview of load determination for wall B.

BELASTINGEN Waarde voor L aangepast naar CLT krachtsafdracht volgens FEM model

OMSCHRIJVING	AFMETINGEN			opp.	PERMANENTE LAST		VERANDERLIJKE LAST				REKENWAARDEN TOT.	
Bouwmuur As C	L	B	H	totaal	g_{rep}	G_{rep}	q_{rep}	Q_{rep}	ψ_0	$\psi_0 * Q_{rep}$	1,2G+1,5Q	1,35G+1,5Q[M]
	[m]	[m]	[m]	[m²]	[kN/m²]	[kN]	[kN/m²]	[kN]		[kN]	[kN]	[kN]
q-lasten												
Dak	6,10	1,00		6,1	3,82	23,3	1,00	6,1	0,00	0,0		
Woningscheidende wand KZS		1,00	2,70	2,7	3,85	10,4						
Verd extreem?	NEE	0				33,7		6,1		0,0		
druk net boven 4e verd.						33,7		0,0		0,0	40,4	**45,5**
Verdiepingsvloer CLT	6,10	1,00		6,1	2,70	16,5	2,55	15,6	0,40	6,2		
Woningscheidende wand KZS		1,00	2,70	2,7	3,85	10,4						
Verd extreem?	JA	1				26,9		15,6		6,2		
druk net boven 3e verd.						60,6		15,6		6,2	**96,0**	91,1
Verdiepingsvloer CLT	6,10	1,00		6,1	2,70	16,5	2,55	15,6	0,40	6,2		
Woningscheidende wand KZS		1,00	2,70	2,7	3,85	10,4						
Verd extreem?	JA	1				26,9		15,6		6,2		
druk net boven 2e verd.						87,4		31,1		12,4	**151,6**	136,7
Verdiepingsvloer CLT	6,10	1,00		6,1	2,70	16,5	2,55	15,6	0,40	6,2		
Woningscheidende wand KZS		1,00	2,70	2,7	3,85	10,4						
Verd extreem?	NEE	0				26,9		15,6		6,2		
druk net boven 1e verd.						114,3		37,3		18,7	**193,1**	182,3
Verdiepingsvloer CLT	6,10	1,00		6,1	2,70	16,5	2,55	15,6	0,40	6,2		
Woningscheidende wand KZS		1,00	2,70	2,7	3,85	10,4						
Verd extreem?	NEE					26,9		15,6		6,2		
druk net boven b.g.						141,2		43,6		24,9	**234,7**	227,9
Kanaalplaatvloer hout BG	6,82	1,00		6,8	2,20	15,0	2,55	17,4	0,40	7,0		
Lege regel		1,00	2,70	2,7	0,00	0,0	0,00	0,0	0,00	0,0		
Verd extreem?	NEE	0				15,0		17,4		7,0		
druk op de palen						156,2		50,5		31,8	**263,2**	258,6

Verandelijke belasting tbv invoer in TS balkrooster	2 *Verdiepingen extreem:*	31,1	kN/m
	Resterende verdiepingen extreem:	54,6	kN/m

Figure C.23: Overview of load determination for wall C.

BELASTINGEN Waarde voor L aangepast naar CLT krachtsafdracht volgens FEM model

OMSCHRIJVING	AFMETINGEN			opp.	PERMANENTE LAST		VERANDERLIJKE LAST				REKENWAARDEN TOT.	
Stabiliteitsmuur	L	B	H	totaal	g_{rep}	G_{rep}	q_{rep}	Q_{rep}	ψ_0	$\psi_0 * Q_{rep}$	1,2G+1,5Q	1,35G+1,5Q[M]
	[m]	[m]	[m]	[m²]	[kN/m²]	[kN]	[kN/m²]	[kN]		[kN]	[kN]	[kN]
q-lasten												
Dak	3,00	1,00		3,0	3,82	11,5	1,00	3,0	0,00	0,0		
Stabiliteitsmuur beton + gevel		1,00	2,70	2,7	5,50	14,9						
Verd extreem?	NEE	0				26,3		3,0		0,0		
druk net boven 4e verd.						26,3		0,0		0,0	31,6	**35,5**
Verdiepingsvloer CLT	3,00	1,00		3,0	2,70	8,1	2,55	7,7	0,40	3,1		
Stabiliteitsmuur beton + gevel		1,00	2,70	2,7	5,50	14,9						
Verd extreem?	JA	1				23,0		7,7		3,1		
druk net boven 4e verd.						49,3		7,7		3,1	70,6	**71,1**
Verdiepingsvloer CLT	3,00	1,00		3,0	2,70	8,1	2,55	7,7	0,40	3,1		
Stabiliteitsmuur beton + gevel		1,00	2,70	2,7	5,50	14,9						
Verd extreem?	JA	1				23,0		7,7		3,1		
druk net boven 4e verd.						72,2		15,3		6,1	**109,6**	106,7
Verdiepingsvloer CLT	3,00	1,00		3,0	2,70	8,1	2,55	7,7	0,40	3,1		
Stabiliteitsmuur beton + gevel		1,00	2,70	2,7	5,50	14,9						
Verd extreem?	NEE	0				23,0		7,7		3,1		
druk net boven 4e verd.						95,2		18,4		9,2	141,7	**142,2**
Verdiepingsvloer CLT	3,00	1,00		3,0	2,70	8,1	2,55	7,7	0,40	3,1		
Stabiliteitsmuur beton + gevel		1,00	2,70	2,7	5,50	14,9						
Verd extreem?	NEE	0				23,0		7,7		3,1		
druk net boven b.g.						118,1		21,4		12,2	173,9	**177,8**
Lege regel	0,00	0,00		0,0	0,00	0,0	0,00	0,0	0,00	0,0		
Verd extreem?	NEE	0				0,0		0,0		0,0		
druk op de palen						118,1		21,4		12,2	173,9	**177,8**

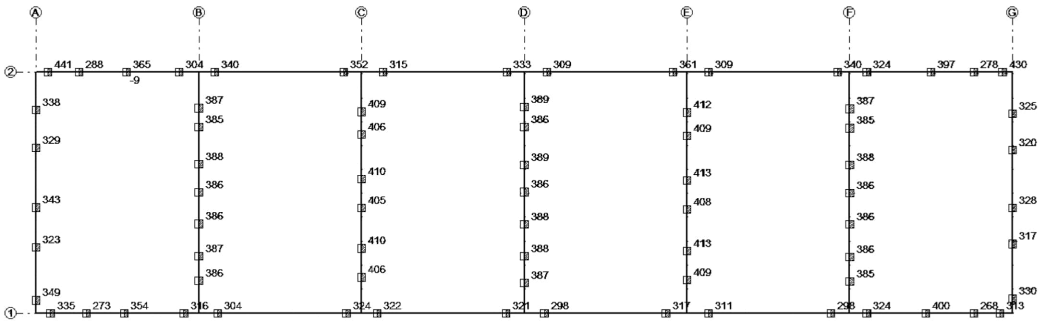
Verandelijke belasting tbv invoer in TS balkrooster	2 *Verdiepingen extreem:*	15,3	kN/m
	Resterende verdiepingen extreem:	18,3	kN/m

Figure C.24: Overview of load determination for a stability wall.

Variant 6.2

Below, an overview of foundation piles is provided for variant 6.2, along with the used loads during calculation. Calculations have been performed using Technosoft Balkrooster, optimised for forces in foundation piles. Besides, the bending moment capacity of foundation beams has been checked.

75 piles (+15) – concrete prefab square 320x320 – length 17m – *loads on piles:*



Based on the following loads:

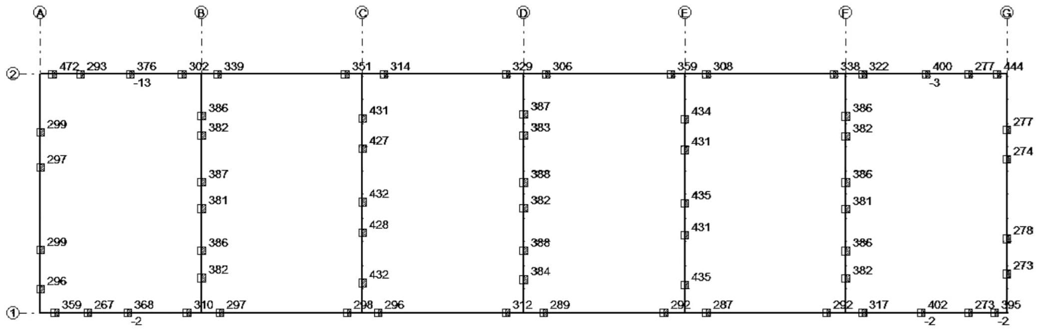
Kopgevelbalk as A / G	Q-last - permanent	Q,g	=	**98,8**	kN/m	
	Q-last - variabele extreem	Q,var1	=	**9,2**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**19,7**	kN/m	
	F-last - permanent	F,g	=	**0,0**	kN	langstgevel lasten worden door stabiliteitsmuur afgedragen
	F-last - variabele extreem	F,var1	=	**0,0**	kN	
	F-last - variabele niet extreem	F,var2	=	**0,0**	kN	
Bouwmuurbalk as B / D / F	Q-last - permanent	Q,g	=	**166,2**	kN/m	
	Q-last - variabele extreem	Q,var1	=	**35,7**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**60,1**	kN/m	
	F-last - permanent	F,g	=	**262,1**	kN	puntenlasten vanuit gevels en balkon/gallerij op uiteinde dwarsmuren
	F-last - variabele extreem	F,var1	=	**37,2**	kN	
	F-last - variabele niet extreem	F,var2	=	**37,2**	kN	
Bouwmuurbalk as C / E	Q-last - permanent	Q,g	=	**153,5**	kN/m	
	Q-last - variabele extreem	Q,var1	=	**31,1**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**54,6**	kN/m	
	F-last - permanent	F,g	=	**270,6**	kN	puntenlasten vanuit gevels en balkon/gallerij op uiteinde dwarsmuren
	F-last - variabele extreem	F,var1	=	**38,4**	kN	
	F-last - variabele niet extreem	F,var2	=	**38,4**	kN	
Stabiliteitsmuur	Q-last - permanent	Q,g	=	**116,8**	kN/m	bevat ook deel van vloerbelasting, vandaar reductie bij kopgevelbalk A / G
	Q-last - variabele extreem	Q,var1	=	**15,3**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**18,3**	kN/m	

Figure C.25: Overview of foundations piles and used loads during calculation for variant 6.2.

Variant 6.3

Below, an overview of foundation piles is provided for variant 6.3, along with the used loads during calculation. Calculations have been performed using Technosoft Balkrooster, optimised for forces in foundation piles. Besides, the bending moment capacity of foundation beams has been checked.

68 piles (+15) – concrete prefab square 320x320 – length 17m – *loads on piles:*



Based on the following loads:

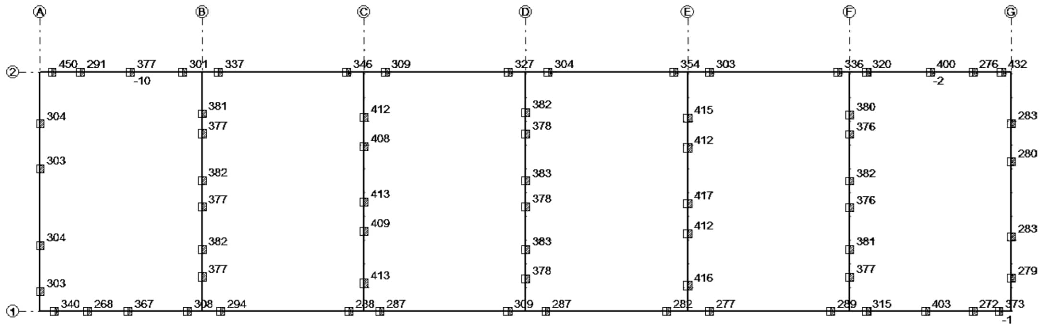
Kopgevelbalk as A / G	Q-last - permanent	Q,g	=	**65,4**	kN/m	
	Q-last - variabele extreem	Q,var1	=	**9,2**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**19,7**	kN/m	
	F-last - permanent	F,g	=	**0,0**	kN	langstgevel lasten worden door stabiliteitsmuur afgedragen
	F-last - variabele extreem	F,var1	=	**0,0**	kN	
	F-last - variabele niet extreem	F,var2	=	**0,0**	kN	
Bouwmuurbalk as B / D / F	Q-last - permanent	Q,g	=	**131,8**	kN/m	
	Q-last - variabele extreem	Q,var1	=	**35,7**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**60,1**	kN/m	
	F-last - permanent	F,g	=	**262,1**	kN	puntenlasten vanuit gevels en balkon/gallerij op uiteinde dwarsmuren
	F-last - variabele extreem	F,var1	=	**37,2**	kN	
	F-last - variabele niet extreem	F,var2	=	**37,2**	kN	
Bouwmuurbalk as C / E	Q-last - permanent	Q,g	=	**126,1**	kN/m	
	Q-last - variabele extreem	Q,var1	=	**31,1**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**54,6**	kN/m	
	F-last - permanent	F,g	=	**270,6**	kN	puntenlasten vanuit gevels en balkon/gallerij op uiteinde dwarsmuren
	F-last - variabele extreem	F,var1	=	**38,4**	kN	
	F-last - variabele niet extreem	F,var2	=	**38,4**	kN	
Stabiliteitsmuur	Q-last - permanent	Q,g	=	**118,1**	kN/m	bevat ook deel van vloerbelasting, vandaar reductie bij kopgevelbalk A / G
	Q-last - variabele extreem	Q,var1	=	**15,3**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**18,3**	kN/m	

Figure C.26: Overview of foundations piles and used loads during calculation for variant 6.3.

Variant 6.4

Below, an overview of foundation piles is provided for variant 6.4, along with the used loads during calculation. Calculations have been performed using Technosoft Balkrooster, optimised for forces in foundation piles. Besides, the bending moment capacity of foundation beams has been checked.

68 piles (+15) – concrete prefab square 320x320 – length 17m – *loads on piles:*



Based on the following loads:

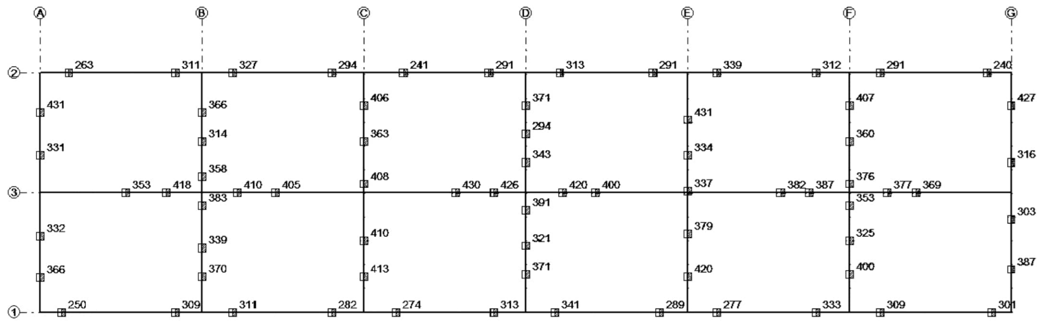
Kopgevelbalk as A / G	Q-last - permanent	Q,g	=	**64,6**	kN/m	
	Q-last - variabele extreem	Q,var1	=	**9,2**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**19,7**	kN/m	
	F-last - permanent	F,g	=	**0,0**	kN	langstgevel lasten worden door stabiliteitsmuur afgedragen
	F-last - variabele extreem	F,var1	=	**0,0**	kN	
	F-last - variabele niet extreem	F,var2	=	**0,0**	kN	
Bouwmuurbalk as B / D / F	Q-last - permanent	Q,g	=	**128,7**	kN/m	
	Q-last - variabele extreem	Q,var1	=	**35,7**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**60,1**	kN/m	
	F-last - permanent	F,g	=	**262,1**	kN	puntenlasten vanuit gevels en balkon/gallerij op uiteinde dwarsmuren
	F-last - variabele extreem	F,var1	=	**37,2**	kN	
	F-last - variabele niet extreem	F,var2	=	**37,2**	kN	
Bouwmuurbalk as C / E	Q-last - permanent	Q,g	=	**115,9**	kN/m	
	Q-last - variabele extreem	Q,var1	=	**31,1**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**54,6**	kN/m	
	F-last - permanent	F,g	=	**270,6**	kN	puntenlasten vanuit gevels en balkon/gallerij op uiteinde dwarsmuren
	F-last - variabele extreem	F,var1	=	**38,4**	kN	
	F-last - variabele niet extreem	F,var2	=	**38,4**	kN	
Stabiliteitsmuur	Q-last - permanent	Q,g	=	**116,8**	kN/m	bevat ook deel van vloerbelasting, vandaar reductie bij kopgevelbalk A / G
	Q-last - variabele extreem	Q,var1	=	**15,3**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**18,3**	kN/m	

Figure C.27: Overview of foundations piles and used loads during calculation for variant 6.4.

Variant 6.5

Below, an overview of foundation piles is provided for variant 6.5, along with the used loads during calculation. Calculations have been performed using Technosoft Balkrooster, optimised for forces in foundation piles. Besides, the bending moment capacity of foundation beams has been checked.

72 piles (+15) – concrete prefab square 320x320 – length 17m – *loads on piles:*



Based on the following loads:

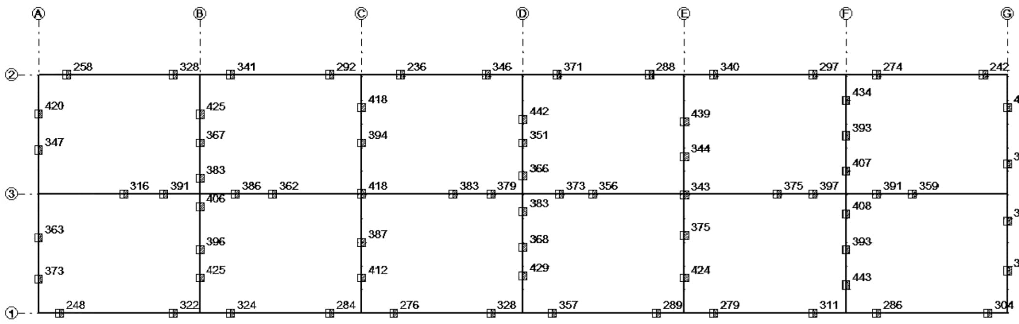
Kopgevelbalk as A / G	Q-last - permanent	Q,g	=	**75,7**	kN/m	
	Q-last - variabele extreem	Q,var1	=	**12,8**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**23,9**	kN/m	
	F-last - permanent	F,g	=	**131,1**	kN	puntenlasten vanuit gevels en balkon/gallerij op uiteinde dwarsmuren
	F-last - variabele extreem	F,var1	=	**18,6**	kN	
	F-last - variabele niet extreem	F,var2	=	**18,6**	kN	
Bouwmuurbalk as B / D / F	Q-last - permanent	Q,g	=	**96,7**	kN/m	
	Q-last - variabele extreem	Q,var1	=	**23,5**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**45,5**	kN/m	
	F-last - permanent	F,g	=	**338,2**	kN	puntenlasten vanuit gevels en balkon/gallerij op uiteinde dwarsmuren
	F-last - variabele extreem	F,var1	=	**48,0**	kN	
	F-last - variabele niet extreem	F,var2	=	**48,0**	kN	
Bouwmuurbalk as C / E	Q-last - permanent	Q,g	=	**110,1**	kN/m	
	Q-last - variabele extreem	Q,var1	=	**25,5**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**47,9**	kN/m	
	F-last - permanent	F,g	=	**262,1**	kN	puntenlasten vanuit gevels en balkon/gallerij op uiteinde dwarsmuren
	F-last - variabele extreem	F,var1	=	**37,2**	kN	
	F-last - variabele niet extreem	F,var2	=	**37,2**	kN	
Stabiliteitsmuur	Q-last - permanent	Q,g	=	**137,1**	kN/m	bevat ook deel van vloerbelasting, vandaar reductie bij Bouwmuurbalk as B / D / F
	Q-last - variabele extreem	Q,var1	=	**21,9**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**26,2**	kN/m	

Figure C.28: Overview of foundations piles and used loads during calculation for variant 6.5.

Variant 6.6

Below, an overview of foundation piles is provided for variant 6.6, along with the used loads during calculation. Calculations have been performed using Technosoft Balkrooster, optimised for forces in foundation piles. Besides, the bending moment capacity of foundation beams has been checked.

72 piles (+15) – concrete prefab square 320x320 – length 17m – *loads on piles:*



Based on the following loads:

Kopgevelbalk as A / G	Q-last - permanent	Q,g	=	**75,3**	kN/m	
	Q-last - variabele extreem	Q,var1	=	**15,8**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**27,6**	kN/m	
	F-last - permanent	F,g	=	**131,1**	kN	puntenlasten vanuit gevels en balkon/gallerij op uiteinde dwarsmuren
	F-last - variabele extreem	F,var1	=	**18,6**	kN	
	F-last - variabele niet extreem	F,var2	=	**18,6**	kN	
Bouwmuurbalk as B / D / F	Q-last - permanent	Q,g	=	**119,8**	kN/m	
	Q-last - variabele extreem	Q,var1	=	**38,8**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**65,7**	kN/m	
	F-last - permanent	F,g	=	**321,3**	kN	puntenlasten vanuit gevels en balkon/gallerij op uiteinde dwarsmuren
	F-last - variabele extreem	F,var1	=	**45,6**	kN	
	F-last - variabele niet extreem	F,var2	=	**45,6**	kN	
Bouwmuurbalk as C / E	Q-last - permanent	Q,g	=	**106,9**	kN/m	
	Q-last - variabele extreem	Q,var1	=	**30,6**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**54,0**	kN/m	
	F-last - permanent	F,g	=	**262,1**	kN	puntenlasten vanuit gevels en balkon/gallerij op uiteinde dwarsmuren
	F-last - variabele extreem	F,var1	=	**37,2**	kN	
	F-last - variabele niet extreem	F,var2	=	**37,2**	kN	
Stabiliteitsmuur	Q-last - permanent	Q,g	=	**113,9**	kN/m	bevat ook deel van vloerbelasting, vandaar reductie bij Bouwmuurbalk as B / D / F
	Q-last - variabele extreem	Q,var1	=	**11,0**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**15,3**	kN/m	

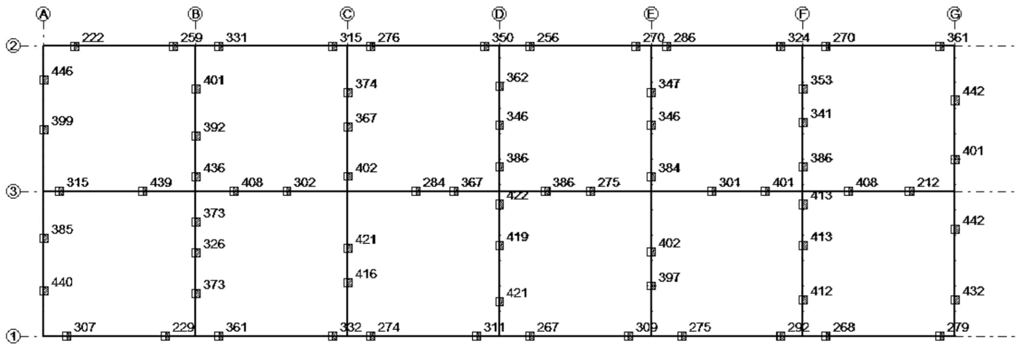
Figure C.29: Overview of foundations piles and used loads during calculation for variant 6.6.

Variants 7.1 + 7.2

Below, an overview of foundation piles is provided for variants 7.1 and 7.2, along with the used loads during calculation. Calculations have been performed using Technosoft Balkrooster, optimised for forces in foundation piles. Besides, the bending moment capacity of foundation beams has been checked.

Due to the similarity in weight within the redesigns of the previous chapter, these variants have been assumed to have an equal loading on foundation.

72 piles (+10) – concrete prefab square 320x320 – length 17m – *loads on piles:*



Based on the following loads:

Kopgevelbalk as A / G	Q-last - permanent	Q,g	=	**102,3**	kN/m	
	Q-last - variabele extreem	Q,var1	=	**10,7**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**20,5**	kN/m	
	F-last - permanent	F,g	=	**118,4**	kN	puntenlasten vanuit gevels en balkon/gallerij op uiteinde dwarsmuren
	F-last - variabele extreem	F,var1	=	**16,8**	kN	
	F-last - variabele niet extreem	F,var2	=	**16,8**	kN	
Bouwmuurbalk as B / D / F	Q-last - permanent	Q,g	=	**116,2**	kN/m	
	Q-last - variabele extreem	Q,var1	=	**20,7**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**32,4**	kN/m	
	F-last - permanent	F,g	=	**283,2**	kN	puntenlasten vanuit gevels en balkon/gallerij op uiteinde dwarsmuren
	F-last - variabele extreem	F,var1	=	**40,2**	kN	
	F-last - variabele niet extreem	F,var2	=	**40,2**	kN	
Bouwmuurbalk as C / E	Q-last - permanent	Q,g	=	**124,9**	kN/m	
	Q-last - variabele extreem	Q,var1	=	**21,4**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**40,9**	kN/m	
	F-last - permanent	F,g	=	**236,7**	kN	puntenlasten vanuit gevels en balkon/gallerij op uiteinde dwarsmuren
	F-last - variabele extreem	F,var1	=	**33,6**	kN	
	F-last - variabele niet extreem	F,var2	=	**33,6**	kN	
Stabiliteitsmuur	Q-last - permanent	Q,g	=	**104,2**	kN/m	bevat ook deel van vloerbelasting, vandaar reductie bij Bouwmuurbalk as B / D / F
	Q-last - variabele extreem	Q,var1	=	**20,4**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**24,4**	kN/m	

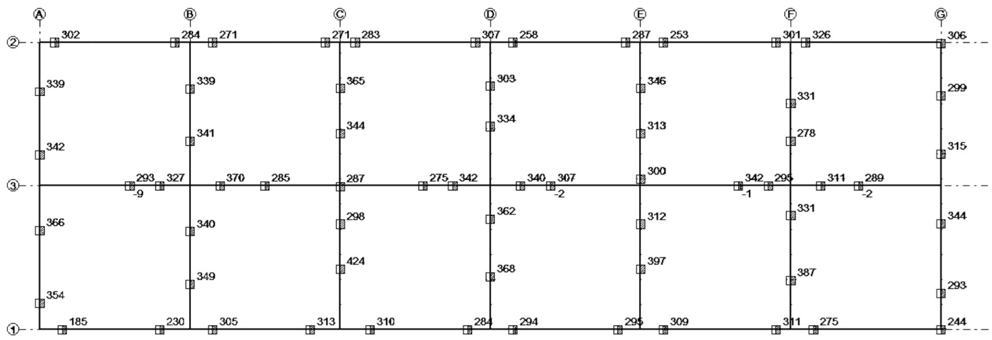
Figure C.30: Overview of foundations piles and used loads during calculation for variants 7.1 and 7.2.

Variants 7.3 + 7.4

Below, an overview of foundation piles is provided for variants 7.3 and 7.4, along with the used loads during calculation. Calculations have been performed using Technosoft Balkrooster, optimised for forces in foundation piles. Besides, the bending moment capacity of foundation beams has been checked.

Due to the similarity in weight within the redesigns of the previous chapter, these variants have been assumed to have an equal loading on foundation.

66 piles (+10) – concrete prefab square 320x320 – length 17m – *loads on piles:*



Based on the following loads:

Kopgevelbalk as A / G	Q-last - permanent	Q,g	=	**68,1**	kN/m	
	Q-last - variabele extreem	Q,var1	=	**10,7**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**20,5**	kN/m	
	F-last - permanent	F,g	=	**118,4**	kN	puntenlasten vanuit gevels en balkon/gallerij op uiteinde dwarsmuren
	F-last - variabele extreem	F,var1	=	**16,8**	kN	
	F-last - variabele niet extreem	F,var2	=	**16,8**	kN	
Bouwmuurbalk as B / D / F	Q-last - permanent	Q,g	=	**78,7**	kN/m	
	Q-last - variabele extreem	Q,var1	=	**20,7**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**32,4**	kN/m	
	F-last - permanent	F,g	=	**283,2**	kN	puntenlasten vanuit gevels en balkon/gallerij op uiteinde dwarsmuren
	F-last - variabele extreem	F,var1	=	**40,2**	kN	
	F-last - variabele niet extreem	F,var2	=	**40,2**	kN	
Bouwmuurbalk as C / E	Q-last - permanent	Q,g	=	**94,9**	kN/m	
	Q-last - variabele extreem	Q,var1	=	**21,4**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**40,9**	kN/m	
	F-last - permanent	F,g	=	**236,7**	kN	puntenlasten vanuit gevels en balkon/gallerij op uiteinde dwarsmuren
	F-last - variabele extreem	F,var1	=	**33,6**	kN	
	F-last - variabele niet extreem	F,var2	=	**33,6**	kN	
Stabiliteitsmuur	Q-last - permanent	Q,g	=	**71,4**	kN/m	bevat ook deel van vloerbelasting, vandaar reductie bij Bouwmuurbalk as B / D / F
	Q-last - variabele extreem	Q,var1	=	**20,4**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**24,4**	kN/m	

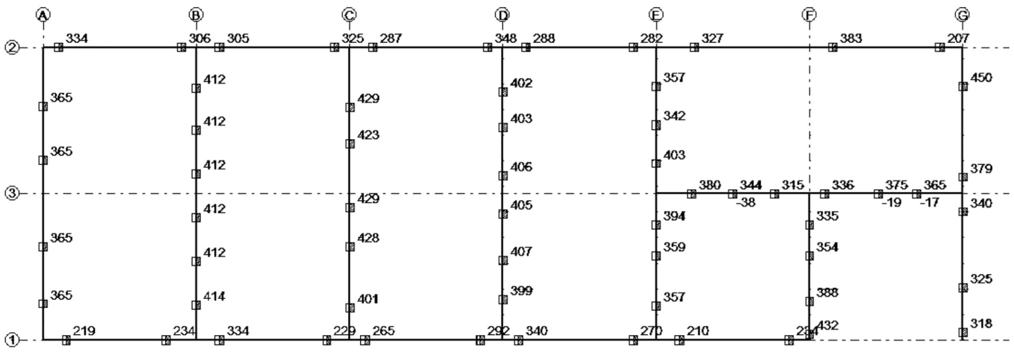
Figure C.31: Overview of foundations piles and used loads during calculation for variants 7.3 and 7.4.

Variants 7.5 + 7.6

Below, an overview of foundation piles is provided for variants 7.5 and 7.6, along with the used loads during calculation. Calculations have been performed using Technosoft Balkrooster, optimised for forces in foundation piles. Besides, the bending moment capacity of foundation beams has been checked.

Due to the similarity in weight within the redesigns of the previous chapter, these variants have been assumed to have an equal loading on foundation.

63 piles (+10) – concrete prefab square 320x320 – length 17m – *loads on piles:*



Based on the following loads:

Kopgevelbalk as A / G	Q-last - permanent	Q,g	=	**75,2**	kN/m	
	Q-last - variabele extreem	Q,var1	=	**13,3**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**23,5**	kN/m	
	F-last - permanent	F,g	=	**109,9**	kN	puntenlasten vanuit gevels en balkon/gallerij op uiteinde dwarsmuren
	F-last - variabele extreem	F,var1	=	**15,6**	kN	
	F-last - variabele niet extreem	F,var2	=	**15,6**	kN	
Bouwmuurbalk as B / D / F	Q-last - permanent	Q,g	=	**121,5**	kN/m	
	Q-last - variabele extreem	Q,var1	=	**33,7**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**55,6**	kN/m	
	F-last - permanent	F,g	=	**279,0**	kN	puntenlasten vanuit gevels en balkon/gallerij op uiteinde dwarsmuren
	F-last - variabele extreem	F,var1	=	**39,6**	kN	
	F-last - variabele niet extreem	F,var2	=	**39,6**	kN	
Bouwmuurbalk as C / E	Q-last - permanent	Q,g	=	**110,6**	kN/m	
	Q-last - variabele extreem	Q,var1	=	**27,0**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**47,6**	kN/m	
	F-last - permanent	F,g	=	**224,1**	kN	puntenlasten vanuit gevels en balkon/gallerij op uiteinde dwarsmuren
	F-last - variabele extreem	F,var1	=	**31,8**	kN	
	F-last - variabele niet extreem	F,var2	=	**31,8**	kN	
Stabiliteitsmuur	Q-last - permanent	Q,g	=	**71,4**	kN/m	bevat ook deel van vloerbelasting, vandaar reductie bij Bouwmuurbalk as B / D / F
	Q-last - variabele extreem	Q,var1	=	**20,4**	kN/m	
	Q-last - variabele niet extreem	Q,var2	=	**24,4**	kN/m	

Figure C.32: Overview of foundations piles and used loads during calculation for variants 7.5 and 7.6.

D

Details on assessment and analysis of redesigns

D.1. Overview of analysis of results

In the figures on the following pages, bar plots for the various assessment indicators are given for all variants. Besides, the contribution of each category is shown.

Bar plots for GWP-GHG

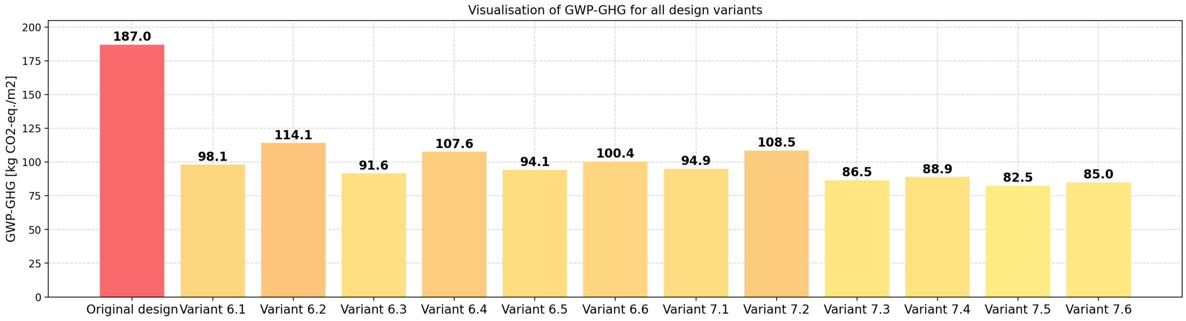


Figure D.1: Bar plot of GWP-GHG values for all designs

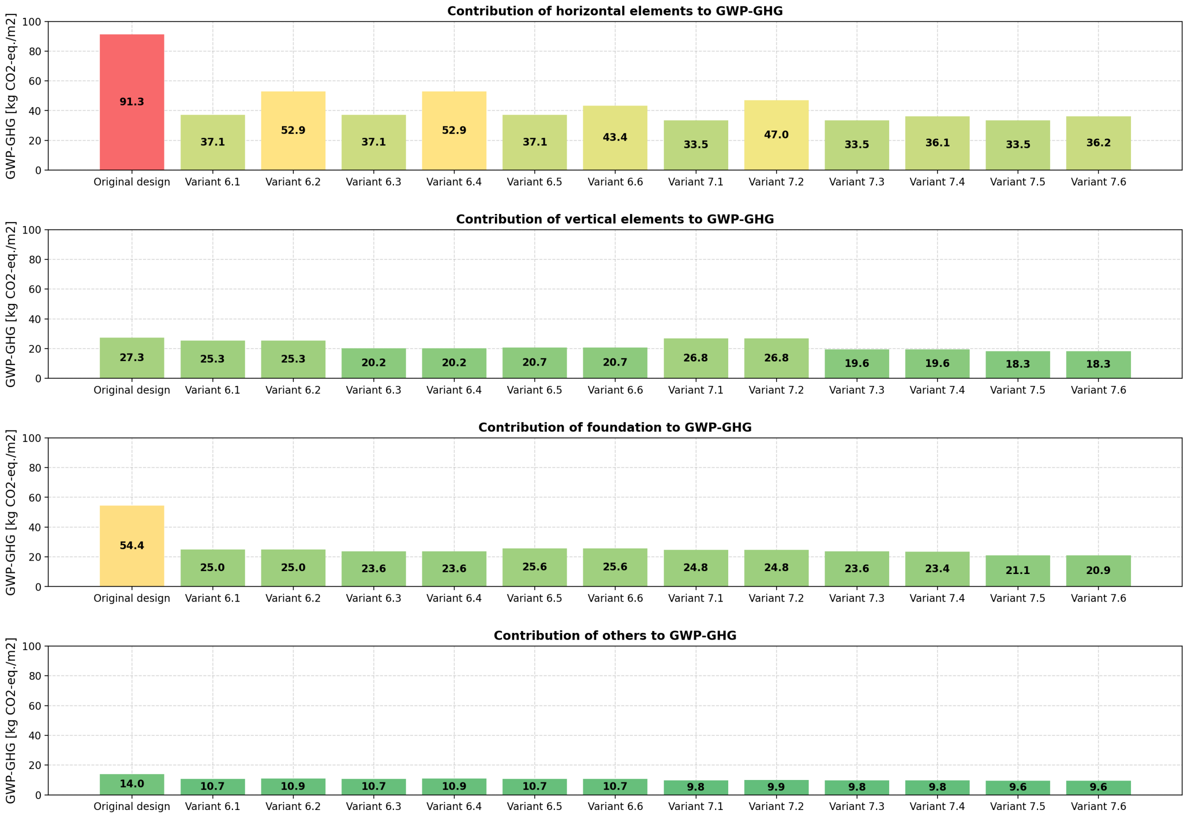


Figure D.2: Bar plots for contribution of various categories to GWP-GHG, given for all designs

Bar plots for GWP-total

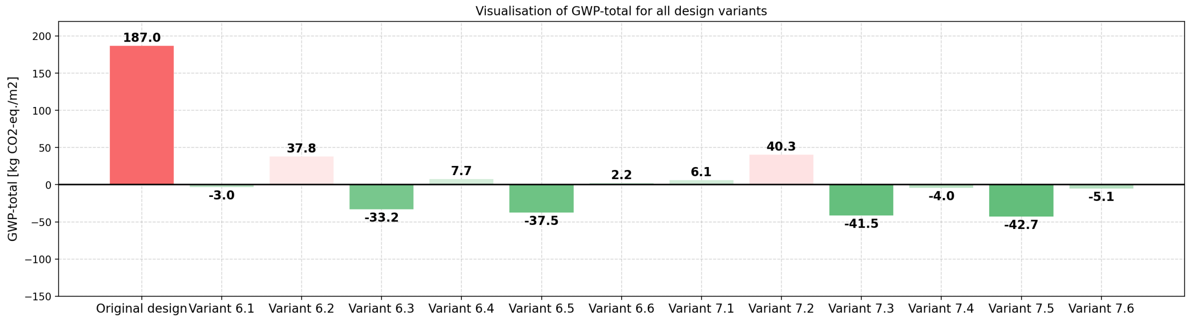


Figure D.3: Bar plot of GWP-total values for all designs

Figure D.4: Bar plots for contribution of various categories to GWP-total, given for all designs

Bar plots for costs

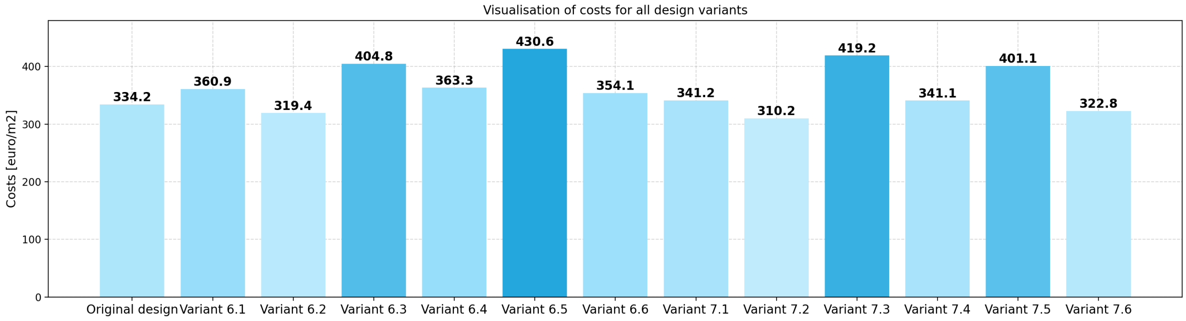


Figure D.5: Bar plot of cost values for all designs

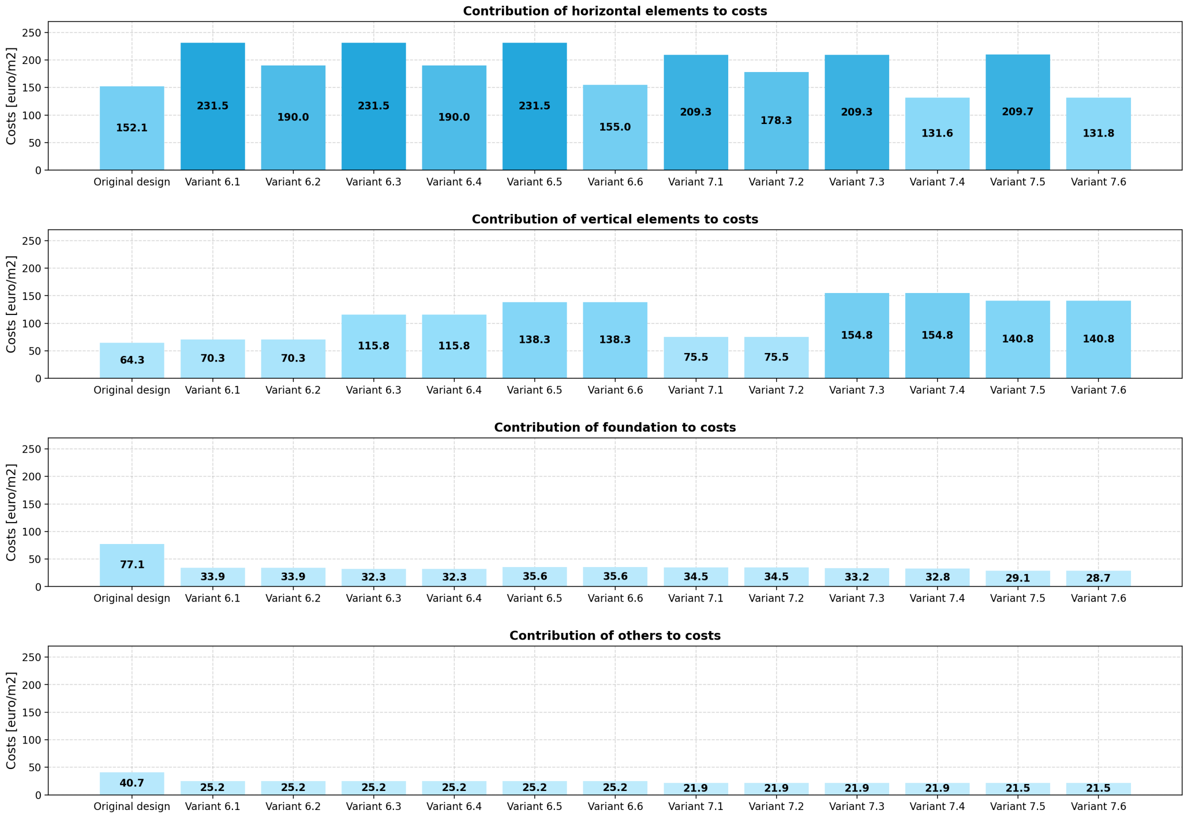


Figure D.6: Bar plots for contribution of various categories to costs, given for all designs

D.2. Overview of assessment results

Comparison between variants for Chapter 6

		Variant 6.1				Variant 6.2				Variant 6.3			
		GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs													
Main building	**Roofs**	4,9	-4,4	29,4	69,9	4,9	-4,4	29,4	69,9	4,9	-4,4	29,4	69,9
Main building	**Storey floors**	23,8	-39,4	165,6	419,2	38,7	-1,2	123,2	244,5	23,8	-39,4	165,6	419,2
Main building	**Ground floors**	6,2	-2,0	22,2	0,0	6,2	-2,0	22,2	0,0	6,2	-2,0	22,2	0,0
Entrance building	**Roofs**	0,3	-0,3	2,0	4,8	0,3	-0,3	2,0	4,8	0,3	-0,3	2,0	4,8
Entrance building	**Storey floors**	1,6	-2,7	11,5	29,0	2,6	-0,2	12,3	29,0	1,6	-2,7	11,5	29,0
Entrance building	**Ground floors**	0,2	-0,1	0,8	0,0	0,2	-0,1	0,8	0,0	0,2	-0,1	0,8	0,0
Walls, facades													
Main building	**Transverse outer walls**	2,8	2,8	6,9	0,0	2,8	2,8	6,9	0,0	2,5	-3,1	18,0	40,2
Main building	**Transverse inner walls**	13,0	13,0	23,9	0,0	13,0	13,0	23,9	0,0	8,2	-9,9	58,2	129,6
Main building	**Stability walls**	3,5	3,5	6,8	0	3,5	3,5	6,8	0,0	3,5	3,5	6,8	0,0
Main building	**Longitudinal facades**	0,9	-1,1	22,9	0,0	0,9	-1,1	22,9	0,0	0,9	-1,1	22,9	0,0
Entrance building	**Inner walls**	5,1	5,1	9,9	0,0	5,1	5,1	9,9	0,0	5,1	5,1	9,9	0,0
Foundation													
Main building	**Beam**	5,6	5,6	11,1	0,0	5,6	5,6	11,1	0,0	5,6	5,6	11,1	0,0
Main building	**Piles**	15,1	15,1	17,1	0,0	15,1	15,1	17,1	0,0	13,7	13,7	15,5	0,0
Entrance building	**Beam**	1,3	1,3	2,3	0,0	1,3	1,3	2,3	0,0	1,3	1,3	2,3	0,0
Entrance building	**Piles**	3,0	3,0	3,4	0,0	3,0	3,0	3,4	0,0	3,0	3,0	3,4	0,0
Others													
Main building	**Balconies**	3,6	-0,9	8,7	35,6	3,6	-0,9	8,7	35,6	3,6	-0,9	8,7	35,6
Main building	**Galleries**	6,6	-2,0	16,5	67,9	6,6	-2,0	16,5	67,9	6,6	-2,0	16,5	67,9
Both buildings	**Connections**	0,5	0,5	0,0	0,0	0,7	0,7	0,0	0,0	0,5	0,5	0,0	
	TOTAL	**98,2**	**-3,0**	**360,9**	**626,4**	**114,1**	**37,9**	**319,4**	**451,7**	**91,6**	**-33,2**	**404,8**	**796,2**

		Variant 6.4				Variant 6.5				Variant 6.6			
		GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs													
Main building	**Roofs**	4,9	-4,4	29,4	69,9	4,9	-4,4	29,4	69,9	6,1	-0,1	21,0	26,2
Main building	**Storey floors**	38,7	-1,2	123,2	244,5	23,8	-39,4	165,6	419,2	28,5	-6,5	102,4	146,7
Main building	**Ground floors**	6,2	-2,0	22,2	0,0	6,2	-2,0	22,2	0,0	6,2	-2,0	22,2	0,0
Entrance building	**Roofs**	0,3	-0,3	2,0	4,8	0,3	-0,3	2,0	4,8	0,4	0,0	1,5	1,8
Entrance building	**Storey floors**	2,6	-0,2	12,3	0,0	1,6	-2,7	11,5	29,0	2,0	-0,4	7,1	10,2
Entrance building	**Ground floors**	0,2	-0,1	0,8	0,0	0,2	-0,1	0,8	0,0	0,2	-0,1	0,8	0,0
Walls, facades													
Main building	**Transverse outer walls**	2,5	-3,1	18,0	40,2	2,5	-3,1	18,0	40,2	2,5	-3,1	18,0	40,2
Main building	**Transverse inner walls**	8,2	-9,9	58,2	129,6	8,2	-9,9	58,2	129,6	8,2	-9,9	58,2	129,6
Main building	**Stability walls**	3,5	3,5	6,8	0	3,8	-2,6	23,8	43,7	3,8	-2,6	23,8	43,7
Main building	**Longitudinal facades**	0,9	-1,1	22,9	0,0	1,1	-1,4	28,3	0,0	1,1	-1,4	28,3	0,0
Entrance building	**Inner walls**	5,1	5,1	9,9	0,0	5,1	5,1	9,9	0,0	5,1	5,1	9,9	0,0
Foundation													
Main building	**Beam**	5,6	5,6	11,1	0,0	6,7	6,7	13,5	0,0	6,7	6,7	13,5	0,0
Main building	**Piles**	13,7	13,7	15,5	0,0	14,5	14,5	16,4	0,0	14,5	14,5	16,4	0,0
Entrance building	**Beam**	1,3	1,3	2,3	0,0	1,3	1,3	2,3	0,0	1,3	1,3	2,3	0,0
Entrance building	**Piles**	3,0	3,0	3,4	0,0	3,0	3,0	3,4	0,0	3,0	3,0	3,4	0,0
Others													
Main building	**Balconies**	3,6	-0,9	8,7	35,6	3,6	-0,9	8,7	35,6	3,6	-0,9	8,7	35,6
Main building	**Galleries**	6,6	-2,0	16,5	67,9	6,6	-2,0	16,5	67,9	6,6	-2,0	16,5	67,9
Both buildings	**Connections**	0,7	0,7	0,0	0,0	0,5	0,5	0,0	0,0	0,5	0,5	0,0	0,0
	TOTAL	**107,6**	**7,7**	**363,3**	**592,5**	**94,1**	**-37,6**	**430,6**	**839,9**	**100,3**	**2,1**	**354,2**	**501,9**

Comparison between variants for Chapter 7

		Variant 7.1				Variant 7.2				Variant 7.3			
		GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs													
Main building	**Roofs**	5,1	-4,6	30,4	69,9	5,1	-4,6	30,4	69,9	5,1	-4,6	30,4	69,9
Main building	**Storey floors**	21,6	-33,9	148,6	349,3	34,3	-2,0	119,5	214,8	21,6	-33,9	148,6	349,3
Main building	**Ground floors**	4,9	-1,2	18,1	0,0	4,9	-1,2	18,1	0,0	4,9	-1,2	18,1	0,0
Entrance building	**Roofs**	0,3	-0,3	2,0	4,5	0,3	-0,3	2,0	4,5	0,3	-0,3	2,0	4,5
Entrance building	**Storey floors**	1,4	-2,2	9,6	22,7	2,2	-0,1	7,8	13,6	1,4	-2,2	9,6	22,7
Entrance building	**Ground floors**	0,2	0,0	0,6	0,0	0,2	0,0	0,6	0,0	0,2	0,0	0,6	0,0
Walls, facades													
Main building	**Transverse outer walls**	3,8	3,8	9,3	0,0	3,8	3,8	9,3	0,0	3,4	-4,2	24,5	52,8
Main building	**Transverse inner walls**	16,5	16,5	30,2	0,0	16,5	16,5	30,2	0,0	10,3	-12,5	73,6	158,8
Main building	**Stability walls**	4,1	4,1	7,9	0,0	4,1	4,1	7,9	0,0	3,9	-2,7	24,6	43,7
Main building	**Longitudinal facades**	1,0	-1,2	25,3	0,0	1,0	-1,2	25,3	0,0	1,0	-1,2	25,3	0,0
Entrance building	**Inner walls**	1,5	1,5	2,8	0,0	1,5	1,5	2,8	0,0	0,9	-1,2	6,8	14,6
Foundation													
Main building	**Beam**	6,7	6,7	13,4	0,0	6,7	6,7	13,4	0,0	6,8	6,8	13,5	0,0
Main building	**Piles**	15,0	15,0	17,0	0,0	15,0	15,0	17,0	0,0	13,7	13,7	15,5	0,0
Entrance building	**Beam**	1,0	1,0	1,7	0,0	1,0	1,0	1,7	0,0	1,0	1,0	1,7	0,0
Entrance building	**Piles**	2,1	2,1	2,4	0,0	2,1	2,1	2,4	0,0	2,1	2,1	2,4	0,0
Others													
Main building	**Balconies**	3,7	-1,0	9,0	35,6	3,7	-1,0	9,0	35,6	3,7	-1,0	9,0	35,6
Main building	**Galleries**	5,5	-0,7	12,9	49,0	5,5	-0,7	12,9	49,0	5,5	-0,7	12,9	49,0
Both buildings	**Connections**	0,6	0,6	0,0	0,0	0,7	0,7	0,0	0,0	0,6	0,6	0,0	0,0
	TOTAL	**94,9**	**6,1**	**341,1**	**531,0**	**108,5**	**40,2**	**310,2**	**387,4**	**86,5**	**-41,4**	**419,1**	**800,9**

		Variant 7.4				Variant 7.5				Variant 7.6			
		GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs													
Main building	**Roofs**	6,3	-0,2	21,7	43,7	5,0	-4,5	29,8	69,9	6,2	-0,2	21,3	26,2
Main building	**Storey floors**	22,8	-2,9	84,3	244,5	21,2	-33,2	145,8	349,3	22,4	-2,8	82,7	104,8
Main building	**Ground floors**	4,9	-1,2	18,1	0,0	4,8	-1,2	17,8	0,0	4,8	-1,2	17,8	0,0
Entrance building	**Roofs**	0,4	0,0	1,4	2,8	0,4	-0,4	2,6	6,2	0,6	0,0	1,9	2,3
Entrance building	**Storey floors**	1,5	-0,2	5,5	15,9	1,9	-2,9	12,9	30,9	2,0	-0,2	7,3	9,3
Entrance building	**Ground floors**	0,2	0,0	0,6	0,0	0,2	-0,1	0,8	0,0	0,2	-0,1	0,8	0,0
Walls, facades													
Main building	**Transverse outer walls**	3,4	-4,2	24,5	52,8	4,9	-6,0	35,1	77,3	4,9	-6,0	35,1	77,3
Main building	**Transverse inner walls**	10,3	-12,5	73,6	158,8	10,1	-12,3	72,2	158,8	10,1	-12,3	72,2	158,8
Main building	**Stability walls**	3,9	-2,7	24,6	43,7	2,1	-1,4	13,4	24,3	2,1	-1,4	13,4	24,3
Main building	**Longitudinal facades**	1,0	-1,2	25,3	0,0	0,7	-0,9	18,6	0,0	0,7	-0,9	18,6	0,0
Entrance building	**Inner walls**	0,9	-1,2	6,8	14,6	0,4	0,3	1,4	0,0	0,4	0,3	1,4	0,0
Foundation													
Main building	**Beam**	6,6	6,6	13,2	0,0	6,2	6,2	12,2	0,0	6,0	6,0	11,9	0,0
Main building	**Piles**	13,7	13,7	15,5	0,0	14,9	14,9	16,9	0,0	14,9	14,9	16,9	0,0
Entrance building	**Beam**	1,0	1,0	1,7	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Entrance building	**Piles**	2,1	2,1	2,4	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Others													
Main building	**Balconies**	3,7	-1,0	9,0	35,6	3,7	-0,9	8,8	35,6	3,7	-0,9	8,8	35,6
Main building	**Galleries**	5,5	-0,7	12,9	49,0	5,4	-0,7	12,6	49,0	5,4	-0,7	12,6	49,0
Both buildings	**Connections**	0,6	0,6	0,0	0,0	0,5	0,5	0,0	0,0	0,5	0,5	0,0	0,0
	TOTAL	**88,9**	**-3,9**	**341,1**	**661,4**	**82,5**	**-42,6**	**401,1**	**801,2**	**85,0**	**-5,0**	**322,9**	**487,5**

Overview of results for the estimated impact of using concrete

Below, the results of the assessments for the adjusted variants using concrete instead of calcium silicate bricks are given, as used in the discussion. Renewed sizes are based on substituting calcium silicate brick walls with concrete elements of the same weight. No further changes or verifications were made.

	GWP-GHG	Δ	GWP-total	Δ	costs	Δ	volume timber
	[kg CO2-eq./m2]	vs. variant 0	[kg CO2-eq./m2]	vs. variant 0	[euro/m2]	vs. variant 0	[m3]
Existing design	187,0		187,0		334,2		0
Variant 6.1	98,2	-47%	-3,0	-102%	360,9	8%	626
Variant 6.2	114,1	-39%	37,9	-80%	319,4	-4%	452
Variant 7.1	94,9	-49%	6,1	-97%	341,1	2%	531
Variant 7.2	108,5	-42%	40,2	-78%	310,2	-7%	387

	GWP-GHG	Δ	GWP-total	Δ	costs	Δ	volume timber
	[kg CO2-eq./m2]	vs. variant 0	[kg CO2-eq./m2]	vs. variant 0	[euro/m2]	vs. variant 0	[m3]
Adjusted variant 6.1	105,3	-44%	4,2	-98%	365,8	9%	626
Adjusted variant 6.2	121,3	-35%	45,0	-76%	324,4	-3%	452
Adjusted variant 7.1	104,1	-44%	15,3	-92%	347,5	4%	531
Adjusted variant 7.2	117,7	-37%	49,4	-74%	316,6	-5%	387

Below, the differences between calcium silicate brick walls and concrete walls are given, sorted by variants of Chapter 6 and Chapter 7.

Impact of wall system change	Δ GWP-GHG	Δ GWP-total	Δ costs	Δ GWP-GHG / costs	Δ GWP-total / costs
	[kg CO2-eq./m2]	[kg CO2-eq./m2]	[euro/m2]	[kg co2-eq./euro]	[kg co2-eq./euro]
Calcium silicate brick to concrete, variants of Chapter 6	7,1	7,1	5,0	1,43	1,43
Calcium silicate brick to concrete, variants of Chapter 7	9,2	9,2	6,4	1,44	1,44

D.3. Details of assessment

Detailed assessment of existing design

				per unit				total			
Floors, roofs				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Roofs**			**93,70**		**179,69**		**4,1E+04**		**7,8E+04**	
	Concrete wide slab 250	436,6	m2	80,00		128,90		3,5E+04		5,6E+04	
	Finishing (insulation + gravel)	436,6	m2	13,70		50,79		6,0E+03		2,2E+04	
Main building	**Storey floors**			**93,75**		**157,47**		**1,6E+05**		**2,8E+05**	
	Concrete wide slab 250	1746,5	m2	80,00		128,90		1,4E+05		2,3E+05	
	Concrete screed 70 + insulation 2(	1746,5	m2	13,75		28,57		2,4E+04		5,0E+04	
Main building	**Ground floors**			**79,15**		**100,78**		**3,2E+04**		**4,1E+04**	
	Hollow core slab 260	409,7	m2	65,40		72,21		2,7E+04		3,0E+04	
	Concrete screed 70 + insulation 2(	409,7	m2	13,75		28,57		5,6E+03		1,2E+04	
Entrance building	**Roofs**			**93,70**		**179,69**		**2,8E+03**		**5,4E+03**	
	Concrete wide slab 250	30,2	m2	80,00		128,90		2,4E+03		3,9E+03	
	Finishing (insulation + gravel)	30,2	m2	13,70		50,79		4,1E+02		1,5E+03	
Entrance building	**Storey floors**			**93,75**		**157,47**		**1,1E+04**		**1,9E+04**	
	Concrete wide slab 250	120,9	m2	80,00		128,90		9,7E+03		1,6E+04	
	Concrete screed 70 + insulation 2(	120,9	m2	13,75		28,57		1,7E+03		3,5E+03	
Entrance building	**Ground floors**			**79,15**		**100,78**		**1,2E+03**		**1,5E+03**	
	Hollow core slab 260	14,8	m2	65,40		72,21		9,7E+02		1,1E+03	
	Concrete screed 70 + insulation 2(	14,8	m2	13,75		28,57		2,0E+02		4,2E+02	
				per unit				total			
Walls, facades				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Transverse outer walls**			**35,00**		**85,00**		**8,4E+03**		**2,0E+04**	
	CSB 175mm CS36	239,0	m2	35,00		85,00		8,4E+03		2,0E+04	
Main building	**Transverse inner walls**			**50,00**		**91,64**		**3,7E+04**		**6,8E+04**	
	CSB 250mm CS36	746,9	m2	50,00		91,64		3,7E+04		6,8E+04	
Main building	**Longitudinal facades**			**17,22**		**69,41**		**1,5E+04**		**6,1E+04**	
	CSB 150mm CS12	873,6	m2	17,22		69,41		1,5E+04		6,1E+04	
Entrance building	**Inner walls**			**48,00**		**93,24**		**1,5E+04**		**2,8E+04**	
	Concrete 150mm	305,2	m2	48,00		93,24		1,5E+04		2,8E+04	
				per unit				total			
Foundation				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Beam**			**307,20**		**570,54**		**1,6E+04**		**3,0E+04**	
	Beam 400x600	83,2	m	76,80		158,75		6,4E+03		1,3E+04	
	Beam 550x600	62,0	m	105,60		194,11		6,5E+03		1,2E+04	
	Beam 650x600	21,4	m	124,80		217,68		2,7E+03		4,7E+03	
Main building	**Piles**			**1861,44**		**2502,50**		**1,1E+05**		**1,5E+05**	
	Piles Vibro 456 - 35m	60,0	pcs	1861,44		2502,50		1,1E+05		1,5E+05	
Entrance building	**Beam**			**124,80**		**217,68**		**4,7E+03**		**8,1E+03**	
	Beam 650x600	37,3	m	124,80		217,68		4,7E+03		8,1E+03	
Entrance building	**Piles**			**1861,44**		**2502,50**		**1,9E+04**		**2,5E+04**	
	Piles Vibro 456 - 35m	10,0	pcs	1861,44		2502,50		1,9E+04		2,5E+04	
				per unit				total			
Others				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Balconies**			**89,60**		**260,90**		**1,3E+04**		**3,9E+04**	
	Balconies	148,3	m2	89,60		260,90					
Main building	**Galleries**			**89,60**		**260,90**		**2,5E+04**		**7,4E+04**	
	Galleries	282,9	m2	89,60		260,90		2,5E+04		7,4E+04	
	Columns	0,0	m					0,0E+00		0,0E+00	

units	
costs	[euro]
GWP	[kg CO2-eq.]
Volume	[m3]

gross floor area		
GFA main building excl.	2183	m2
GFA balconies and galleries	431	m2
GFA main building total	**2614**	**m2**
GFA entry building + storage	**151**	**m2**
GFA TOTAL	**2765**	**m2**

		total value				value per m2 (GFA total)				value per m2 (GFA main building)				value per m2 (GFA entrance building)			
		GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs																	
Main building	**Roofs**	4,1E+04	0,0E+00	7,8E+04	0,0E+00	14,8		28,4		15,6		30,0					
Main building	**Storey floors**	1,6E+05	0,0E+00	2,8E+05	0,0E+00	59,2		99,4		62,6		105,2					
Main building	**Ground floors**	3,2E+04	0,0E+00	4,1E+04	0,0E+00	11,7		14,9		12,4		15,8					
Entrance building	**Roofs**	2,8E+03	0,0E+00	5,4E+03	0,0E+00	1,0		2,0						18,7		35,9	
Entrance building	**Storey floors**	1,1E+04	0,0E+00	1,9E+04	0,0E+00	4,1		6,9						75,0		126,0	
Entrance building	**Ground floors**	1,2E+03	0,0E+00	1,5E+03	0,0E+00	0,4		0,5						7,7		9,9	
Walls, facades																	
Main building	**Transverse outer walls**	8,4E+03	0,0E+00	2,0E+04	0,0E+00	3,0		7,3		3,2		7,8					
Main building	**Transverse inner walls**	3,7E+04	0,0E+00	6,8E+04	0,0E+00	13,5		24,8		14,3		26,2					
Main building	**Longitudinal facades**	1,5E+04	0,0E+00	6,1E+04	0,0E+00	5,4		21,9		5,8		23,2					
Entrance building	**Inner walls**	1,5E+04	0,0E+00	2,8E+04	0,0E+00	5,3		10,3						96,9		188,3	
Foundation																	
Main building	**Beam**	1,6E+04	0,0E+00	3,0E+04	0,0E+00	5,6		10,8		6,0		11,4					
Main building	**Piles**	1,1E+05	0,0E+00	1,5E+05	0,0E+00	40,4		54,3		42,7		57,4					
Entrance building	**Beam**	4,7E+03	0,0E+00	8,1E+03	0,0E+00	1,7		2,9						30,8		53,8	
Entrance building	**Piles**	1,9E+04	0,0E+00	2,5E+04	0,0E+00	6,7		9,0						123,1		165,6	
Others																	
Main building	**Balconies**	1,3E+04	0,0E+00	3,9E+04	0,0E+00	4,8		14,0		5,1		14,8					
Main building	**Galleries**	2,5E+04	0,0E+00	7,4E+04	0,0E+00	9,2		26,7		9,7		28,2					
					TOTAL	**187,0**		**334,2**		**177,4**	**0,0**	**320,1**		**352,4**	**0,0**	**579,4**	

	value per m2 (GFA total)				value per m2 (GFA main building)				value per m2 (GFA entrance building)			
	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs, beams	91,3		152,1		90,7		151,0		101,5		171,8	
Walls, facades, columns	27,3		64,3		23,2		57,1		96,9		188,3	
Foundation	54,4		77,1		48,7		68,9		154,0		219,3	
Others	14,0		40,7		14,8		43,0		0,0		0,0	
TOTAL	**187,0**		**334,2**		**177,4**		**320,1**		**352,4**		**579,4**	
	percentages				percentages				percentages			
	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs, beams	49%		46%		51%		47%		29%		30%	
Walls, facades, columns	15%		19%		13%		18%		28%		32%	
Foundation	29%		23%		27%		22%		44%		38%	
Others	7%		12%		8%		13%		0%		0%	
TOTAL	**100%**		**100%**		**100%**		**100%**		**100%**		**100%**	

Detailed assessment of variant 6.1

				per unit				total			
Floors, roofs				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	Roofs			31,03	-27,98	186,13	0,16	1,4E+04	-1,2E+04	8,1E+04	7,0E+01
	CLT 160 L5s	436,6	m2	17,33	-41,68	135,34	0,16	7,6E+03	-1,8E+04	5,9E+04	7,0E+01
	Finishing (insulation + gravel)	436,6	m2	13,70	13,70	50,79		6,0E+03	6,0E+03	2,2E+04	
Main building	Storey floors			37,71	-62,35	262,17	0,24	6,6E+04	-1,1E+05	4,6E+05	4,2E+02
	CLT 240 L7s	1746,5	m2	25,99	-62,52	204,20	0,24	4,5E+04	-1,1E+05	3,6E+05	4,2E+02
	Insulation and cladding	1746,5	m2	11,72	0,18	57,97		2,0E+04	3,1E+02	1,0E+05	
Main building	Ground floors			41,74	-13,77	149,89	0,08	1,7E+04	-5,6E+03	6,1E+04	0,0E+00
	Timber hollow core slab 280	409,7	m2	35,21	-20,51	115,50	0,08	1,4E+04	-8,4E+03	4,7E+04	
	Insulation and cladding GF	409,7	m2	6,53	6,74	34,39		2,7E+03	2,8E+03	1,4E+04	
Entrance building	Roofs			31,03	-27,98	186,13	0,16	9,4E+02	-8,5E+02	5,6E+03	4,8E+00
	CLT 160 L5s	30,2	m2	17,33	-41,68	135,34	0,16	5,2E+02	-1,3E+03	4,1E+03	4,8E+00
	Finishing (insulation + gravel)	30,2	m2	13,70	13,70	50,79		4,1E+02	4,1E+02	1,5E+03	
Entrance building	Storey floors			37,71	-62,35	262,17	0,24	4,6E+03	-7,5E+03	3,2E+04	2,9E+01
	CLT 240 L7s	120,9	m2	25,99	-62,52	204,20	0,24	3,1E+03	-7,6E+03	2,5E+04	2,9E+01
	Insulation and cladding	120,9	m2	11,72	0,18	57,97		1,4E+03	2,2E+01	7,0E+03	
Entrance building	Ground floors			41,74	-13,77	149,89	0,08	6,2E+02	-2,0E+02	2,2E+03	0,0E+00
	Timber hollow core slab 280	14,8	m2	35,21	-20,51	115,50	0,08	5,2E+02	-3,0E+02	1,7E+03	
	Insulation and cladding GF	14,8	m2	6,53	6,74	34,39		9,7E+01	1,0E+02	5,1E+02	

				per unit				total			
Walls, facades				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	Transverse outer walls			35,00	43,75	85,00	0,00	7,8E+03	7,8E+03	1,9E+04	0,0E+00
	CSB 175mm CS36	223,3	m2	35,00	35,00	85,00		7,8E+03	7,8E+03	1,9E+04	
Main building	Transverse inner walls			50,00	62,66	91,64	0,00	3,6E+04	3,6E+04	6,6E+04	0,0E+00
	CSB 250mm CS36	720,2	m2	50,00	50,00	91,64		3,6E+04	3,6E+04	6,6E+04	
Main building	Stability walls			44,80	44,80	87,02	0,00	9,7E+03	9,7E+03	1,9E+04	0,0E+00
	Concrete 140mm	216,0	m2	44,80	44,80	87,02		9,7E+03	9,7E+03	1,9E+04	
Main building	Longitudinal facades			3,55	-4,53	92,89	0,02	2,4E+03	-3,1E+03	6,3E+04	0,0E+00
	HSB facade inner wall	680,4	m2	3,55	-4,53	92,89	0,02	2,4E+03	-3,1E+03	6,3E+04	
Entrance building	Inner walls			48,00	48,00	93,24	0,00	1,4E+04	1,4E+04	2,7E+04	0,0E+00
	Concrete 150mm	294,3	m2	48,00	48,00	93,24		1,4E+04	1,4E+04	2,7E+04	

				per unit				total			
Foundation				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	Beam							1,5E+04	1,5E+04	3,1E+04	0,0E+00
	Beam 400x600	83,2	m	76,80	76,80	158,75		6,4E+03	6,4E+03	1,3E+04	
	Beam 500x600	62,0	m	96,00	96,00	194,11		6,0E+03	6,0E+03	1,2E+04	
	Beam 650x600	24,8	m	124,80	124,80	217,68		3,1E+03	3,1E+03	5,4E+03	
Main building	Piles			557,06	557,06	630,70	0,00	4,2E+04	4,2E+04	4,7E+04	0,0E+00
	Prefab piles 320x320 - 17m	75,0	pcs	557,06	557,06	630,70		4,2E+04	4,2E+04	4,7E+04	
Entrance building	Beam			124,80	124,80	217,68	0,00	3,6E+03	3,6E+03	6,3E+03	0,0E+00
	Beam 650x600	28,8	m	124,80	124,80	217,68		3,6E+03	3,6E+03	6,3E+03	
Entrance building	Piles			557,06	557,06	630,70	0,00	8,4E+03	8,4E+03	9,5E+03	0,0E+00
	Prefab piles 320x320 - 17m	15,0	pcs	557,06	557,06	630,70		8,4E+03	8,4E+03	9,5E+03	

				per unit				total			
Others				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	Balconies			67,52	-16,04	163,68	0,24	10005,15	-2567,57	24131,95	3,6E+01
	CLT140	148,3	m2	14,98	-83,49	118,00	0,24	2,2E+03	-1,2E+04	1,8E+04	3,6E+01
	Supports (beams, steel)	153,6	m	46,25	55,50	37,20		7,1E+03	8,5E+03	5,7E+03	
	Supports (ties, steel)	108,0	m	6,29	11,95	8,48		6,8E+02	1,3E+03	9,2E+02	
Main building	Galleries			114,33	52,55	211,00	0,24	1,8E+04	-5,5E+03	4,6E+04	6,8E+01
	CLT140	282,9	m2	14,98	-83,49	118,00	0,24	4,2E+03	-2,4E+04	3,3E+04	6,8E+01
	Supports (beams, steel)	204,0	m	46,44	55,53	37,20		9,5E+03	1,1E+04	7,6E+03	
	Supports (columns, steel)	84,0	m	52,91	80,51	55,80		4,4E+03	6,8E+03	4,7E+03	
Both buildings	Connections (steel)	0,8	m3	1850,00	1850,00	0,00	0,00	1,5E+03	1,5E+03	0,0E+00	0,0E+00

Only GWP, costs included in CLT element costs

units	
costs	[euro]
GWP	[kg CO2-eq.]
Volume	[m3]

gross floor area		
GFA main building excl.	2183	m2
GFA balconies and galleries	431	m2
GFA main building total	2614	m2
GFA entry building + storage	151	m2
GFA TOTAL	2765	m2

floor and building heights		
h-cladding	0,14	m
h-vloer	0,24	m
h-free	2,70	m
h-storey	3,08	m
h-outer-tot	15,39	m
h-inner-tot	13,50	m

		total value				value per m2 (GFA total)				value per m2 (GFA main building)				value per m2 (GFA entrance building)			
		GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs																	
Main building	Roofs	1,4E+04	-1,2E+04	8,1E+04	7,0E+01	4,9	-4,4	29,4	69,9	5,2	-4,7	31,1	69,9				
Main building	Storey floors	6,6E+04	-1,1E+05	4,6E+05	4,2E+02	23,8	-39,4	165,6	419,2	25,2	-41,6	175,1	419,2				
Main building	Ground floors	1,7E+04	-5,6E+03	6,1E+04	0,0E+00	6,2	-2,0	22,2	0,0	6,5	-2,2	23,5	0,0				
Entrance building	Roofs	9,4E+02	-8,5E+02	5,6E+03	4,8E+00	0,3	-0,3	2,0	4,8					6,2	-5,6	37,2	4,8
Entrance building	Storey floors	4,6E+03	-7,5E+03	3,2E+04	2,9E+01	1,6	-2,7	11,5	29,0					30,2	-49,9	209,7	29,0
Entrance building	Ground floors	6,2E+02	-2,0E+02	2,2E+03	0,0E+00	0,2	-0,1	0,8	0,0					4,1	-1,3	14,7	0,0
Walls, facades																	
Main building	Transverse outer walls	7,8E+03	7,8E+03	1,9E+04	0,0E+00	2,8	2,8	6,9	0,0	3,0	3,0	7,3	0,0				
Main building	Transverse inner walls	3,6E+04	3,6E+04	6,6E+04	0,0E+00	13,0	13,0	23,9	0,0	13,8	13,8	25,2	0,0				
Main building	Stability walls	9,7E+03	9,7E+03	1,9E+04	0,0E+00	3,5	3,5	6,8	0,0	3,7	3,7	7,2	0,0				
Main building	Longitudinal facades	2,4E+03	-3,1E+03	6,3E+04	0,0E+00	0,9	-1,1	22,9	0,0	0,9	-1,2	24,2	0,0				
Entrance building	Inner walls	1,4E+04	1,4E+04	2,7E+04	0,0E+00	5,1	5,1	9,9	0,0					93,5	93,5	181,5	0,0
Foundation																	
Main building	Beam	1,5E+04	1,5E+04	3,1E+04	0,0E+00	5,6	5,6	11,1	0,0	5,9	5,9	11,7	0,0				
Main building	Piles	4,2E+04	4,2E+04	4,7E+04	0,0E+00	15,1	15,1	17,1	0,0	16,0	16,0	18,1	0,0				
Entrance building	Beam	3,6E+03	3,6E+03	6,3E+03	0,0E+00	1,3	1,3	2,3	0,0					23,8	23,8	41,5	0,0
Entrance building	Piles	8,4E+03	8,4E+03	9,5E+03	0,0E+00	3,0	3,0	3,4	0,0					55,3	55,3	62,6	0,0
Others																	
Main building	Balconies	1,0E+04	-2,6E+03	2,4E+04	3,6E+01	3,6	-0,9	8,7	35,6	3,8	-1,0	9,2	35,6				
Main building	Galleries	1,8E+04	-5,5E+03	4,6E+04	6,8E+01	6,6	-2,0	16,5	67,9	6,9	-2,1	17,5	67,9				
Both buildings	Connections	1,5E+03	1,5E+03	0,0E+00	0,0E+00	0,5	0,5	0,0	0,0								
					TOTAL	98,2	-3,0	360,9	626,36	91,0	-10,4	350,1	592,5	213,0	115,7	547,2	33,9

	value per m2 (GFA total)				value per m2 (GFA main building)				value per m2 (GFA entrance building)			
	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs, beams	37,1	-48,9	231,5	522,9	36,9	-48,5	229,7	489,0	40,5	-56,8	261,6	33,9
Walls, facades, columns	25,3	23,3	70,3	0,0	21,4	19,3	63,9	0,0	93,5	93,5	181,5	0,0
Foundation	25,0	25,0	33,9	0,0	21,9	21,9	29,8	0,0	79,1	79,1	104,1	0,0
Others	10,7	-2,4	25,2	103,5	10,8	-3,1	26,7	103,5	0,0	0,0	0,0	0,0
TOTAL	98,2	-3,0	360,9	626,4	91,0	-10,4	350,1	592,5	213,0	115,7	547,2	33,9

	percentages				percentages				percentages			
	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs, beams	38%		64%	83%	41%		66%	83%	19%		48%	100%
Walls, facades, columns	26%		19%	0%	24%		18%	0%	44%		33%	0%
Foundation	25%		9%	0%	24%		9%	0%	37%		19%	0%
Others	11%		7%	17%	12%		8%	17%	0%		0%	0%
TOTAL	100%		100%	100%	100%		100%	100%	100%		100%	100%

Detailed assessment of variant 6.2

				per unit				total			
Floors, roofs				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Roofs**			**31,03**	**-27,98**	**186,13**	**0,16**	**1,4E+04**	**-1,2E+04**	**8,1E+04**	**7,0E+01**
	CLT 160 L5s	436,6	m2	17,33	-41,68	135,34	0,16	7,6E+03	-1,8E+04	5,9E+04	7,0E+01
	Finishing (insulation + gravel)	436,6	m2	13,70	13,70	50,79		6,0E+03	6,0E+03	2,2E+04	
Main building	**Storey floors**			**61,31**	**-1,84**	**195,15**	**0,14**	**1,1E+05**	**-3,2E+03**	**3,4E+05**	**2,4E+02**
	CLT 140 L5s	1746,5	m2	15,16	-36,47	118,13	0,14	2,6E+04	-6,4E+04	2,1E+05	2,4E+02
	Concrete floor 100mm	1746,5	m2	32,00	32,00	19,05		5,6E+04	5,6E+04	3,3E+04	
	Insulation and cladding	1746,5	m2	14,15	2,63	57,97		2,5E+04	4,6E+03	1,0E+05	
Main building	**Ground floors**			**41,74**	**-13,77**	**149,89**	**0,08**	**1,7E+04**	**-5,6E+03**	**6,1E+04**	**0,0E+00**
	Timber hollow core slab 280	409,7	m2	35,21	-20,51	115,50	0,08	1,4E+04	-8,4E+03	4,7E+04	
	Insulation and cladding GF	409,7	m2	6,53	6,74	34,39		2,7E+03	2,8E+03	1,4E+04	
Entrance building	**Roofs**			**31,03**	**-27,98**	**186,13**	**0,16**	**9,4E+02**	**-8,5E+02**	**5,6E+03**	**4,8E+00**
	CLT 160 L5s	30,2	m2	17,33	-41,68	135,34	0,16	5,2E+02	-1,3E+03	4,1E+03	4,8E+00
	Finishing (insulation + gravel)	30,2	m2	13,70	13,70	50,79		4,1E+02	4,1E+02	1,5E+03	
Entrance building	**Storey floors**			**58,88**	**-4,29**	**281,22**	**0,24**	**7,1E+03**	**-5,2E+02**	**3,4E+04**	**2,9E+01**
	CLT 140 L5s	120,9	m2	15,16	-36,47	204,20	0,24	1,8E+03	-4,4E+03	2,5E+04	2,9E+01
	Concrete floor 100mm	120,9		32,00	32,00	19,05		3,9E+03	3,9E+03	2,3E+03	
	Insulation and cladding	120,9	m2	11,72	0,18	57,97		1,4E+03	2,2E+01	7,0E+03	
Entrance building	**Ground floors**			**41,74**	**-13,77**	**149,89**	**0,08**	**6,2E+02**	**-2,0E+02**	**2,2E+03**	**0,0E+00**
	Timber hollow core slab 280	14,8	m2	35,21	-20,51	115,50	0,08	5,2E+02	-3,0E+02	1,7E+03	
	Insulation and cladding GF	14,8	m2	6,53	6,74	34,39		9,7E+01	1,0E+02	5,1E+02	
				per unit				total			
Walls, facades				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Transverse outer walls**			**35,00**	**43,75**	**85,00**	**0,00**	**7,8E+03**	**7,8E+03**	**1,9E+04**	**0,0E+00**
	CSB 175mm CS36	223,3	m2	35,00	35,00	85,00		7,8E+03	7,8E+03	1,9E+04	
Main building	**Transverse inner walls**			**50,00**	**62,66**	**91,64**	**0,00**	**3,6E+04**	**3,6E+04**	**6,6E+04**	**0,0E+00**
	CSB 250mm CS36	720,2	m2	50,00	50,00	91,64		3,6E+04	3,6E+04	6,6E+04	
Main building	**Stability walls**			**44,80**	**44,80**	**87,02**	**0,00**	**9,7E+03**	**9,7E+03**	**1,9E+04**	**0,0E+00**
	Concrete 140mm	216,0	m2	44,80	44,80	87,02		9,7E+03	9,7E+03	1,9E+04	
Main building	**Longitudinal facades**			**3,55**	**-4,53**	**92,89**	**0,02**	**2,4E+03**	**-3,1E+03**	**6,3E+04**	**0,0E+00**
	HSB facade inner wall	680,4	m2	3,55	-4,53	92,89	0,02	2,4E+03	-3,1E+03	6,3E+04	
Entrance building	**Inner walls**			**48,00**	**48,00**	**93,24**	**0,00**	**1,4E+04**	**1,4E+04**	**2,7E+04**	**0,0E+00**
	Concrete 150mm	294,3	m2	48,00	48,00	93,24		1,4E+04	1,4E+04	2,7E+04	
				per unit				total			
Foundation				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Beam**							**1,5E+04**	**1,5E+04**	**3,1E+04**	**0,0E+00**
	Beam 400x600	83,2	m	76,80	76,80	158,75		6,4E+03	6,4E+03	1,3E+04	
	Beam 500x600	62,0	m	96,00	96,00	194,11		6,0E+03	6,0E+03	1,2E+04	
	Beam 650x600	24,8	m	124,80	124,80	217,68		3,1E+03	3,1E+03	5,4E+03	
Main building	**Piles**			**557,06**	**557,06**	**630,70**	**0,00**	**4,2E+04**	**4,2E+04**	**4,7E+04**	**0,0E+00**
	Prefab piles 320x320 - 17m	75,0	pcs	557,06	557,06	630,70		4,2E+04	4,2E+04	4,7E+04	
Entrance building	**Beam**			**124,80**	**124,80**	**217,68**	**0,00**	**3,6E+03**	**3,6E+03**	**6,3E+03**	**0,0E+00**
	Beam 650x600	28,8	m	124,80	124,80	217,68		3,6E+03	3,6E+03	6,3E+03	
Entrance building	**Piles**			**557,06**	**557,06**	**630,70**	**0,00**	**8,4E+03**	**8,4E+03**	**9,5E+03**	**0,0E+00**
	Prefab piles 320x320 - 17m	15,0	pcs	557,06	557,06	630,70		8,4E+03	8,4E+03	9,5E+03	
				per unit				total			
Others				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Balconies**			**67,52**	**-16,04**	**163,68**	**0,24**	**10005,15**	**-2567,57**	**24131,95**	**3,6E+01**
	CLT140	148,3	m2	14,98	-83,49	118,00	0,24	2,2E+03	-1,2E+04	1,8E+04	3,6E+01
	Supports (beams, steel)	153,6	m	46,25	55,50	37,20		7,1E+03	8,5E+03	5,7E+03	
	Supports (ties, steel)	108,0	m	6,29	11,95	8,48		6,8E+02	1,3E+03	9,2E+02	
Main building	**Galleries**			**114,33**	**52,55**	**211,00**	**0,24**	**1,8E+04**	**-5,5E+03**	**4,6E+04**	**6,8E+01**
	CLT140	282,9	m2	14,98	-83,49	118,00	0,24	4,2E+03	-2,4E+04	3,3E+04	6,8E+01
	Supports (beams, steel)	204,0	m	46,44	55,53	37,20		9,5E+03	1,1E+04	7,6E+03	
	Supports (columns, steel)	84,0	m	52,91	80,51	55,80		4,4E+03	6,8E+03	4,7E+03	
Both buildings	**Connections (steel)**	**1,0**	**m3**	**1850,00**	**1850,00**	**0,00**	**0,00**	**1,9E+03**	**1,9E+03**	**0,0E+00**	**0,0E+00**

Only GWP, costs included in CLT element costs

units	
costs	[euro]
GWP	[kg CO2-eq.]
Volume	[m3]

gross floor area		
GFA main building excl.	2183	m2
GFA balconies and galleries	431	m2
GFA main building total	**2614**	**m2**
GFA entry building + storage	**151**	**m2**
GFA TOTAL	**2765**	**m2**

floor and building heights		
h-cladding	0,06	m
h-vloer	0,24	m
h-free	2,70	m
h-storey	**3,00**	**m**
h-outer-tot	**14,99**	**m**
h-inner-tot	**13,50**	**m**

		total value				value per m2 (GFA total)				value per m2 (GFA main building)				value per m2 (GFA entrance building)			
		GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs																	
Main building	**Roofs**	1,4E+04	-1,2E+04	8,1E+04	7,0E+01	4,9	-4,4	29,4	69,9	5,2	-4,7	31,1	69,9				
Main building	**Storey floors**	1,1E+05	-3,2E+03	3,4E+05	2,4E+02	38,7	-1,2	123,2	244,5	41,0	-1,2	130,4	244,5				
Main building	**Ground floors**	1,7E+04	-5,6E+03	6,1E+04	0,0E+00	6,2	-2,0	22,2	0,0	6,5	-2,2	23,5	0,0				
Entrance building	**Roofs**	9,4E+02	-8,5E+02	5,6E+03	4,8E+00	0,3	-0,3	2,0	4,8					6,2	-5,6	37,2	4,8
Entrance building	**Storey floors**	7,1E+03	-5,2E+02	3,4E+04	2,9E+01	2,6	-0,2	12,3	29,0					47,1	-3,4	225,0	29,0
Entrance building	**Ground floors**	6,2E+02	-2,0E+02	2,2E+03	0,0E+00	0,2	-0,1	0,8	0,0					4,1	-1,3	14,7	0,0
Walls, facades																	
Main building	**Transverse outer walls**	7,8E+03	7,8E+03	1,9E+04	0,0E+00	2,8	2,8	6,9	0,0	3,0	3,0	7,3	0,0				
Main building	**Transverse inner walls**	3,6E+04	3,6E+04	6,6E+04	0,0E+00	13,0	13,0	23,9	0,0	13,8	13,8	25,2	0,0				
Main building	**Stability walls**	9,7E+03	9,7E+03	1,9E+04	0,0E+00	3,5	3,5	6,8	0,0	3,7	3,7	7,2	0,0				
Main building	**Longitudinal facades**	2,4E+03	-3,1E+03	6,3E+04	0,0E+00	0,9	-1,1	22,9	0,0	0,9	-1,2	24,2	0,0				
Entrance building	**Inner walls**	1,4E+04	1,4E+04	2,7E+04	0,0E+00	5,1	5,1	9,9	0,0					93,5	93,5	181,5	0,0
Foundation																	
Main building	**Beam**	1,5E+04	1,5E+04	3,1E+04	0,0E+00	5,6	5,6	11,1	0,0	5,9	5,9	11,7	0,0				
Main building	**Piles**	4,2E+04	4,2E+04	4,7E+04	0,0E+00	15,1	15,1	17,1	0,0	16,0	16,0	18,1	0,0				
Entrance building	**Beam**	3,6E+03	3,6E+03	6,3E+03	0,0E+00	1,3	1,3	2,3	0,0					23,8	23,8	41,5	0,0
Entrance building	**Piles**	8,4E+03	8,4E+03	9,5E+03	0,0E+00	3,0	3,0	3,4	0,0					55,3	55,3	62,6	0,0
Others																	
Main building	**Balconies**	1,0E+04	-2,6E+03	2,4E+04	3,6E+01	3,6	-0,9	8,7	35,6	3,8	-1,0	9,2	35,6				
Main building	**Galleries**	1,8E+04	-5,5E+03	4,6E+04	6,8E+01	6,6	-2,0	16,5	67,9	6,9	-2,1	17,5	67,9				
Both buildings	**Connections**	1,9E+03	1,9E+03	0,0E+00	0,0E+00	0,7	0,7	0,0	0,0								
					TOTAL	**114,1**	**37,9**	**319,4**	**451,7**	**106,7**	**30,0**	**305,3**	**417,9**	**229,9**	**162,1**	**562,5**	**33,9**

	value per m2 (GFA total)				value per m2 (GFA main building)				value per m2 (GFA entrance building)			
	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs, beams	52,9	-8,2	190,0	348,2	52,7	-8,1	184,9	314,4	57,4	-10,4	276,9	33,9
Walls, facades, columns	25,3	23,3	70,3	0,0	21,4	19,3	63,9	0,0	93,5	93,5	181,5	0,0
Foundation	25,0	25,0	33,9	0,0	21,9	21,9	29,8	0,0	79,1	79,1	104,1	0,0
Others	10,9	-2,3	25,2	103,5	10,8	-3,1	26,7	103,5	0,0	0,0	0,0	0,0
TOTAL	**114,1**	**37,9**	**319,4**	**451,7**	**106,7**	**30,0**	**305,3**	**417,9**	**229,9**	**162,1**	**562,5**	**33,9**

	percentages				percentages				percentages			
	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs, beams	46%		59%	77%	49%		61%	75%	25%		49%	100%
Walls, facades, columns	22%		22%	0%	20%		21%	0%	41%		32%	0%
Foundation	22%		11%	0%	21%		10%	0%	34%		19%	0%
Others	10%		8%	23%	10%		9%	25%	0%		0%	0%
TOTAL	**100%**		**100%**	**100%**	**100%**		**100%**	**100%**	**100%**		**100%**	**100%**

Detailed assessment of variant 6.3

				per unit				total			
Floors, roofs				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Roofs**			**31,03**	**-27,98**	**186,13**	**0,16**	**1,4E+04**	**-1,2E+04**	**8,1E+04**	**7,0E+01**
	CLT 160 L5s	436,6	m2	17,33	-41,68	135,34	0,16	7,6E+03	-1,8E+04	5,9E+04	7,0E+01
	Finishing (insulation + gravel)	436,6	m2	13,70	13,70	50,79		6,0E+03	6,0E+03	2,2E+04	
Main building	**Storey floors**			**37,71**	**-62,35**	**262,17**	**0,24**	**6,6E+04**	**-1,1E+05**	**4,6E+05**	**4,2E+02**
	CLT 240 L7s	1746,5	m2	25,99	-62,52	204,20	0,24	4,5E+04	-1,1E+05	3,6E+05	4,2E+02
	Insulation and cladding	1746,5	m2	11,72	0,18	57,97		2,0E+04	3,1E+02	1,0E+05	
Main building	**Ground floors**			**41,74**	**-13,77**	**149,89**	**0,08**	**1,7E+04**	**-5,6E+03**	**6,1E+04**	**0,0E+00**
	Timber hollow core slab 280	409,7	m2	35,21	-20,51	115,50	0,08	1,4E+04	-8,4E+03	4,7E+04	
	Insulation and cladding GF	409,7	m2	6,53	6,74	34,39		2,7E+03	2,8E+03	1,4E+04	
Entrance building	**Roofs**			**31,03**	**-27,98**	**186,13**	**0,16**	**9,4E+02**	**-8,5E+02**	**5,6E+03**	**4,8E+00**
	CLT 160 L5s	30,2	m2	17,33	-41,68	135,34	0,16	5,2E+02	-1,3E+03	4,1E+03	4,8E+00
	Finishing (insulation + gravel)	30,2	m2	13,70	13,70	50,79		4,1E+02	4,1E+02	1,5E+03	
Entrance building	**Storey floors**			**37,71**	**-62,35**	**262,17**	**0,24**	**4,6E+03**	**-7,5E+03**	**3,2E+04**	**2,9E+01**
	CLT 240 L7s	120,9	m2	25,99	-62,52	204,20	0,24	3,1E+03	-7,6E+03	2,5E+04	2,9E+01
	Insulation and cladding	120,9	m2	11,72	0,18	57,97		1,4E+03	2,2E+01	7,0E+03	
Entrance building	**Ground floors**			**41,74**	**-13,77**	**149,89**	**0,08**	**6,2E+02**	**-2,0E+02**	**2,2E+03**	**0,0E+00**
	Timber hollow core slab 280	14,8	m2	35,21	-20,51	115,50	0,08	5,2E+02	-3,0E+02	1,7E+03	
	Insulation and cladding GF	14,8	m2	6,53	6,74	34,39		9,7E+01	1,0E+02	5,1E+02	
				per unit				total			
Walls, facades				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Transverse outer walls**			**31,33**	**-38,07**	**223,46**	**0,18**	**7,0E+03**	**-8,5E+03**	**5,0E+04**	**4,0E+01**
	CLT 180 L5s - type 3	223,3	m2	19,49	-46,89	175,50	0,18	4,4E+03	-1,0E+04	3,9E+04	4,0E+01
	Insulation and cladding	223,3	m2	11,84	8,82	47,96		2,6E+03	2,0E+03	1,1E+04	
Main building	**Transverse inner walls**			**31,33**	**-38,07**	**223,46**	**0,18**	**2,3E+04**	**-2,7E+04**	**1,6E+05**	**1,3E+02**
	CLT 180 L5s - type 3	720,2	m2	19,49	-46,89	175,50	0,18	1,4E+04	-3,4E+04	1,3E+05	1,3E+02
	Insulation and cladding	720,2	m2	11,84	8,82	47,96		8,5E+03	6,4E+03	3,5E+04	
Main building	**Stability walls**			**44,80**	**44,80**	**87,02**	**0,00**	**9,7E+03**	**9,7E+03**	**1,9E+04**	**0,0E+00**
	Concrete 140mm	216,0	m2	44,80	44,80	87,02		9,7E+03	9,7E+03	1,9E+04	
Main building	**Longitudinal facades**			**3,55**	**-4,53**	**92,89**	**0,02**	**2,4E+03**	**-3,1E+03**	**6,3E+04**	**0,0E+00**
	HSB facade inner wall	680,4	m2	3,55	-4,53	92,89	0,02	2,4E+03	-3,1E+03	6,3E+04	
Entrance building	**Inner walls**			**48,00**	**48,00**	**93,24**	**0,00**	**1,4E+04**	**1,4E+04**	**2,7E+04**	**0,0E+00**
	Concrete 150mm	294,3	m2	48,00	48,00	93,24		1,4E+04	1,4E+04	2,7E+04	
				per unit				total			
Foundation				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Beam**							**1,5E+04**	**1,5E+04**	**3,1E+04**	**0,0E+00**
	Beam 400x600	83,2	m	76,80	76,80	158,75		6,4E+03	6,4E+03	1,3E+04	
	Beam 500x600	62,0	m	96,00	96,00	194,11		6,0E+03	6,0E+03	1,2E+04	
	Beam 650x600	24,8	m	124,80	124,80	217,68		3,1E+03	3,1E+03	5,4E+03	
Main building	**Piles**			**557,06**	**557,06**	**630,70**	**0,00**	**3,8E+04**	**3,8E+04**	**4,3E+04**	**0,0E+00**
	Prefab piles 320x320 - 17m	68,0	pcs	557,06	557,06	630,70		3,8E+04	3,8E+04	4,3E+04	
Entrance building	**Beam**			**124,80**	**124,80**	**217,68**	**0,00**	**3,6E+03**	**3,6E+03**	**6,3E+03**	**0,0E+00**
	Beam 650x600	28,8	m	124,80	124,80	217,68		3,6E+03	3,6E+03	6,3E+03	
Entrance building	**Piles**			**557,06**	**557,06**	**630,70**	**0,00**	**8,4E+03**	**8,4E+03**	**9,5E+03**	**0,0E+00**
	Prefab piles 320x320 - 17m	15,0	pcs	557,06	557,06	630,70		8,4E+03	8,4E+03	9,5E+03	
				per unit				total			
Others				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Balconies**			**67,52**	**-16,04**	**163,68**	**0,24**	**10005,15**	**-2567,57**	**24131,95**	**3,6E+01**
	CLT140	148,3	m2	14,98	-83,49	118,00	0,24	2,2E+03	-1,2E+04	1,8E+04	3,6E+01
	Supports (beams, steel)	153,6	m	46,25	55,50	37,20		7,1E+03	8,5E+03	5,7E+03	
	Supports (ties, steel)	108,0	m	6,29	11,95	8,48		6,8E+02	1,3E+03	9,2E+02	
Main building	**Galleries**			**114,33**	**52,55**	**211,00**	**0,24**	**1,8E+04**	**-5,5E+03**	**4,6E+04**	**6,8E+01**
	CLT140	282,9	m2	14,98	-83,49	118,00	0,24	4,2E+03	-2,4E+04	3,3E+04	6,8E+01
	Supports (beams, steel)	204,0	m	46,44	55,53	37,20		9,5E+03	1,1E+04	7,6E+03	
	Supports (columns, steel)	84,0	m	52,91	80,51	55,80		4,4E+03	6,8E+03	4,7E+03	
Both buildings	**Connections (steel)**	**0,8**	**m3**	**1850,00**	**1850,00**	**0,00**	**0,00**	**1,5E+03**	**1,5E+03**	**0,0E+00**	**0,0E+00**

Only GWP, costs included in CLT element costs

units	
costs	[euro]
GWP	[kg CO2-eq.]
Volume	[m3]

gross floor area		
GFA main building excl.	2183	m2
GFA balconies and galleries	431	m2
GFA main building total	**2614**	**m2**
GFA entry building + storage	**151**	**m2**
GFA TOTAL	**2765**	**m2**

floor and building heights		
h-cladding	0,14	m
h-vloer	0,24	m
h-free	2,70	m
h-storey	**3,08**	m
h-outer-tot	**15,39**	**m**
h-inner-tot	**13,50**	**m**

		total value				value per m2 (GFA total)				value per m2 (GFA main building)				value per m2 (GFA entrance building)			
		GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs																	
Main building	**Roofs**	1,4E+04	-1,2E+04	8,1E+04	7,0E+01	4,9	-4,4	29,4	69,9	5,2	-4,7	31,1	69,9				
Main building	**Storey floors**	6,6E+04	-1,1E+05	4,6E+05	4,2E+02	23,8	-39,4	165,6	419,2	25,2	-41,6	175,1	419,2				
Main building	**Ground floors**	1,7E+04	-5,6E+03	6,1E+04	0,0E+00	6,2	-2,0	22,2	0,0	6,5	-2,2	23,5	0,0				
Entrance building	**Roofs**	9,4E+02	-8,5E+02	5,6E+03	4,8E+00	0,3	-0,3	2,0	4,8					6,2	-5,6	37,2	4,8
Entrance building	**Storey floors**	4,6E+03	-7,5E+03	3,2E+04	2,9E+01	1,6	-2,7	11,5	29,0					30,2	-49,9	209,7	29,0
Entrance building	**Ground floors**	6,2E+02	-2,0E+02	2,2E+03	0,0E+00	0,2	-0,1	0,8	0,0					4,1	-1,3	14,7	0,0
Walls, facades																	
Main building	**Transverse outer walls**	7,0E+03	-8,5E+03	5,0E+04	4,0E+01	2,5	-3,1	18,0	40,2	2,7	-3,3	19,1	40,2				
Main building	**Transverse inner walls**	2,3E+04	-2,7E+04	1,6E+05	1,3E+02	8,2	-9,9	58,2	129,6	8,6	-10,5	61,6	129,6				
Main building	**Stability walls**	9,7E+03	9,7E+03	1,9E+04	0,0E+00	3,5	3,5	6,8	0,0	3,7	3,7	7,2	0,0				
Main building	**Longitudinal facades**	2,4E+03	-3,1E+03	6,3E+04	0,0E+00	0,9	-1,1	22,9	0,0	0,9	-1,2	24,2	0,0				
Entrance building	**Inner walls**	1,4E+04	1,4E+04	2,7E+04	0,0E+00	5,1	5,1	9,9	0,0					93,5	93,5	181,5	0,0
Foundation																	
Main building	**Beam**	1,5E+04	1,5E+04	3,1E+04	0,0E+00	5,6	5,6	11,1	0,0	5,9	5,9	11,7	0,0				
Main building	**Piles**	3,8E+04	3,8E+04	4,3E+04	0,0E+00	13,7	13,7	15,5	0,0	14,5	14,5	16,4	0,0				
Entrance building	**Beam**	3,6E+03	3,6E+03	6,3E+03	0,0E+00	1,3	1,3	2,3	0,0					23,8	23,8	41,5	0,0
Entrance building	**Piles**	8,4E+03	8,4E+03	9,5E+03	0,0E+00	3,0	3,0	3,4	0,0					55,3	55,3	62,6	0,0
Others																	
Main building	**Balconies**	1,0E+04	-2,6E+03	2,4E+04	3,6E+01	3,6	-0,9	8,7	35,6	3,8	-1,0	9,2	35,6				
Main building	**Galleries**	1,8E+04	-5,5E+03	4,6E+04	6,8E+01	6,6	-2,0	16,5	67,9	6,9	-2,1	17,5	67,9				
Both buildings	**Connections**	1,5E+03	1,5E+03	0,0E+00	0,0E+00	0,5	0,5	0,0	0,0								
					TOTAL	**91,6**	**-33,2**	**404,8**	**796,2**	**84,0**	**-42,4**	**396,6**	**762,3**	**213,0**	**115,7**	**547,2**	**33,9**

	value per m2 (GFA total)				value per m2 (GFA main building)				value per m2 (GFA entrance building)			
	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs, beams	37,1	-48,9	231,5	522,9	36,9	-48,5	229,7	489,0	40,5	-56,8	261,6	33,9
Walls, facades, columns	20,2	-5,5	115,8	169,8	15,9	-11,2	112,0	169,8	93,5	93,5	181,5	0,0
Foundation	23,6	23,6	32,3	0,0	20,4	20,4	28,1	0,0	79,1	79,1	104,1	0,0
Others	10,7	-2,4	25,2	103,5	10,8	-3,1	26,7	103,5	0,0	0,0	0,0	0,0
TOTAL	**91,6**	**-33,2**	**404,8**	**796,2**	**84,0**	**-42,4**	**396,6**	**762,3**	**213,0**	**115,7**	**547,2**	**33,9**
	percentages				percentages				percentages			
	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs, beams	41%		57%	66%	44%		58%	64%	19%		48%	100%
Walls, facades, columns	22%		29%	21%	19%		28%	22%	44%		33%	0%
Foundation	26%		8%	0%	24%		7%	0%	37%		19%	0%
Others	12%		6%	13%	13%		7%	14%	0%		0%	0%
TOTAL	**100%**		**100%**	**100%**	**100%**		**100%**	**100%**	**100%**		**100%**	**100%**

Detailed assessment of variant 6.4

				per unit				total			
Floors, roofs				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Roofs**			**31,03**	**-27,98**	**186,13**	**0,16**	**1,4E+04**	**-1,2E+04**	**8,1E+04**	**7,0E+01**
	CLT 160 L5s	436,6	m2	17,33	-41,68	135,34	0,16	7,6E+03	-1,8E+04	5,9E+04	7,0E+01
	Finishing (insulation + gravel)	436,6	m2	13,70	13,70	50,79		6,0E+03	6,0E+03	2,2E+04	
Main building	**Storey floors**			**61,31**	**-1,84**	**195,15**	**0,14**	**1,1E+05**	**-3,2E+03**	**3,4E+05**	**2,4E+02**
	CLT 140 L5s	1746,5	m2	15,16	-36,47	118,13	0,14	2,6E+04	-6,4E+04	2,1E+05	2,4E+02
	Concrete floor 100mm	1746,5	m2	32,00	32,00	19,05		5,6E+04	5,6E+04	3,3E+04	
	Insulation and cladding	1746,5	m2	14,15	2,63	57,97		2,5E+04	4,6E+03	1,0E+05	
Main building	**Ground floors**			**41,74**	**-13,77**	**149,89**	**0,08**	**1,7E+04**	**-5,6E+03**	**6,1E+04**	**0,0E+00**
	Timber hollow core slab 280	409,7	m2	35,21	-20,51	115,50	0,08	1,4E+04	-8,4E+03	4,7E+04	
	Insulation and cladding GF	409,7	m2	6,53	6,74	34,39		2,7E+03	2,8E+03	1,4E+04	
Entrance building	**Roofs**			**31,03**	**-27,98**	**186,13**	**0,16**	**9,4E+02**	**-8,5E+02**	**5,6E+03**	**4,8E+00**
	CLT 160 L5s	30,2	m2	17,33	-41,68	135,34	0,16	5,2E+02	-1,3E+03	4,1E+03	4,8E+00
	Finishing (insulation + gravel)	30,2	m2	13,70	13,70	50,79		4,1E+02	4,1E+02	1,5E+03	
Entrance building	**Storey floors**			**58,88**	**-4,29**	**281,22**	**0,24**	**7,1E+03**	**-5,2E+02**	**3,4E+04**	**0,0E+00**
	CLT 140 L5s	120,9	m2	15,16	-36,47	204,20	0,24	1,8E+03	-4,4E+03	2,5E+04	
	Concrete floor 100mm	120,9		32,00	32,00	19,05		3,9E+03	3,9E+03	2,3E+03	0,0E+00
	Insulation and cladding	120,9	m2	11,72	0,18	57,97		1,4E+03	2,2E+01	7,0E+03	
Entrance building	**Ground floors**			**41,74**	**-13,77**	**149,89**	**0,08**	**6,2E+02**	**-2,0E+02**	**2,2E+03**	**0,0E+00**
	Timber hollow core slab 280	14,8	m2	35,21	-20,51	115,50	0,08	5,2E+02	-3,0E+02	1,7E+03	
	Insulation and cladding GF	14,8	m2	6,53	6,74	34,39		9,7E+01	1,0E+02	5,1E+02	
				per unit				total			
Walls, facades				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Transverse outer walls**			**31,33**	**-38,07**	**223,46**	**0,18**	**7,0E+03**	**-8,5E+03**	**5,0E+04**	**4,0E+01**
	CLT 180 L5s - type 3	223,3	m2	19,49	-46,89	175,50	0,18	4,4E+03	-1,0E+04	3,9E+04	4,0E+01
	Insulation and cladding	223,3	m2	11,84	8,82	47,96		2,6E+03	2,0E+03	1,1E+04	
Main building	**Transverse inner walls**			**31,33**	**-38,07**	**223,46**	**0,18**	**2,3E+04**	**-2,7E+04**	**1,6E+05**	**1,3E+02**
	CLT 180 L5s - type 3	720,2	m2	19,49	-46,89	175,50	0,18	1,4E+04	-3,4E+04	1,3E+05	1,3E+02
	Insulation and cladding	720,2	m2	11,84	8,82	47,96		8,5E+03	6,4E+03	3,5E+04	
Main building	**Stability walls**			**44,80**	**44,80**	**87,02**	**0,00**	**9,7E+03**	**9,7E+03**	**1,9E+04**	**0,0E+00**
	Concrete 140mm	216,0	m2	44,80	44,80	87,02		9,7E+03	9,7E+03	1,9E+04	
Main building	**Longitudinal facades**			**3,55**	**-4,53**	**92,89**	**0,02**	**2,4E+03**	**-3,1E+03**	**6,3E+04**	**0,0E+00**
	HSB facade inner wall	680,4	m2	3,55	-4,53	92,89	0,02	2,4E+03	-3,1E+03	6,3E+04	
Entrance building	**Inner walls**			**48,00**	**48,00**	**93,24**	**0,00**	**1,4E+04**	**1,4E+04**	**2,7E+04**	**0,0E+00**
	Concrete 150mm	294,3	m2	48,00	48,00	93,24		1,4E+04	1,4E+04	2,7E+04	
				per unit				total			
Foundation				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Beam**							**1,5E+04**	**1,5E+04**	**3,1E+04**	**0,0E+00**
	Beam 400x600	83,2	m	76,80	76,80	158,75		6,4E+03	6,4E+03	1,3E+04	
	Beam 500x600	62,0	m	96,00	96,00	194,11		6,0E+03	6,0E+03	1,2E+04	
	Beam 650x600	24,8	m	124,80	124,80	217,68		3,1E+03	3,1E+03	5,4E+03	
Main building	**Piles**			**557,06**	**557,06**	**630,70**	**0,00**	**3,8E+04**	**3,8E+04**	**4,3E+04**	**0,0E+00**
	Prefab piles 320x320 - 17m	68,0	pcs	557,06	557,06	630,70		3,8E+04	3,8E+04	4,3E+04	
Entrance building	**Beam**			**124,80**	**124,80**	**217,68**	**0,00**	**3,6E+03**	**3,6E+03**	**6,3E+03**	**0,0E+00**
	Beam 650x600	28,8	m	124,80	124,80	217,68		3,6E+03	3,6E+03	6,3E+03	
Entrance building	**Piles**			**557,06**	**557,06**	**630,70**	**0,00**	**8,4E+03**	**8,4E+03**	**9,5E+03**	**0,0E+00**
	Prefab piles 320x320 - 17m	15,0	pcs	557,06	557,06	630,70		8,4E+03	8,4E+03	9,5E+03	
				per unit				total			
Others				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Balconies**			**67,52**	**-16,04**	**163,68**	**0,24**	**10005,15**	**-2567,57**	**24131,95**	**3,6E+01**
	CLT140	148,3	m2	14,98	-83,49	118,00	0,24	2,2E+03	-1,2E+04	1,8E+04	3,6E+01
	Supports (beams, steel)	153,6	m	46,25	55,50	37,20		7,1E+03	8,5E+03	5,7E+03	
	Supports (ties, steel)	108,0	m	6,29	11,95	8,48		6,8E+02	1,3E+03	9,2E+02	
Main building	**Galleries**			**114,33**	**52,55**	**211,00**	**0,24**	**1,8E+04**	**-5,5E+03**	**4,6E+04**	**6,8E+01**
	CLT140	282,9	m2	14,98	-83,49	118,00	0,24	4,2E+03	-2,4E+04	3,3E+04	6,8E+01
	Supports (beams, steel)	204,0	m	46,44	55,53	37,20		9,5E+03	1,1E+04	7,6E+03	
	Supports (columns, steel)	84,0	m	52,91	80,51	55,80		4,4E+03	6,8E+03	4,7E+03	
Both buildings	**Connections (steel)**	**1,1**	**m3**	**1850,00**	**1850,00**	**0,00**	**0,00**	**2,0E+03**	**2,0E+03**	**0,0E+00**	**0,0E+00**

Only GWP, costs included in CLT element costs

units	
costs	[euro]
GWP	[kg CO2-eq.]
Volume	[m3]

gross floor area		
GFA main building excl.	2183	m2
GFA balconies and galleries	431	m2
GFA main building total	**2614**	**m2**
GFA entry building + storage	**151**	**m2**
GFA TOTAL	**2765**	**m2**

floor and building heights		
h-cladding	0,06	m
h-vloer	0,24	m
h-free	2,70	m
h-storey	**3,00**	m
h-outer-tot	**14,99**	**m**
h-inner-tot	**13,50**	**m**

		total value				value per m2 (GFA total)				value per m2 (GFA main building)				value per m2 (GFA entrance building)			
		GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs																	
Main building	**Roofs**	1,4E+04	-1,2E+04	8,1E+04	7,0E+01	4,9	-4,4	29,4	69,9	5,2	-4,7	31,1	69,9				
Main building	**Storey floors**	1,1E+05	-3,2E+03	3,4E+05	2,4E+02	38,7	-1,2	123,2	244,5	41,0	-1,2	130,4	244,5				
Main building	**Ground floors**	1,7E+04	-5,6E+03	6,1E+04	0,0E+00	6,2	-2,0	22,2	0,0	6,5	-2,2	23,5	0,0				
Entrance building	**Roofs**	9,4E+02	-8,5E+02	5,6E+03	4,8E+00	0,3	-0,3	2,0	4,8					6,2	-5,6	37,2	4,8
Entrance building	**Storey floors**	7,1E+03	-5,2E+02	3,4E+04	0,0E+00	2,6	-0,2	12,3	0,0					47,1	-3,4	225,0	0,0
Entrance building	**Ground floors**	6,2E+02	-2,0E+02	2,2E+03	0,0E+00	0,2	-0,1	0,8	0,0					4,1	-1,3	14,7	0,0
Walls, facades																	
Main building	**Transverse outer walls**	7,0E+03	-8,5E+03	5,0E+04	4,0E+01	2,5	-3,1	18,0	40,2	2,7	-3,3	19,1	40,2				
Main building	**Transverse inner walls**	2,3E+04	-2,7E+04	1,6E+05	1,3E+02	8,2	-9,9	58,2	129,6	8,6	-10,5	61,6	129,6				
Main building	**Stability walls**	9,7E+03	9,7E+03	1,9E+04	0,0E+00	3,5	3,5	6,8	0,0	3,7	3,7	7,2	0,0				
Main building	**Longitudinal facades**	2,4E+03	-3,1E+03	6,3E+04	0,0E+00	0,9	-1,1	22,9	0,0	0,9	-1,2	24,2	0,0				
Entrance building	**Inner walls**	1,4E+04	1,4E+04	2,7E+04	0,0E+00	5,1	5,1	9,9	0,0					93,5	93,5	181,5	0,0
Foundation																	
Main building	**Beam**	1,5E+04	1,5E+04	3,1E+04	0,0E+00	5,6	5,6	11,1	0,0	5,9	5,9	11,7	0,0				
Main building	**Piles**	3,8E+04	3,8E+04	4,3E+04	0,0E+00	13,7	13,7	15,5	0,0	14,5	14,5	16,4	0,0				
Entrance building	**Beam**	3,6E+03	3,6E+03	6,3E+03	0,0E+00	1,3	1,3	2,3	0,0					23,8	23,8	41,5	0,0
Entrance building	**Piles**	8,4E+03	8,4E+03	9,5E+03	0,0E+00	3,0	3,0	3,4	0,0					55,3	55,3	62,6	0,0
Others																	
Main building	**Balconies**	1,0E+04	-2,6E+03	2,4E+04	3,6E+01	3,6	-0,9	8,7	35,6	3,8	-1,0	9,2	35,6				
Main building	**Galleries**	1,8E+04	-5,5E+03	4,6E+04	6,8E+01	6,6	-2,0	16,5	67,9	6,9	-2,1	17,5	67,9				
Both buildings	**Connections**	2,0E+03	2,0E+03	0,0E+00	0,0E+00	0,7	0,7	0,0	0,0								
					TOTAL	**107,6**	**7,7**	**363,3**	**592,5**	**99,8**	**-2,0**	**351,8**	**587,7**	**229,9**	**162,1**	**562,5**	**4,8**

	value per m2 (GFA total)				value per m2 (GFA main building)				value per m2 (GFA entrance building)			
	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs, beams	52,9	-8,2	190,0	319,2	52,7	-8,1	184,9	314,4	57,4	-10,4	276,9	4,8
Walls, facades, columns	20,2	-5,5	115,8	169,8	15,9	-11,2	112,0	169,8	93,5	93,5	181,5	0,0
Foundation	23,6	23,6	32,3	0,0	20,4	20,4	28,1	0,0	79,1	79,1	104,1	0,0
Others	10,9	-2,2	25,2	103,5	10,8	-3,1	26,7	103,5	0,0	0,0	0,0	0,0
TOTAL	**107,6**	**7,7**	**363,3**	**592,5**	**99,8**	**-2,0**	**351,8**	**587,7**	**229,9**	**162,1**	**562,5**	**4,8**
	percentages				percentages				percentages			
	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs, beams	49%		52%	54%	53%		53%	53%	25%		49%	100%
Walls, facades, columns	19%		32%	29%	16%		32%	29%	41%		32%	0%
Foundation	22%		9%	0%	20%		8%	0%	34%		19%	0%
Others	10%		7%	17%	11%		8%	18%	0%		0%	0%
TOTAL	**100%**		**100%**	**100%**	**100%**		**100%**	**100%**	**100%**		**100%**	**100%**

Detailed assessment of variant 6.5

				per unit				total			
Floors, roofs				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Roofs**			**31,03**	**-27,98**	**186,13**	**0,16**	**1,4E+04**	**-1,2E+04**	**8,1E+04**	**7,0E+01**
	CLT 160 L5s	436,6	m2	17,33	-41,68	135,34	0,16	7,6E+03	-1,8E+04	5,9E+04	7,0E+01
	Finishing (insulation + gravel)	436,6	m2	13,70	13,70	50,79		6,0E+03	6,0E+03	2,2E+04	
Main building	**Storey floors**			**37,71**	**-62,35**	**262,17**	**0,24**	**6,6E+04**	**-1,1E+05**	**4,6E+05**	**4,2E+02**
	CLT 240 L7s	1746,5	m2	25,99	-62,52	204,20	0,24	4,5E+04	-1,1E+05	3,6E+05	4,2E+02
	Insulation and cladding	1746,5	m2	11,72	0,18	57,97		2,0E+04	3,1E+02	1,0E+05	
Main building	**Ground floors**			**41,74**	**-13,77**	**149,89**	**0,08**	**1,7E+04**	**-5,6E+03**	**6,1E+04**	**0,0E+00**
	Timber hollow core slab 280	409,7	m2	35,21	-20,51	115,50	0,08	1,4E+04	-8,4E+03	4,7E+04	
	Insulation and cladding GF	409,7	m2	6,53	6,74	34,39		2,7E+03	2,8E+03	1,4E+04	
Entrance building	**Roofs**			**31,03**	**-27,98**	**186,13**	**0,16**	**9,4E+02**	**-8,5E+02**	**5,6E+03**	**4,8E+00**
	CLT 160 L5s	30,2	m2	17,33	-41,68	135,34	0,16	5,2E+02	-1,3E+03	4,1E+03	4,8E+00
	Finishing (insulation + gravel)	30,2	m2	13,70	13,70	50,79		4,1E+02	4,1E+02	1,5E+03	
Entrance building	**Storey floors**			**37,71**	**-62,35**	**262,17**	**0,24**	**4,6E+03**	**-7,5E+03**	**3,2E+04**	**2,9E+01**
	CLT 240 L7s	120,9	m2	25,99	-62,52	204,20	0,24	3,1E+03	-7,6E+03	2,5E+04	2,9E+01
	Insulation and cladding	120,9	m2	11,72	0,18	57,97		1,4E+03	2,2E+01	7,0E+03	
Entrance building	**Ground floors**			**41,74**	**-13,77**	**149,89**	**0,22**	**6,2E+02**	**-2,0E+02**	**2,2E+03**	**0,0E+00**
	Timber hollow core slab 280	14,8	m2	35,21	-20,51	115,50	0,14	5,2E+02	-3,0E+02	1,7E+03	
	Insulation and cladding GF	14,8	m2	6,53	6,74	34,39	0,08	9,7E+01	1,0E+02	5,1E+02	
				per unit				total			
Walls, facades				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Transverse outer walls**			**31,33**	**-38,07**	**223,46**	**0,18**	**7,0E+03**	**-8,5E+03**	**5,0E+04**	**4,0E+01**
	CLT 180 L5s - type 3	223,3	m2	19,49	-46,89	175,50	0,18	4,4E+03	-1,0E+04	3,9E+04	4,0E+01
	Insulation and cladding	223,3	m2	11,84	8,82	47,96		2,6E+03	2,0E+03	1,1E+04	
Main building	**Transverse inner walls**			**31,33**	**-38,07**	**223,46**	**0,18**	**2,3E+04**	**-2,7E+04**	**1,6E+05**	**1,3E+02**
	CLT 180 L5s - type 3	720,2	m2	19,49	-46,89	175,50	0,18	1,4E+04	-3,4E+04	1,3E+05	1,3E+02
	Insulation and cladding	720,2	m2	11,84	8,82	47,96		8,5E+03	6,4E+03	3,5E+04	
Main building	**Stability walls**			**31,33**	**-38,07**	**223,46**	**0,18**	**1,0E+04**	**-7,1E+03**	**6,6E+04**	**4,4E+01**
	CLT 180 L5s - type 3	243,0	m2	19,49	-46,89	175,50	0,18	4,7E+03	-1,1E+04	4,3E+04	4,4E+01
	Insulation and cladding	486,0	m2	11,84	8,82	47,96		5,8E+03	4,3E+03	2,3E+04	
Main building	**Longitudinal facades**			**3,55**	**-4,53**	**92,89**	**0,02**	**3,0E+03**	**-3,8E+03**	**7,8E+04**	**0,0E+00**
	HSB facade inner wall	842,4	m2	3,55	-4,53	92,89	0,02	3,0E+03	-3,8E+03	7,8E+04	
Entrance building	**Inner walls**			**48,00**	**48,00**	**93,24**	**0,00**	**1,4E+04**	**1,4E+04**	**2,7E+04**	**0,0E+00**
	Concrete 150mm	294,3	m2	48,00	48,00	93,24		1,4E+04	1,4E+04	2,7E+04	
				per unit				total			
Foundation				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Beam**							**1,9E+04**	**1,9E+04**	**3,7E+04**	**0,0E+00**
	Beam 400x600	124,8	m	76,80	76,80	158,75		9,6E+03	9,6E+03	2,0E+04	
	Beam 500x600	62,0	m	96,00	96,00	194,11		6,0E+03	6,0E+03	1,2E+04	
	Beam 650x600	24,8	m	124,80	124,80	217,68		3,1E+03	3,1E+03	5,4E+03	
Main building	**Piles**			**557,06**	**557,06**	**630,70**	**0,00**	**4,0E+04**	**4,0E+04**	**4,5E+04**	**0,0E+00**
	Prefab piles 320x320 - 17m	72,0	pcs	557,06	557,06	630,70		4,0E+04	4,0E+04	4,5E+04	
Entrance building	**Beam**			**124,80**	**124,80**	**217,68**	**0,00**	**3,6E+03**	**3,6E+03**	**6,3E+03**	**0,0E+00**
	Beam 650x600	28,8	m	124,80	124,80	217,68		3,6E+03	3,6E+03	6,3E+03	
Entrance building	**Piles**			**557,06**	**557,06**	**630,70**	**0,00**	**8,4E+03**	**8,4E+03**	**9,5E+03**	**0,0E+00**
	Prefab piles 320x320 - 17m	15,0	pcs	557,06	557,06	630,70		8,4E+03	8,4E+03	9,5E+03	
				per unit				total			
Others				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Balconies**			**67,52**	**-16,04**	**163,68**	**0,24**	**10005,15**	**-2567,57**	**24131,95**	**3,6E+01**
	CLT140	148,3	m2	14,98	-83,49	118,00	0,24	2,2E+03	-1,2E+04	1,8E+04	3,6E+01
	Supports (beams, steel)	153,6	m	46,25	55,50	37,20		7,1E+03	8,5E+03	5,7E+03	
	Supports (ties, steel)	108,0	m	6,29	11,95	8,48		6,8E+02	1,3E+03	9,2E+02	
Main building	**Galleries**			**114,33**	**52,55**	**211,00**	**0,24**	**1,8E+04**	**-5,5E+03**	**4,6E+04**	**6,8E+01**
	CLT140	282,9	m2	14,98	-83,49	118,00	0,24	4,2E+03	-2,4E+04	3,3E+04	6,8E+01
	Supports (beams, steel)	204,0	m	46,44	55,53	37,20		9,5E+03	1,1E+04	7,6E+03	
	Supports (columns, steel)	84,0	m	52,91	80,51	55,80		4,4E+03	6,8E+03	4,7E+03	
Both buildings	**Connections (steel)**	**0,8**	**m3**	**1850,00**	**1850,00**	**0,00**	**0,00**	**1,5E+03**	**1,5E+03**	**0,0E+00**	**0,0E+00**

Only GWP, costs included in CLT element costs

units	
costs	[euro]
GWP	[kg CO2-eq.]
Volume	[m3]

gross floor area		
GFA main building excl.	2183	m2
GFA balconies and galleries	431	m2
GFA main building total	**2614**	**m2**
GFA entry building + storage	**151**	**m2**
GFA TOTAL	**2765**	**m2**

floor and building heights		
h-cladding	0,14	m
h-vloer	0,24	m
h-free	2,70	m
h-storey	**3,08**	m
h-outer-tot	**15,39**	**m**
h-inner-tot	**13,50**	**m**

		total value				value per m2 (GFA total)				value per m2 (GFA main building)				value per m2 (GFA entrance building)			
		GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs																	
Main building	**Roofs**	1,4E+04	-1,2E+04	8,1E+04	7,0E+01	4,9	-4,4	29,4	69,9	5,2	-4,7	31,1	69,9				
Main building	**Storey floors**	6,6E+04	-1,1E+05	4,6E+05	4,2E+02	23,8	-39,4	165,6	419,2	25,2	-41,6	175,1	419,2				
Main building	**Ground floors**	1,7E+04	-5,6E+03	6,1E+04	0,0E+00	6,2	-2,0	22,2	0,0	6,5	-2,2	23,5	0,0				
Entrance building	**Roofs**	9,4E+02	-8,5E+02	5,6E+03	4,8E+00	0,3	-0,3	2,0	4,8					6,2	-5,6	37,2	4,8
Entrance building	**Storey floors**	4,6E+03	-7,5E+03	3,2E+04	2,9E+01	1,6	-2,7	11,5	29,0					30,2	-49,9	209,7	29,0
Entrance building	**Ground floors**	6,2E+02	-2,0E+02	2,2E+03	0,0E+00	0,2	-0,1	0,8	0,0					4,1	-1,3	14,7	0,0
Walls, facades																	
Main building	**Transverse outer walls**	7,0E+03	-8,5E+03	5,0E+04	4,0E+01	2,5	-3,1	18,0	40,2	2,7	-3,3	19,1	40,2				
Main building	**Transverse inner walls**	2,3E+04	-2,7E+04	1,6E+05	1,3E+02	8,2	-9,9	58,2	129,6	8,6	-10,5	61,6	129,6				
Main building	**Stability walls**	1,0E+04	-7,1E+03	6,6E+04	4,4E+01	3,8	-2,6	23,8	43,7	4,0	-2,7	25,2	43,7				
Main building	**Longitudinal facades**	3,0E+03	-3,8E+03	7,8E+04	0,0E+00	1,1	-1,4	28,3	0,0	1,1	-1,5	29,9	0,0				
Entrance building	**Inner walls**	1,4E+04	1,4E+04	2,7E+04	0,0E+00	5,1	5,1	9,9	0,0					93,5	93,5	181,5	0,0
Foundation																	
Main building	**Beam**	1,9E+04	1,9E+04	3,7E+04	0,0E+00	6,7	6,7	13,5	0,0	7,1	7,1	14,2	0,0				
Main building	**Piles**	4,0E+04	4,0E+04	4,5E+04	0,0E+00	14,5	14,5	16,4	0,0	15,3	15,3	17,4	0,0				
Entrance building	**Beam**	3,6E+03	3,6E+03	6,3E+03	0,0E+00	1,3	1,3	2,3	0,0					23,8	23,8	41,5	0,0
Entrance building	**Piles**	8,4E+03	8,4E+03	9,5E+03	0,0E+00	3,0	3,0	3,4	0,0					55,3	55,3	62,6	0,0
Others																	
Main building	**Balconies**	1,0E+04	-2,6E+03	2,4E+04	3,6E+01	3,6	-0,9	8,7	35,6	3,8	-1,0	9,2	35,6				
Main building	**Galleries**	1,8E+04	-5,5E+03	4,6E+04	6,8E+01	6,6	-2,0	16,5	67,9	6,9	-2,1	17,5	67,9				
Both buildings	**Connections**	1,5E+03	1,5E+03	0,0E+00	0,0E+00	0,5	0,5	0,0	0,0								
					TOTAL	**94,1**	**-37,6**	**430,6**	**839,9**	**86,6**	**-47,0**	**423,8**	**806,1**	**213,0**	**115,7**	**547,2**	**33,9**

	value per m2 (GFA total)				value per m2 (GFA main building)				value per m2 (GFA entrance building)			
	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs, beams	37,1	-48,9	231,5	522,9	36,9	-48,5	229,7	489,0	40,5	-56,8	261,6	33,9
Walls, facades, columns	20,7	-11,8	138,3	213,6	16,5	-17,9	135,8	213,6	93,5	93,5	181,5	0,0
Foundation	25,6	25,6	35,6	0,0	22,5	22,5	31,6	0,0	79,1	79,1	104,1	0,0
Others	10,7	-2,4	25,2	103,5	10,8	-3,1	26,7	103,5	0,0	0,0	0,0	0,0
TOTAL	**94,1**	**-37,6**	**430,6**	**839,9**	**86,6**	**-47,0**	**423,8**	**806,1**	**213,0**	**115,7**	**547,2**	**33,9**

	percentages				percentages				percentages			
	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs, beams	39%		54%	62%	43%		54%	61%	19%		48%	100%
Walls, facades, columns	22%		32%	25%	19%		32%	26%	44%		33%	0%
Foundation	27%		8%	0%	26%		7%	0%	37%		19%	0%
Others	11%		6%	12%	12%		6%	13%	0%		0%	0%
TOTAL	**100%**		**100%**	**100%**	**100%**		**100%**	**100%**	**100%**		**100%**	**100%**

Detailed assessment of variant 6.6

				per unit				total			
Floors, roofs				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Roofs**			**38,85**	**-0,95**	**133,29**	**0,06**	**1,7E+04**	**-4,1E+02**	**5,8E+04**	**2,6E+01**
	Timber hollow core slab 200 RF	436,6	m2	25,15	-14,65	82,50	0,06	1,1E+04	-6,4E+03	3,6E+04	2,6E+01
	Finishing (insulation + gravel) RF	436,6	m2	13,70	13,70	50,79		6,0E+03	6,0E+03	2,2E+04	
Main building	**Storey floors**			**45,06**	**-10,25**	**162,19**	**0,08**	**7,9E+04**	**-1,8E+04**	**2,8E+05**	**1,5E+02**
	Timber hollow core slab 280	1746,5	m2	35,21	-20,51	115,50	0,08	6,1E+04	-3,6E+04	2,0E+05	1,5E+02
	Insulation and cladding	1746,5	m2	9,85	10,26	46,69		1,7E+04	1,8E+04	8,2E+04	
Main building	**Ground floors**			**41,74**	**-13,77**	**149,89**	**0,08**	**1,7E+04**	**-5,6E+03**	**6,1E+04**	**0,0E+00**
	Timber hollow core slab 280	409,7	m2	35,21	-20,51	115,50	0,08	1,4E+04	-8,4E+03	4,7E+04	
	Insulation and cladding GF	409,7	m2	6,53	6,74	34,39		2,7E+03	2,8E+03	1,4E+04	
Entrance building	**Roofs**			**38,85**	**-0,95**	**133,29**	**0,06**	**1,2E+03**	**-2,9E+01**	**4,0E+03**	**1,8E+00**
	Timber hollow core slab 200 RF	30,2	m2	25,15	-14,65	82,50	0,06	7,6E+02	-4,4E+02	2,5E+03	1,8E+00
	Finishing (insulation + gravel) RF	30,2	m2	13,70	13,70	50,79		4,1E+02	4,1E+02	1,5E+03	
Entrance building	**Storey floors**			**45,06**	**-10,25**	**162,19**	**0,08**	**5,4E+03**	**-1,2E+03**	**2,0E+04**	**1,0E+01**
	Timber hollow core slab 280	120,9	m2	35,21	-20,51	115,50	0,08	4,3E+03	-2,5E+03	1,4E+04	1,0E+01
	Insulation and cladding	120,9	m2	9,85	10,26	46,69		1,2E+03	1,2E+03	5,6E+03	
Entrance building	**Ground floors**			**41,74**	**-13,77**	**149,89**	**0,08**	**6,2E+02**	**-2,0E+02**	**2,2E+03**	**0,0E+00**
	Timber hollow core slab 280	14,8	m2	35,21	-20,51	115,50	0,08	5,2E+02	-3,0E+02	1,7E+03	
	Insulation and cladding GF	14,8	m2	6,53	6,74	34,39		9,7E+01	1,0E+02	5,1E+02	
				per unit				total			
Walls, facades				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Transverse outer walls**			**31,33**	**-38,07**	**223,46**	**0,18**	**7,0E+03**	**-8,5E+03**	**5,0E+04**	**4,0E+01**
	CLT 180 L5s - type 3	223,3	m2	19,49	-46,89	175,50	0,18	4,4E+03	-1,0E+04	3,9E+04	4,0E+01
	Insulation and cladding	223,3	m2	11,84	8,82	47,96		2,6E+03	2,0E+03	1,1E+04	
Main building	**Transverse inner walls**			**31,33**	**-38,07**	**223,46**	**0,18**	**2,3E+04**	**-2,7E+04**	**1,6E+05**	**1,3E+02**
	CLT 180 L5s - type 3	720,2	m2	19,49	-46,89	175,50	0,18	1,4E+04	-3,4E+04	1,3E+05	1,3E+02
	Insulation and cladding	720,2	m2	11,84	8,82	47,96		8,5E+03	6,4E+03	3,5E+04	
Main building	**Stability walls**			**31,33**	**-38,07**	**223,46**	**0,18**	**1,0E+04**	**-7,1E+03**	**6,6E+04**	**4,4E+01**
	CLT 180 L5s - type 3	243,0	m2	19,49	-46,89	175,50	0,18	4,7E+03	-1,1E+04	4,3E+04	4,4E+01
	Insulation and cladding	486,0	m2	11,84	8,82	47,96		5,8E+03	4,3E+03	2,3E+04	
Main building	**Longitudinal facades**			**3,55**	**-4,53**	**92,89**	**0,02**	**3,0E+03**	**-3,8E+03**	**7,8E+04**	**0,0E+00**
	HSB facade inner wall	842,4	m2	3,55	-4,53	92,89	0,02	3,0E+03	-3,8E+03	7,8E+04	
Entrance building	**Inner walls**			**48,00**	**48,00**	**93,24**	**0,00**	**1,4E+04**	**1,4E+04**	**2,7E+04**	**0,0E+00**
	Concrete 150mm	294,3	m2	48,00	48,00	93,24		1,4E+04	1,4E+04	2,7E+04	
				per unit				total			
Foundation				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Beam**							**1,9E+04**	**1,9E+04**	**3,7E+04**	**0,0E+00**
	Beam 400x600	124,8	m	76,80	76,80	158,75		9,6E+03	9,6E+03	2,0E+04	
	Beam 500x600	62,0	m	96,00	96,00	194,11		6,0E+03	6,0E+03	1,2E+04	
	Beam 650x600	24,8	m	124,80	124,80	217,68		3,1E+03	3,1E+03	5,4E+03	
Main building	**Piles**			**557,06**	**557,06**	**630,70**	**0,00**	**4,0E+04**	**4,0E+04**	**4,5E+04**	**0,0E+00**
	Prefab piles 320x320 - 17m	72,0	pcs	557,06	557,06	630,70		4,0E+04	4,0E+04	4,5E+04	
Entrance building	**Beam**			**124,80**	**124,80**	**217,68**	**0,00**	**3,6E+03**	**3,6E+03**	**6,3E+03**	**0,0E+00**
	Beam 650x600	28,8	m	124,80	124,80	217,68		3,6E+03	3,6E+03	6,3E+03	
Entrance building	**Piles**			**557,06**	**557,06**	**630,70**	**0,00**	**8,4E+03**	**8,4E+03**	**9,5E+03**	**0,0E+00**
	Prefab piles 320x320 - 17m	15,0	pcs	557,06	557,06	630,70		8,4E+03	8,4E+03	9,5E+03	
				per unit				total			
Others				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Balconies**			**67,52**	**-16,04**	**163,68**	**0,24**	**10005,15**	**-2567,57**	**24131,95**	**3,6E+01**
	CLT140	148,3	m2	14,98	-83,49	118,00	0,24	2,2E+03	-1,2E+04	1,8E+04	3,6E+01
	Supports (beams, steel)	153,6	m	46,25	55,50	37,20		7,1E+03	8,5E+03	5,7E+03	
	Supports (ties, steel)	108,0	m	6,29	11,95	8,48		6,8E+02	1,3E+03	9,2E+02	
Main building	**Galleries**			**114,33**	**52,55**	**211,00**	**0,24**	**1,8E+04**	**-5,5E+03**	**4,6E+04**	**6,8E+01**
	CLT140	282,9	m2	14,98	-83,49	118,00	0,24	4,2E+03	-2,4E+04	3,3E+04	6,8E+01
	Supports (beams, steel)	204,0	m	46,44	55,53	37,20		9,5E+03	1,1E+04	7,6E+03	
	Supports (columns, steel)	84,0	m	52,91	80,51	55,80		4,4E+03	6,8E+03	4,7E+03	
Both buildings	**Connections (steel)**	**0,8**	**m3**	**1850,00**	**1850,00**	**0,00**	**0,00**	**1,5E+03**	**1,5E+03**	**0,0E+00**	**0,0E+00**

Only GWP, costs included in CLT element costs

units	
costs	[euro]
GWP	[kg CO2-eq.]
Volume	[m3]

gross floor area		
GFA main building excl.	2183	m2
GFA balconies and galleries	431	m2
GFA main building total	**2614**	**m2**
GFA entry building + storage	**151**	**m2**
GFA TOTAL	**2765**	**m2**

floor and building heights		
h-cladding	0,10	m
h-vloer	0,28	m
h-free	2,70	m
h-storey	**3,08**	m
h-outer-tot	**15,40**	**m**
h-inner-tot	**13,50**	**m**

		total value				value per m2 (GFA total)				value per m2 (GFA main building)				value per m2 (GFA entrance building)			
		GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs																	
Main building	**Roofs**	1,7E+04	-4,1E+02	5,8E+04	2,6E+01	6,1	-0,1	21,0	26,2	6,5	-0,2	22,3	26,2				
Main building	**Storey floors**	7,9E+04	-1,8E+04	2,8E+05	1,5E+02	28,5	-6,5	102,4	146,7	30,1	-6,8	108,4	146,7				
Main building	**Ground floors**	1,7E+04	-5,6E+03	6,1E+04	0,0E+00	6,2	-2,0	22,2	0,0	6,5	-2,2	23,5	0,0				
Entrance building	**Roofs**	1,2E+03	-2,9E+01	4,0E+03	1,8E+00	0,4	0,0	1,5	1,8					7,8	-0,2	26,7	1,8
Entrance building	**Storey floors**	5,4E+03	-1,2E+03	2,0E+04	1,0E+01	2,0	-0,4	7,1	10,2					36,0	-8,2	129,8	10,2
Entrance building	**Ground floors**	6,2E+02	-2,0E+02	2,2E+03	0,0E+00	0,2	-0,1	0,8	0,0					4,1	-1,3	14,7	0,0
Walls, facades																	
Main building	**Transverse outer walls**	7,0E+03	-8,5E+03	5,0E+04	4,0E+01	2,5	-3,1	18,0	40,2	2,7	-3,3	19,1	40,2				
Main building	**Transverse inner walls**	2,3E+04	-2,7E+04	1,6E+05	1,3E+02	8,2	-9,9	58,2	129,6	8,6	-10,5	61,6	129,6				
Main building	**Stability walls**	1,0E+04	-7,1E+03	6,6E+04	4,4E+01	3,8	-2,6	23,8	43,7	4,0	-2,7	25,2	43,7				
Main building	**Longitudinal facades**	3,0E+03	-3,8E+03	7,8E+04	0,0E+00	1,1	-1,4	28,3	0,0	1,1	-1,5	29,9	0,0				
Entrance building	**Inner walls**	1,4E+04	1,4E+04	2,7E+04	0,0E+00	5,1	5,1	9,9	0,0					93,5	93,5	181,5	0,0
Foundation																	
Main building	**Beam**	1,9E+04	1,9E+04	3,7E+04	0,0E+00	6,7	6,7	13,5	0,0	7,1	7,1	14,2	0,0				
Main building	**Piles**	4,0E+04	4,0E+04	4,5E+04	0,0E+00	14,5	14,5	16,4	0,0	15,3	15,3	17,4	0,0				
Entrance building	**Beam**	3,6E+03	3,6E+03	6,3E+03	0,0E+00	1,3	1,3	2,3	0,0					23,8	23,8	41,5	0,0
Entrance building	**Piles**	8,4E+03	8,4E+03	9,5E+03	0,0E+00	3,0	3,0	3,4	0,0					55,3	55,3	62,6	0,0
Others																	
Main building	**Balconies**	1,0E+04	-2,6E+03	2,4E+04	3,6E+01	3,6	-0,9	8,7	35,6	3,8	-1,0	9,2	35,6				
Main building	**Galleries**	1,8E+04	-5,5E+03	4,6E+04	6,8E+01	6,6	-2,0	16,5	67,9	6,9	-2,1	17,5	67,9				
Both buildings	**Connections**	1,5E+03	1,5E+03	0,0E+00	0,0E+00	0,5	0,5	0,0	0,0								
					TOTAL	**100,3**	**1,6**	**354,2**	**501,9**	**92,8**	**-7,7**	**348,2**	**490,0**	**220,4**	**162,8**	**456,7**	**12,0**

	value per m2 (GFA total)				value per m2 (GFA main building)				value per m2 (GFA entrance building)			
	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs, beams	43,4	-9,2	155,0	184,9	43,1	-9,2	154,1	172,9	47,9	-9,7	171,1	12,0
Walls, facades, columns	20,7	-11,8	138,3	213,6	16,5	-17,9	135,8	213,6	93,5	93,5	181,5	0,0
Foundation	25,6	25,6	35,6	0,0	22,5	22,5	31,6	0,0	79,1	79,1	104,1	0,0
Others	10,7	-2,4	25,2	103,5	10,8	-3,1	26,7	103,5	0,0	0,0	0,0	0,0
TOTAL	**100,3**	**2,1**	**354,2**	**501,9**	**92,8**	**-7,7**	**348,2**	**490,0**	**220,4**	**162,8**	**456,7**	**12,0**
	percentages				percentages				percentages			
	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs, beams	43%		44%	37%	46%		44%	35%	22%		37%	100%
Walls, facades, columns	21%		39%	43%	18%		39%	44%	42%		40%	0%
Foundation	25%		10%	0%	24%		9%	0%	36%		23%	0%
Others	11%		7%	21%	12%		8%	21%	0%		0%	0%
TOTAL	**100%**		**100%**	**100%**	**100%**		**100%**	**100%**	**100%**		**100%**	**100%**

Detailed assessment of variant 7.1

				per unit				total			
Floors, roofs				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Roofs**			**31,03**	**-27,99**	**186,13**	**0,16**	**1,4E+04**	**-1,2E+04**	**8,1E+04**	**7,0E+01**
	CLT 160 L5s	436,7	m2	17,33	-41,69	135,34	0,16	7,6E+03	-1,8E+04	5,9E+04	7,0E+01
	Finishing (insulation + gravel)	436,7	m2	13,70	13,70	50,79		6,0E+03	6,0E+03	2,2E+04	
Main building	**Storey floors**			**33,15**	**-51,92**	**227,74**	**0,20**	**5,8E+04**	**-9,1E+04**	**4,0E+05**	**3,5E+02**
	CLT 200 L7s	1746,7	m2	21,43	-52,10	169,77	0,20	3,7E+04	-9,1E+04	3,0E+05	3,5E+02
	Insulation and cladding	1746,7	m2	11,72	0,18	57,97		2,0E+04	3,1E+02	1,0E+05	
Main building	**Ground floors**			**31,68**	**-7,91**	**116,89**	**0,06**	**1,3E+04**	**-3,3E+03**	**4,8E+04**	**0,0E+00**
	Timber hollow core slab 200	414,8	m2	25,15	-14,65	82,50	0,06	1,0E+04	-6,1E+03	3,4E+04	
	Insulation and cladding GF	414,8	m2	6,53	6,74	34,39		2,7E+03	2,8E+03	1,4E+04	
Entrance building	**Roofs**			**31,03**	**-27,99**	**186,13**	**0,16**	**8,8E+02**	**-7,9E+02**	**5,3E+03**	**4,5E+00**
	CLT 160 L5s	28,3	m2	17,33	-41,69	135,34	0,16	4,9E+02	-1,2E+03	3,8E+03	4,5E+00
	Finishing (insulation + gravel)	28,3	m2	13,70	13,70	50,79		3,9E+02	3,9E+02	1,4E+03	
Entrance building	**Storey floors**			**33,15**	**-51,92**	**227,74**	**0,20**	**3,8E+03**	**-5,9E+03**	**2,6E+04**	**2,3E+01**
	CLT 200 L7s	113,3	m2	21,43	-52,10	169,77	0,20	2,4E+03	-5,9E+03	1,9E+04	2,3E+01
	Insulation and cladding	113,3	m2	11,72	0,18	57,97		1,3E+03	2,0E+01	6,6E+03	
Entrance building	**Ground floors**			**31,68**	**-7,91**	**116,89**	**0,06**	**4,5E+02**	**-1,1E+02**	**1,7E+03**	**0,0E+00**
	Timber hollow core slab 200	14,2	m2	25,15	-14,65	82,50	0,06	3,6E+02	-2,1E+02	1,2E+03	
	Insulation and cladding GF	14,2	m2	6,53	6,74	34,39		9,2E+01	9,5E+01	4,9E+02	
				per unit				total			
Walls, facades				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Transverse outer walls**			**35,00**	**43,75**	**85,00**	**0,00**	**1,0E+04**	**1,0E+04**	**2,5E+04**	**0,0E+00**
	CSB 175mm CS36	293,2	m2	35,00	35,00	85,00		1,0E+04	1,0E+04	2,5E+04	
Main building	**Transverse inner walls**			**50,00**	**62,66**	**91,64**	**0,00**	**4,4E+04**	**4,4E+04**	**8,1E+04**	**0,0E+00**
	CSB 250mm CS36	882,2	m2	50,00	50,00	91,64		4,4E+04	4,4E+04	8,1E+04	
Main building	**Stability walls**			**44,80**	**44,80**	**87,02**	**0,00**	**1,1E+04**	**1,1E+04**	**2,1E+04**	**0,0E+00**
	Concrete 140mm	243,0	m2	44,80	44,80	87,02		1,1E+04	1,1E+04	2,1E+04	
Main building	**Longitudinal facades**			**3,55**	**-4,53**	**92,89**	**0,02**	**2,6E+03**	**-3,3E+03**	**6,8E+04**	**0,0E+00**
	HSB facade inner wall	729,0	m2	3,55	-4,53	92,89	0,02	2,6E+03	-3,3E+03	6,8E+04	
Entrance building	**Inner walls**			**48,00**	**48,00**	**93,24**	**0,00**	**3,9E+03**	**3,9E+03**	**7,6E+03**	**0,0E+00**
	Concrete 150mm	81,0	m2	48,00	48,00	93,24		3,9E+03	3,9E+03	7,6E+03	
				per unit				total			
Foundation				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Beam**							**1,8E+04**	**1,8E+04**	**3,6E+04**	**0,0E+00**
	Beam 400x600	108,0	m	76,80	76,80	158,75		8,3E+03	8,3E+03	1,7E+04	
	Beam 500x600	69,2	m	96,00	96,00	194,11		6,6E+03	6,6E+03	1,3E+04	
	Beam 650x600	24,6	m	124,80	124,80	217,68		3,1E+03	3,1E+03	5,4E+03	
Main building	**Piles**			**557,06**	**557,06**	**630,70**	**0,00**	**4,0E+04**	**4,0E+04**	**4,5E+04**	**0,0E+00**
	Prefab piles 320x320 - 17m	72,0	pcs	557,06	557,06	630,70		4,0E+04	4,0E+04	4,5E+04	
Entrance building	**Beam**			**124,80**	**124,80**	**217,68**	**0,00**	**2,7E+03**	**2,7E+03**	**4,7E+03**	**0,0E+00**
	Beam 650x600	21,4	m	124,80	124,80	217,68		2,7E+03	2,7E+03	4,7E+03	
Entrance building	**Piles**			**557,06**	**557,06**	**630,70**	**0,00**	**5,6E+03**	**5,6E+03**	**6,3E+03**	**0,0E+00**
	Prefab piles 320x320 - 17m	10,0	pcs	557,06	557,06	630,70		5,6E+03	5,6E+03	6,3E+03	
				per unit				total			
Others				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Balconies**			**67,52**	**-16,04**	**163,68**	**0,24**	**10005,15**	**-2567,57**	**24131,95**	**3,6E+01**
	CLT140	148,3	m2	14,98	-83,49	118,00	0,24	2,2E+03	-1,2E+04	1,8E+04	3,6E+01
	Supports (beams, steel)	153,6	m	46,25	55,50	37,20		7,1E+03	8,5E+03	5,7E+03	
	Supports (ties, steel)	108,0	m	6,29	11,95	8,48		6,8E+02	1,3E+03	9,2E+02	
Main building	**Galleries**			**114,33**	**52,55**	**211,00**	**0,24**	**1,5E+04**	**-1,8E+03**	**3,4E+04**	**4,9E+01**
	CLT140	204,0	m2	14,98	-83,49	118,00	0,24	3,1E+03	-1,7E+04	2,4E+04	4,9E+01
	Supports (beams, steel)	170,0	m	46,44	55,53	37,20		7,9E+03	9,4E+03	6,3E+03	
	Supports (columns, steel)	72,0	m	52,91	80,51	55,80		3,8E+03	5,8E+03	4,0E+03	
Both buildings	**Connections (steel)**	**0,8**	**m3**	**1850,00**	**1850,00**	**0,00**	**0,00**	**1,5E+03**	**1,5E+03**	**0,0E+00**	**0,0E+00**

Only GWP, costs included in CLT element costs

units	
costs	[euro]
GWP	[kg CO2-eq.]
Volume	[m3]

gross floor area		
GFA main building excl.	2183,4	m2
GFA balconies and galleries	352,3	m2
GFA main building total	**2535,7**	**m2**
GFA entry building + storage	141,6	m2
GFA TOTAL	**2677,3**	**m2**

floor and building heights		
h-cladding	0,14	m
h-vloer	0,20	m
h-free	2,70	m
h-storey	**3,04**	m
h-outer-tot	**15,19**	**m**
h-inner-tot	**13,50**	**m**

		total value				value per m2 (GFA total)				value per m2 (GFA main building)				value per m2 (GFA entrance building)			
		GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs																	
Main building	**Roofs**	1,4E+04	-1,2E+04	8,1E+04	7,0E+01	5,1	-4,6	30,4	69,9	5,3	-4,8	32,1	69,9				
Main building	**Storey floors**	5,8E+04	-9,1E+04	4,0E+05	3,5E+02	21,6	-33,9	148,6	349,3	22,8	-35,8	156,9	349,3				
Main building	**Ground floors**	1,3E+04	-3,3E+03	4,8E+04	0,0E+00	4,9	-1,2	18,1	0,0	5,2	-1,3	19,1	0,0				
Entrance building	**Roofs**	8,8E+02	-7,9E+02	5,3E+03	4,5E+00	0,3	-0,3	2,0	4,5					6,2	-5,6	37,2	4,5
Entrance building	**Storey floors**	3,8E+03	-5,9E+03	2,6E+04	2,3E+01	1,4	-2,2	9,6	22,7					26,5	-41,5	182,2	22,7
Entrance building	**Ground floors**	4,5E+02	-1,1E+02	1,7E+03	0,0E+00	0,2	0,0	0,6	0,0					3,2	-0,8	11,7	0,0
Walls, facades																	
Main building	**Transverse outer walls**	1,0E+04	1,0E+04	2,5E+04	0,0E+00	3,8	3,8	9,3	0,0	4,0	4,0	9,8	0,0				
Main building	**Transverse inner walls**	4,4E+04	4,4E+04	8,1E+04	0,0E+00	16,5	16,5	30,2	0,0	17,4	17,4	31,9	0,0				
Main building	**Stability walls**	1,1E+04	1,1E+04	2,1E+04	0,0E+00	4,1	4,1	7,9	0,0	4,3	4,3	8,3	0,0				
Main building	**Longitudinal facades**	2,6E+03	-3,3E+03	6,8E+04	0,0E+00	1,0	-1,2	25,3	0,0	1,0	-1,3	26,7	0,0				
Entrance building	**Inner walls**	3,9E+03	3,9E+03	7,6E+03	0,0E+00	1,5	1,5	2,8	0,0					27,5	27,5	53,3	0,0
Foundation																	
Main building	**Beam**	1,8E+04	1,8E+04	3,6E+04	0,0E+00	6,7	6,7	13,4	0,0	7,1	7,1	14,2	0,0				
Main building	**Piles**	4,0E+04	4,0E+04	4,5E+04	0,0E+00	15,0	15,0	17,0	0,0	15,8	15,8	17,9	0,0				
Entrance building	**Beam**	2,7E+03	2,7E+03	4,7E+03	0,0E+00	1,0	1,0	1,7	0,0					18,9	18,9	32,9	0,0
Entrance building	**Piles**	5,6E+03	5,6E+03	6,3E+03	0,0E+00	2,1	2,1	2,4	0,0					39,3	39,3	44,5	0,0
Others																	
Main building	**Balconies**	1,0E+04	-2,6E+03	2,4E+04	3,6E+01	3,7	-1,0	9,0	35,6	3,9	-1,0	9,5	35,6				
Main building	**Galleries**	1,5E+04	-1,8E+03	3,4E+04	4,9E+01	5,5	-0,7	12,9	49,0	5,8	-0,7	13,6	49,0				
Both buildings	**Connections**	1,5E+03	1,5E+03	0,0E+00	0,0E+00	0,6	0,6	0,0	0,0								
					TOTAL	**94,9**	**6,1**	**341,1**	**531,0**	**92,8**	**3,8**	**340,0**	**503,8**	**121,6**	**37,7**	**361,9**	**27,2**

	value per m2 (GFA total)				value per m2 (GFA main building)				value per m2 (GFA entrance building)			
	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs, beams	33,5	-42,2	209,3	446,4	33,4	-41,9	208,1	419,2	35,9	-47,9	231,1	27,2
Walls, facades, columns	26,8	24,6	75,5	0,0	26,8	24,4	76,8	0,0	27,5	27,5	53,3	0,0
Foundation	24,8	24,8	34,5	0,0	22,9	22,9	32,1	0,0	58,2	58,2	77,4	0,0
Others	9,8	-1,1	21,9	84,6	9,8	-1,7	23,1	84,6	0,0	0,0	0,0	0,0
TOTAL	**94,9**	**6,1**	**341,1**	**531,0**	**92,8**	**3,8**	**340,0**	**503,8**	**121,6**	**37,7**	**361,9**	**27,2**
	percentages				percentages				percentages			
	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs, beams	35%		61%	84%	36%		61%	83%	30%		64%	100%
Walls, facades, columns	28%		22%	0%	29%		23%	0%	23%		15%	0%
Foundation	26%		10%	0%	25%		9%	0%	48%		21%	0%
Others	10%		6%	16%	11%		7%	17%	0%		0%	0%
TOTAL	**100%**		**100%**	**100%**	**100%**		**100%**	**100%**	**100%**		**100%**	**100%**

Detailed assessment of variant 7.2

				per unit				total			
Floors, roofs				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Roofs**			**31,03**	**-27,99**	**186,13**	**0,16**	**1,4E+04**	**-1,2E+04**	**8,1E+04**	**7,0E+01**
	CLT 160 L5s	436,7	m2	17,33	-41,69	135,34	0,16	7,6E+03	-1,8E+04	5,9E+04	7,0E+01
	Finishing (insulation + gravel)	436,7	m2	13,70	13,70	50,79		6,0E+03	6,0E+03	2,2E+04	
Main building	**Storey floors**			**52,61**	**-5,66**	**183,21**	**0,12**	**9,2E+04**	**-5,3E+03**	**3,2E+05**	**2,1E+02**
	CLT 120 L5s	1746,7	m2	12,86	-31,26	110,00	0,12	2,2E+04	-5,5E+04	1,9E+05	2,1E+02
	Concrete floor 80mm	1746,7	m2	25,60	25,60	15,24		4,5E+04	4,5E+04	2,7E+04	
	Insulation and cladding	1746,7	m2	14,15	2,63	57,97		2,5E+04	4,6E+03	1,0E+05	
Main building	**Ground floors**			**31,68**	**-7,91**	**116,89**	**0,06**	**1,3E+04**	**-3,3E+03**	**4,8E+04**	**0,0E+00**
	Timber hollow core slab 200	414,8	m2	25,15	-14,65	82,50	0,06	1,0E+04	-6,1E+03	3,4E+04	
	Insulation and cladding GF	414,8	m2	6,53	6,74	34,39		2,7E+03	2,8E+03	1,4E+04	
Entrance building	**Roofs**			**31,03**	**-27,99**	**186,13**	**0,16**	**8,8E+02**	**-7,9E+02**	**5,3E+03**	**4,5E+00**
	CLT 160 L5s	28,3	m2	17,33	-41,69	135,34	0,16	4,9E+02	-1,2E+03	3,8E+03	4,5E+00
	Finishing (insulation + gravel)	28,3	m2	13,70	13,70	50,79		3,9E+02	3,9E+02	1,4E+03	
Entrance building	**Storey floors**			**52,61**	**-5,66**	**183,21**	**0,12**	**6,0E+03**	**-3,4E+02**	**2,1E+04**	**1,4E+01**
	CLT 140 L5s	113,3	m2	12,86	-31,26	110,00	0,12	1,5E+03	-3,5E+03	1,2E+04	1,4E+01
	Concrete floor 100mm	113,3		25,60	25,60	15,24		2,9E+03	2,9E+03	1,7E+03	
	Insulation and cladding	113,3	m2	14,15	2,63	57,97		1,6E+03	3,0E+02	6,6E+03	
Entrance building	**Ground floors**			**31,68**	**-7,91**	**116,89**	**0,06**	**4,5E+02**	**-1,1E+02**	**1,7E+03**	**0,0E+00**
	Timber hollow core slab 200	14,2	m2	25,15	-14,65	82,50	0,06	3,6E+02	-2,1E+02	1,2E+03	
	Insulation and cladding GF	14,2	m2	6,53	6,74	34,39		9,2E+01	9,5E+01	4,9E+02	

units	
costs	[euro]
GWP	[kg CO2-eq.]
Volume	[m3]

gross floor area		
GFA main building excl.	2183,4	m2
GFA balconies and galleries	352,3	m2
GFA main building total	**2535,7**	**m2**
GFA entry building + storage	141,6	**m2**
GFA TOTAL	**2677,3**	**m2**

floor and building heights		
h-cladding	0,06	m
h-vloer	0,20	m
h-free	2,70	m
h-storey	**2,96**	m
h-outer-tot	**14,79**	**m**
h-inner-tot	**13,50**	**m**

				per unit				total			
Walls, facades				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Transverse outer walls**			**35,00**	**35,00**	**85,00**	**0,00**	**1,0E+04**	**1,0E+04**	**2,5E+04**	**0,0E+00**
	CSB 175mm CS36	293,2	m2	35,00	35,00	85,00		1,0E+04	1,0E+04	2,5E+04	
Main building	**Transverse inner walls**			**50,00**	**50,00**	**91,64**	**0,00**	**4,4E+04**	**4,4E+04**	**8,1E+04**	**0,0E+00**
	CSB 250mm CS36	882,2	m2	50,00	50,00	91,64		4,4E+04	4,4E+04	8,1E+04	
Main building	**Stability walls**			**44,80**	**44,80**	**87,02**	**0,00**	**1,1E+04**	**1,1E+04**	**2,1E+04**	**0,0E+00**
	Concrete 140mm	243,0	m2	44,80	44,80	87,02		1,1E+04	1,1E+04	2,1E+04	
Main building	**Longitudinal facades**			**3,55**	**-4,53**	**92,89**	**0,02**	**2,6E+03**	**-3,3E+03**	**6,8E+04**	**0,0E+00**
	HSB facade inner wall	729,0	m2	3,55	-4,53	92,89	0,02	2,6E+03	-3,3E+03	6,8E+04	
Entrance building	**Inner walls**			**48,00**	**48,00**	**93,24**	**0,00**	**3,9E+03**	**3,9E+03**	**7,6E+03**	**0,0E+00**
	Concrete 150mm	81,0	m2	48,00	48,00	93,24		3,9E+03	3,9E+03	7,6E+03	

				per unit				total			
Foundation				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Beam**							**1,8E+04**	**1,8E+04**	**3,6E+04**	**0,0E+00**
	Beam 400x600	108,0	m	76,80	76,80	158,75		8,3E+03	8,3E+03	1,7E+04	
	Beam 500x600	69,2	m	96,00	96,00	194,11		6,6E+03	6,6E+03	1,3E+04	
	Beam 650x600	24,6	m	124,80	124,80	217,68		3,1E+03	3,1E+03	5,4E+03	
Main building	**Piles**			**557,06**	**557,06**	**630,70**	**0,00**	**4,0E+04**	**4,0E+04**	**4,5E+04**	**0,0E+00**
	Prefab piles 320x320 - 17m	72,0	pcs	557,06	557,06	630,70		4,0E+04	4,0E+04	4,5E+04	
Entrance building	**Beam**			**124,80**	**124,80**	**217,68**	**0,00**	**2,7E+03**	**2,7E+03**	**4,7E+03**	**0,0E+00**
	Beam 650x600	21,4	m	124,80	124,80	217,68		2,7E+03	2,7E+03	4,7E+03	
Entrance building	**Piles**			**557,06**	**557,06**	**630,70**	**0,00**	**5,6E+03**	**5,6E+03**	**6,3E+03**	**0,0E+00**
	Prefab piles 320x320 - 17m	10,0	pcs	557,06	557,06	630,70		5,6E+03	5,6E+03	6,3E+03	

				per unit				total			
Others				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Balconies**			**67,52**	**-16,04**	**163,68**	**0,24**	**10005,15**	**-2567,57**	**24131,95**	**3,6E+01**
	CLT140	148,3	m2	14,98	-83,49	118,00	0,24	2,2E+03	-1,2E+04	1,8E+04	3,6E+01
	Supports (beams, steel)	153,6	m	46,25	55,50	37,20		7,1E+03	8,5E+03	5,7E+03	
	Supports (ties, steel)	108,0	m	6,29	11,95	8,48		6,8E+02	1,3E+03	9,2E+02	
Main building	**Galleries**			**114,33**	**52,55**	**211,00**	**0,24**	**1,5E+04**	**-1,8E+03**	**3,4E+04**	**4,9E+01**
	CLT140	204,0	m2	14,98	-83,49	118,00	0,24	3,1E+03	-1,7E+04	2,4E+04	4,9E+01
	Supports (beams, steel)	170,0	m	46,44	55,53	37,20		7,9E+03	9,4E+03	6,3E+03	
	Supports (columns, steel)	72,0	m	52,91	80,51	55,80		3,8E+03	5,8E+03	4,0E+03	
Both buildings	**Connections (steel)**	**1,0**	**m3**	**1850,00**	**1850,00**	**0,00**	**0,00**	**1,9E+03**	**1,9E+03**	**0,0E+00**	**0,0E+00**

Only GWP, costs included in CLT element costs

		total value				value per m2 (GFA total)				value per m2 (GFA main building)				value per m2 (GFA entrance building)			
		GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs																	
Main building	**Roofs**	1,4E+04	-1,2E+04	8,1E+04	7,0E+01	5,1	-4,6	30,4	69,9	5,3	-4,8	32,1	69,9				
Main building	**Storey floors**	9,2E+04	-5,3E+03	3,2E+05	2,1E+02	34,3	-2,0	119,5	214,8	36,2	-2,1	126,2	214,8				
Main building	**Ground floors**	1,3E+04	-3,3E+03	4,8E+04	0,0E+00	4,9	-1,2	18,1	0,0	5,2	-1,3	19,1	0,0				
Entrance building	**Roofs**	8,8E+02	-7,9E+02	5,3E+03	4,5E+00	0,3	-0,3	2,0	4,5					6,2	-5,6	37,2	4,5
Entrance building	**Storey floors**	6,0E+03	-3,4E+02	2,1E+04	1,4E+01	2,2	-0,1	7,8	13,6					42,1	-2,4	146,6	13,6
Entrance building	**Ground floors**	4,5E+02	-1,1E+02	1,7E+03	0,0E+00	0,2	0,0	0,6	0,0					3,2	-0,8	11,7	0,0
Walls, facades																	
Main building	**Transverse outer walls**	1,0E+04	1,0E+04	2,5E+04	0,0E+00	3,8	3,8	9,3	0,0	4,0	4,0	9,8	0,0				
Main building	**Transverse inner walls**	4,4E+04	4,4E+04	8,1E+04	0,0E+00	16,5	16,5	30,2	0,0	17,4	17,4	31,9	0,0				
Main building	**Stability walls**	1,1E+04	1,1E+04	2,1E+04	0,0E+00	4,1	4,1	7,9	0,0	4,3	4,3	8,3	0,0				
Main building	**Longitudinal facades**	2,6E+03	-3,3E+03	6,8E+04	0,0E+00	1,0	-1,2	25,3	0,0	1,0	-1,3	26,7	0,0				
Entrance building	**Inner walls**	3,9E+03	3,9E+03	7,6E+03	0,0E+00	1,5	1,5	2,8	0,0					27,5	27,5	53,3	0,0
Foundation																	
Main building	**Beam**	1,8E+04	1,8E+04	3,6E+04	0,0E+00	6,7	6,7	13,4	0,0	7,1	7,1	14,2	0,0				
Main building	**Piles**	4,0E+04	4,0E+04	4,5E+04	0,0E+00	15,0	15,0	17,0	0,0	15,8	15,8	17,9	0,0				
Entrance building	**Beam**	2,7E+03	2,7E+03	4,7E+03	0,0E+00	1,0	1,0	1,7	0,0					18,9	18,9	32,9	0,0
Entrance building	**Piles**	5,6E+03	5,6E+03	6,3E+03	0,0E+00	2,1	2,1	2,4	0,0					39,3	39,3	44,5	0,0
Others																	
Main building	**Balconies**	1,0E+04	-2,6E+03	2,4E+04	3,6E+01	3,7	-1,0	9,0	35,6	3,9	-1,0	9,5	35,6				
Main building	**Galleries**	1,5E+04	-1,8E+03	3,4E+04	4,9E+01	5,5	-0,7	12,9	49,0	5,8	-0,7	13,6	49,0				
Both buildings	**Connections**	1,9E+03	1,9E+03	0,0E+00	0,0E+00	0,7	0,7	0,0	0,0								
					TOTAL	**108,5**	**40,2**	**310,2**	**387,4**	**106,2**	**37,4**	**309,3**	**369,3**	**137,1**	**76,8**	**326,3**	**18,1**

	value per m2 (GFA total)				value per m2 (GFA main building)				value per m2 (GFA entrance building)			
	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs, beams	47,0	-8,2	178,3	302,8	46,8	-8,2	177,4	284,7	51,5	-8,8	195,5	18,1
Walls, facades, columns	26,8	24,6	75,5	0,0	26,8	24,4	76,8	0,0	27,5	27,5	53,3	0,0
Foundation	24,8	24,8	34,5	0,0	22,9	22,9	32,1	0,0	58,2	58,2	77,4	0,0
Others	9,9	-0,9	21,9	84,6	9,8	-1,7	23,1	84,6	0,0	0,0	0,0	0,0
TOTAL	**108,5**	**40,2**	**310,2**	**387,4**	**106,2**	**37,4**	**309,3**	**369,3**	**137,1**	**76,8**	**326,3**	**18,1**

	percentages				percentages				percentages			
	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs, beams	43%		57%	78%	44%		57%	77%	38%		60%	100%
Walls, facades, columns	25%		24%	0%	25%		25%	0%	20%		16%	0%
Foundation	23%		11%	0%	22%		10%	0%	42%		24%	0%
Others	9%		7%	22%	9%		7%	23%	0%		0%	0%
TOTAL	**100%**		**100%**	**100%**	**100%**		**100%**	**100%**	**100%**		**100%**	**100%**

Detailed assessment of variant 7.3

				per unit				total				
Floors, roofs				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	
Main building	**Roofs**			**31,03**	**-27,99**	**186,13**	**0,16**	**1,4E+04**	**-1,2E+04**	**8,1E+04**	**7,0E+01**	
	CLT 160 L5s	436,7	m2	17,33	-41,69	135,34	0,16	7,6E+03	-1,8E+04	5,9E+04	7,0E+01	
	Finishing (insulation + gravel)	436,7	m2	13,70	13,70	50,79		6,0E+03	6,0E+03	2,2E+04		
Main building	**Storey floors**			**33,15**	**-51,92**	**227,74**	**0,20**	**5,8E+04**	**-9,1E+04**	**4,0E+05**	**3,5E+02**	
	CLT 200 L7s	1746,7	m2	21,43	-52,10	169,77	0,20	3,7E+04	-9,1E+04	3,0E+05	3,5E+02	
	Insulation and cladding	1746,7	m2	11,72	0,18	57,97		2,0E+04	3,1E+02	1,0E+05		
Main building	**Ground floors**			**31,68**	**-7,91**	**116,89**	**0,06**	**1,3E+04**	**-3,3E+03**	**4,8E+04**	**0,0E+00**	
	Timber hollow core slab 200	414,8	m2	25,15	-14,65	82,50	0,06	1,0E+04	-6,1E+03	3,4E+04		
	Insulation and cladding GF	414,8	m2	6,53	6,74	34,39		2,7E+03	2,8E+03	1,4E+04		
Entrance building	**Roofs**			**31,03**	**-27,99**	**186,13**	**0,16**	**8,8E+02**	**-7,9E+02**	**5,3E+03**	**4,5E+00**	
	CLT 160 L5s	28,3	m2	17,33	-41,69	135,34	0,16	4,9E+02	-1,2E+03	3,8E+03	4,5E+00	
	Finishing (insulation + gravel)	28,3	m2	13,70	13,70	50,79		3,9E+02	3,9E+02	1,4E+03		
Entrance building	**Storey floors**			**33,15**	**-51,92**	**227,74**	**0,20**	**3,8E+03**	**-5,9E+03**	**2,6E+04**	**2,3E+01**	
	CLT 200 L7s	113,3	m2	21,43	-52,10	169,77	0,20	2,4E+03	-5,9E+03	1,9E+04	2,3E+01	
	Insulation and cladding	113,3	m2	11,72	0,18	57,97		1,3E+03	2,0E+01	6,6E+03		
Entrance building	**Ground floors**			**31,68**	**-7,91**	**116,89**	**0,06**	**4,5E+02**	**-1,1E+02**	**1,7E+03**	**0,0E+00**	
	Timber hollow core slab 200	14,2	m2	25,15	-14,65	82,50	0,06	3,6E+02	-2,1E+02	1,2E+03		
	Insulation and cladding GF	14,2	m2	6,53	6,74	34,39		9,2E+01	9,5E+01	4,9E+02		
				per unit				**total**				
Walls, facades				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	
Main building	**Transverse outer walls**			**31,33**	**-38,07**	**223,46**	**0,18**	**9,2E+03**	**-1,1E+04**	**6,6E+04**	**5,3E+01**	
	CLT 180 L5s - type 3	293,2	m2	19,49	-46,89	175,50	0,18	5,7E+03	-1,4E+04	5,1E+04	5,3E+01	
	Insulation and cladding	293,2	m2	11,84	8,82	47,96		3,5E+03	2,6E+03	1,4E+04		
Main building	**Transverse inner walls**			**31,33**	**-38,07**	**223,46**	**0,18**	**2,8E+04**	**-3,4E+04**	**2,0E+05**	**1,6E+02**	
	CLT 180 L5s - type 3	882,2	m2	19,49	-46,89	175,50	0,18	1,7E+04	-4,1E+04	1,5E+05	1,6E+02	
	Insulation and cladding	882,2	m2	11,84	8,82	47,96		1,0E+04	7,8E+03	4,2E+04		
Main building	**Stability walls**			**31,33**	**-38,07**	**223,46**	**0,18**	**1,0E+04**	**-7,1E+03**	**6,6E+04**	**4,4E+01**	
	CLT 180 L5s - type 3	243,0	m2	19,49	-46,89	175,50	0,18	4,7E+03	-1,1E+04	4,3E+04	4,4E+01	
	Insulation and cladding	486,0	m2	11,84	8,82	47,96		5,8E+03	4,3E+03	2,3E+04		
Main building	**Longitudinal facades**			**3,55**	**-4,53**	**92,89**	**0,02**	**2,6E+03**	**-3,3E+03**	**6,8E+04**	**0,0E+00**	
	HSB facade inner wall	729,0	m2	3,55	-4,53	92,89	0,02	2,6E+03	-3,3E+03	6,8E+04		
Entrance building	**Inner walls**			**31,33**	**-38,07**	**223,46**	**0,18**	**2,5E+03**	**-3,1E+03**	**1,8E+04**	**1,5E+01**	
	CLT 180 L5s - type 3	81,0	m2	19,49	-46,89	175,50	0,18	1,6E+03	-3,8E+03	1,4E+04	1,5E+01	
	Insulation and cladding	81,0	m2	11,84	8,82	47,96		9,6E+02	7,1E+02	3,9E+03		
				per unit				**total**				
Foundation				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	
Main building	**Beam**							**1,8E+04**	**1,8E+04**	**3,6E+04**	**0,0E+00**	
	Beam 400x600	108,0	m	76,80	76,80	158,75		8,3E+03	8,3E+03	1,7E+04		
	Beam 500x600	69,2	m	96,00	96,00	194,11		6,6E+03	6,6E+03	1,3E+04		
	Beam 650x600	26,0	m	124,80	124,80	217,68		3,2E+03	3,2E+03	5,7E+03		
Main building	**Piles**			**557,06**	**557,06**	**630,70**	**0,00**	**3,7E+04**	**3,7E+04**	**4,2E+04**	**0,0E+00**	
	Prefab piles 320x320 - 17m	66,0	pcs	557,06	557,06	630,70		3,7E+04	3,7E+04	4,2E+04		
Entrance building	**Beam**			**124,80**	**124,80**	**217,68**	**0,00**	**2,7E+03**	**2,7E+03**	**4,7E+03**	**0,0E+00**	
	Beam 650x600	21,4	m	124,80	124,80	217,68		2,7E+03	2,7E+03	4,7E+03		
Entrance building	**Piles**			**557,06**	**557,06**	**630,70**	**0,00**	**5,6E+03**	**5,6E+03**	**6,3E+03**	**0,0E+00**	
	Prefab piles 320x320 - 17m	10,0	pcs	557,06	557,06	630,70		5,6E+03	5,6E+03	6,3E+03		
				per unit				**total**				
Others				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	
Main building	**Balconies**			**67,52**	**-16,04**	**163,68**	**0,24**	**10005,15**	**-2567,57**	**24131,95**	**3,6E+01**	
	CLT140	148,3	m2	14,98	-83,49	118,00	0,24	2,2E+03	-1,2E+04	1,8E+04	3,6E+01	
	Supports (beams, steel)	153,6	m	46,25	55,50	37,20		7,1E+03	8,5E+03	5,7E+03		
	Supports (ties, steel)	108,0	m	6,29	11,95	8,48		6,8E+02	1,3E+03	9,2E+02		
Main building	**Galleries**			**114,33**	**52,55**	**211,00**	**0,24**	**1,5E+04**	**-1,8E+03**	**3,4E+04**	**4,9E+01**	
	CLT140	204,0	m2	14,98	-83,49	118,00	0,24	3,1E+03	-1,7E+04	2,4E+04	4,9E+01	
	Supports (beams, steel)	170,0	m	46,44	55,53	37,20		7,9E+03	9,4E+03	6,3E+03		
	Supports (columns, steel)	72,0	m	52,91	80,51	55,80		3,8E+03	5,8E+03	4,0E+03		
Both buildings	**Connections (steel)**	**0,8**	**m3**	**1850,00**	**1850,00**	**0,00**	**0,00**	**1,5E+03**	**1,5E+03**	**0,0E+00**	**0,0E+00**	Only GWP, costs included in CLT element costs

units	
costs	[euro]
GWP	[kg CO2-eq.]
Volume	[m3]

gross floor area		
GFA main building excl.	2183,4	m2
GFA balconies and galleries	352,3	m2
GFA main building total	**2535,7**	**m2**
GFA entry building + storage	141,6	**m2**
GFA TOTAL	**2677,3**	**m2**

floor and building heights		
h-cladding	0,14	m
h-vloer	0,20	m
h-free	2,70	m
h-storey	**3,04**	m
h-outer-tot	**15,19**	**m**
h-inner-tot	**13,50**	**m**

		total value				value per m2 (GFA total)				value per m2 (GFA main building)				value per m2 (GFA entrance building)			
		GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs																	
Main building	**Roofs**	1,4E+04	-1,2E+04	8,1E+04	7,0E+01	5,1	-4,6	30,4	69,9	5,3	-4,8	32,1	69,9				
Main building	**Storey floors**	5,8E+04	-9,1E+04	4,0E+05	3,5E+02	21,6	-33,9	148,6	349,3	22,8	-35,8	156,9	349,3				
Main building	**Ground floors**	1,3E+04	-3,3E+03	4,8E+04	0,0E+00	4,9	-1,2	18,1	0,0	5,2	-1,3	19,1	0,0				
Entrance building	**Roofs**	8,8E+02	-7,9E+02	5,3E+03	4,5E+00	0,3	-0,3	2,0	4,5					6,2	-5,6	37,2	4,5
Entrance building	**Storey floors**	3,8E+03	-5,9E+03	2,6E+04	2,3E+01	1,4	-2,2	9,6	22,7					26,5	-41,5	182,2	22,7
Entrance building	**Ground floors**	4,5E+02	-1,1E+02	1,7E+03	0,0E+00	0,2	0,0	0,6	0,0					3,2	-0,8	11,7	0,0
Walls, facades																	
Main building	**Transverse outer walls**	9,2E+03	-1,1E+04	6,6E+04	5,3E+01	3,4	-4,2	24,5	52,8	3,6	-4,4	25,8	52,8				
Main building	**Transverse inner walls**	2,8E+04	-3,4E+04	2,0E+05	1,6E+02	10,3	-12,5	73,6	158,8	10,9	-13,2	77,7	158,8				
Main building	**Stability walls**	1,0E+04	-7,1E+03	6,6E+04	4,4E+01	3,9	-2,7	24,6	43,7	4,1	-2,8	26,0	43,7				
Main building	**Longitudinal facades**	2,6E+03	-3,3E+03	6,8E+04	0,0E+00	1,0	-1,2	25,3	0,0	1,0	-1,3	26,7	0,0				
Entrance building	**Inner walls**	2,5E+03	-3,1E+03	1,8E+04	1,5E+01	0,9	-1,2	6,8	14,6					17,9	-21,8	127,8	14,6
Foundation																	
Main building	**Beam**	1,8E+04	1,8E+04	3,6E+04	0,0E+00	6,8	6,8	13,5	0,0	7,2	7,2	14,3	0,0				
Main building	**Piles**	3,7E+04	3,7E+04	4,2E+04	0,0E+00	13,7	13,7	15,5	0,0	14,5	14,5	16,4	0,0				
Entrance building	**Beam**	2,7E+03	2,7E+03	4,7E+03	0,0E+00	1,0	1,0	1,7	0,0					18,9	18,9	32,9	0,0
Entrance building	**Piles**	5,6E+03	5,6E+03	6,3E+03	0,0E+00	2,1	2,1	2,4	0,0					39,3	39,3	44,5	0,0
Others																	
Main building	**Balconies**	1,0E+04	-2,6E+03	2,4E+04	3,6E+01	3,7	-1,0	9,0	35,6	3,9	-1,0	9,5	35,6				
Main building	**Galleries**	1,5E+04	-1,8E+03	3,4E+04	4,9E+01	5,5	-0,7	12,9	49,0	5,8	-0,7	13,6	49,0				
Both buildings	**Connections**	1,5E+03	1,5E+03	0,0E+00	0,0E+00	0,6	0,6	0,0	0,0								
					TOTAL	**86,5**	**-41,4**	**419,1**	**800,9**	**84,5**	**-43,7**	**418,1**	**759,1**	**112,0**	**-11,5**	**436,4**	**41,8**

	value per m2 (GFA total)				value per m2 (GFA main building)				value per m2 (GFA entrance building)			
	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs, beams	33,5	-42,2	209,3	446,4	33,4	-41,9	208,1	419,2	35,9	-47,9	231,1	27,2
Walls, facades, columns	19,6	-21,8	154,8	269,9	19,7	-21,8	156,3	255,3	17,9	-21,8	127,8	14,6
Foundation	23,6	23,6	33,2	0,0	21,7	21,7	30,7	0,0	58,2	58,2	77,4	0,0
Others	9,8	-1,1	21,9	84,6	9,8	-1,7	23,1	84,6	0,0	0,0	0,0	0,0
TOTAL	**86,5**	**-41,4**	**419,1**	**800,9**	**84,5**	**-43,7**	**418,1**	**759,1**	**112,0**	**-11,5**	**436,4**	**41,8**

	percentages				percentages				percentages			
	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs, beams	39%		50%	56%	39%		50%	55%	32%		53%	65%
Walls, facades, columns	23%		37%	34%	23%		37%	34%	16%		29%	35%
Foundation	27%		8%	0%	26%		7%	0%	52%		18%	0%
Others	11%		5%	11%	12%		6%	11%	0%		0%	0%
TOTAL	**100%**		**100%**	**100%**	**100%**		**100%**	**100%**	**100%**		**100%**	**100%**

Detailed assessment of variant 7.4

				per unit				total			
Floors, roofs				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	Roofs			38,85	-0,95	133,29	0,10	1,7E+04	-4,1E+02	5,8E+04	4,4E+01
	Timber hollow core slab 200 RF	436,7	m2	25,15	-14,65	82,50	0,10	1,1E+04	-6,4E+03	3,6E+04	4,4E+01
	Finishing (insulation + gravel) RF	436,7	m2	13,70	13,70	50,79		6,0E+03	6,0E+03	2,2E+04	
Main building	Storey floors			35,00	-4,39	129,19	0,14	6,1E+04	-7,7E+03	2,3E+05	2,4E+02
	Timber hollow core slab 200	1746,7	m2	25,15	-14,65	82,50	0,14	4,4E+04	-2,6E+04	1,4E+05	2,4E+02
	Insulation and cladding	1746,7	m2	9,85	10,26	46,69		1,7E+04	1,8E+04	8,2E+04	
Main building	Ground floors			31,68	-7,91	116,89	0,06	1,3E+04	-3,3E+03	4,8E+04	0,0E+00
	Timber hollow core slab 200	414,8	m2	25,15	-14,65	82,50	0,06	1,0E+04	-6,1E+03	3,4E+04	
	Insulation and cladding GF	414,8	m2	6,53	6,74	34,39		2,7E+03	2,8E+03	1,4E+04	
Entrance building	Roofs			38,85	-0,95	133,29	0,10	1,1E+03	-2,7E+01	3,8E+03	2,8E+00
	Timber hollow core slab 200 RF	28,3	m2	25,15	-14,65	82,50	0,10	7,1E+02	-4,1E+02	2,3E+03	2,8E+00
	Finishing (insulation + gravel) RF	28,3	m2	13,70	13,70	50,79		3,9E+02	3,9E+02	1,4E+03	
Entrance building	Storey floors			35,00	-4,39	129,19	0,14	4,0E+03	-5,0E+02	1,5E+04	1,6E+01
	Timber hollow core slab 200	113,3	m2	25,15	-14,65	82,50	0,14	2,8E+03	-1,7E+03	9,3E+03	1,6E+01
	Insulation and cladding	113,3	m2	9,85	10,26	46,69		1,1E+03	1,2E+03	5,3E+03	
Entrance building	Ground floors			31,68	-7,91	116,89	0,06	4,5E+02	-1,1E+02	1,7E+03	0,0E+00
	Timber hollow core slab 200	14,2	m2	25,15	-14,65	82,50	0,06	3,6E+02	-2,1E+02	1,2E+03	
	Insulation and cladding GF	14,2	m2	6,53	6,74	34,39		9,2E+01	9,5E+01	4,9E+02	

units		
costs	[euro]	
GWP	[kg CO2-eq.]	
Volume	[m3]	

gross floor area		
GFA main building excl.	2183,4	m2
GFA balconies and galleries	352,3	m2
GFA main building total	2535,7	m2
GFA entry building + storage	141,6	m2
GFA TOTAL	2677,3	m2

floor and building heights		
h-cladding	0,10	m
h-vloer	0,20	m
h-free	2,70	m
h-storey	3,00	m
h-outer-tot	15,00	m
h-inner-tot	13,50	m

				per unit				total			
Walls, facades				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	Transverse outer walls			31,33	-38,07	223,46	0,18	9,2E+03	-1,1E+04	6,6E+04	5,3E+01
	CLT 180 L5s - type 3	293,2	m2	19,49	-46,89	175,50	0,18	5,7E+03	-1,4E+04	5,1E+04	5,3E+01
	Insulation and cladding	293,2	m2	11,84	8,82	47,96		3,5E+03	2,6E+03	1,4E+04	
Main building	Transverse inner walls			31,33	-38,07	223,46	0,18	2,8E+04	-3,4E+04	2,0E+05	1,6E+02
	CLT 180 L5s - type 3	882,2	m2	19,49	-46,89	175,50	0,18	1,7E+04	-4,1E+04	1,5E+05	1,6E+02
	Insulation and cladding	882,2	m2	11,84	8,82	47,96		1,0E+04	7,8E+03	4,2E+04	
Main building	Stability walls			31,33	-38,07	223,46	0,18	1,0E+04	-7,1E+03	6,6E+04	4,4E+01
	CLT 180 L5s - type 3	243,0	m2	19,49	-46,89	175,50	0,18	4,7E+03	-1,1E+04	4,3E+04	4,4E+01
	Insulation and cladding	486,0	m2	11,84	8,82	47,96		5,8E+03	4,3E+03	2,3E+04	
Main building	Longitudinal facades			3,55	-4,53	92,89	0,02	2,6E+03	-3,3E+03	6,8E+04	0,0E+00
	HSB facade inner wall	729,0	m2	3,55	-4,53	92,89	0,02	2,6E+03	-3,3E+03	6,8E+04	
Entrance building	Inner walls			31,33	-38,07	223,46	0,18	2,5E+03	-3,1E+03	1,8E+04	1,5E+01
	CLT 180 L5s - type 3	81,0	m2	19,49	-46,89	175,50	0,18	1,6E+03	-3,8E+03	1,4E+04	1,5E+01
	Insulation and cladding	81,0	m2	11,84	8,82	47,96		9,6E+02	7,1E+02	3,9E+03	

				per unit				total			
Foundation				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	Beam							1,8E+04	1,8E+04	3,5E+04	0,0E+00
	Beam 400x600	108,0	m	76,80	76,80	158,75		8,3E+03	8,3E+03	1,7E+04	
	Beam 500x600	65,7	m	96,00	96,00	194,11		6,3E+03	6,3E+03	1,3E+04	
	Beam 650x600	24,6	m	124,80	124,80	217,68		3,1E+03	3,1E+03	5,4E+03	
Main building	Piles			557,06	557,06	630,70	0,00	3,7E+04	3,7E+04	4,2E+04	0,0E+00
	Prefab piles 320x320 - 17m	66,0	pcs	557,06	557,06	630,70		3,7E+04	3,7E+04	4,2E+04	
Entrance building	Beam			124,80	124,80	217,68	0,00	2,7E+03	2,7E+03	4,7E+03	0,0E+00
	Beam 650x600	21,4	m	124,80	124,80	217,68		2,7E+03	2,7E+03	4,7E+03	
Entrance building	Piles			557,06	557,06	630,70	0,00	5,6E+03	5,6E+03	6,3E+03	0,0E+00
	Prefab piles 320x320 - 17m	10,0	pcs	557,06	557,06	630,70		5,6E+03	5,6E+03	6,3E+03	

				per unit				total			
Others				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	Balconies			67,52	-16,04	163,68	0,24	10005,15	-2567,57	24131,95	3,6E+01
	CLT140	148,3	m2	14,98	-83,49	118,00	0,24	2,2E+03	-1,2E+04	1,8E+04	3,6E+01
	Supports (beams, steel)	153,6	m	46,25	55,50	37,20		7,1E+03	8,5E+03	5,7E+03	
	Supports (ties, steel)	108,0	m	6,29	11,95	8,48		6,8E+02	1,3E+03	9,2E+02	
Main building	Galleries			114,33	52,55	211,00	0,24	1,5E+04	-1,8E+03	3,4E+04	4,9E+01
	CLT140	204,0	m2	14,98	-83,49	118,00	0,24	3,1E+03	-1,7E+04	2,4E+04	4,9E+01
	Supports (beams, steel)	170,0	m	46,44	55,53	37,20		7,9E+03	9,4E+03	6,3E+03	
	Supports (columns, steel)	72,0	m	52,91	80,51	55,80		3,8E+03	5,8E+03	4,0E+03	
Both buildings	Connections (steel)	0,8	m3	1850,00	1850,00	0,00	0,00	1,5E+03	1,5E+03	0,0E+00	0,0E+00

Only GWP, costs included in CLT element costs

		total value				value per m2 (GFA total)				value per m2 (GFA main building)				value per m2 (GFA entrance building)			
		GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs																	
Main building	Roofs	1,7E+04	-4,1E+02	5,8E+04	4,4E+01	6,3	-0,2	21,7	43,7	6,7	-0,2	23,0	43,7				
Main building	Storey floors	6,1E+04	-7,7E+03	2,3E+05	2,4E+02	22,8	-2,9	84,3	244,5	24,1	-3,0	89,0	244,5				
Main building	Ground floors	1,3E+04	-3,3E+03	4,8E+04	0,0E+00	4,9	-1,2	18,1	0,0	5,2	-1,3	19,1	0,0				
Entrance building	Roofs	1,1E+03	-2,7E+01	3,8E+03	2,8E+00	0,4	0,0	1,4	2,8					7,8	-0,2	26,7	2,8
Entrance building	Storey floors	4,0E+03	-5,0E+02	1,5E+04	1,6E+01	1,5	-0,2	5,5	15,9					28,0	-3,5	103,4	15,9
Entrance building	Ground floors	4,5E+02	-1,1E+02	1,7E+03	0,0E+00	0,2	0,0	0,6	0,0					3,2	-0,8	11,7	0,0
Walls, facades																	
Main building	Transverse outer walls	9,2E+03	-1,1E+04	6,6E+04	5,3E+01	3,4	-4,2	24,5	52,8	3,6	-4,4	25,8	52,8				
Main building	Transverse inner walls	2,8E+04	-3,4E+04	2,0E+05	1,6E+02	10,3	-12,5	73,6	158,8	10,9	-13,2	77,7	158,8				
Main building	Stability walls	1,0E+04	-7,1E+03	6,6E+04	4,4E+01	3,9	-2,7	24,6	43,7	4,1	-2,8	26,0	43,7				
Main building	Longitudinal facades	2,6E+03	-3,3E+03	6,8E+04	0,0E+00	1,0	-1,2	25,3	0,0	1,0	-1,3	26,7	0,0				
Entrance building	Inner walls	2,5E+03	-3,1E+03	1,8E+04	1,5E+01	0,9	-1,2	6,8	14,6					17,9	-21,8	127,8	14,6
Foundation																	
Main building	Beam	1,8E+04	1,8E+04	3,5E+04	0,0E+00	6,6	6,6	13,2	0,0	7,0	7,0	13,9	0,0				
Main building	Piles	3,7E+04	3,7E+04	4,2E+04	0,0E+00	13,7	13,7	15,5	0,0	14,5	14,5	16,4	0,0				
Entrance building	Beam	2,7E+03	2,7E+03	4,7E+03	0,0E+00	1,0	1,0	1,7	0,0					18,9	18,9	32,9	0,0
Entrance building	Piles	5,6E+03	5,6E+03	6,3E+03	0,0E+00	2,1	2,1	2,4	0,0					39,3	39,3	44,5	0,0
Others																	
Main building	Balconies	1,0E+04	-2,6E+03	2,4E+04	3,6E+01	3,7	-1,0	9,0	35,6	3,9	-1,0	9,5	35,6				
Main building	Galleries	1,5E+04	-1,8E+03	3,4E+04	4,9E+01	5,5	-0,7	12,9	49,0	5,8	-0,7	13,6	49,0				
Both buildings	Connections	1,5E+03	1,5E+03	0,0E+00	0,0E+00	0,6	0,6	0,0	0,0								
					TOTAL	88,4	-4,5	341,1	661,4	86,9	-6,5	340,8	628,1	115,1	31,9	347,0	33,3

	value per m2 (GFA total)				value per m2 (GFA main building)				value per m2 (GFA entrance building)			
	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs, beams	36,1	-4,5	131,6	306,9	36,0	-4,5	131,1	288,2	38,9	-4,5	141,7	18,7
Walls, facades, columns	19,6	-21,8	154,8	269,9	19,7	-21,8	156,3	255,3	17,9	-21,8	127,8	14,6
Foundation	23,4	23,4	32,8	0,0	21,5	21,5	30,3	0,0	58,2	58,2	77,4	0,0
Others	9,8	-1,1	21,9	84,6	9,8	-1,7	23,1	84,6	0,0	0,0	0,0	0,0
TOTAL	88,9	-3,9	341,1	661,4	86,9	-6,5	340,8	628,1	115,1	31,9	347,0	33,3

	percentages				percentages				percentages			
	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs, beams	41%		39%	46%	41%		38%	46%	34%		41%	56%
Walls, facades, columns	22%		45%	41%	23%		46%	41%	16%		37%	44%
Foundation	26%		10%	0%	25%		9%	0%	51%		22%	0%
Others	11%		6%	13%	11%		7%	13%	0%		0%	0%
TOTAL	100%		100%	100%	100%		100%	100%	100%		100%	100%

Detailed assessment of variant 7.5

				per unit				total			
Floors, roofs				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Roofs**			**31,03**	**-27,99**	**186,13**	**0,16**	**1,4E+04**	**-1,2E+04**	**8,1E+04**	**7,0E+01**
	CLT 160 L5s	436,7	m2	17,33	-41,69	135,34	0,16	7,6E+03	-1,8E+04	5,9E+04	7,0E+01
	Finishing (insulation + gravel)	436,7	m2	13,70	13,70	50,79		6,0E+03	6,0E+03	2,2E+04	
Main building	**Storey floors**			**33,15**	**-51,92**	**227,74**	**0,20**	**5,8E+04**	**-9,1E+04**	**4,0E+05**	**3,5E+02**
	CLT 200 L7s	1746,7	m2	21,43	-52,10	169,77	0,20	3,7E+04	-9,1E+04	3,0E+05	3,5E+02
	Insulation and cladding	1746,7	m2	11,72	0,18	57,97		2,0E+04	3,1E+02	1,0E+05	
Main building	**Ground floors**			**31,68**	**-7,91**	**116,89**	**0,06**	**1,3E+04**	**-3,3E+03**	**4,8E+04**	**0,0E+00**
	Timber hollow core slab 200	414,8	m2	25,15	-14,65	82,50	0,06	1,0E+04	-6,1E+03	3,4E+04	
	Insulation and cladding GF	414,8	m2	6,53	6,74	34,39		2,7E+03	2,8E+03	1,4E+04	
Entrance building	**Roofs**			**31,03**	**-27,99**	**186,13**	**0,16**	**1,2E+03**	**-1,1E+03**	**7,2E+03**	**6,2E+00**
	CLT 160 L5s	38,6	m2	17,33	-41,69	135,34	0,16	6,7E+02	-1,6E+03	5,2E+03	6,2E+00
	Finishing (insulation + gravel)	38,6	m2	13,70	13,70	50,79		5,3E+02	5,3E+02	2,0E+03	
Entrance building	**Storey floors**			**33,15**	**-51,92**	**227,74**	**0,20**	**5,1E+03**	**-8,0E+03**	**3,5E+04**	**3,1E+01**
	CLT 200 L7s	154,6	m2	21,43	-52,10	169,77	0,20	3,3E+03	-8,1E+03	2,6E+04	3,1E+01
	Insulation and cladding	154,6	m2	11,72	0,18	57,97		1,8E+03	2,8E+01	9,0E+03	
Entrance building	**Ground floors**			**31,68**	**-7,91**	**116,89**	**0,06**	**6,1E+02**	**-1,5E+02**	**2,3E+03**	**0,0E+00**
	Timber hollow core slab 200	19,3	m2	25,15	-14,65	82,50	0,06	4,9E+02	-2,8E+02	1,6E+03	
	Insulation and cladding GF	19,3	m2	6,53	6,74	34,39		1,3E+02	1,3E+02	6,6E+02	
				per unit				total			
Walls, facades				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Transverse outer walls**			**31,33**	**-38,07**	**223,46**	**0,18**	**1,3E+04**	**-1,6E+04**	**9,6E+04**	**7,7E+01**
	CLT 180 L5s - type 3	429,2	m2	19,49	-46,89	175,50	0,18	8,4E+03	-2,0E+04	7,5E+04	7,7E+01
	Insulation and cladding	429,2	m2	11,84	8,82	47,96		5,1E+03	3,8E+03	2,1E+04	
Main building	**Transverse inner walls**			**31,33**	**-38,07**	**223,46**	**0,18**	**2,8E+04**	**-3,4E+04**	**2,0E+05**	**1,6E+02**
	CLT 180 L5s - type 3	882,2	m2	19,49	-46,89	175,50	0,18	1,7E+04	-4,1E+04	1,5E+05	1,6E+02
	Insulation and cladding	882,2	m2	11,84	8,82	47,96		1,0E+04	7,8E+03	4,2E+04	
Main building	**Stability walls**			**31,33**	**-38,07**	**223,46**	**0,18**	**5,8E+03**	**-3,9E+03**	**3,7E+04**	**2,4E+01**
	CLT 180 L5s - type 3	135,0	m2	19,49	-46,89	175,50	0,18	2,6E+03	-6,3E+03	2,4E+04	2,4E+01
	Insulation and cladding	270,0	m2	11,84	8,82	47,96		3,2E+03	2,4E+03	1,3E+04	
Main building	**Longitudinal facades**			**3,55**	**-4,53**	**92,89**	**0,02**	**1,9E+03**	**-2,5E+03**	**5,1E+04**	**0,0E+00**
	HSB facade inner wall	546,8	m2	3,55	-4,53	92,89	0,02	1,9E+03	-2,5E+03	5,1E+04	
Entrance building	**Inner walls**			**31,33**	**-38,07**	**223,46**	**0,18**	**9,6E+02**	**7,1E+02**	**3,9E+03**	**0,0E+00**
	CLT 180 L5s - type 3	81,0	m2	19,49	-46,89	175,50	0,18				
	Insulation and cladding	81,0	m2	11,84	8,82	47,96		9,6E+02	7,1E+02	3,9E+03	
				per unit				total			
Foundation				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Beam**							**1,7E+04**	**1,7E+04**	**3,3E+04**	**0,0E+00**
	Beam 400x600	84,1	m	76,80	76,80	158,75		6,5E+03	6,5E+03	1,3E+04	
	Beam 500x600	67,5	m	96,00	96,00	194,11		6,5E+03	6,5E+03	1,3E+04	
	Beam 650x600	32,0	m	124,80	124,80	217,68		4,0E+03	4,0E+03	7,0E+03	
Main building	**Piles**			**557,06**	**557,06**	**630,70**	**0,00**	**4,1E+04**	**4,1E+04**	**4,6E+04**	**0,0E+00**
	Prefab piles 320x320 - 17m	73,0	pcs	557,06	557,06	630,70		4,1E+04	4,1E+04	4,6E+04	
Entrance building	**Beam**			**124,80**	**124,80**	**217,68**	**0,00**	**0,0E+00**	**0,0E+00**	**0,0E+00**	**0,0E+00**
	Beam 650x600		m	124,80	124,80	217,68		0,0E+00	0,0E+00	0,0E+00	
Entrance building	**Piles**			**557,06**	**557,06**	**630,70**	**0,00**	**0,0E+00**	**0,0E+00**	**0,0E+00**	**0,0E+00**
	Prefab piles 320x320 - 17m		pcs	557,06	557,06	630,70		0,0E+00	0,0E+00	0,0E+00	
				per unit				total			
Others				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Balconies**			**67,52**	**-16,04**	**163,68**	**0,24**	**10005,15**	**-2567,57**	**24131,95**	**3,6E+01**
	CLT140	148,3	m2	14,98	-83,49	118,00	0,24	2,2E+03	-1,2E+04	1,8E+04	3,6E+01
	Supports (beams, steel)	153,6	m	46,25	55,50	37,20		7,1E+03	8,5E+03	5,7E+03	
	Supports (ties, steel)	108,0	m	6,29	11,95	8,48		6,8E+02	1,3E+03	9,2E+02	
Main building	**Galleries**			**114,33**	**52,55**	**211,00**	**0,24**	**1,5E+04**	**-1,8E+03**	**3,4E+04**	**4,9E+01**
	CLT140	204,0	m2	14,98	-83,49	118,00	0,24	3,1E+03	-1,7E+04	2,4E+04	4,9E+01
	Supports (beams, steel)	170,0	m	46,44	55,53	37,20		7,9E+03	9,4E+03	6,3E+03	
	Supports (columns, steel)	72,0	m	52,91	80,51	55,80		3,8E+03	5,8E+03	4,0E+03	
Both buildings	**Connections (steel)**	**0,8**	**m3**	**1850,00**	**1850,00**	**0,00**	**0,00**	**1,5E+03**	**1,5E+03**	**0,0E+00**	**0,0E+00**

Only GWP, costs included in CLT element costs

units	
costs	[euro]
GWP	[kg CO2-eq.]
Volume	[m3]

gross floor area		
GFA main building excl.	2183,4	m2
GFA balconies and galleries	352,3	m2
GFA main building total	**2535,7**	**m2**
GFA entry building + storage	193,2	**m2**
GFA TOTAL	**2728,9**	**m2**

floor and building heights		
h-cladding	0,14	m
h-vloer	0,20	m
h-free	2,70	m
h-storey	**3,04**	m
h-outer-tot	**15,19**	**m**
h-inner-tot	**13,50**	**m**

		total value				value per m2 (GFA total)				value per m2 (GFA main building)				value per m2 (GFA entrance building)			
		GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs																	
Main building	**Roofs**	1,4E+04	-1,2E+04	8,1E+04	7,0E+01	5,0	-4,5	29,8	69,9	5,3	-4,8	32,1	69,9				
Main building	**Storey floors**	5,8E+04	-9,1E+04	4,0E+05	3,5E+02	21,2	-33,2	145,8	349,3	22,8	-35,8	156,9	349,3				
Main building	**Ground floors**	1,3E+04	-3,3E+03	4,8E+04	0,0E+00	4,8	-1,2	17,8	0,0	5,2	-1,3	19,1	0,0				
Entrance building	**Roofs**	1,2E+03	-1,1E+03	7,2E+03	6,2E+00	0,4	-0,4	2,6	6,2					6,2	-5,6	37,2	6,2
Entrance building	**Storey floors**	5,1E+03	-8,0E+03	3,5E+04	3,1E+01	1,9	-2,9	12,9	30,9					26,5	-41,5	182,2	30,9
Entrance building	**Ground floors**	6,1E+02	-1,5E+02	2,3E+03	0,0E+00	0,2	-0,1	0,8	0,0					3,2	-0,8	11,7	0,0
Walls, facades																	
Main building	**Transverse outer walls**	1,3E+04	-1,6E+04	9,6E+04	7,7E+01	4,9	-6,0	35,1	77,3	5,3	-6,4	37,8	77,3				
Main building	**Transverse inner walls**	2,8E+04	-3,4E+04	2,0E+05	1,6E+02	10,1	-12,3	72,2	158,8	10,9	-13,2	77,7	158,8				
Main building	**Stability walls**	5,8E+03	-3,9E+03	3,7E+04	2,4E+01	2,1	-1,4	13,4	24,3	2,3	-1,6	14,5	24,3				
Main building	**Longitudinal facades**	1,9E+03	-2,5E+03	5,1E+04	0,0E+00	0,7	-0,9	18,6	0,0	0,8	-1,0	20,0	0,0				
Entrance building	**Inner walls**	9,6E+02	7,1E+02	3,9E+03	0,0E+00	0,4	0,3	1,4	0,0					5,0	3,7	20,1	0,0
Foundation																	
Main building	**Beam**	1,7E+04	1,7E+04	3,3E+04	0,0E+00	6,2	6,2	12,2	0,0	6,7	6,7	13,2	0,0				
Main building	**Piles**	4,1E+04	4,1E+04	4,6E+04	0,0E+00	14,9	14,9	16,9	0,0	16,0	16,0	18,2	0,0				
Entrance building	**Beam**	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0	0,0	0,0	0,0					0,0	0,0	0,0	0,0
Entrance building	**Piles**	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0	0,0	0,0	0,0					0,0	0,0	0,0	0,0
Others																	
Main building	**Balconies**	1,0E+04	-2,6E+03	2,4E+04	3,6E+01	3,7	-0,9	8,8	35,6	3,9	-1,0	9,5	35,6				
Main building	**Galleries**	1,5E+04	-1,8E+03	3,4E+04	4,9E+01	5,4	-0,7	12,6	49,0	5,8	-0,7	13,6	49,0				
Both buildings	**Connections**	1,5E+03	1,5E+03	0,0E+00	0,0E+00	0,5	0,5	0,0	0,0								
					TOTAL	**82,5**	**-42,6**	**401,1**	**801,2**	**85,1**	**-43,1**	**412,5**	**764,1**	**40,9**	**-44,2**	**251,2**	**37,1**

	value per m2 (GFA total)				value per m2 (GFA main building)				value per m2 (GFA entrance building)			
	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs, beams	33,5	-42,3	209,7	456,3	33,4	-41,9	208,1	419,2	35,9	-47,9	231,1	37,1
Walls, facades, columns	18,3	-20,4	140,8	260,4	19,3	-22,2	150,0	260,4	5,0	3,7	20,1	0,0
Foundation	21,1	21,1	29,1	0,0	22,7	22,7	31,3	0,0	0,0	0,0	0,0	0,0
Others	9,6	-1,1	21,5	84,6	9,8	-1,7	23,1	84,6	0,0	0,0	0,0	0,0
TOTAL	**82,5**	**-42,6**	**401,1**	**801,2**	**85,1**	**-43,1**	**412,5**	**764,1**	**40,9**	**-44,2**	**251,2**	**37,1**

	percentages				percentages				percentages			
	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs, beams	41%		52%	57%	39%		50%	55%	88%		92%	100%
Walls, facades, columns	22%		35%	32%	23%		36%	34%	12%		8%	0%
Foundation	26%		7%	0%	27%		8%	0%	0%		0%	0%
Others	12%		5%	11%	11%		6%	11%	0%		0%	0%
TOTAL	**100%**		**100%**	**100%**	**100%**		**100%**	**100%**	**100%**		**100%**	**100%**

Detailed assessment of variant 7.6

				per unit				total			
Floors, roofs				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Roofs**			**38,85**	**-0,95**	**133,29**	**0,06**	**1,7E+04**	**-4,1E+02**	**5,8E+04**	**2,6E+01**
	Timber hollow core slab 200 RF	436,7	m2	25,15	-14,65	82,50	0,06	1,1E+04	-6,4E+03	3,6E+04	2,6E+01
	Finishing (insulation + gravel) RF	436,7	m2	13,70	13,70	50,79		6,0E+03	6,0E+03	2,2E+04	
Main building	**Storey floors**			**35,00**	**-4,39**	**129,19**	**0,06**	**6,1E+04**	**-7,7E+03**	**2,3E+05**	**1,0E+02**
	Timber hollow core slab 200	1746,7	m2	25,15	-14,65	82,50	0,06	4,4E+04	-2,6E+04	1,4E+05	1,0E+02
	Insulation and cladding	1746,7	m2	9,85	10,26	46,69		1,7E+04	1,8E+04	8,2E+04	
Main building	**Ground floors**			**31,68**	**-7,91**	**116,89**	**0,06**	**1,3E+04**	**-3,3E+03**	**4,8E+04**	**0,0E+00**
	Timber hollow core slab 200	414,8	m2	25,15	-14,65	82,50	0,06	1,0E+04	-6,1E+03	3,4E+04	
	Insulation and cladding GF	414,8	m2	6,53	6,74	34,39		2,7E+03	2,8E+03	1,4E+04	
Entrance building	**Roofs**			**38,85**	**-0,95**	**133,29**	**0,06**	**1,5E+03**	**-3,7E+01**	**5,2E+03**	**2,3E+00**
	Timber hollow core slab 200 RF	38,6	m2	25,15	-14,65	82,50	0,06	9,7E+02	-5,7E+02	3,2E+03	2,3E+00
	Finishing (insulation + gravel) RF	38,6	m2	13,70	13,70	50,79		5,3E+02	5,3E+02	2,0E+03	
Entrance building	**Storey floors**			**35,00**	**-4,39**	**129,19**	**0,06**	**5,4E+03**	**-6,8E+02**	**2,0E+04**	**9,3E+00**
	Timber hollow core slab 200	154,6	m2	25,15	-14,65	82,50	0,06	3,9E+03	-2,3E+03	1,3E+04	9,3E+00
	Insulation and cladding	154,6	m2	9,85	10,26	46,69		1,5E+03	1,6E+03	7,2E+03	
Entrance building	**Ground floors**			**31,68**	**-7,91**	**116,89**	**0,06**	**6,1E+02**	**-1,5E+02**	**2,3E+03**	**0,0E+00**
	Timber hollow core slab 200	19,3	m2	25,15	-14,65	82,50	0,06	4,9E+02	-2,8E+02	1,6E+03	
	Insulation and cladding GF	19,3	m2	6,53	6,74	34,39		1,3E+02	1,3E+02	6,6E+02	
				per unit				total			
Walls, facades				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Transverse outer walls**			**31,33**	**-38,07**	**223,46**	**0,18**	**1,3E+04**	**-1,6E+04**	**9,6E+04**	**7,7E+01**
	CLT 180 L5s - type 3	429,2	m2	19,49	-46,89	175,50	0,18	8,4E+03	-2,0E+04	7,5E+04	7,7E+01
	Insulation and cladding	429,2	m2	11,84	8,82	47,96		5,1E+03	3,8E+03	2,1E+04	
Main building	**Transverse inner walls**			**31,33**	**-38,07**	**223,46**	**0,18**	**2,8E+04**	**-3,4E+04**	**2,0E+05**	**1,6E+02**
	CLT 180 L5s - type 3	882,2	m2	19,49	-46,89	175,50	0,18	1,7E+04	-4,1E+04	1,5E+05	1,6E+02
	Insulation and cladding	882,2	m2	11,84	8,82	47,96		1,0E+04	7,8E+03	4,2E+04	
Main building	**Stability walls**			**31,33**	**-38,07**	**223,46**	**0,18**	**5,8E+03**	**-3,9E+03**	**3,7E+04**	**2,4E+01**
	CLT 180 L5s - type 3	135,0	m2	19,49	-46,89	175,50	0,18	2,6E+03	-6,3E+03	2,4E+04	2,4E+01
	Insulation and cladding	270,0	m2	11,84	8,82	47,96		3,2E+03	2,4E+03	1,3E+04	
Main building	**Longitudinal facades**			**3,55**	**-4,53**	**92,89**	**0,02**	**1,9E+03**	**-2,5E+03**	**5,1E+04**	**0,0E+00**
	HSB facade inner wall	546,8	m2	3,55	-4,53	92,89	0,02	1,9E+03	-2,5E+03	5,1E+04	
Entrance building	**Inner walls**			**31,33**	**-38,07**	**223,46**	**0,18**	**9,6E+02**	**7,1E+02**	**3,9E+03**	**0,0E+00**
	CLT 180 L5s - type 3	81,0	m2	19,49	-46,89	175,50	0,18				
	Insulation and cladding	81,0	m2	11,84	8,82	47,96		9,6E+02	7,1E+02	3,9E+03	
				per unit				total			
Foundation				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Beam**							**1,6E+04**	**1,6E+04**	**3,2E+04**	**0,0E+00**
	Beam 400x600	84,0	m	76,80	76,80	158,75		6,5E+03	6,5E+03	1,3E+04	
	Beam 500x600	64,0	m	96,00	96,00	194,11		6,1E+03	6,1E+03	1,2E+04	
	Beam 650x600	30,6	m	124,80	124,80	217,68		3,8E+03	3,8E+03	6,7E+03	
Main building	**Piles**			**557,06**	**557,06**	**630,70**	**0,00**	**4,1E+04**	**4,1E+04**	**4,6E+04**	**0,0E+00**
	Prefab piles 320x320 - 17m	73,0	pcs	557,06	557,06	630,70		4,1E+04	4,1E+04	4,6E+04	
Entrance building	**Beam**			**124,80**	**124,80**	**217,68**	**0,00**	**0,0E+00**	**0,0E+00**	**0,0E+00**	**0,0E+00**
	Beam 650x600		m	124,80	124,80	217,68		0,0E+00	0,0E+00	0,0E+00	
Entrance building	**Piles**			**557,06**	**557,06**	**630,70**	**0,00**	**0,0E+00**	**0,0E+00**	**0,0E+00**	**0,0E+00**
	Prefab piles 320x320 - 17m		pcs	557,06	557,06	630,70		0,0E+00	0,0E+00	0,0E+00	
				per unit				total			
Others				GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Main building	**Balconies**			**67,52**	**-16,04**	**163,68**	**0,24**	**10005,15**	**-2567,57**	**24131,95**	**3,6E+01**
	CLT140	148,3	m2	14,98	-83,49	118,00	0,24	2,2E+03	-1,2E+04	1,8E+04	3,6E+01
	Supports (beams, steel)	153,6	m	46,25	55,50	37,20		7,1E+03	8,5E+03	5,7E+03	
	Supports (ties, steel)	108,0	m	6,29	11,95	8,48		6,8E+02	1,3E+03	9,2E+02	
Main building	**Galleries**			**114,33**	**52,55**	**211,00**	**0,24**	**1,5E+04**	**-1,8E+03**	**3,4E+04**	**4,9E+01**
	CLT140	204,0	m2	14,98	-83,49	118,00	0,24	3,1E+03	-1,7E+04	2,4E+04	4,9E+01
	Supports (beams, steel)	170,0	m	46,44	55,53	37,20		7,9E+03	9,4E+03	6,3E+03	
	Supports (columns, steel)	72,0	m	52,91	80,51	55,80		3,8E+03	5,8E+03	4,0E+03	
Both buildings	**Connections (steel)**	**0,8**	**m3**	**1850,00**	**1850,00**	**0,00**	**0,00**	**1,5E+03**	**1,5E+03**	**0,0E+00**	**0,0E+00**

Only GWP, costs included in CLT element costs

units	
costs	[euro]
GWP	[kg CO2-eq.]
Volume	[m3]

gross floor area		
GFA main building excl.	2183,4	m2
GFA balconies and galleries	352,3	m2
GFA main building total	**2535,7**	**m2**
GFA entry building + storage	193,2	**m2**
GFA TOTAL	**2728,9**	**m2**

floor and building heights		
h-cladding	0,10	m
h-vloer	0,20	m
h-free	2,70	m
h-storey	**3,00**	m
h-outer-tot	**15,00**	**m**
h-inner-tot	**13,50**	**m**

		total value				value per m2 (GFA total)				value per m2 (GFA main building)				value per m2 (GFA entrance building)			
		GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs																	
Main building	**Roofs**	1,7E+04	-4,1E+02	5,8E+04	2,6E+01	6,2	-0,2	21,3	26,2	6,7	-0,2	23,0	26,2				
Main building	**Storey floors**	6,1E+04	-7,7E+03	2,3E+05	1,0E+02	22,4	-2,8	82,7	104,8	24,1	-3,0	89,0	104,8				
Main building	**Ground floors**	1,3E+04	-3,3E+03	4,8E+04	0,0E+00	4,8	-1,2	17,8	0,0	5,2	-1,3	19,1	0,0				
Entrance building	**Roofs**	1,5E+03	-3,7E+01	5,2E+03	2,3E+00	0,6	0,0	1,9	2,3					7,8	-0,2	26,7	2,3
Entrance building	**Storey floors**	5,4E+03	-6,8E+02	2,0E+04	9,3E+00	2,0	-0,2	7,3	9,3					28,0	-3,5	103,4	9,3
Entrance building	**Ground floors**	6,1E+02	-1,5E+02	2,3E+03	0,0E+00	0,2	-0,1	0,8	0,0					3,2	-0,8	11,7	0,0
Walls, facades																	
Main building	**Transverse outer walls**	1,3E+04	-1,6E+04	9,6E+04	7,7E+01	4,9	-6,0	35,1	77,3	5,3	-6,4	37,8	77,3				
Main building	**Transverse inner walls**	2,8E+04	-3,4E+04	2,0E+05	1,6E+02	10,1	-12,3	72,2	158,8	10,9	-13,2	77,7	158,8				
Main building	**Stability walls**	5,8E+03	-3,9E+03	3,7E+04	2,4E+01	2,1	-1,4	13,4	24,3	2,3	-1,6	14,5	24,3				
Main building	**Longitudinal facades**	1,9E+03	-2,5E+03	5,1E+04	0,0E+00	0,7	-0,9	18,6	0,0	0,8	-1,0	20,0	0,0				
Entrance building	**Inner walls**	9,6E+02	7,1E+02	3,9E+03	0,0E+00	0,4	0,3	1,4	0,0					5,0	3,7	20,1	0,0
Foundation																	
Main building	**Beam**	1,6E+04	1,6E+04	3,2E+04	0,0E+00	6,0	6,0	11,9	0,0	6,5	6,5	12,8	0,0				
Main building	**Piles**	4,1E+04	4,1E+04	4,6E+04	0,0E+00	14,9	14,9	16,9	0,0	16,0	16,0	18,2	0,0				
Entrance building	**Beam**	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0	0,0	0,0	0,0					0,0	0,0	0,0	0,0
Entrance building	**Piles**	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0	0,0	0,0	0,0					0,0	0,0	0,0	0,0
Others																	
Main building	**Balconies**	1,0E+04	-2,6E+03	2,4E+04	3,6E+01	3,7	-0,9	8,8	35,6	3,9	-1,0	9,5	35,6				
Main building	**Galleries**	1,5E+04	-1,8E+03	3,4E+04	4,9E+01	5,4	-0,7	12,6	49,0	5,8	-0,7	13,6	49,0				
Both buildings	**Connections**	1,5E+03	1,5E+03	0,0E+00	0,0E+00	0,5	0,5	0,0	0,0								
					TOTAL	**85,0**	**-5,0**	**322,9**	**487,5**	**87,5**	**-5,9**	**335,1**	**475,9**	**43,9**	**-0,8**	**161,8**	**11,6**

	value per m2 (GFA total)				value per m2 (GFA main building)				value per m2 (GFA entrance building)			
	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs, beams	36,2	-4,5	131,8	142,6	36,0	-4,5	131,1	131,0	38,9	-4,5	141,7	11,6
Walls, facades, columns	18,3	-20,4	140,8	260,4	19,3	-22,2	150,0	260,4	5,0	3,7	20,1	0,0
Foundation	20,9	20,9	28,7	0,0	22,5	22,5	30,9	0,0	0,0	0,0	0,0	0,0
Others	9,6	-1,1	21,5	84,6	9,8	-1,7	23,1	84,6	0,0	0,0	0,0	0,0
TOTAL	**85,0**	**-5,0**	**322,9**	**487,5**	**87,5**	**-5,9**	**335,1**	**475,9**	**43,9**	**-0,8**	**161,8**	**11,6**
	percentages				percentages				percentages			
	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber	GWP-GHG	GWP-total	costs	volume timber
Floors, roofs, beams	43%		41%	29%	41%		39%	28%	89%		88%	100%
Walls, facades, columns	21%		44%	53%	22%		45%	55%	11%		12%	0%
Foundation	25%		9%	0%	26%		9%	0%	0%		0%	0%
Others	11%		7%	17%	11%		7%	18%	0%		0%	0%
TOTAL	**100%**		**100%**	**100%**	**100%**		**100%**	**100%**	**100%**		**100%**	**100%**