Changing a Concrete and/or Steel Building in order to Reach the Paris Proof Agreement

By Changing the Structure Into a Timber-Hybrid Structure

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VAN ROSSUM RAADGEVENDE INGENIEURS

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by

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Preface

With this thesis ends this part of my life as a student. It has been a turbulent, but very exciting journey. I started as a student Applied Earth Sciences at the TU Delft, but after completing the Bachelor's degree and one year of the Master's degree in Geo-Engineering, I figured that my heart was not in this line of work. I made the decision to bridge to the Master's degree in Building Engineering, which would ultimately be the right decision.

I have finally completed my thesis after a year of hard work and ups and downs. This could not have been done without the help of my thesis committee. First, I want to thank the chair of my committee Henk Jonkers, for your guidance on a subject I was not very familiar with. To Maria Felicita, your feedback on both my research and report has been invaluable to me. To Laura Āboltiņa, for always being there whenever I had a question and for helping me to feel at home at Van Rossum. To Roel Schipper, for completing my thesis committee in the last phase. I also want to thank Geert Ravenshorst, for your guidance as chair of my committee for a large part of my thesis.

I also want to give a special thanks to my family and friends. My mother, Agniet, my brother, Hjalmar and my lovely girlfriend, Manon, you were always there for me, in good and in bad times. I am very lucky to have you in my life. Lastly, I want to thank my father, Maurice. It has been more than five years since you are gone, but I am still using the lessons you have taught me. I will miss you forever.

Now that my student life is over, I am excited for what lies ahead in the future. Thank you TU Delft, maybe we will meet again!

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Summary

The issue of climate change has become highly important over the last decades. All sectors need to find solutions in order to reduce the carbon footprint and the built environment sector is definitely not an exception to this. One of the solutions is to use more biobased materials, such as timber. The use in timber is not only limited to low-rise buildings, more mid- and high-rise buildings are being built as well. The number of buildings including timber with at least six stories was increased from 32 in 2015 to 115 in 2023.

Even though the number of timber buildings is increasing, the actual environmental impact is largely unknown. This is because there is no commonly-used method to calculate the carbon footprint of a building which is complete and correct. Currently, the MPG (MilieuPrestatie Gebouwen) and the method described in the Paris Proof Agreement are mainly used in the Netherlands. The MPG uses the Environmental Product Declarations (EPDs) from the database from the NMD viewer, but this viewer does not provide the essential information for the user to choose the proper EPD. The Paris Proof Agreement disregards the end-of-life phases, which leads to incomplete results.

Therefore, another method was developed to calculate the carbon footprint and to determine the difference in carbon footprint between a concrete and/or steel structure with a timber-hybrid structure. This method uses two sets of phases: phases A-C and phases A1-A5. The former uses all relevant LCA phases and will provide the most accurate results, while the latter can be used to compare the results to the Paris Proof Agreement limits. Phases A4 and C2 (transport to and from the building site) and modified to fit the current projects.

Two case studies were used for this research. The first case study is KasseNova aan de Vaart, a seven-story residential building made of concrete. The carbon footprint is calculated for this concrete design, as well as three design variants including CLT floors, CLT walls and a combination of the two. The second case study is Apollolaan 171, a six-storey office building made of steel and concrete. The design variants include glulam columns, CLT floors and beams and a combination. For all variants, design calculations of the timber elements were performed.

For CLT elements, two end-of-life scenarios were considered: 100% recycling and 100% incineration. The current design of KasseNova aan de Vaart has a carbon footprint of 3,145 ton CO_2-eq. when phases A-C are considered. In the scenario that the floors and walls are replaced by CLT, the carbon footprint is decreased by 63.1% when the CLT is recycled, while this is decrease is 12.7% when the CLT is incinerated. When phases A1-A5 are considered, the current design has a carbon footprint of 222.46 kg CO_2-eq./m^2 (above the 2021 Paris Proof limit of 220 kg/m^2) and the CLT floor and wall design variant has a carbon footprint of 35.12 kg CO_2-eq./m^2 (below the 2050 limit of 50 kg/m^2), including biogenic carbon uptake.

The current design of Apollolaan 171 has a carbon footprint of 1,671 ton CO_2-eq. (phases A-C). For the scenario in which the floors, beams and columns are replaced by CLT and glulam, the carbon footprint is reduced by 89.2% (CLT recycled) and 49.8% (CLT incinerated). Considering phases A1-A5, the carbon footprint of the current structure is 255.17 kg CO_2-eq./m^2 (above the 2021 limit of 250 kg/m^2), while the carbon footprint of the structure including CLT and glulam elements is -44.93 kg CO_2-eq./m^2 (below the 2050 of 50 kg/m^2).

These results show that an increase in timber in the structure leads to a reduction in carbon footprint. This is because timber takes up carbon in the product stage. However, the amount of reduction depends on several factors. If the CLT is recycled at the end of its lifetime, the reduction will be more significant than if the CLT is incinerated. When the structure includes concrete, the carbon footprint depends on the type of cement being used in the concrete. CEM I will lead to a higher carbon footprint than CEM III. For structures including steel, a higher percentage of recycled steel leads to a lower carbon footprint. Also, in general, the country of production influences the carbon footprint. If a country has a high percentage of coal in its energy mix, the carbon footprint will be higher.

Contents

1 Introduction

1.1. Research Context

Sustainability is a hot topic in today's society. This is not an exception in the built environment sector, from which 37% of all global emissions originate (UNEP, 2023). This did not go unnoticed in the Netherlands, where the Paris Proof Agreement was created by the Dutch Green Building Council (DGBC) (Spitsbaard & van Leeuwen, 2021). The DGBC is an organisation with over 400 partners which has the goal to make the built environment sector future-proof in terms of sustainability. The Paris Proof Agreement is based on the Paris Agreement from 2015, which states that the global temperature rise in 2050 should be reduced to 1.5 °C compared to pre-industrial levels. The Paris Proof Agreement contains limits to which the carbon footprint of a building should be below of in order to reach this limit. These limits are based on the contribution from the built environment sector to the total carbon footprint and the rate of buildings being built. If all buildings in the Netherlands comply to these limits, the goal of limiting the temperature rise to 1.5 °C will be met, provided that the other sectors and countries will also reach their respective goals.

The limits, which can be viewed in Table 3.3 and 3.4 in Chapter 3 are reducing in value every decade until 2050. While today's buildings might reach the current limits, this is a larger challenge in the future. This leads to biobased materials, such as timber, which are becoming more appealing. These timber buildings are not only limited to low-rise buildings, the amount of mid- to high-rise buildings is increasing as well. The number of buildings including timber with at least six stories increased from 32 in 2015 to 115 in 2023 (Tall Timber Center, n.d.). This change in material use is often seen as the more sustainable choice, but the question remains how much more sustainable it is compared to the more conventional concrete and steel buildings.

1.2. Problem Background

Currently, there is no global consensus on how the carbon footprint is calculated. This is important in understanding how effective it is to build with timber. There is a consensus in the Netherlands, where the MPG (MilieuPrestatie Gebouwen) is used. This method uses all life cycle phases, includes all environmental impact categories from EN 15804+A2 and expresses the impact in shadow costs. There is a lack in transparency on the input values (which are obtained from Environmental Product Declarations, or EPDs), which means that the user will not have sufficient information to make a proper decision on which EPD to use. Therefore, this method has a high likelihood to lead to incorrect results.

Secondly, the method stated in the Paris Proof Agreement is often used. However, since the Paris Proof Agreement only considers the scenario until 2050, only the first life cycle phases of a building are used. The later life cycles are disregarded, which leads to incomplete results.

Therefore, there currently is no commonly-used method to calculate the carbon footprint of a building which is complete and correct. Once this method does exist, a comparison of the carbon footprint between concrete/steel buildings and its timber-hybrid variant can be done. This will give insight in how effective it is for the carbon footprint to use timber elements instead of concrete or steel.

1.3. Objectives

The following objectives are set for the research:

1. To use a method for the calculation of the carbon footprint which can be easily understood and used by people in the industry.
2. To investigate the possibility of reaching (future) Paris Proof limits by using timber elements instead of concrete/steel elements.

1.4. Research Questions

In this thesis report, the following main research question will be answered:

> What is the impact on the carbon footprint when a concrete and/or steel structure is changed into a timber-hybrid structure, including various end-of-life scenarios for timber?

In order to answer this main research question, the following sub-questions have been formulated:

- Sub question 1: How are the threshold values in the Paris Proof Agreement obtained and how can these be used in design?
- Sub question 2: How does the floor plan change, using a realistic solution, when a structure is changed from a concrete and/or steel structure into a timber-hybrid structure?
- Sub question 3: What is the impact on the foundation when a concrete and/or steel structure is changed into a timber-hybrid structure?

1.5. Methodology

Literature Study
In the literature study, the existing literature on the comparison of the carbon footprint between concrete/steel buildings and timber(-hybrid) variants is covered. Not only the results are compared, but also the methodology which was used to obtain the carbon footprint. This is used to get an understanding of the importance of which method to use and to compare the results from this research to.

Creation of Design Variants
The concrete and/or steel buildings are being transformed into timber-hybrid buildings, which is done by replacing concrete/steel elements into timber elements. The timber elements need to be dimensioned and calculated and the floor plan and foundation needs to be adjusted in order to fit the newly created design.

Carbon Footprint Calculation
The carbon footprint of the current design and design variants are calculated, for which the list of materials are needed and the input values from the EPDs. These EPDs need to be adjusted in order to fit to the current project. These results are used to answer the research questions.

2

Literature Study

2.1. Calculating Carbon Footprint of Timber Buildings

A significant amount of studies have been published in which the carbon footprint of a timber(-hybrid) structure is calculated (Younis & Dodoo, 2022). In these studies, the carbon footprint is related to the same structure which uses a different material (timber versus concrete or steel). However, there is a wide variety in this research in terms of location of the structure, type of structure, used life cycle and end-of-life scenario. It is important to consider that each material decays differently and that this has an impact on the end-of-life scenario. Unprotected timber structures exposed to moisture will decay rapidly, meaning that these elements are unable to be reused. If the material is not reused, the carbon footprint will be higher.

The purpose of this part of the literature study is to highlight the differences in existing literature and to display the impact of these differences on the resulting carbon footprint. This is used to show that research which was performed with a different set of boundary conditions cannot be compared to this research. There are studies use similar boundary conditions (LCA phases, structure type, etc.) as the research in this report. While these results from these studies might not be entirely comparable, these can be used as an indication. Therefore, several existing studies using the same LCA phases are described in the later part of this literature study.

2.1.1. Differences in Existing Literature

This part of the literature study displays the main differences between existing literature and how these differences yield different results.

Using EN 15804+A1 or EN 15804+A2

In 2013, European standard EN 15804+A1 was published, which described the core rules for the product category of construction products (NEN, 2013a). This standard included seven parameters describing environmental impacts, with only a single parameter used for the description of the global warming potential (GWP). In 2019, a new standard was published, EN 15804+A2 (NEN, 2019), in which LCA phases A-D are included rather than A-C. This standard included three global warming parameters: fossil fuels (GWP-fossil), biogenic (GWP-biogenic) and land use and land use change (GWP-luluc). These parameters are combined into the total global warming potential (GWP-total). This division into different parameters led to a change in calculation of the carbon footprint. Existing literature which uses EN 15804+A1 therefore uses a largely non-transparent (not always including LCA phases C and D) and outdated calculation method.

Location

Liu et al. (2016) describe a carbon footprint research which has been performed on CLT structures in two different regions in China: Harbin and Xi'an. Harbin is a colder region, while Xi'an is a warmer region in China. The results display that when 90% of the CLT is recycled, the carbon emission of the structure in Harbin is 35.6% higher than the same CLT structure in Xi'an. This is mainly due to the fact that there is a much higher energy consumption in Harbin than in Xi'an, leading to higher CO_2 emissions. Other studies include carbon footprint research of CLT structures which are built in Australia (Durlinger et al., 2013), the UK (Darby et al., 2013) and Finland (Rinne et al., 2022), amongst other locations. The climate is not the only contributing factor to the differences between locations. The source of the timber depends on the location as well, as displayed in Table 2.1. This is due to the fact that different manufacturers around the world use different sources of energy for the production of the CLT elements, leading to differences in carbon footprint. For instance, the electricity in Australia mix is mainly made up of brown coal, which leads to relatively high carbon footprints (Durlinger et al., 2013). Sweden on the other hand uses only 3.3% of coal for the electricity mix, leading to lower carbon footprints (International Energy Agency, 2021c). This can also be seen in Table 2.1, where the GWP excluding biogenic carbon uptake of CLT made in Sweden is more then ten times lower than that of CLT made in Australia. Additionally, the carbon uptake differs between timber types, as the unit weight varies. This also leads to differences in carbon footprint between CLT elements (Younis & Dodoo, 2022).

Manufacturer	**Geographical scope**	**CLT unit weight (kg/m^3)**	**GWP excl. biogenic ($kg\ CO_2$-eq./m^2)**	**GWP incl. biogenic ($kg\ CO_2$-eq./m^2)**
Södra Building Systems	Sweden	430	34	-670
Stora Enso	Austria	470	60	-671
KLH Massivholz GmbH	Austria	480	192.9	-601.3
Binderholz Bausysteme GmbH	Germany	471	200	-761
Egoin	France	500-550	174.1	-685.5
Xlam	Australia	480	447	-293
Schilliger Holz AG	Switzerland	424	70	-623
SmartLam North America	Alabama, US	561	126	-779
SmartLam North America	Montana, US	561	178	-727
Nordic X-Lam	Quebec, Canada	411	121.9	-591
Structurlam	BC, Canada	420	89.8	-678.3

Table 2.1: GWP per 1 m^3 CLT production (modules A1-A3), as provided by different manufacturers (Younis & Dodoo, 2022)

Structure Type

The existing literature on carbon footprint studies performed on CLT structures also shows a variety of structure types, more specifically the number of floors in the structure. Skullestad et al. (2016) compared the carbon footprint of CLT buildings with 3, 7, 12 and 21 storeys. It was found that the 3-storey building had a carbon footprint of 26.3 kg CO_2-eq./m^2, while the 21-storey building had a carbon footprint of 67.3 kg CO_2-eq./m^2. This increase in the carbon footprint is due to the fact that the building's superstructure, which usually is made of concrete, increases with increasing building height. Similarly, the contribution of the concrete core walls to the total carbon footprint increase with increasing building height.

Included Life Cycle Phases

Existing LCA studies can also be distinguished between the life cycle phases which are included in the research. The following life cycle stages are defined:

- Phase A1-A3: Production stage
- Phase A4-A5: Construction process stage
- Phase B1-B7: Use stage
- Phase C1-C4: End of life stage
- Phase D: Benefits and loads beyond the system boundary

While EN 15804+A2 specifies that LCA phases A-D need to be used, this does not always happen. Younis & Dodoo (2022) describe the results from 25 different carbon footprint stories on timber(-hybrid) structures, which use both EN 15804+A1 and +A2. Table 2.2 gives a description of the phases which were included in these 25 studies.

Phases included in LCA	Number of studies
A1-A5	5
A-D	4
A-D (excluding B3-B5)	4
A-D (excluding B)	3
A1-A5 + B6	2
A-D (excluding B1, B5-B7, C4)	1
A-D (excluding A5, B1-B7, C1)	1
A-D (excluding B1, B3-B7, C3-C4, partly D)	1
A-D (excluding B1-B3, B5, B7)	1
A-D (excluding B1-B5, B7)	1
A1-A4	1
A1-A3	1

Table 2.2: Description of Used Phases in the LCA Study of Younis & Dodoo (2022)

Most carbon footprint studies on timber(-hybrid) structures use a cradle-to-gate (A1-A5) or cradle-to-grave (A-D) approach, in which certain phases might or might not be excluded. Especially phases in the use stage (phase B) are often excluded from the research.

The end-of-life scenario for CLT influences the total carbon footprint of a building. There are four scenarios specific to CLT: (a) reuse, (b) recycle, (c) incineration and (d) landfill. During the growth of a tree, the wood absorbs carbon from the atmosphere. This is called carbon sequestration, or biogenic carbon. This carbon is stored in the wood until it is released at the end of its lifetime. If the CLT element is incinerated or landfilled at the end of the life cycle of the building, the carbon is released in that particular life cycle. If the CLT element is reused or recycled at the end of the life cycle of the building, the carbon is released in a later life cycle. When the end-of-life phase is taken into account, it needs to be specified in the LCA study which end-of-life scenario is used for the CLT element. Since most of the current CLT buildings are the first of their kind and have yet to reach their end of life, reliable assumptions for end-of-life scenarios for CLT are not available (Younis & Dodoo, 2022). A possibility is to compare the carbon footprint when different end-of-life scenarios are used. Darby et al. (2013) compares the carbon footprint of the entire life cycle when five different end-of-life scenarios are used for a 721-ton CLT structure. The results are displayed in Table 2.3:

	Ton CO_2-eq.				
	Re-use	Re-engineer	Incinerate	Incinerate with energy recovery	Landfill
To end of construction	-1100	-1100	-1100	-1100	-1100
Demolition	22	22	22	22	22
Transport	12	12	12	12	12
Manufacture		10			
Transport		12			
Construction	45	45			
Combustion			1192	1192	
Energy from combustion				-628	
Emissions from landfill					1013
Total	-1021	-999	126	-502	-53

Table 2.3: LCA Study on 721-ton CLT Structure with Five Different End-of-Life Scenarios (Darby et al., 2013)

Since the biogenic carbon is released in the end-of-life scenarios of incineration and landfilling, the total carbon footprint is significantly higher than for the other end-of-life scenarios. In the scenarios of incineration with energy recovery, the energy recovery is counted as a negative value. This is included in module D, since it is used in another life cycle. It is counted as a negative value, since future energy usage (thus carbon emission) is prevented. In total, the incinerate scenario is the only scenario leading to a positive value in carbon footprint. The re-use scenario has the highest negative value for the carbon footprint, making it the best carbon footprint scenario.

2.1.2. Existing Literature Using Phases A1-A5

The Paris Proof Commitment uses phases A1-A5 for the assessment of the carbon footprint. Younis & Dodoo included four studies which used these phases for the research. For the calculation of the carbon footprint in these studies, EN 15804+A2 was used.

Study 1: 8-Storey Residential Building

The first study including phases A1-A5 for the carbon footprint calculation compares an 8-storey residential building built in timber with the same building, built in concrete (Chen et al., 2021). The building consists of walls, floors and foundation. For the timber floors, gypsum concrete is added. Both buildings use fiberglass batt, gypsum wallboard and metal studs for the walls. The final results are obtained by dividing the carbon footprint by the total area of the building, which is 3,524 m^2. The input data for the impacts of materials was obtained from an earlier study (Chen, Pierobon, & Ganguly, 2019), survey and interview, while the input data for the electricity and fuel consumption data were derived from the ecoinvent 3 and USEI 2.2 databases. The timber used for the CLT panels was Picea abies, also known as European spruce or Norway spruce. The total carbon footprint per m^2 floor area in the timber building is 221.3 kg CO_2-eq., while for the concrete building this value is 295.9 kg CO_2-eq. This means that when timber is used in the wall, the carbon footprint is reduced by 25%. The contribution of the building assemblies to the total carbon footprint is displayed in Table 2.4:

	Total A1-A5 (kg CO_2-eq./m^2 floor)	
Building assembly	**Timber**	**Concrete**
Floor	125.34	108.15
Foundation	12.87	29.95
Wall	83.09	157.45
Total	221.30	295.55

Table 2.4: Contribution Building Assemblies to Total Carbon Footprint (Chen et al., 2021)

For the timber building, the foundation has the lowest impact on the total carbon footprint: 12.87 kg CO_2-eq./m^2, or 5.82% of the total value. The carbon footprint of the wall assemblies are 83.09 kg, or 37.55% of the total value. The highest contribution to the carbon footprint are the floor assemblies, with a value of 125.34 kg, or 56.64% of the total value. For the concrete building, the wall assemblies contribute most to the carbon footprint (157.45 kg, 53.37%), followed by the floor assemblies (108.15 kg, 36.66%) and the foundation (10.13%).

Study 2: 12-Storey Mixed-Use Building

The second study which uses phases A1-A5 for the research uses a 12-storey mixed-use building (Liang et al., 2020). Similar to the first study, the carbon footprint of a timber variant of the building is compared to a concrete variant. The timber variant of the building uses a combination of CLT and glulam. The building consists of ceiling and roofs, floors, foundations, post and beams and walls. Additional finishing layers are included for these building assemblies. It is not specified which type of timber is used for the CLT and glulam. The results are obtained by dividing the carbon footprint by the floor area, which is 8,360 m^2. The environmental impact data was obtained by the SimaPro 8.5 software and AIE for Building 5.6 software. The resulting carbon footprint per m^2 for the timber structure was calculated to be 193 kg CO_2-eq./m^2, while for the concrete structure this value equals 237 kg CO_2-eq./m^2. This means that using a timber variant leads to a carbon footprint reduction of 18%. The biggest contribution to the total carbon footprint are the floor assemblies for both the timber and concrete building (40% and

45% of the total carbon footprint, respectively). This is followed by the wall assemblies (35% and 38%), post and beams (14% and 8%), foundation (6% and 7%) and ceiling and roofs (5% and 2%).

Study 3: 8-Storey Commercial Building
The third study mentioned in Younis & Dodoo is a 8-floor commercial building, in which once again a timber and concrete variant are compared (Pierobon et al., 2019). The buildings use shear walls, curtain walls, columns, beams, roofs and floors in its design, as well as three below-grade parking spaces. For the research, input data was obtained from other research, as well as the ecoinvent, USLCI and ELCD databases. In the study, a mixture of 55.7% Douglas-fir and 44.3% hem-fir was used for the CLT, which is present in the U.S. Pacific Northwest. The research considers two scenarios for the CLT: fireproofing and charring scenario. In the fireproofing scenario, a gypsum wallboard is used. In the charring scenario, two extra CLT layers are added to the panel, which ensures 2-hour fire protection. The resulting carbon footprint for the CLT building with gypsum equals 333.52 kg CO_2-eq./m^2 of total floor area. For the scenario with charring, this value is 327.53 kg CO_2-eq./m^2. For the reinforced concrete building, the carbon footprint equals 450.36 kg CO_2-eq./m^2. Using CLT instead of concrete results in a reduction of 26% and 27% for the fireproofing and charring scenarios, respectively. Table 2.5 displays the contribution of each building assembly to the total carbon footprint. For the two CLT scenarios, the contribution of the structure, below-grade, lateral system and exterior wall are almost equal and nearly add up to the total carbon footprint. For the concrete building, the structure contributes 45% to the total carbon footprint, while the below-grade, lateral system and exterior wall each contribute nearly the same to the total carbon footprint.

	Contribution to total carbon footprint				
Building	**Structure**	**Below-grade**	**Lateral system**	**Exterior wall**	**Roof**
CLT (gypsum)	26%	21%	25%	26%	2%
CLT (charring)	25%	22%	25%	27%	1%
Concrete	45%	16%	18%	19%	2%

Table 2.5: Contribution Building Elements to Total Carbon Footprint (Pierobon et al., 2019)

Study 4: Three Mixed-Use Buildings
The fourth study which uses phases A1-A5 in the research uses three buildings of 8, 12 and 18 stories, used for residential and commercial purposes (Puettmann et al., 2021). Concrete and steel variants were compared against a timber variant. The buildings use columns, walls, floors and foundations in its design. The carbon footprint is divided by the floor area of the buildings to get the final resulting value. These floor areas are 9,476, 14,214 and 21,321 m^2 for the 8-, 12- and 18-storey building, respectively. The LCA data was obtained by using the SimaPro LCA software, along with the USLCI, ecoinvent and DATASMART 2019 databases. This study distinguishes between regions in the United States, where the energy mixes and timber species are different. These regions are the Pacific Northwest (PNW), Northeast (NE) and Southeast (SE). The results for the carbon footprint per m^2 for the different building systems for the different regions are displayed in Table 2.6:

		Carbon Footprint (kg CO_2-eq./m^2)		
Building System		**PNW**	**NE**	**SE**
8-storey	Mass timber	129.1	106.3	121.7
	Concrete	226.0	213.8	202.8
12-storey	Mass timber	157.3	141.0	158.6
	Concrete	281.4	267.0	253.5
18-storey	Mass timber	167.3	149.1	172.0
	Concrete	238.9	207.4	220.9

Table 2.6: Carbon Footprint of Different Buildings in Three Regions (Puettmann et al., 2021)

The reduction of the carbon footprint when concrete was used instead of timber ranges between 22 and 50%. The difference in carbon footprint between regions are attributed to the regional building code requirements, production differences and electricity grid differences.

As this chapter displayed, there are many differences between existing studies of the carbon footprint of timber structures. Therefore, it is difficult to compare studies. Since currently no literature exist which uses the same location, structure type, life cycle phases, etc. as used in this report, similar research on this topic has not been done before.

3
Methodology

The literature study highlighted several methods for quantifying sustainability. From these methods, the carbon footprint is the one which will be used during this research. There are multiple reasons why this method is the most suitable one. First, the design part of this research only consists of changing a concrete/steel structure into a timber-hybrid structure. The focus is solely on the type and amount of materials used both in the current structure and in the modified structure. Both the MPG and carbon footprint only include these factors into the quantification. BREEAM-NL and LEED also include other factors, such as energy, management and neighbourhood development. Therefore, these last two methods are not suitable for this research.
Second, while both the MPG and carbon footprint can be linked to threshold values, the threshold for MPG is a unitless value which is less tangible than the carbon footprint value, which can be related to the Paris Proof Commitment which uses a temperature rise of 1.5 °C. It is a possibility to separate the MPG into the individual indicators in order to make the results more tangible, but it was decided that the individual indicators in the MPG are not equally important. At the moment at which the research was conducted, global warming was assumed to be the most pressing issue in terms of sustainability. Therefore, the method of carbon footprint is used in this research for quantifying sustainability.

This chapter first describes the methodology used to calculate the carbon footprint of a structure. The second part consists of displaying and describing the thresholds for the carbon footprint, as described in the Paris Proof Commitment.

3.1. Calculating Carbon Footprint

Calculating the carbon footprint of a building requires a stepwise approach. A decision needs to be made on which life cycle phases to be included in the research. The next step is to acquire information on the quantity of materials used in the construction and the carbon footprint per unit material. Furthermore, the information on the carbon footprint needs to be adjusted in order to fit to the project. Finally, the carbon footprint can be calculated with the amount of materials and modified carbon footprint per material. The next part of this chapter will provide a more in-depth explanation of these steps.

Step 1: Decide which life cycle stages are included in the calculation of the carbon footprint
As described in Chapter D, the Life Cycle Assessment (LCA) uses life cycle stages, which are standardized into the following five stages:

- A1-A3: Product stage
- A4-A5: Construction process stage
- B1-B7: Use stage
- C1-C4: End of life stage
- D: Benefits and loads beyond the system boundary

The EPDs, which will be discussed in the next step, also divide the data into these five stages. The manufacturer of the EPD is not required to provide information on every life cycle stage, only the product stage is required. However, this stage is not the only stage to contribute to the total carbon footprint of a building. Therefore, it is required before a project to decide which life cycle stages are included.

There are two objectives in this research. The first objective is to calculate the total carbon footprint of a concrete or steel building and compare this to its timber-hybrid design variants. In order for the carbon footprint calculation to be complete, the total life cycle needs to be included. However, this calculation ends at the end of the life cycle of the construction. This means that module D: 'Benefits and loads beyond the system boundary' is irrelevant, since this includes the benefits or loads of the next life cycle of the material. Therefore, the life cycle stages which are included are modules A-C.

The second objective of the research presented in this thesis is to make the results tangible, so that it is easier to understand and visualize the differences in carbon footprint between design cases. One method for achieving this is to link the carbon footprint to the limits set in the Paris Proof Commitment, which are described at the end of this chapter. These limits describe a global temperature rise until the year 2050, which is an easy concept to grasp. Since the Paris Proof Commitment only considers the carbon footprint until 2050, most buildings which are built between now and 2050 have not met the end of life stage by this time. Therefore, the Paris Proof Commitment only considers modules A1-A5, which are the product and construction process stage. In order to reach both objectives, the research calculates the carbon footprint considering modules A-C, as well as modules A1-A5. This means that two types of results are presented, both completing a different objective.

Step 2: Create a list of materials
In order to calculate the carbon footprint of a building, information about the used materials is required. A list of materials needs to be created, including the type of element and type and amount of material. An example is given in Table 3.1:

Element	Material Type	Quantity	Unit
Floors	Cast in-situ concrete C30/37	1,000	m^3
Walls	Cast in-situ concrete C30/37	500	m^3
Foundation piles	Precast concrete pile 400x400 mm	5,000	m
Windows	PVC Windows, HR++	1,500	m^2
Finishing floor layer	Wooden flooring	200	m^2
Central heating boiler	System boiler	4	

Table 3.1: Example List of Materials

In order to calculate the complete carbon footprint, every single element of the building needs to be included in this list of materials. This not only includes the elements used for the structure of the building, but also the building envelope, installations, etc. It might not be possible to obtain the information on all elements, since this information is not always available. The carbon footprint will then be calculated of the combined elements for which there is available information.

The two main sources of information on the type and amount of materials are models and drawings. Models, such as Revit models, can be used to easily obtain the dimensions of the elements in a building. The downside of using a model is that smaller elements are more easily overlooked. These smaller elements are often better visualized in drawings. Also, depending on the design stage of a structure, models are not always complete or even available at all. If the carbon footprint is calculated for a building which is in an early design stage, only drawings may be available to use.

Step 3: Find an EPD for every material used in design
The Environmental Product Declaration (EPD) is used to obtain data on the carbon footprint per unit of material. EPDs are created by the manufacturers of the product and follow a certain Product Category Rule (PCR). PCRs are used to ensure that the information in EPDs is objective and follows the same set of rules. All EPDs which are used in this research need to follow EN 15804+A2, since this PCR is the current version for construction products. EN 15804+A2 includes the indicator 'Climate change - total' (also named 'GWP-total'), which is used as the indicator for the carbon footprint. The other indicators from EN 15804+A2 are not used in this research, since these focus on other parts of sustainability.

As mentioned in step 1, the data in the EPD is given per life cycle phase. It is a possibility that a material does not emit or take up any CO_2 during a certain phase. The value for this phase is often displayed as MNR (Mode Not Relevant) or zero. Whenever a positive value is displayed, it means that CO_2 is emitted (negative carbon footprint), while a negative value means that CO_2 is taken up by the product during a phase (positive carbon footprint). In Table 3.2, an example is given for an EPD which can be used during the research. The values in this table is per m^3 of CLT.

Results per declared unit - 1 m^3 CLT by Stora Enso							
Indicator	**Unit**	**A1**	**A2**	**A3**	**A1-A3**	**A4**	**A5**
GWP-total	kg CO_2 eq.	-729	8.72	11.6	-708	25.9	5.38

Indicator	**Unit**	**B1-B7**	**C1**	**C2**	**C3**	**C4**	**D**
GWP-total	kg CO_2 eq.	0	4.01	2.05	782	0	-268

Table 3.2: EPD for 1 m^3 of CLT (Stora Enso, 2023)

In this example, the CLT is incinerated at the end of its lifetime. The carbon which was taken up by the CLT in A1 is released in phase C3. Incineration leads to energy being generated. This is included in phase D as a negative value, since this means that there is a prevention of fossil fuels being burned to generate the same amount of energy.

Attention is required in deciding which EPD to use for the calculations, as there are many EPDs available. If possible, the EPD from the supplier of the element which is used in design is used. However, the person performing the calculation might not know who produces the elements in the project, unless this person works as a contractor. Therefore, it is unknown if the EPD which this person uses is from the same manufacturer as the producer of the EPD. This means that an uncertainty is introduced in the calculation.

A method for finding EPDs is by using the library of The International EPD System: `https://environdec.com/library` (The International EPD System, n.d.). The EPDs on these websites are submitted by companies worldwide and tested by third parties. There can be differences in data between companies who produce the same product, as the method of production might be different. Therefore, care needs to be taken to find the EPD of the product which closest corresponds to the product used in design (or the same, if possible). This means that the information about the product itself in the EPD needs to be studied carefully, including the end-of-life scenario, before deciding which EPD to use. It is possible to use EPDs which are not in the library of The International EPD System, as long as EN 15804+A2 is followed and the data is tested by a third party.

Step 4: Modifying data - Phases A4 and C2
Phases A4 and C2 are the transport in the construction process stage and end of life stage, respectively. One of the inputs for the computation of this value is the transportation distance. As the transportation distance is different for each project, it cannot be specified in the EPD and be correct for every single case. Therefore, the EPD uses a fictional value for the distance. This might be a value which is made up by the manufacturer, but it might also be a default value from a PCR. For instance, the PCR for steel, aluminum and iron construction products, EN 17662, states that for the transportation distance from the deconstruction site to the scrap processing plant a value of 100 km needs to be used (NEN, 2021). In order to relate the EPD data from phases A4 and C2 to the project, a realistic value for the transportation

distance in these phases needs to be used.

The information on the distance from the production plant to the building site and from the building site to the end-of-life location is often not available. Especially during the design stages of the construction, this information is not yet known. If this is the case, a realistic scenario needs to be created in order to find the transportation distance. For phase A4, it means that a supplier of the material needs to be found and the distance from the supplier to the building site is to be computed. It is more likely for a supplier to be in the same region as the building site, this needs to be included. For phase C2, the end-of-life location needs to be found and the distance from the building site to this location is to be computed. Again, it is more likely for this location to be in the same region as the building site. The value for A4 and C2 was assumed to change linearly with the transportation distance.

Step 5: Modifying data - Biogenic carbon uptake
The biogenic carbon uptake is the amount of CO_2 which is taken up by biobased products during the growth of the product. This value is taken into account in phase A1 as a negative value. If the product is landfilled or incinerated at the end of the life cycle, the CO_2 is emitted. This emission is included as a positive value in phase C3 and is equal (but positive) to the value in A1. When using the data in the EPD, one needs to take care that this emission in C3 is not included in the EPD if the product is not landfilled or incinerated. If it is, it needs to be set at zero.

Step 6: Modifying data - Match unit in EPD to the unit in the project
It might occur that the unit which is used in the EPD is different than the unit used in the list of materials, stated in step 2. If this is the case, the two units need to be matched. It does not matter whether the units from the EPD or the units from the project are used, but it is best to be consistent. In this project, the units from the EPD were changed to the units used in the project.

Step 7: Calculate the carbon footprint
After the list of materials is obtained and the EPDs are obtained and fit to the current project, the carbon footprint can be calculated. For each material, the amount of material is multiplied by the carbon footprint per life cycle phase. By adding the contribution of each phase, the total carbon footprint per element is obtained. If the contribution of each element is summed, the total carbon footprint of the entire building is calculated. In the Paris Proof Commitment, the carbon footprint depends on the gross floor area as well. Therefore, the carbon footprint needs to be divided by the gross floor area in this scenario.

3.2. Carbon Footprint and the Paris Proof Commitment

The goal of the Paris Proof Commitment is to prevent the global temperature rise from reaching above 1.5 °C by 2050. The Dutch Green Building Council calculated the budget of CO_2 which the building sector in the Netherlands could use before this limit was reached (Spitsbaard & van Leeuwen, 2021). The carbon footprint for each type of building was also calculated, which is shown in Section D.2. These threshold values are once again displayed in Tables 3.3 and 3.4.

Building Type	**Carbon Footprint [kg CO_2 per m^2]**			
	2021	2030	2040	2050
Residential building (single-family home)	200	126	65	45
Residential building (multi-family home)	220	139	83	50
Office	250	158	94	56
Retail real estate	260	164	98	59
Industry	240	151	91	54

Table 3.3: Threshold Values for Paris Proof Buildings, New Building Projects (Spitsbaard & van Leeuwen, 2021)

Building Type	Carbon Footprint [kg CO_2 per m^2]			
	2021	2030	2040	2050
Residential building (single-family home)	100	63	38	23
Residential building (multi-family home)	100	63	38	23
Office	125	79	47	28
Retail real estate	125	79	47	28
Industry	100	63	38	23

Table 3.4: Threshold Values for Paris Proof Buildings, Renovated Building Projects (Spitsbaard & van Leeuwen, 2021)

The Paris Proof Agreement uses the term of embodied carbon, but this is used interchangeably with carbon footprint throughout this report. As mentioned earlier in this chapter, the Paris Proof Commitment only uses the phases A1-A5 in the calculation of the carbon footprint. This is done because the buildings which are currently built will probably not reach its end of life before 2050. One exception which is introduced in this research is when the end of life of a single material is reached before 2050. Since this element is replaced before 2050, the carbon footprint of all life cycle phases need to be included, not only A1-A5.

4 Case Studies

For the research, two case studies are used. These case studies are low- to mid-rise buildings which are actually being built or have been built already. The first case study is called KasseNova aan de Vaart, which is a residential building made out of concrete. The second case study is Apollolaan 171, which is an office building built in steel and concrete. Chapter 3 provides a method to calculate the carbon footprint of a building. This method is used on these two structures, as well as three design variants of both of these structures. In the design variants, groups of concrete and/or steel elements are replaced by timber elements, making the structure a timber-hybrid structure. In order to ensure that the design changes result in new structures which are designs which can actually be built, rather than being concepts, design calculations are performed. The results for these design calculations are covered in this chapter as well.

4.1. Case Study 1: KasseNova aan de Vaart

The first case study is a residential building called KasseNova aan de Vaart (Figure 4.1). The construction of this building started in Q4 of 2023 and is projected to be completed in Q2 of 2025. It is located in 's-Gravenzande, which is part of the municipality of Westland. The main structure consists of concrete floors and walls, with two concrete elevator shafts which contribute to the stability of the building. The structure has seven floors, totalling to a height of 21 metres. The ground floor and basement are used for car and bike parking, as well as serving as an entrance for the users of the building. The floors above the ground floor are used as living space for residents, completed with balconies around the perimeter.

The first case study consists of three design variants for which the carbon footprint is calculated. In these design variants, different concrete elements are replaced by CLT elements:

- Design Variant 1: Concrete floors are replaced by CLT floors
- Design Variant 2: Concrete walls are replaced by CLT walls
- Design Variant 3: Concrete floors and walls are replaced by CLT floors and walls

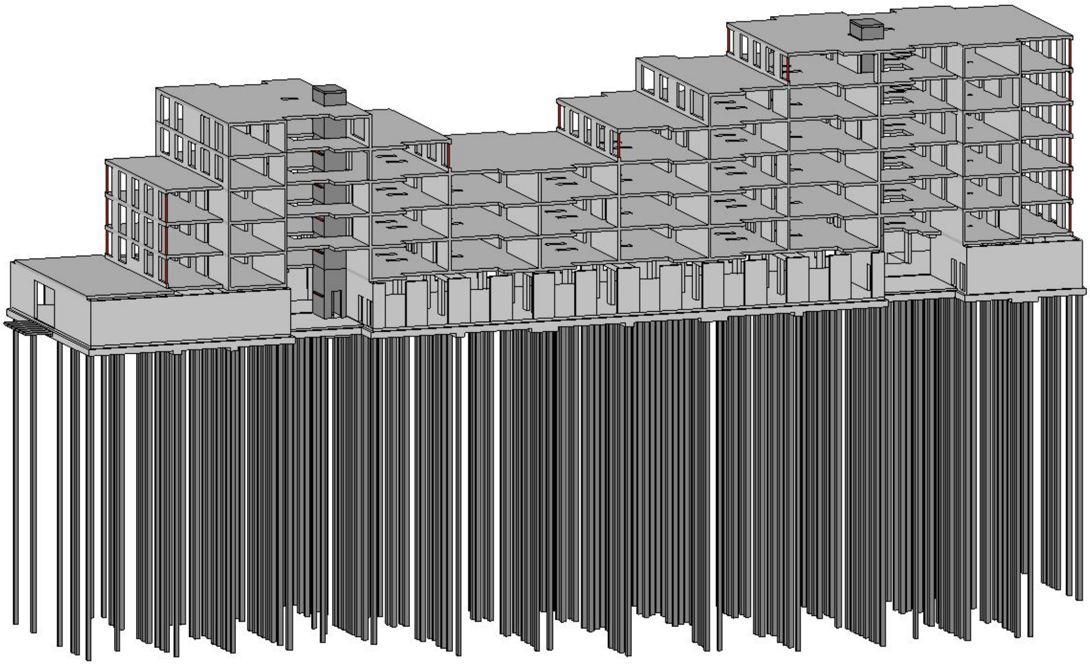

Figure 4.1: KasseNova aan de Vaart

4.1.1. Current Design

The current design of KasseNova aan de Vaart is a concrete design. The cast in-situ concrete floors have a thickness of 280 mm, with exceptions to the ground floor (250 mm) and basement (350 mm). The floors have a span of either 5.4 or 8.1 meter (Figure 4.2). The finishing floor layers consist of a heating and screed layer. The walls are also cast in-situ concrete, with a thickness of 250 mm, again with exceptions to the ground floor (200, 250 and 300 mm) and basement (300 mm). The ground floor has a height of 4.5 m, the six levels on top have a height of 3 m. The structure consists of two cores, which are made of precast concrete walls with a thickness of 200 mm. Around all sides of the building are precast concrete balconies with a thickness of 320 mm. Since there is car parking on the ground floor, meaning that there are columns on this floor to allow for more space. Beams beneath the first floor allow for the loads from the structure above to be distributed along these columns. The foundation consists of beams beneath the ground floor, foundation blocks and foundation piles, which are between 25.90 and 31.10 m in length.

Figure 4.2 displays the floor plan of the third floor of KasseNova aan de Vaart. Most of the floor plans of the other floors in this building are similar to this floor plan.

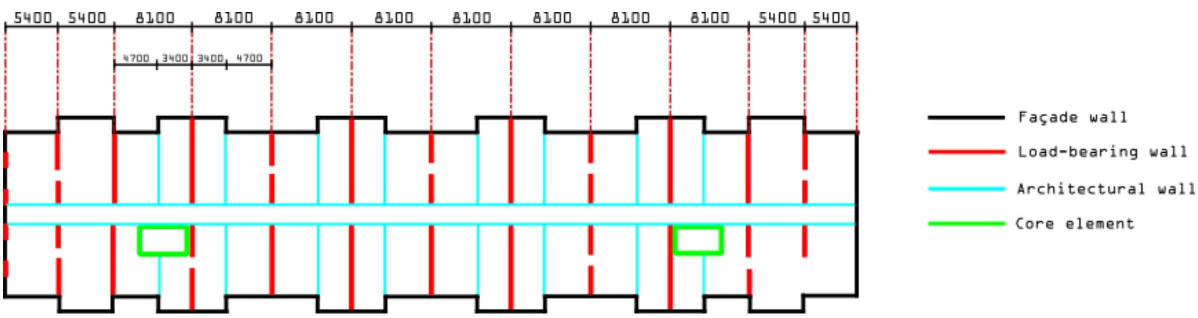

Figure 4.2: Floor Plan KasseNova aan de Vaart - Third Floor

The foundation of the building consists of precast concrete piles with foundation blocks. The piles have cross-sectional dimensions 350x350 or 450x450 mm, as indicated in Figure 4.3. The 350x350 mm piles have a load-bearing capacity of 1400 kN and the 450x450 mm piles 1600 kN.

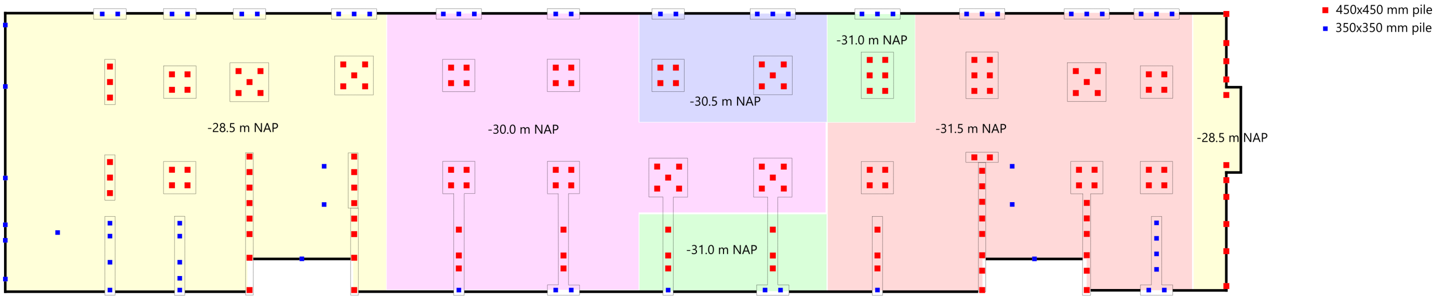

Figure 4.3: Pile Plan - KasseNova aan de Vaart - Current Design

4.1.2. Design Changes

Design Variant 1: CLT Floors

In the first design variant, the concrete floors in the structure are replaced by CLT floors, with the exception of the ground floor and basement. The reason for not replacing the ground floor and basement by CLT elements is that these elements are in contact with the subsurface, which introduces an extra challenge in the design. This challenge is out of the scope of this research. The floor elements which are replaced by CLT floor elements are indicated in red in Figure 4.4.

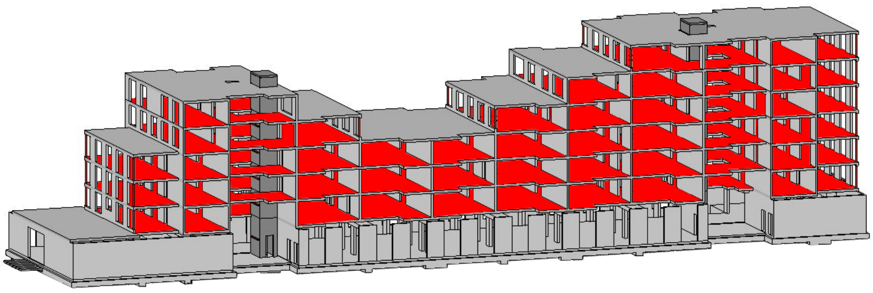

Figure 4.4: Concrete Floors Changed to CLT Floors in Design Variant 1

For consistency purposes, the same type of CLT element is used throughout the entire design. This is a L5s-200 panel with strength C24, which consists of 5 layers of 40 mm each, meaning that the total thickness is 200 mm. The maximum floor span in the current design is 8.1 metres. Figure D.5 displays the maximum span of CLT for different building types. The maximum floor span in this figure is 7.7 m, which means that the floor in KasseNova aan de Vaart cannot be created in CLT as it is. Therefore, the floor plan needs to be modified in order to reduce the maximum floor span. There are two questions which need to be answered before this floor span can be reduced: (1) *How much* does the floor span need to be reduced? (2) *How* can the floor span be reduced?

The first question can be answered in terms of what maximum span is possible. According to Figure D.5, this is 7.7 m. Stora Enso, which is a CLT manufacturer, states that the maximum span of a single-span CLT floor is 7 m (Stora Enso, 2017). KLH Massivholz GmbH, also a CLT manufacturer, similarly states that the maximum span of a CLT floor is 7 m (KLH Massivholz GmbH, 2023). However, to have a span of 7+ meter means that the thickness will be significant. In Figure D.5, for a span width of 7.7 m, a panel thickness of 300 mm is required. The combined thickness of the current floor structure, consisting of concrete and a tacker and screed layer, is equal to 370 mm. The CLT panel will also require finishing layers, such as fibreboard and impact insulation layers, which will further increase the total CLT floor thickness, possibly larger than 370 mm. This means that there is less vertical space in the design variant than in the current design. Therefore, to keep the design requirements intact, the thickness of the CLT floor with its finishing layers should be equal or lower than the thickness of the concrete floor and its finishing layers. A possible combination of finishing layers result in a thickness of 134 mm (this will be discussed later during this chapter), meaning that the maximum possible CLT panel thickness is 230 mm in order to be below the current total floor thickness of 370 mm. The maximum span width of a

CLT panel with thickness 230 mm is 6.8 m (Figure D.5). Therefore, this can be set as the new value to which the maximum floor span needs to be reduced.

In order to answer the question on how the floor span can be reduced, there are several options. The first option is to change the building envelope. For instance, when the building envelope is reduced, the load-bearing walls could be placed closer to each other. An example solution is given in Figure 4.5. In this solution, the maximum span is changed from 8.1 m to 5.5 m.

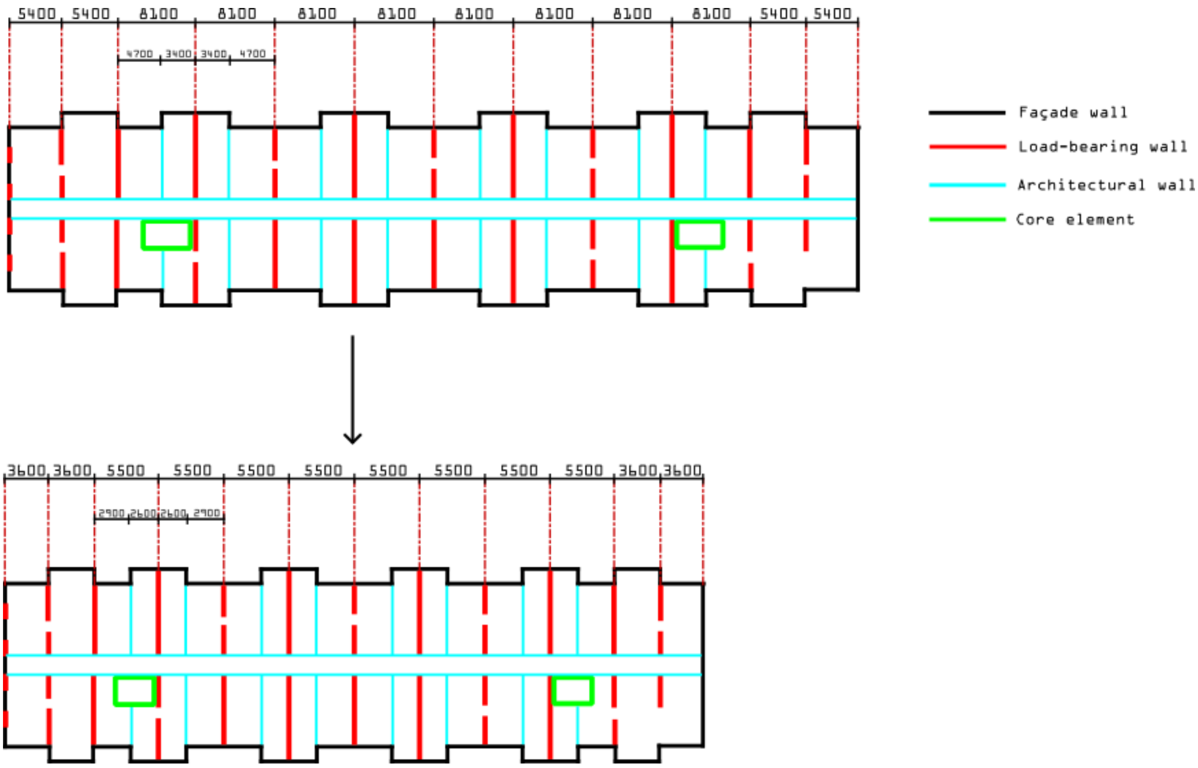

Figure 4.5: Example Solution for Changing Building Envelope to Reduce Floor Span

However, it is also an option to replace architectural walls by load-bearing walls. This is beneficial, as the design requirements are kept intact because the dimensions of the rooms do not change. The wall thickness does increase from 100 mm (architectural wall) to 250 mm (load-bearing wall), but this change has a lower impact than a change in vertical space. Figure 4.6 indicates which architectural walls are replaced by load-bearing walls.

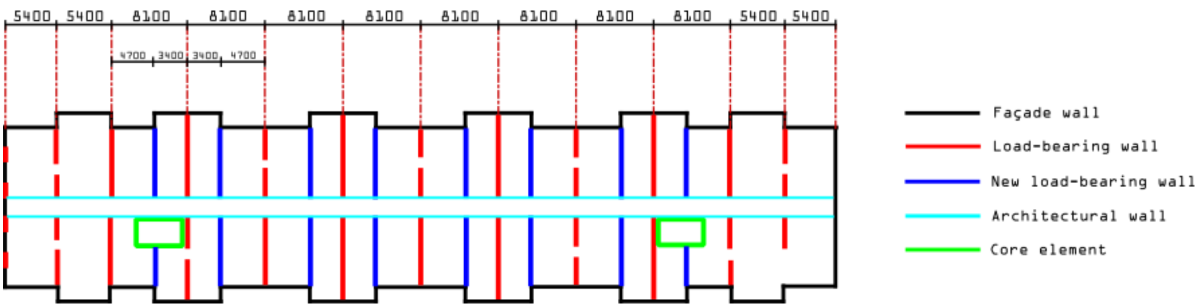

Figure 4.6: Example Solution for Replacing Architectural Walls by Load-Bearing Walls to Reduce Floor Span

While both options for decreasing the maximum floor span are viable options, the second option is the better option. Reducing the building envelope means that the floor area of each living space reduces or the number of living spaces reduces. Either way, the design requirements are not met. Therefore, the second option was chosen as the best possible option in this design variant. For consistency, the new load-bearing walls are the same as the existing load-bearing walls, which are cast in-situ C30/37 concrete and have a thickness of 250 mm. By adding the load-bearing walls, the maximum span of the floors are reduced from 8.1 metres to 5.4 metres.

Figure 4.7 displays what floor structure was used in this design variant. As mentioned earlier, the combined thickness of the floor structure (excluding the CLT slab) is equal to 134 mm.

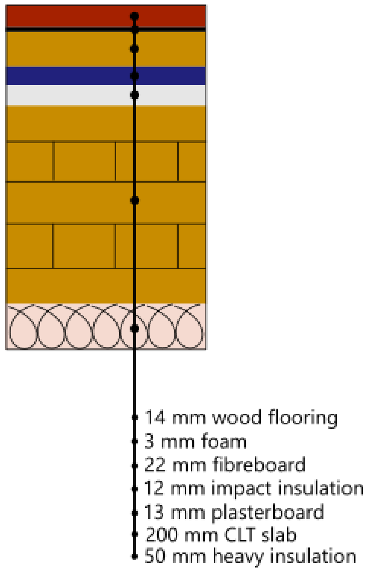

Figure 4.7: Floor Structure of KasseNova aan de Vaart - Design Variant 1

Since timber is used instead of concrete, the total weight of the building decreases. This influences the pile foundation, since the maximum load-bearing capacity of the piles is chosen based on the loads. As explained in Appendix D, There are three methods for adjusting the foundation which will be described: removing/adding piles, decreasing pile dimensions and changing pile type. The only method which will be applied is the removing and adding of piles, while the same type of piles are used as in the current design.

The load on the existing piles decrease, due to the smaller span and lighter weight of the floors. Therefore, several existing piles can be removed. The additional load-bearing walls lead to new foundation piles being added. The pile plan of design variant 1 is displayed in Figure 4.8:

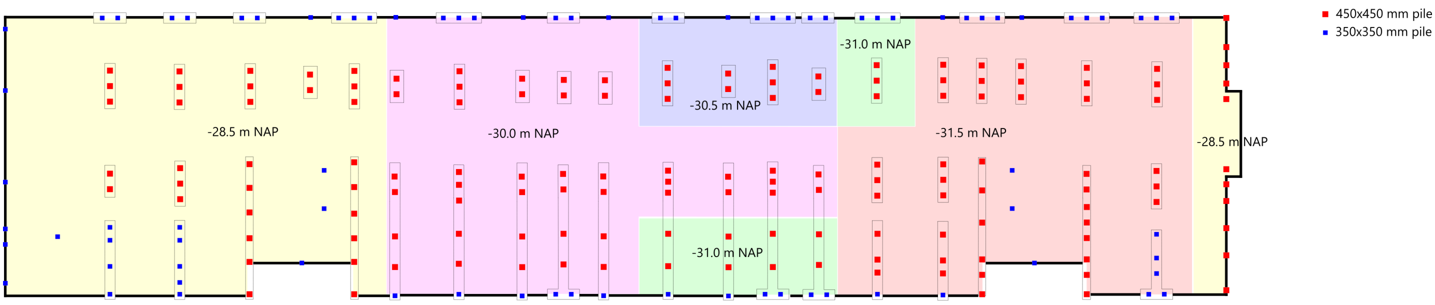

Figure 4.8: Pile Plan - KasseNova aan de Vaart - Design Variant 1

The total number of piles compared to the current design increase by 1.

Design Variant 2: CLT Walls
For the second design variant, the concrete walls in the structure are replaced by CLT walls, with the exception of the walls on the ground floor and the façade walls. The wall elements which were replaced by CLT elements are indicated in Figure 4.9.

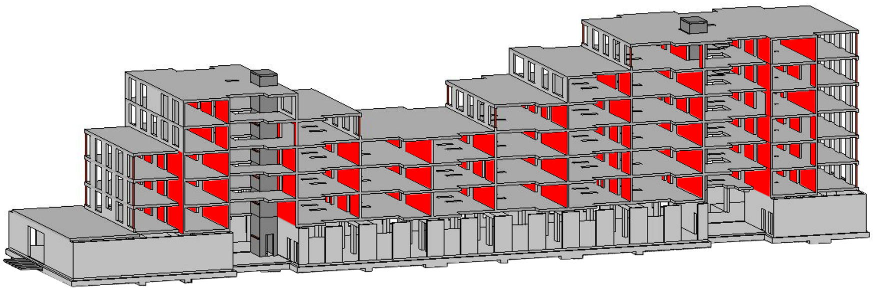

Figure 4.9: Concrete Walls to CLT Walls in Design Variant 2

The CLT panels which are used for the wall design are two C3s-100 panels with strength C24, which are 3-layered panels of 30/40/30 mm. The CLT walls are more lightweight than the present concrete walls, meaning that the concrete floors will be able to take up the loads. Since the walls are becoming more lightweight, the stability needs to be calculated. This is done in a later part of the chapter. Since the material from which the floors are made do not change, there is no need to modify the floor plan.

The CLT wall element is made of an 40 mm thick insulation layer in the middle, two 100 mm CLT panels on both sides and a 15.4 mm thick plasterboard on the outer sides of the wall element (Figure 4.10).

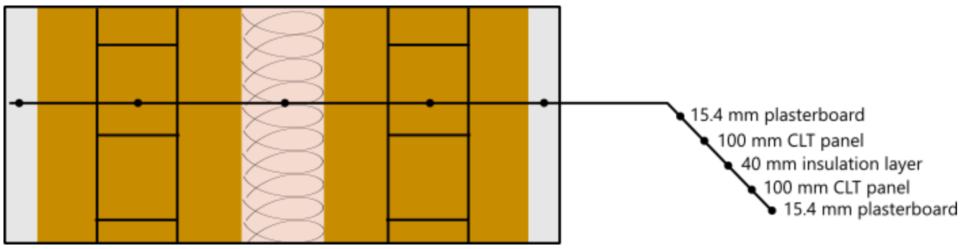

Figure 4.10: Wall Structure of KasseNova aan de Vaart - Design Variant 2

Since the CLT walls are more lightweight than concrete walls, the loads on the foundation decrease. Several existing foundation piles can be removed, as displayed in Figure 4.11.

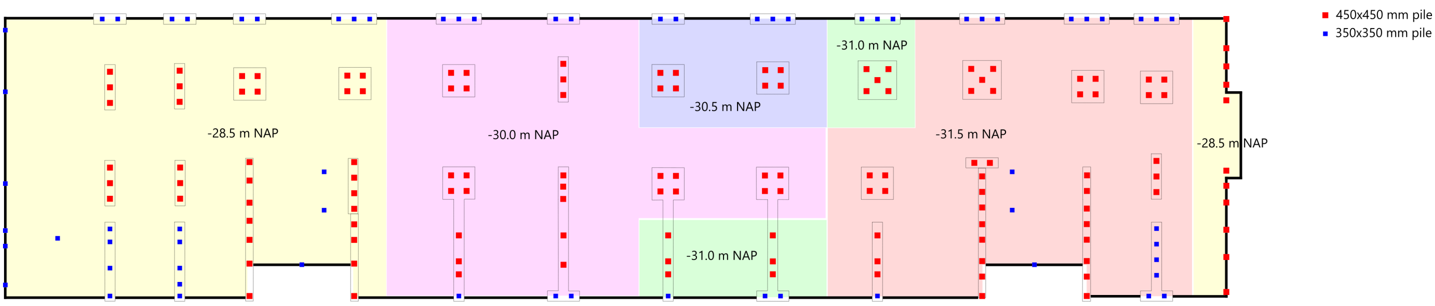

Figure 4.11: Pile Plan - KasseNova aan de Vaart - Design Variant 2

The total number of foundation piles compared to the current design decrease by 30.

Design Variant 3: CLT Floors and Walls
In the third design, both the concrete floors and walls are replaced by CLT walls, with the exceptions of the floors and walls on the ground floor and the façade walls. The elements which are being replaced by CLT elements are indicated in Figure 4.12.

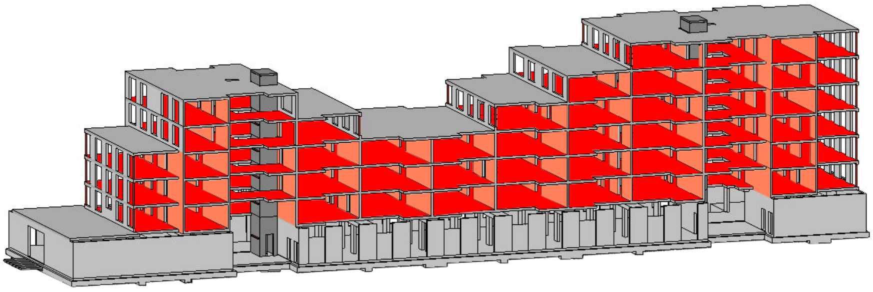

Figure 4.12: Concrete Floors and Walls to CLT Floors and Walls in Design Variant 3

The same CLT floor panel type is used as in the first design variant: L5s-200. Similarly to the first design variant, the floor plan needs to be modified in order to decrease the floor span. This again is done by replacing the architectural walls by load-bearing walls. These newly added load-bearing walls are not made of concrete, such as in Design Variant 1, but of CLT. These are the same CLT walls which are used in the rest of the building, which will be described in the next part of this chapter. The finishing floor layers are displayed in Figure 4.7.

The CLT wall panel consist of two C3s-70 panels. The additional walls due to a change in floor plan are also two C3s-70 panels. The finishing wall layers are displayed in Figure 4.10.

The reduced span and more lightweight material leads to the possibility of several existing foundation piles being removed. The additional load-bearing walls lead to new foundation piles being added. The pile plan is displayed in Figure 4.13:

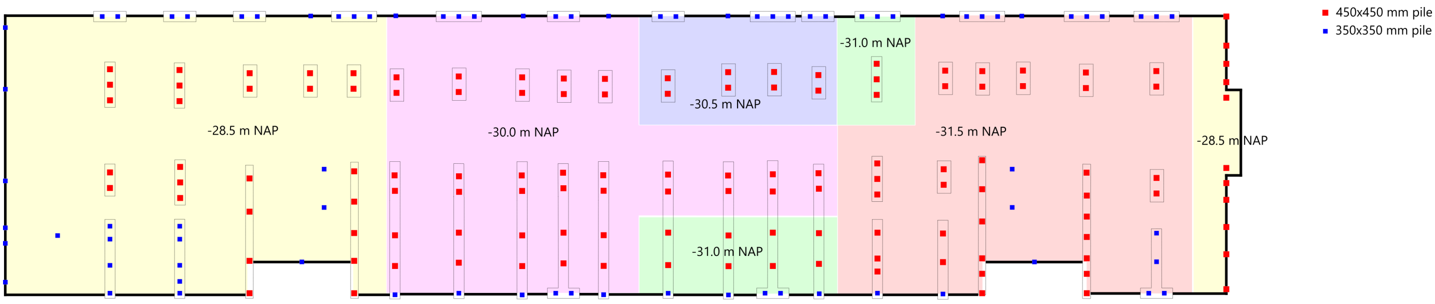

Figure 4.13: Pile Plan - KasseNova aan de Vaart - Design Variant 3

The total number of foundation piles compared to the current design decrease by 21.

4.1.3. Design Calculations

In order to ensure that the changes in design lead to realistic designs, rather than design concepts, calculations need to be performed. These calculations do not only include the strength and stiffness of the building, but also vibrations and fire safety. Timber is a more lightweight material than concrete. In the design variants, there are concrete elements which remain concrete. Since the loads on the remaining concrete decrease, there is no need to recalculate these elements. The only elements for which calculations are done are the CLT elements. The equations which are used are explained in Chapter D.3. This chapter will provide the results of the calculations, but the calculations themselves are described in Chapter C.

Design Variant 1

For design variant 1, where the concrete floors are replaced by CLT floors of type L5s-200, strength C24, the following calculations are performed on the CLT elements:

- Design strength: moment, shear and rolling shear
- Deflection
- Vibrations
- Fire safety

The maximum design moment σ_d, shear force τ_d and rolling shear force $\tau_{Rv,d}$ are compared to the design strengths $f_{m,d}$, $f_{v,d}$ and $f_{Rv,d}$. The results are shown in Table 4.1. The resulting design strengths are well below the design moment and forces, meaning that this member will not fail on moment, shear and rolling shear.

Design Moment Strength $f_{m,d}$	**Design Moment** σ_d	**Calculation**
15.36 MPa	3.67 MPa	$f_{m,d}$: Eq. C.4, σ_d: Eq. C.12

Design Shear Strength $f_{v,d}$	**Design Shear Force** τ_d	**Calculation**
2.56 MPa	0.13 MPa	$f_{v,d}$: Eq. C.5, τ_d: Eq. C.15

Design Rolling Shear Strength $f_{Rv,d}$	**Design Rolling Shear Force** $\tau_{Rv,d}$	**Calculation**
0.90 MPa	0.12 MPa	$f_{Rv,d}$: Eq. C.6, $\tau_{Rv,d}$: Eq. C.18

Table 4.1: Results from Design Calculations of Moments, Shear Force and Rolling Shear Force in CLT

The maximum deflection in the CLT element w_{fin} is compared to the maximum allowed deflection w_{max}. Table 4.2 displays the results from the deflection calculation of the CLT element. The maximum deflection in the CLT floor is slightly below the maximum allowed deflection.

Maximum Allowed Deflection w_{max}	**Maximum Deflection in CLT** w_{fin}	**Calculation**
14.70 mm	13.85 mm	w_{max}: Eq. C.19, w_{fin}: Eq. C.31

Table 4.2: Results from Design Calculations of Deflections in CLT

A number of calculations need to be performed which determines if the CLT floor itself dampens the vibrations sufficiently or if additional damping layers need to be added. The first in this series of calculations is the fundamental frequency f_1. Since humans are sensitive to vibrations below 8 Hz, the value for f_1 should be above 8 Hz. This is the case for the CLT floors in Design Variant 1, as the fundamental frequency is 9.10 Hz (Table 4.3):

Maximum Fundamental Frequency	**Fundamental Frequency** f_1	**Calculation**
8 Hz	9.10 Hz	f_1: Eq. C.33

Table 4.3: Results from Design Calculations of Fundamental Frequency in the CLT Floor

The second calculation for the vibration is the deflection w of the strip due to a point load of 1 kN, which represents a person walking over a strip. This is compared to a maximum value of a, which for the

Netherlands is set at 1 mm/kN. Table 4.4 shows that the deflection over the point load is lower than this value:

Maximum Value a	**Deflection over Point Load** w/F	**Calculation**
1 mm/kN	0.24 mm/kN	w/F: Eq. C.38

Table 4.4: Results from Design Calculations of the Deflection over a Point Load in the CLT Floor

The last vibration calculation is the impulse velocity response v, which determines how disturbing vibrations above 8 Hz are. This is compared against the floor structure quality $v_{max} = b^{(f_1 \xi - 1)}$ (Table 4.5):

Floor Structure Quality v_{max}	**Impulse Velocity Response** v	**Calculation**
0.013	0.0013	v_{max}: Eq. C.40, v: Eq. C.43

Table 4.5: Results from Design Calculations of the Impulse Velocity Response in the CLT Floor

The moment, shear force and rolling shear force is calculated for a fire which lasts 120 minutes. For additional fire protection, a 15.4 mm plasterboard is added. The results are shown in Table 4.6.

Design Moment Strength $f_{m,d,fi}$	**Design Moment** $\sigma_{d,fi}$	**Calculation**
27.60 MPa	6.08 MPa	$f_{m,d,fi}$: Eq. C.53, $\sigma_{d,fi}$: Eq. C.64

Design Shear Strength $f_{v,d,fi}$	**Design Shear Force** $\tau_{d,fi}$	**Calculation**
4.6 MPa	0.17 MPa	$f_{v,d,fi}$: Eq. C.54, $\tau_{d,fi}$: Eq. C.66

Design Rolling Shear Strength $f_{Rv,d,fi}$	**Design Rolling Shear Force** $\tau_{Rv,d,fi}$	**Calculation**
1.61 MPa	0.002 MPa	$f_{Rv,d,fi}$: Eq. C.55, $\tau_{Rv,d,fi}$: Eq. C.68

Table 4.6: Results from Design Calculations of Moments, Shear Force and Rolling Shear Force During Fire with Fibreboard Protection Layer

Design Variant 2

For design variant 2, where the concrete walls are replaced by two CLT walls of type C3s-100, strength C24, the following calculations are performed on the CLT elements:

- Buckling
- Fire safety
- Stability

For the buckling calculation, a unity check was performed, meaning that the combined contribution from the normal load and moment should not exceed 1. The results are displayed in Table 4.7:

Unity Check	**Buckling** $\frac{\sigma_{c,0,d}}{k_{c,y} \cdot f_{c,0,d}} + \frac{\sigma_{m,d}}{f_{m,d}}$	**Calculation**
1	0.67	Eq. C.82

Table 4.7: Results from Unity Check of Buckling CLT Wall

The fire safety for 60 minutes was tested. Another buckling calculation was performed with the reduced cross section, using the loads and resistances under fire condition. The results are displayed in Table 4.8:

Unity Check	Buckling $\frac{\sigma_{c,fi}}{k_{c,fi} \cdot f_{c,fi}} + \frac{\sigma_{m,fi}}{f_{m,fi}}$	Calculation
1	0.57	Eq. C.89

Table 4.8: Results from Unity Check of Buckling CLT Wall after a 60-Minute Fire

For the stability of the building, a calculation was performed to explore if there is tension in the foundation piles. The calculations which are performed are given in Appendix C. It was found that in one of the foundation piles underneath wall 11 there is tension (-335 kN). A possible solution is to place a tension pile underneath this foundation block.

Design Variant 3
For the third design variant, the CLT floors have the same design calculations as in design variant 1. The walls are different than in design variant 2, since the two C3s-70 panels are used instead of C3s-100. A buckling calculation under fire conditions was performed. The result is shown in Table 4.9.

Unity Check	Buckling $\frac{\sigma_{c,fi}}{k_{c,fi} \cdot f_{c,fi}} + \frac{\sigma_{m,fi}}{f_{m,fi}}$	Calculation
1	0.29	Eq. C.95

Table 4.9: Results from Unity Check of Buckling CLT Wall after a 60-Minute Fire

4.2. Case Study 2: Apollolaan 171

The second case study is an office building on the Apollolaan 171 in Amsterdam (Figures 4.14 and 4.15). This is an existing building in which all but the basement is demolished and rebuilt. Apollolaan 171 has a total of six floors, as well as a parking garage in the basement. The main structure consists of steel columns and beams, with the floors being made of concrete. The elevator shafts and stairwells are present in a steel structure consisting of steel columns, beams and crosses. The building is made of two parts which are connected at a right angle at the end of the two parts. The irregular floor plan on each level creates steps in the building.

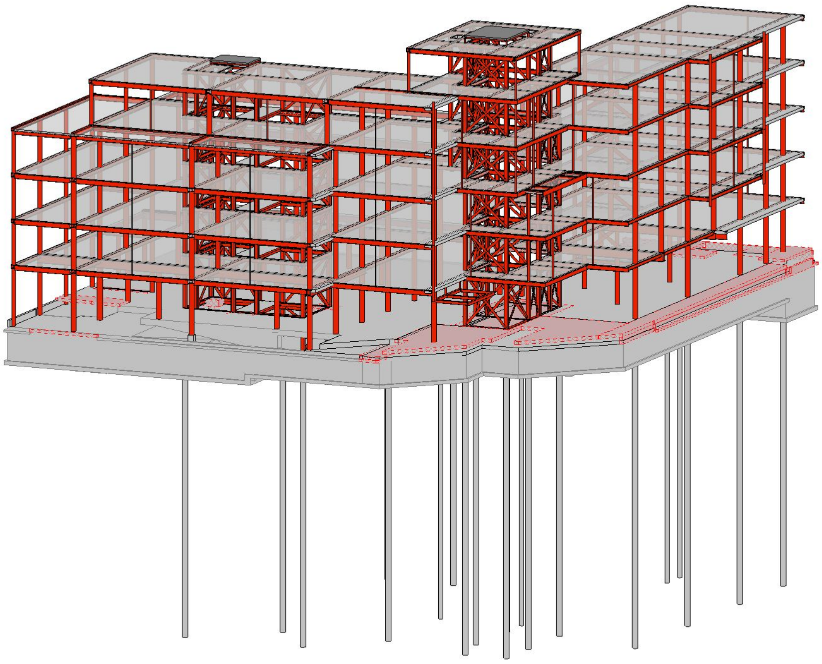

Figure 4.14: Apollolaan 171

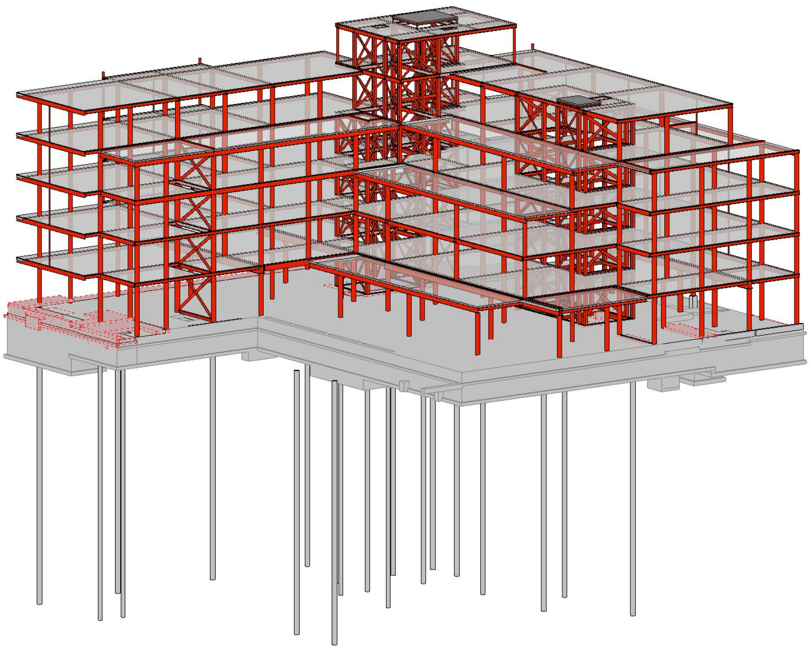

Figure 4.15: Apollolaan 171

The second case study consists of three design variants for which the carbon footprint is calculated, as well as the current design. In these design variants, different different steel and concrete elements are replaced by timber elements:

- Design Variant 1: Steel columns are replaced by glulam columns
- Design Variant 2: Concrete floors are replaced by CLT floors and steel beams are replaced by glulam beams

- Design Variant 3: Steel columns and beams and concrete floors are replaced by glulam columns and beams and CLT floors

The design variants start with a description of which timber element is used, along with any necessary modifications to the existing design. In order to verify that this design is feasible, the calculations which have been discussed in Chapter D.3 are performed. The last step is to calculate the value for the carbon footprint of the entire structure.

4.2.1. Current Design

The current design of Apollolaan 171 is a hybrid steel-concrete design. The floors consist of a hollow core structure with a thickness of 260 mm, as well as a pressure layer of 60 mm. The columns are a combination of circular and rectangular steel tubes, as well as steel H-profiles, with a diameter or width between 300 and 400 mm. These rectangular steel tubes and steel H-profiles are also present in the cores of the building, with steel beams of various sizes in the steel crosses. The steel profiles which are used for beams in the rest of the building are HEA, HEB, HEM, IPE, O- and Top Hat Q-profiles. The basement consists of concrete floors and walls, as well as foundation piles. This basement was part of the existing structure before all top floors were demolished. All steel elements have strength S355, while the concrete hollow floor slab has concrete strength C55/67.

Figure 4.16 displays the floor plan of the first floor of Apollolaan 171. Most of the floor plans of the other floors in this building are similar to this floor plan.

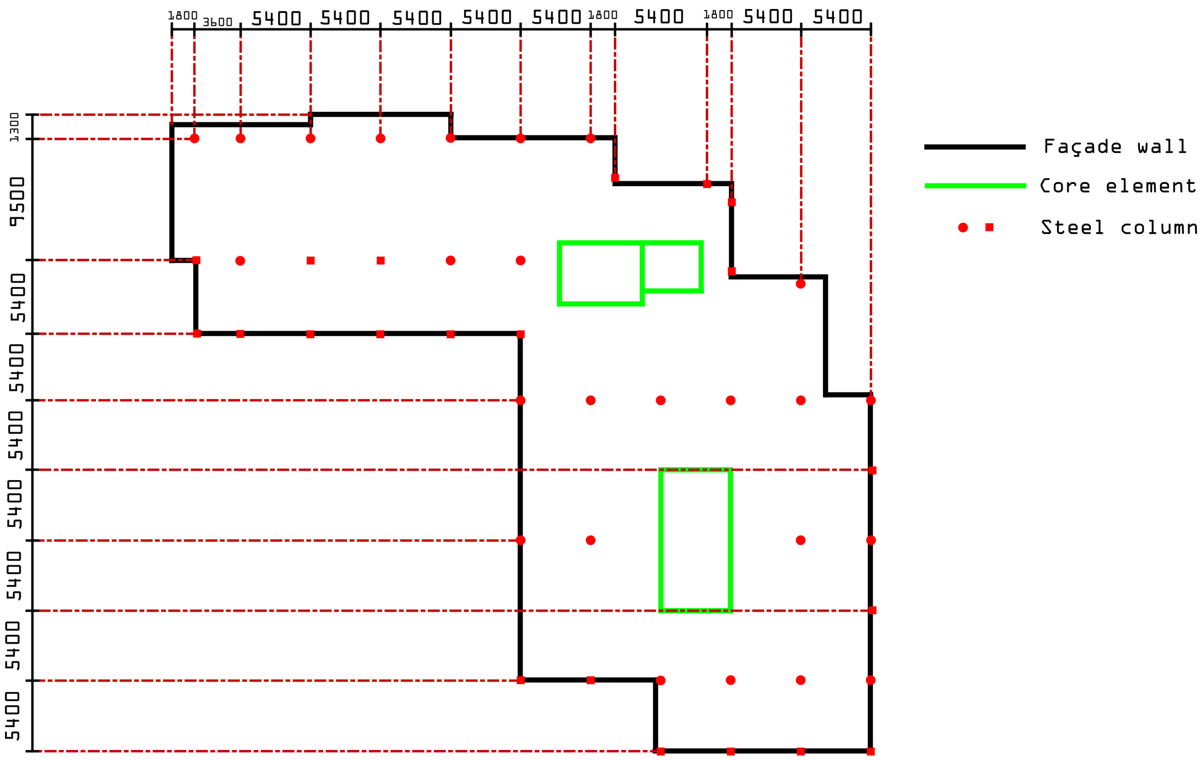

Figure 4.16: Floor Plan Apollolaan 171 - First Floor

4.2.2. Design Changes

Design Variant 1: Glulam Columns

In the first design variant of Apollolaan 171, the steel columns are replaced by glulam columns. The columns which remain steel columns are the core elements, as this will introduce additional challenges which are out of the scope of this research. The columns which are replaced by glulam elements are indicated in blue in Figure 4.17.

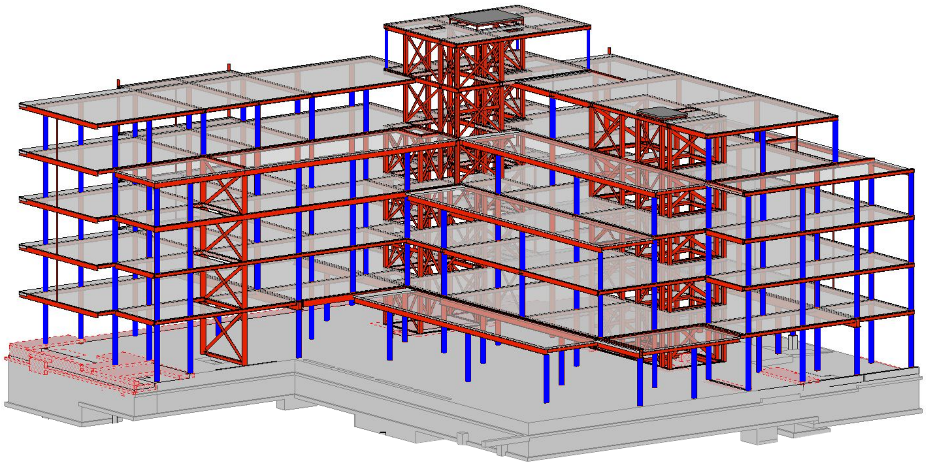

Figure 4.17: Changed Elements in Design Variant 1

For consistency purposes, the same glulam columns were used throughout the entire building: GL24h with dimensions 400 by 400 mm. No modifications to the floor plan are necessary.

Design Variant 2: CLT Floors and Glulam Beams
In the second design variant, the concrete hollow core slab floor with pressure layer is replaced by CLT floors and the steel beams supporting these floors are replaced by glulam beams. The only exceptions are the floors and beams which function as a roof structure and the floors on the ground floor, these elements will not be changed. The floors which will be replaced are indicated in Figure 4.18 in dark blue. The replaced beams are indicated in light blue.

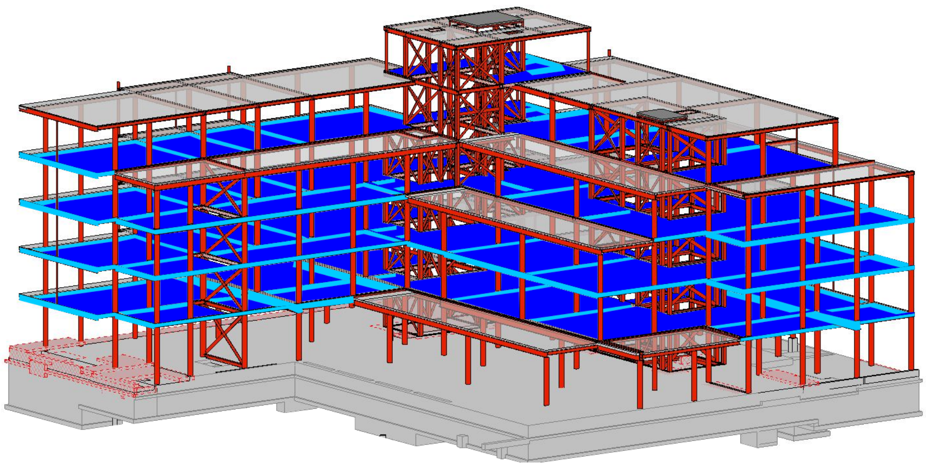

Figure 4.18: Changed Elements in Design Variant 2

The maximum floor span in the current design equals 10.8 m, which cannot be bridged by a CLT element. Therefore, modifications to the floor plan will be needed. By adding the columns indicated in 4.19, this floor span is reduced to 5.4 m. Most of the existing columns are circular steel tubes, therefore the decision was made to choose the same profile for the additional columns. The same CLT floors are used throughout the building: L5s-200 with strength C24, consisting of 5 layers of 40 mm thickness each. The finishing layers consist of plasterboard, foam and an insulation layer, as indicated in Figure 4.20. The glulam beams which are used are of type GL24h with dimensions 400 by 320 mm.

The pressure layer in the current design distributes the horizontal loads to the core of the structure. Since this layer is being replaced, the CLT needs to be able to transfer the horizontal loads. This is one of the properties of CLT, due to the gluing of the layers. Therefore, no additional layer is necessary which can distribute the horizontal loads.

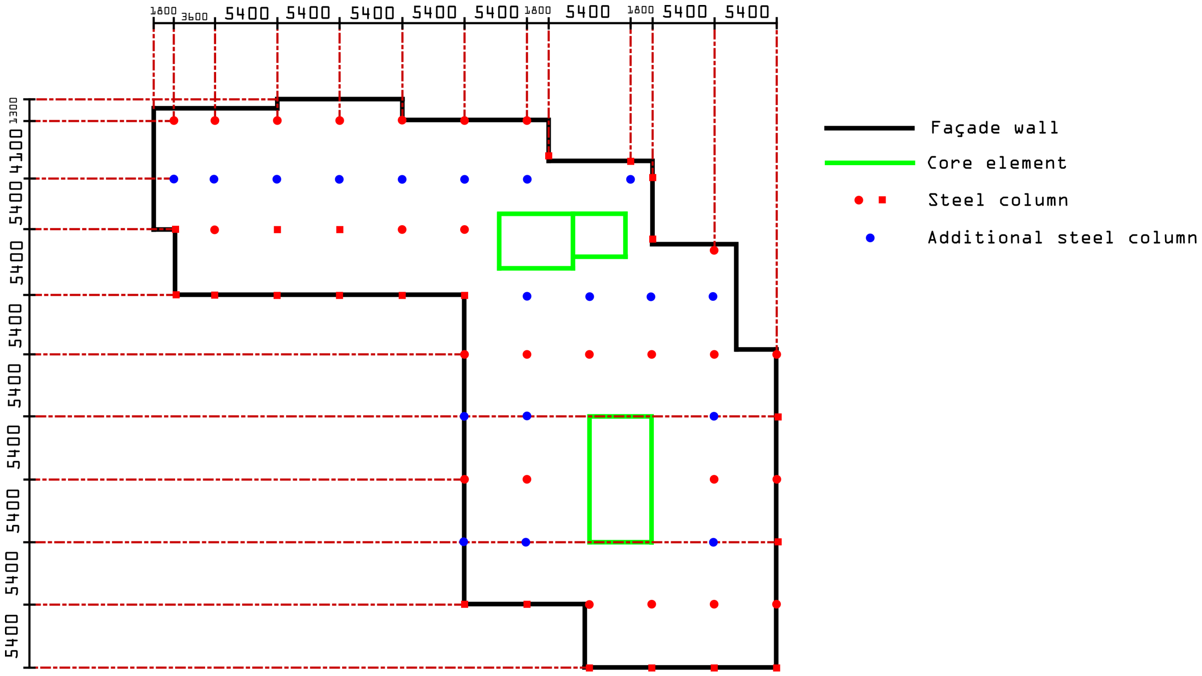

Figure 4.19: Floor Plan Apollolaan 171 with Additional Columns - First Floor

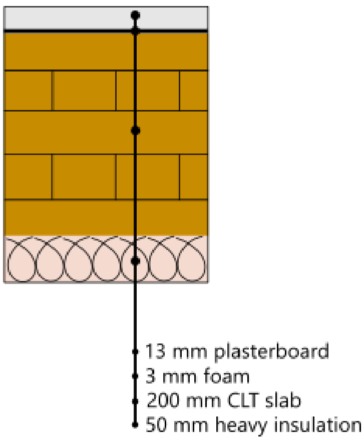

Figure 4.20: Floor Structure of Apollolaan 171

Design Variant 3: Glulam Columns and Beams and CLT Floors

The third design variant combines the design changes from the previous two design variants: the steel columns are replaced by glulam columns, the concrete hollow core slab floors are replaced by CLT floors and the steel beams supporting the floors are replaced by glulam beams. The replaced elements are indicated in Figure 4.21.

Similar to design variant 2, the maximum floor span should be reduced. The same modification is performed: additional columns are added, as indicated in Figure 4.19. These columns will not be steel columns, but glulam. For consistency purposes, the same glulam columns of GL24h of dimensions 400 by 400 mm are used throughout the entire building. The floors which are used are L5s-200, with strength C24. The finishing layers, indicated in Figure 4.20 are once again the same as in the second design variant. The glulam beams which are used are type GL24h beams with dimensions 400 by 320 mm.

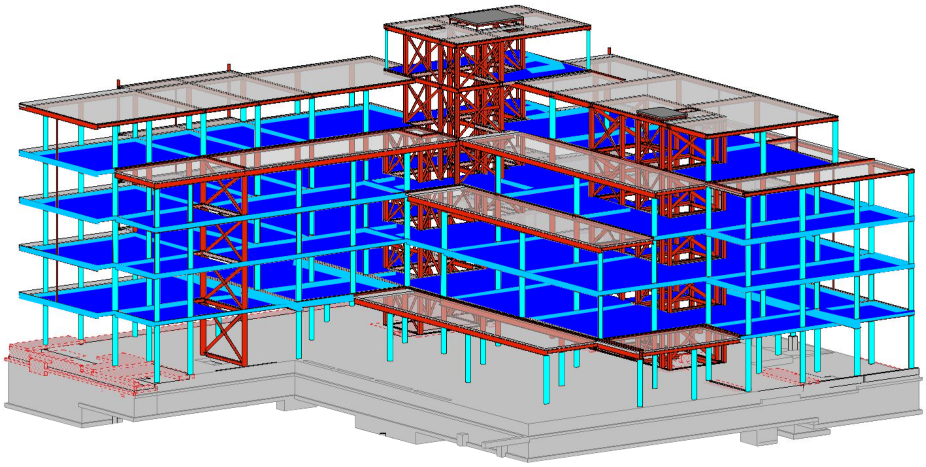

Figure 4.21: Changed Elements in Design Variant 3

4.2.3. Design Calculations

Design Variant 1

In the first design variant, steel columns are replaced by glulam columns. A buckling calculation is performed, for which the results are displayed in Table 4.10:

Unity Check	Buckling $\frac{\sigma_{c,0,d}}{k_{c,y} \cdot f_{c,0,d}} + \frac{\sigma_{m,d}}{f_{m,d}}$	Calculation
1	0.85	Eq. C.102

Table 4.10: Results from Unity Check of Buckling Glulam Column

Design Variant 2

In the second design variant, concrete floors are replaced by CLT floors and the steel beams supporting the floors are replaced by glulam beams. For the CLT floors, the same calculations as in KasseNova aan de Vaart are performed, with the results being shown in Tables 4.11 - 4.14.

Design Moment Strength $f_{m,d}$	Design Moment σ_d	Calculation
15.36 MPa	4.60 MPa	$f_{m,d}$: Eq. C.4, σ_d: Eq. C.103

Design Shear Strength $f_{v,d}$	Design Shear Force τ_d	Calculation
2.56 MPa	0.17 MPa	$f_{v,d}$: Eq. C.5, τ_d: Eq. C.104

Design Rolling Shear Strength $f_{Rv,d}$	Design Rolling Shear Force $\tau_{Rv,d}$	Calculation
0.90 MPa	0.16 MPa	$f_{Rv,d}$: Eq. C.6, $\tau_{Rv,d}$: Eq. C.105

Table 4.11: Results from Design Calculations of Moments, Shear Force and Rolling Shear Force in CLT

Maximum Allowed Deflection w_{max}	Maximum Deflection in CLT w_{fin}	Calculation
16.60 mm	14.06 mm	w_{max}: Eq. C.106, w_{fin}: Eq. C.110

Table 4.12: Results from Design Calculations of Deflections in CLT

Maximum Fundamental Frequency	Fundamental Frequency f_1	Calculation
8 Hz	8.97 Hz	f_1: Eq. C.111

Maximum Value a	Deflection over Point Load w/F	Calculation
1 mm/kN	0.85 mm/kN	w/F: Eq. C.112

Floor Structure Quality v_{max}	Impulse Velocity Response v	Calculation
0.025	0.0024	v_{max}: Eq. C.113, v: Eq. C.114

Table 4.13: Results from Design Calculations of Vibrations in CLT

Design Moment Strength $f_{m,d,fi}$	Design Moment $\sigma_{d,fi}$	Calculation
27.60 MPa	2.95 MPa	$f_{m,d,fi}$: Eq. C.53, $\sigma_{d,fi}$: Eq. C.115

Design Shear Strength $f_{v,d,fi}$	Design Shear Force $\tau_{d,fi}$	Calculation
4.6 MPa	0.094 MPa	$f_{v,d,fi}$: Eq. C.54, $\tau_{d,fi}$: Eq. C.116

Design Rolling Shear Strength $f_{Rv,d,fi}$	Design Rolling Shear Force $\tau_{Rv,d,fi}$	Calculation
1.61 MPa	0.03 MPa	$f_{Rv,d,fi}$: Eq. C.55, $\tau_{Rv,d,fi}$: Eq. C.117

Table 4.14: Results from Design Calculations of Moments, Shear Force and Rolling Shear Force During Fire with Fibreboard Protection Layer

Design Variant 3

Design variant 3 includes replacement of steel columns and beams to glulam columns and beams and concrete floors to CLT floors. Since the same elements are used as in the first and second design variant, it was assumed that these elements would have the same, or an even lower, value for the unity checks. Therefore, no design calculations were performed specifically for this design variant.

5

Results

Chapter 3 describes the methodology which was used in this project to calculate the carbon footprint of a building. Chapter 4 gives a description of the current design and the design variants of both case studies. The information from these chapters was used to calculate the carbon footprint of the current structure and design variants of KasseNova aan de Vaart and Apollolaan 171. The results of these calculations are described in this chapter. This chapter is divided into the two case studies. For each case study, two different sets of phases are used: (1) LCA Phases A-C are used, (2) LCA Phases A1-A5 are used (Paris Proof). Phases A-C are considered to be the "true" scenario, since it considers the carbon footprint over the entire life cycle. For these phases, two end-of-life scenarios are used for CLT elements: recycling and incinerating. In the case that the CLT is incinerated, the carbon which was stored in the timber is released in phase C3.

Phases A1-A5 are included in this research as well, since it can be linked to global temperature rise. Part of this research was for the average person to be able to understand the results from this project, for which the Paris Proof Agreement is more suitable to be used.

5.1. Case Study 1: KasseNova aan de Vaart

For KasseNova aan de Vaart, a total of three design variants were used:

1. Design Variant 1: Concrete floors replaced by CLT floors (exception for ground floor)
2. Design Variant 2: Concrete walls replaced by CLT walls (exception for ground floor walls and façade walls)
3. Design Variant 3: Concrete floors and walls replaced by CLT floors and walls (exception for ground floor and façade walls)

These carbon footprint results of these design variants, as well as the current design, are described in this subchapter. The first part of this subchapter includes the results from LCA Phases A-C, with the second part consisting of the results from LCA Phases A1-A5.

5.1.1. Phases A-C

For the calculation of the carbon footprint, including Phases A-C, the following modifications of the EPDs were performed to fit the input values to the current project:

1. Phase A4 (Transport from construction to building site): Modify the transportation distance to a realistic transportation distance. The value in the EPD changes linearly with distance.
2. Phase C2 (Transport from building site to demolition/recycling plant): Modify the transportation distance to a realistic transportation distance. The value in the EPD changes linearly with distance.
3. Match units used in EPD with units used in design.

4. For reinforcement steel: Phase C is missing in the used EPD. The value for this phase was obtained from a similar EPD.
5. For concrete products: a singular value was used for Phase C1 (Deconstruction), since it was assumed that all concrete products are deconstructed by the same type of machinery.
6. For CLT floors and walls: In the case that CLT is recycled, the emission of CO_2 in Phase C3 (Waste processing) is set to zero.

The calculations which were performed for these modifications can be found in Appendix B. The resulting carbon footprint values per phase for the current design are displayed in Figure 5.1. The C30/37 concrete in this design contains a variability, which results from using different C30/37 concrete EPDs.

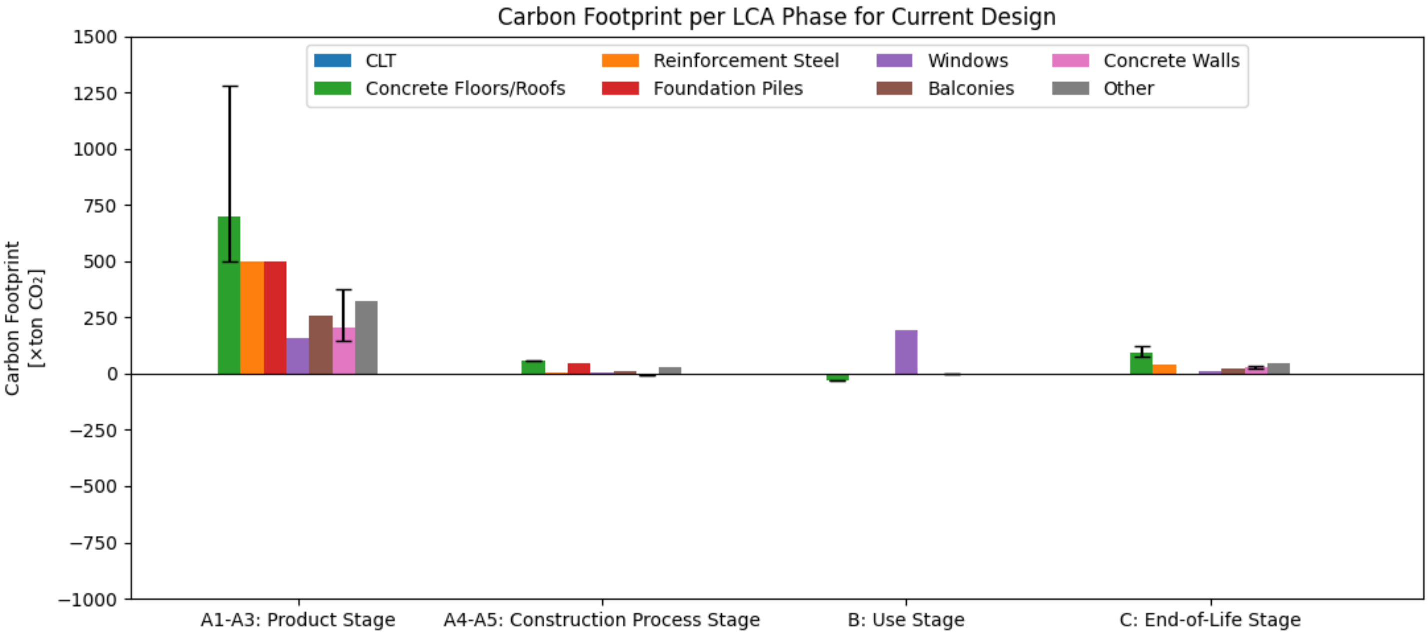

Figure 5.1: Carbon Footprint per LCA Phase for Current Design KasseNova aan de Vaart

The carbon footprint of the current design of KasseNova aan de Vaart is 3,144,547 kg CO_2-equivalent. The largest contributor to these emissions are the concrete floors and roofs, with a carbon footprint of 822,113 kg CO_2-equivalent. The reinforcement steel in the cast in-situ concrete, the foundation piles and windows are among the largest contributors to the concrete emissions as well, with a carbon footprint of 538,332, 495,792 and 364,111 kg CO_2-equivalent for these element types respectively.

In the first design variant, the concrete floors are replaced by CLT floors, with the exception of the floors on the ground floor. The resulting carbon footprint values are displayed in Figure 5.2 for both scenarios. For this design variant, the carbon footprint of the CLT is calculated with a variety of EPDs. This leads to a variance in the results.

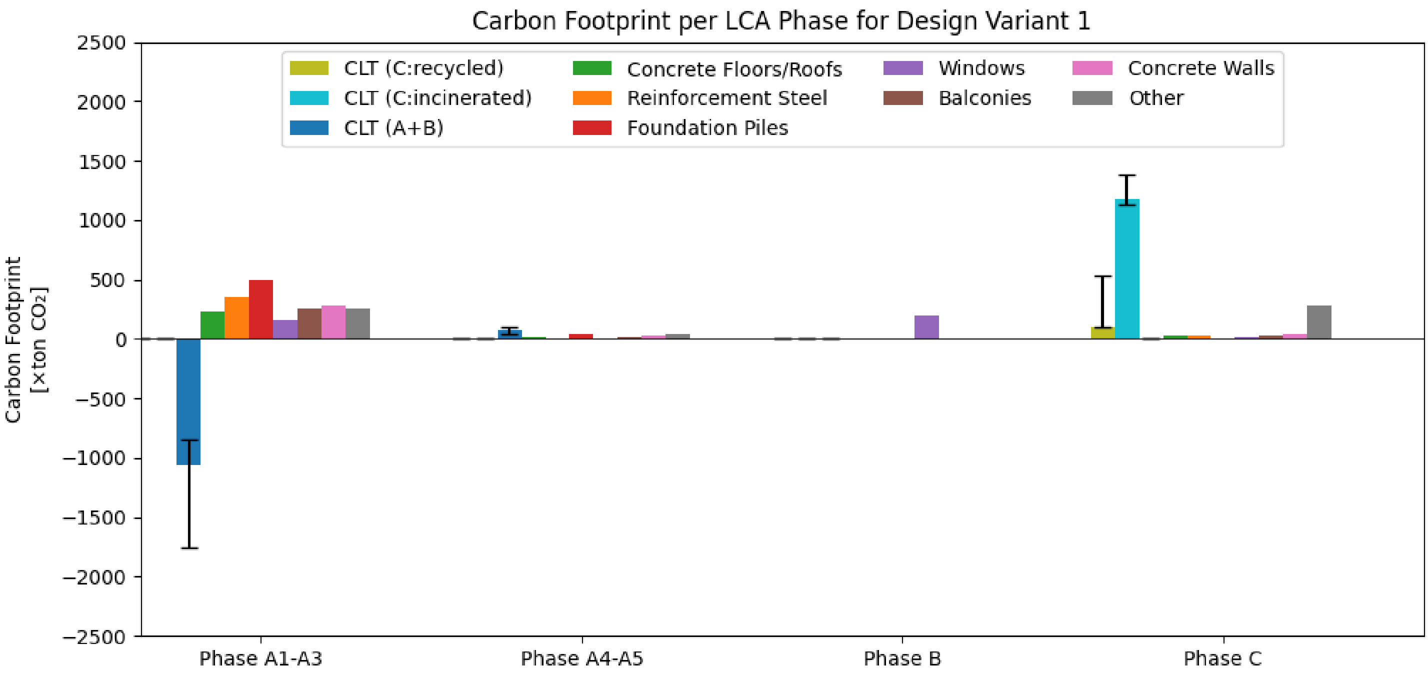

Figure 5.2: Carbon Footprint per LCA Phase for Design Variant 1 of KasseNova aan de Vaart

The end-of-life scenario of the CLT floors impacts the total carbon footprint of the building: 1,814,772 kg CO_2-equivalent when the CLT is recycled, 2,896,385 kg CO_2-equivalent when the CLT is incinerated. The CLT floors have a carbon footprint of -887,278 kg CO_2-equivalent when it is recycled at the end of life, meaning that it will take up more carbon than it will emit over its entire lifespan. When the CLT floors are incinerated at the end of life, this value equals 194,336 kg CO_2-equivalent, meaning that the material will emit more carbon than it will take up over its entire lifespan.

The concrete floors and roofs, which for the current design had the largest carbon footprint of all elements (822,113 kg CO_2-equivalent), now only have a carbon footprint of 269,170 kg CO_2-equivalent. The largest negative contributor to the total carbon footprint for Design Variant 1 are the foundation piles (495,792 kg CO_2-equivalent), followed by the reinforcement steel (381,621 kg CO_2-equivalent) and the windows (364,111 kg CO_2-equivalent).

Similar as in the current design, the Product Stage has the largest contribution in many of the elements. For the CLT, the end-of-life emissions are hugely dependent on the scenario. For the recycling scenario, the carbon footprint in Phase C is 99.0 ton CO_2-eq. This is 1180.6 ton for the incineration scenario.

In the second design variant, the concrete load-bearing walls are replaced by CLT walls, with the exception of the walls on the first floor and the façade walls. The resulting carbon footprint values are displayed in Figure 5.3 for both scenarios. Similar to design variant 1, the variance in results for the CLT elements are due to inputs from different CLT EPDs.

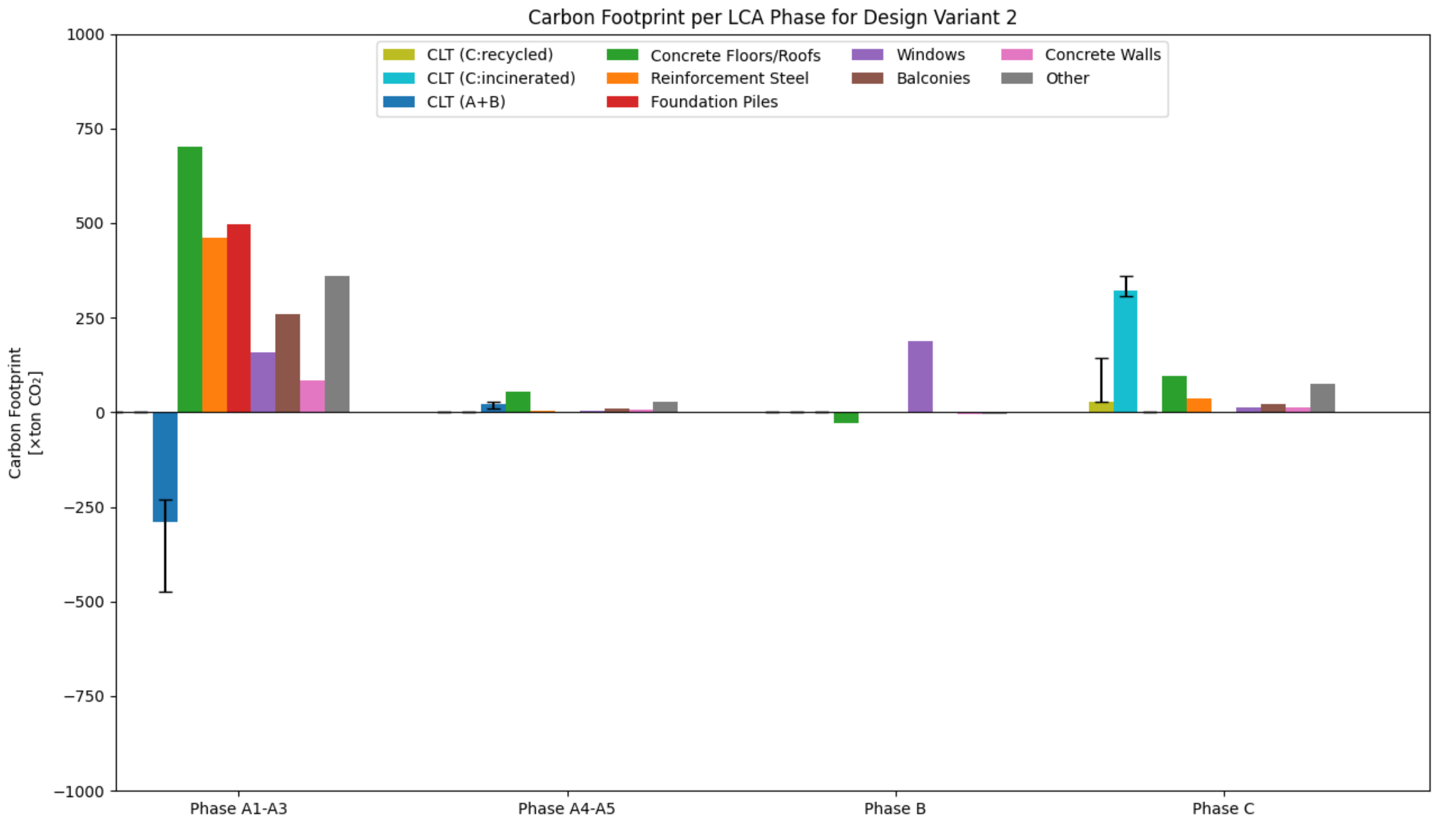

Figure 5.3: Carbon Footprint per LCA Phase for Design Variant 2 of KasseNova aan de Vaart

Similar to Design Variant 1, recycling the CLT panels leads to a lower total carbon footprint than incinerating the CLT panels. However, the differences between the two scenarios and between the current design are smaller than in the previous design variant. The carbon footprint of 3,144,547 kg CO_2-equivalent in the current design is decreased to 2,788,936 kg CO_2-equivalent for the CLT-recycling scenario and 3,083,252 kg CO_2-equivalent for the CLT-incinerating scenario. In the recycling scenario, the CLT panels have a positive impact on the carbon footprint: -241,436 kg CO_2-equivalent. This is different for the incinerating scenario, in which the carbon footprint of the CLT panels are 52,880 kg CO_2-equivalent.

The largest negative contribution to the carbon footprint are the concrete floors and roofs, which have a total impact of 822,113 kg CO_2-equivalent on the carbon footprint. This is followed by the reinforcement steel in the cast in-situ concrete, the foundation piles and the windows, which have a carbon footprint of 498,965, 495,792 and 364,111 kg CO_2-equivalent, respectively.

In the third design variant, both the concrete floors and walls are replaced by CLT floors and walls. The resulting carbon footprint values are displayed in Figure 5.4, including both scenarios.

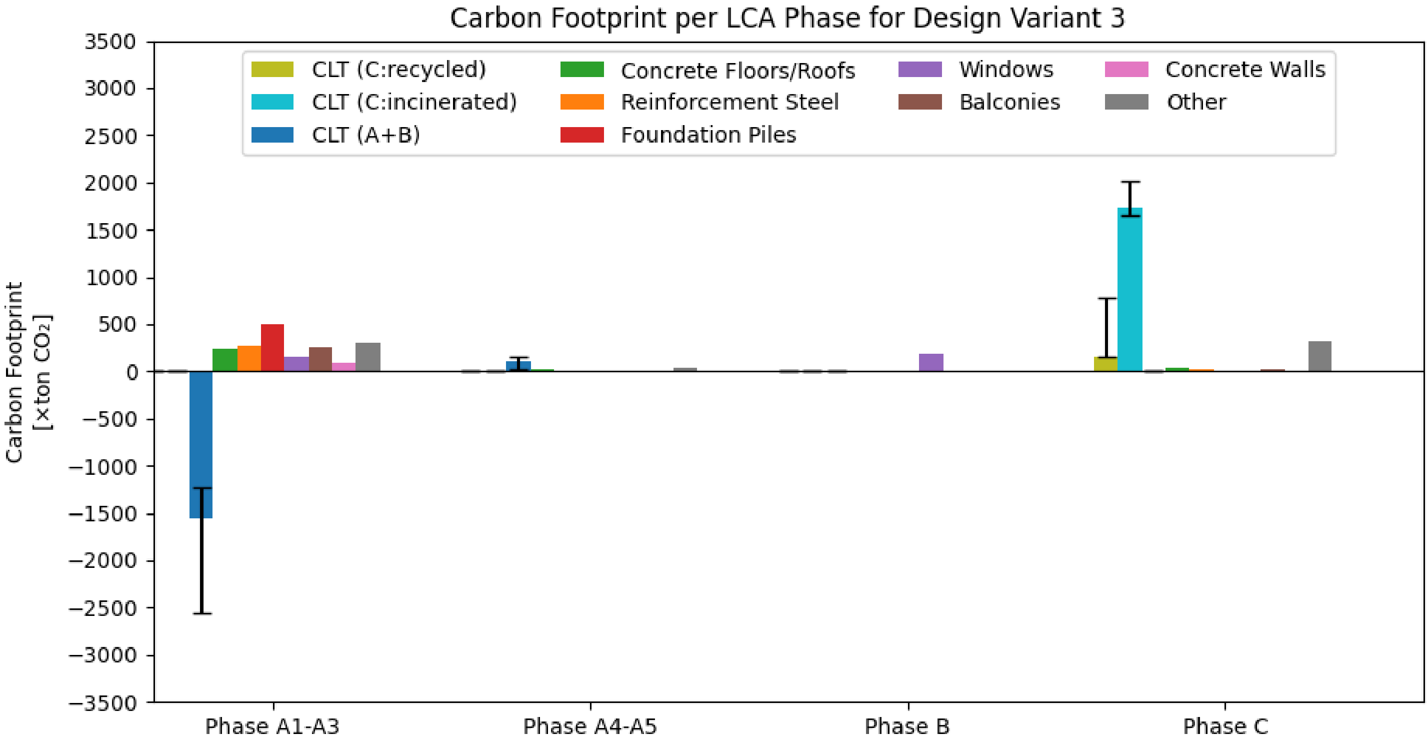

Figure 5.4: Carbon Footprint per LCA Phase for Design Variant 3 of KasseNova aan de Vaart

The difference in the carbon footprint of the entire building between the scenario in which the CLT elements are recycled and the scenario in which the CLT elements are incinerated is very considerate: 1,160,591 kg CO_2-equivalent for the CLT-recycle scenario and 2,744,341 kg CO_2-equivalent for the CLT-incinerate scenario. When comparing this to the carbon footprint of 3,144,547 kg CO_2-equivalent of the current structure, it can be concluded that simply using CLT does not lead to a major reduction of the carbon footprint; the CLT needs to be recycled at the end of its lifespan.

The elements which have the biggest negative impact on the total carbon footprint are the foundation piles (495,792 kg CO_2-equivalent), windows (364,111 kg CO_2-equivalent), balconies (292,052 kg CO_2-equivalent), reinforcement steel in cast in-situ concrete (284,960 kg CO_2-equivalent) and the concrete floors and roofs (269,171 kg CO_2-equivalent). The CLT floors and walls have a combined carbon footprint of -1,299,195 kg CO_2-equivalent when recycled and 284,556 kg CO_2-equivalent when incinerated.

Figure 5.5 displays the combined resulting carbon footprints from the current design and the three design variants. In the current design, the variance in carbon footprint results from different C30/37 EPDs which were used. For the three design variants, the variance is due to different CLT EPDs which were used.

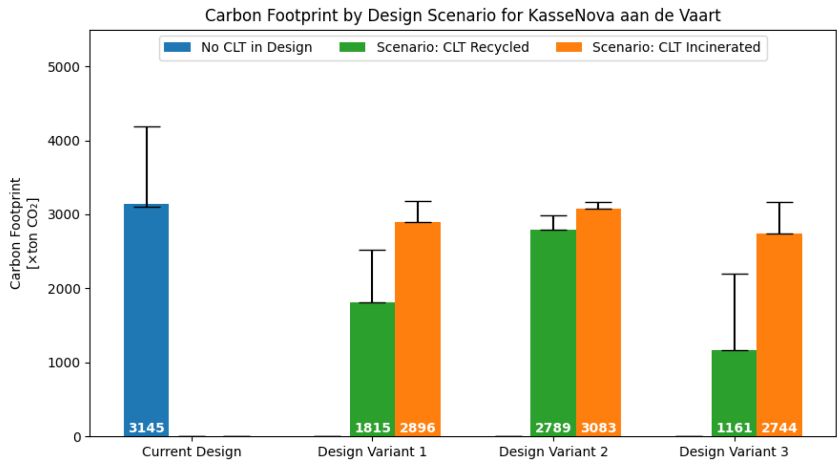

Figure 5.5: Carbon Footprint by Design Scenario for KasseNova aan de Vaart - Phases A-C

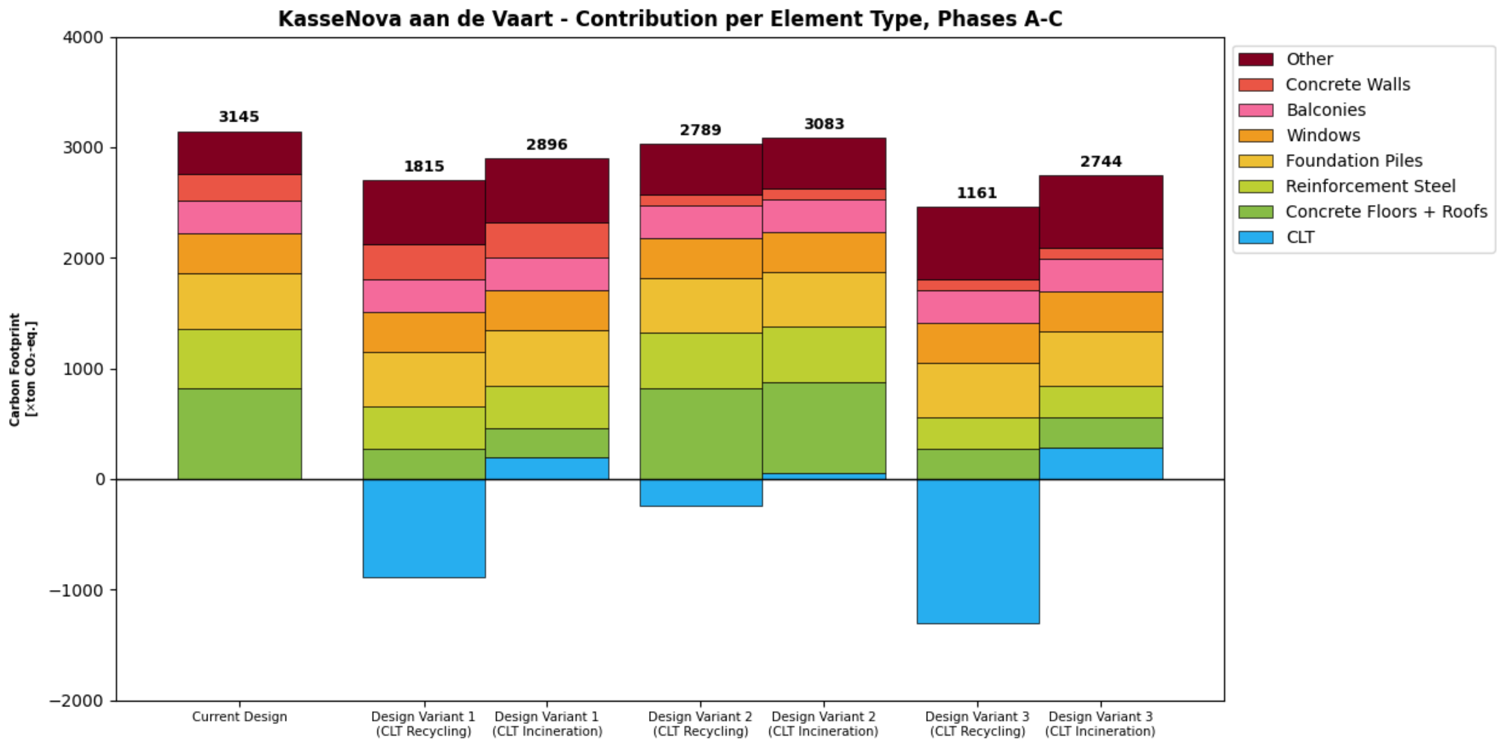

Figure 5.6: KasseNova aan de Vaart - Contribution per Element Type, Phases A-C

The carbon footprint of all design variants are below the carbon footprint for the current design. Design Variant 3 experiences the largest difference in carbon footprint with the current design. This design variant consists of the largest amount of CLT being used instead of concrete. In the scenario in which the CLT is recycled, the carbon footprint is reduced by 63.1% (1161 ton CO_2) in comparison to the current design. In the scenario in which the CLT is incinerated, this reduction equals 12.7% (2744 ton CO_2).

Design Variant 1 has a reduction in carbon footprint of 42.3% (1815 ton CO_2) and 7.9% (2896 ton CO_2) when the CLT is recycled and incinerated, respectively, in comparison to the current design. The smallest reduction of carbon footprint is in Design Variant 2. The carbon footprint is reduced by 11.3% (2789 ton CO_2) when the CLT is recycled and 1.9% (3083 ton CO_2) when the CLT is incinerated at the end of its life cycle.

Even though using CLT in design instead of concrete will decrease the carbon footprint, the end-of-life scenario of the CLT has the largest impact on the overall carbon footprint in KasseNova aan de Vaart.

5.1.2. Phases A1-A5 (Paris Proof Commitment)

The focus of the Paris Proof Commitment is to limit the global temperature rise to 1.5 °C by 2050. Since the assumption is that most buildings which are currently built have not reached the end-of-life phase by 2050, the Paris Proof Commitment excludes these phases in its calculation (Spitsbaard & van Leeuwen, 2021). In fact, the only phases which are considered are the production and construction stages, which are Phases A1-A5.

In order to calculate the carbon footprint of KasseNova aan de Vaart for phases A1-A5, the following modifications of the EPD data were performed to fit the input values to the current project:

1. Phase A4 (Transport from construction to building site): Modify the transportation distance to a realistic transportation distance. The value in the EPD changes linearly with distance.
2. Match units used in EPD with units used in design.

Unlike the carbon footprint in for Phases A-C, the carbon footprint needs to be divided by the gross floor area of the entire building, 12,388 m^2, in order to compare these results to the Paris Proof threshold values.

The results for the current state and three design variants are shown in Figure 5.7. The variance in results are again due to different EPDs being used for the C30/37 concrete (current design) and CLT (design variants 1, 2 and 3).

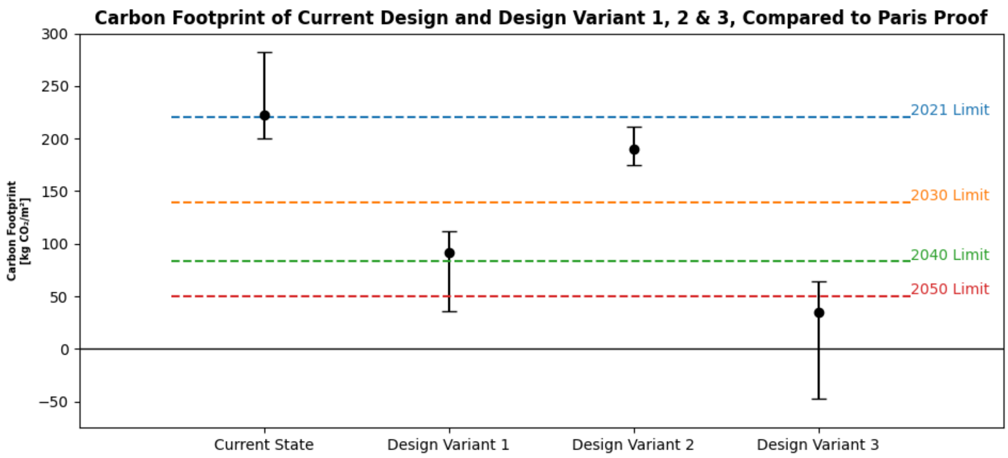

Figure 5.7: Carbon Footprint of Current Design and Design Variant 1, 2 & 3, Compared to Paris Proof

All design variants have a smaller carbon footprint than the current design, which has a carbon footprint of 222.46 kg CO_2/m^2. The current design does not reach the 2021 Paris Proof Commitment limit of 220 kg CO_2/m^2, but all design variants do. However, there are significant differences in results between the design variants. Design Variant 3 has the largest decrease in carbon footprint compared to the current design: 84.37% decrease. The carbon footprint in this design variant is 34.78 kg CO_2-eq./m^2. This not only leads to the current Paris Proof limit to be met, but also all other limits in the future.

Another design variant which leads to a significant change in carbon footprint is Design Variant 1. The decrease in carbon footprint compared to the current design is 58.76%. The carbon footprint of 91.75 kg CO_2-eq./m^2 is below the 2021 and 2030 limits (220 and 139 kg/m^2, respectively), but not below 2040 and 2050 (83 and 50 kg/m^2, respectively). If this design variant would be built after 2040, it would mean that additional design changes are necessary in order to further reduce the carbon footprint.

The smallest change in carbon footprint is with Design Variant 2, in which the carbon footprint is reduced by 14.39% compared to the current design. The carbon footprint of 190.44 kg CO_2-eq./m^2 leads to the current limit being reached, but it is still above all future limits.

5.2. Case Study 2: Apollolaan 171

For Apollolaan 171, a total of three design variants were used:

1. Design Variant 1: Steel columns are replaced by timber columns
2. Design Variant 2: Concrete floors are replaced by CLT floors
3. Design Variant 3: Steel columns and beams and concrete floors are replaced by timber columns, beams and floors

These carbon footprint results of these design variants, as well as the current design, are described in this subchapter. The first part of this subchapter includes the results from LCA Phases A-C, with the second part consisting of the results from LCA Phases A1-A5.

5.2.1. Phases A-C

This part of the chapter consists of the results of the research which includes LCA Phases A-C. Both the quantity and most relevant EPD of each element in the building is required for the calculation of the carbon footprint. The EPD data needs to be adapted to the current project, as described in Chapter 3. The following modifications of the EPDs were performed to fit the input values to the current project:

1. Phase A4 (Transport from construction to building site): Modify the transportation distance to a realistic transportation distance. The value in the EPD changes linearly with distance.
2. Phase C2 (Transport from building site to demolition/recycling plant): Modify the transportation distance to a realistic transportation distance. The value in the EPD changes linearly with distance.
3. The values for A1-B1 for the existing concrete basement floors and walls are set to zero, since these emissions and carbon uptakes were from a previous life cycle. The end-of-life phases are not set to zero, since these emissions and carbon uptakes are from the current life cycle.
4. Match units used in EPD with units used in design.

The current design of Apollolaan 171 consists of steel columns and beams, concrete floors and a concrete basement. The calculations which were performed for these modifications can be found in Appendix B. The resulting carbon footprint values per phase are displayed in Figure 5.8. The results for the steel elements are grouped per steel type. The variance in results for the steel elements are due to EPDs from different manufacturers being used.

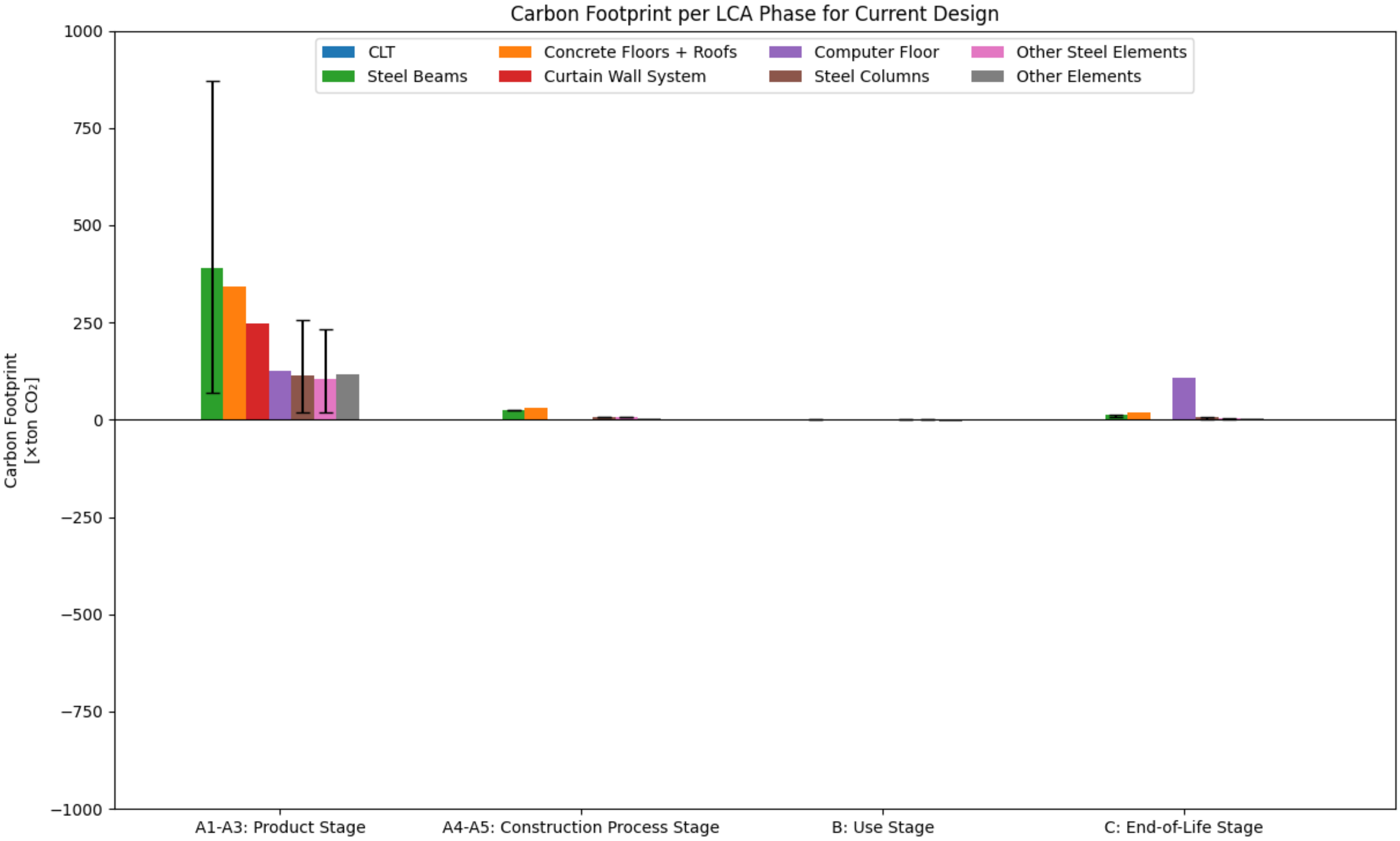

Figure 5.8: Carbon Footprint per LCA Phase for the Current Design of Apollolaan 171

Apollolaan 171 has a total carbon footprint of 1,719,295 kg CO_2-eq. The steel beams consist of different profiles, which together combine for a carbon footprint of 441,230 kg CO_2-eq. The largest part from this carbon footprint occurs in the product stage. Other large contributors are the concrete hollow core slabs which make up the floors and roofs (390,124 kg), the curtain wall system (250,895 kg) and the computer floor (236,080 kg). For most elements, the carbon footprint in stages A4-C are small or even almost negligible compared to stages A1-A3. The only exception is the computer floor, in which the end-of-life stage has a carbon footprint which is only a fraction lower than the product stage (127 ton in the product stage, 107 ton in the end-of-life stage). The end-of-life stage of the computer floor consists of 10% of the galvanised steel and 20% of the particle board being landfilled, while the remaining parts of these elements are recycled. The CO_2 stored in the particle board is released during landfilling.

In the first design variant, the steel columns are replaced by timber columns. The only exceptions are the steel columns in the façade and stability cores, which will not be replaced. The EPD for the glulam columns uses an end-of-life scenario in which most of the glulam is incinerated, which is a realistic scenario when comparing these service lives. The resulting carbon footprint values are given in Figure 5.9.

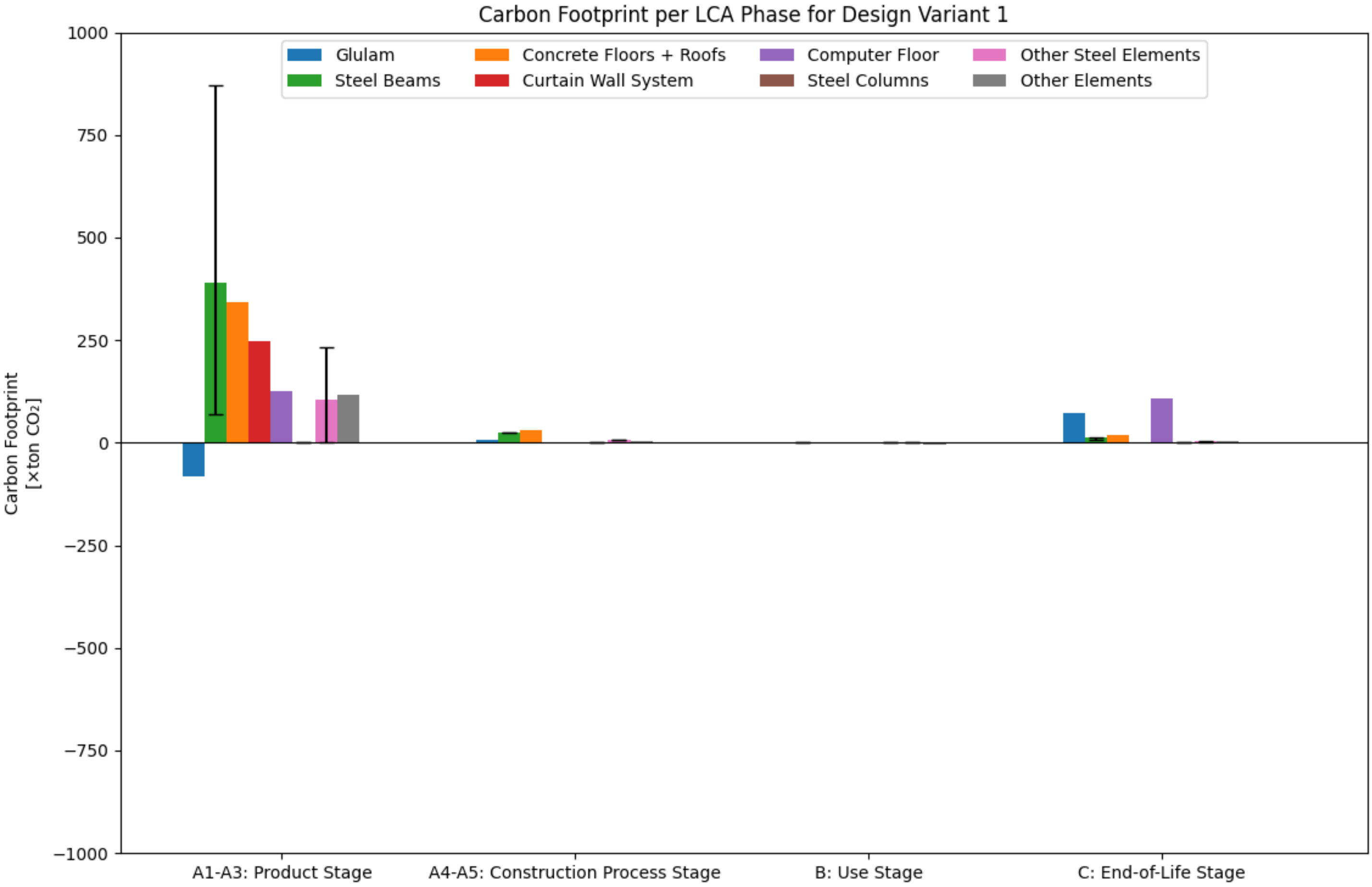

Figure 5.9: Carbon Footprint per LCA Phase for Design Variant 1 of Apollolaan 171

The total carbon footprint of design variant 1 of Apollolaan 171, considering phases A-C, is equal to 1,585,928 kg CO_2-eq. Apart from the beams being changed from steel to timber, there are no additional changes needed to the design. This means that the results for the elements other than the glulam beams are the same as in the current design. During the product stage, glulam takes up carbon from the atmosphere, from which most is released again at the end of its life cycle.

In the second design variant, the concrete hollow core slabs and the steel beams supporting these slabs are replaced by CLT floors. Also, the steel beams are replaced by glulam beams. The only exceptions are the ground floor and roof slabs and beams.

While the glulam only has one end-of-life scenario, the CLT has two: recycling and incineration. Both scenarios are included in the calculation of the carbon footprint. The results are given in Figure 5.10.

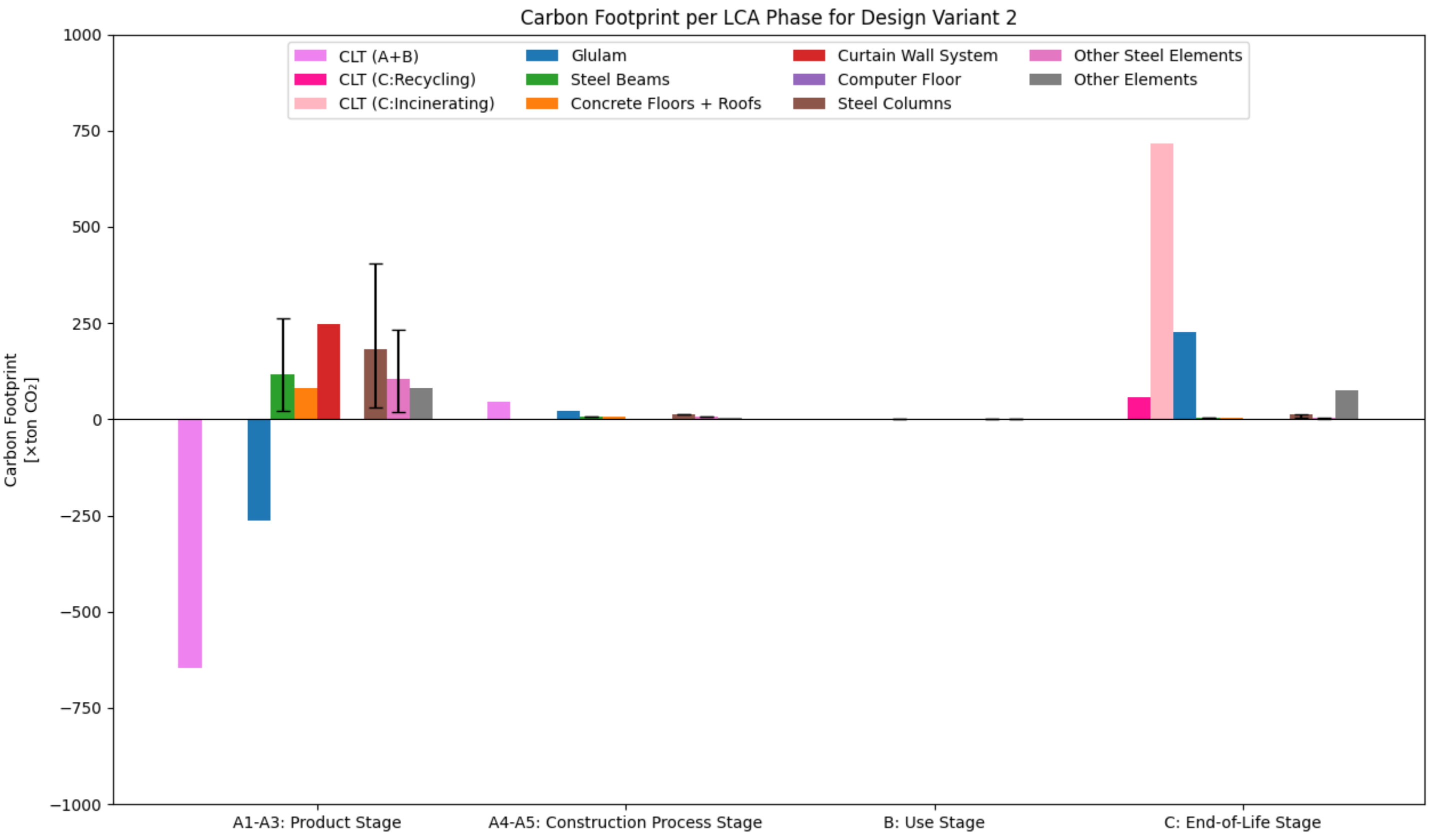

Figure 5.10: Carbon Footprint per LCA Phase for Design Variant 2 of Apollolaan 171

The total carbon footprint of the second design variant in the scenario that the CLT is recycled is equal to 427.263 kg CO_2-eq., while in the scenario that the CLT is incinerated, this value is equal to 1,086,182 kg CO_2-eq. The largest contribution to this carbon footprint is from the curtain wall system, which in total has a carbon footprint of 250,895 kg CO_2-eq. Other elements which have a significant impact on the carbon footprint are the circular steel tubes which make up the steel columns, with a carbon footprint of 204,454 kg CO_2-eq. The product stage makes up most of the carbon footprint for almost all elements, except for the glulam, CLT elements (incineration scenario) and the 'Other Elements'.

In the third design variant, the steel columns are replaced by glulam columns, the hollow core slabs are replaced by CLT floors and the steel beams supporting the hollow core slabs are replaced by glulam beams. The resulting values for the carbon footprint per element are displayed in Figure 5.11.

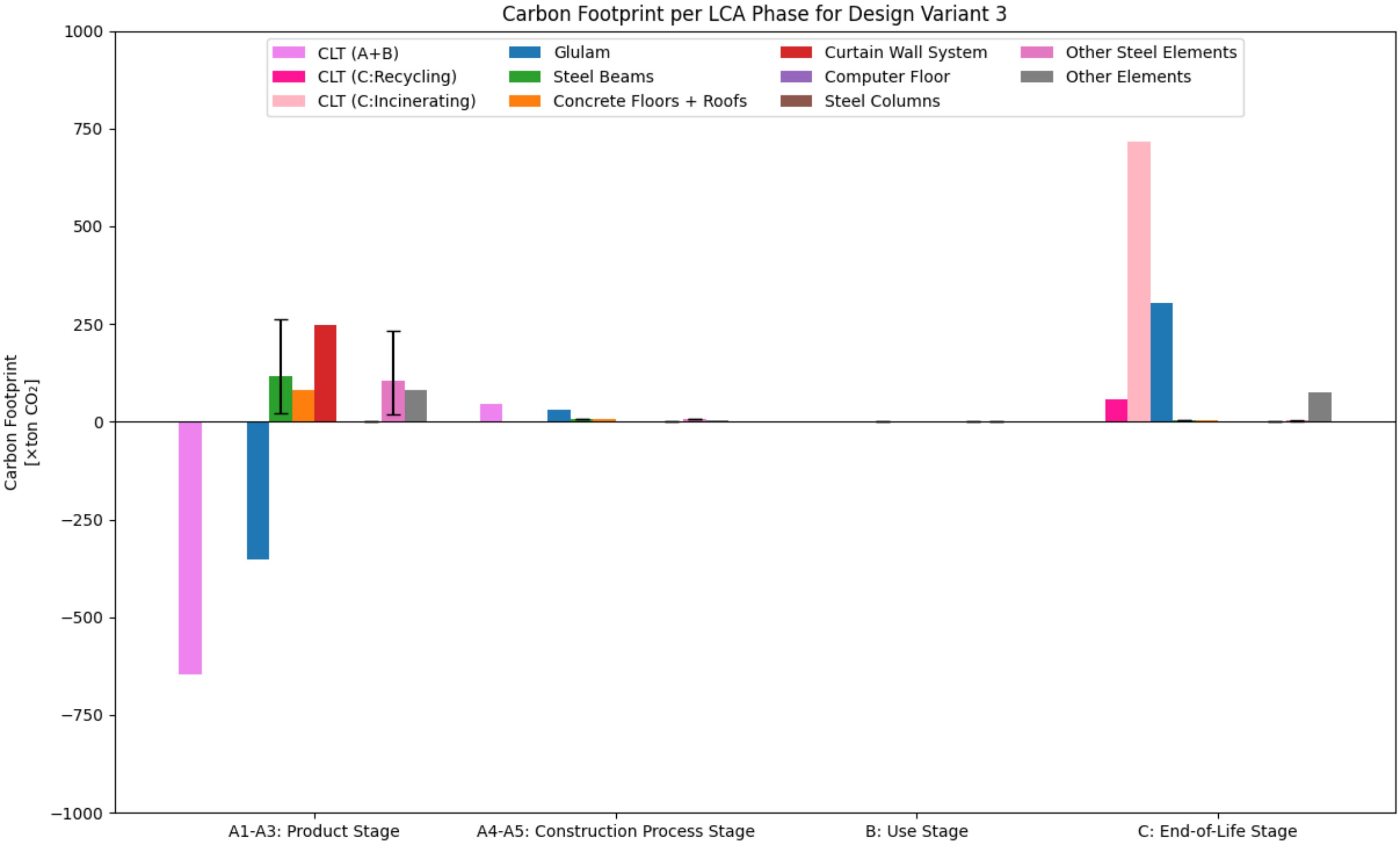

Figure 5.11: Carbon Footprint per LCA Phase for Design Variant 3 of Apollolaan 171

The carbon footprint for design variant 3 is 184.594 kg CO_2-eq. when the CLT is recycled and 843.513 kg CO_2-eq. when the CLT is incinerated. Over its lifetime, CLT captures 544,189 kg CO_2 when recycled and emits 114,730 kg CO_2 when incinerated, a difference of more than 650 ton CO_2. Apart from the CLT, the largest contributor again is the curtain wall system on the north, east and west façade with a carbon footprint of 250,895 kg CO_2-eq.

The combined results from the current design and three design variants are displayed in Figure 5.12. The variance in results for all design variants are due to the use of different manufacturers of the steel EPDs.

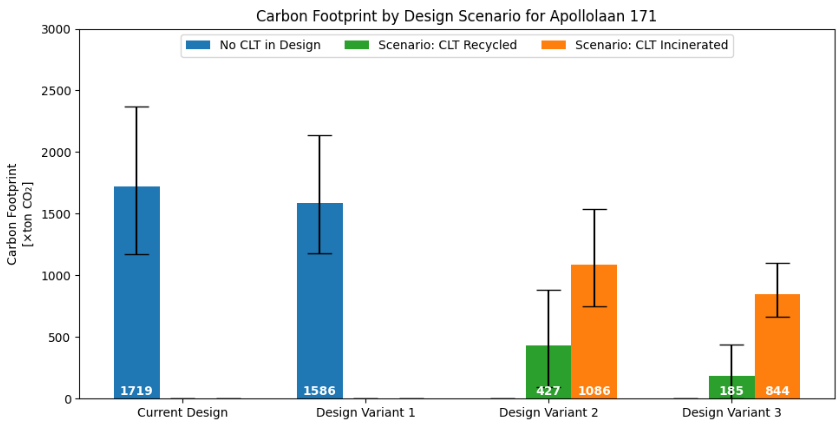

Figure 5.12: Carbon Footprint by Design Scenario for Apollolaan 171 - Phases A-C

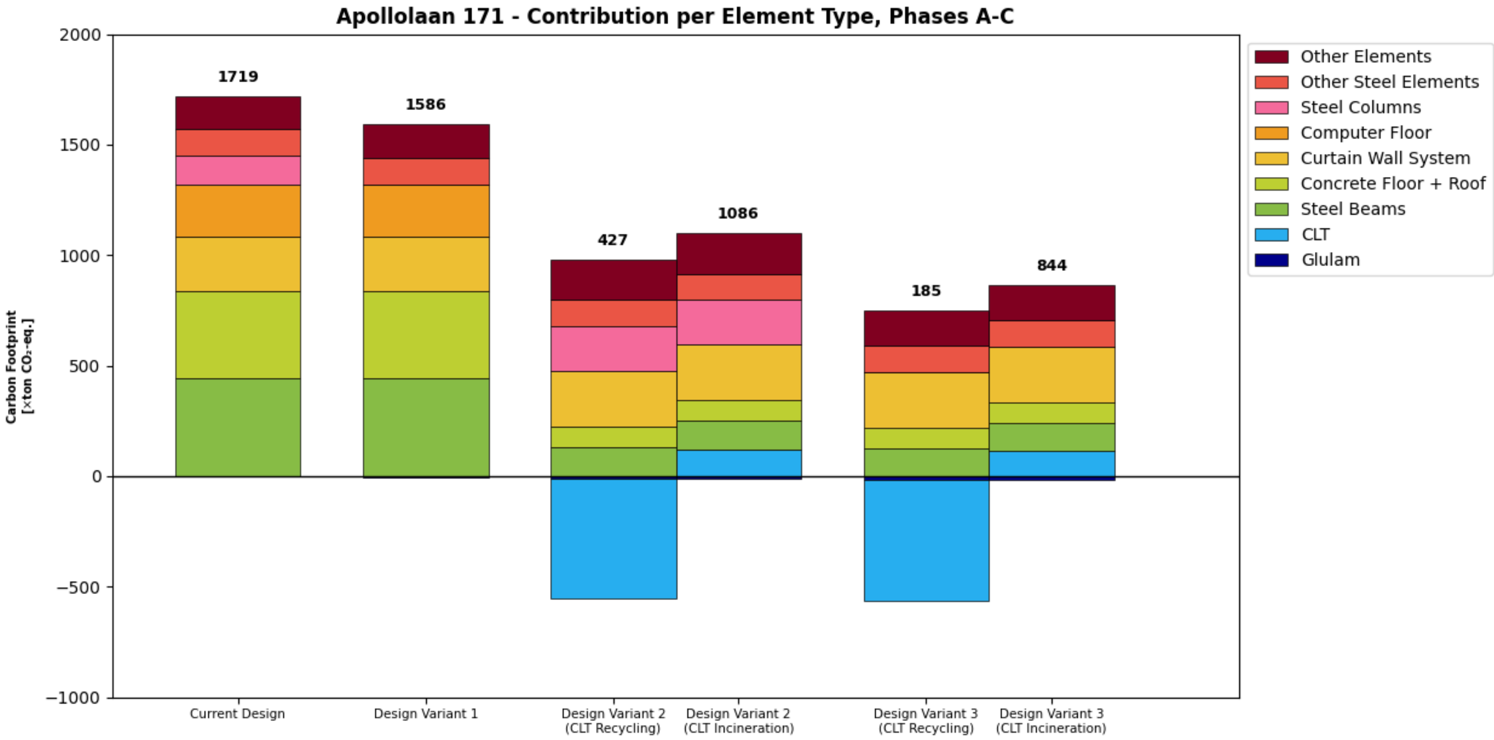

Figure 5.13: Apollolaan 171 - Contribution per Element Type, Phases A-C

The current design has the largest carbon footprint, while the carbon footprint of design variant 1 (steel columns replaced by glulam columns) is only 7.98% lower. In the second design variant, the hollow core slab floors are replaced by CLT floors and the steel beams supporting the floors are replaced by glulam beams. When the CLT is recycled, the reduction in carbon footprint is 76.68%. When the CLT is incinerated, the reduction is 37.26%. In the third design variant, the hollow core slab floors are replaced by CLT floors and the steel columns and beams are replaced by glulam columns and beams. The reduction in carbon footprint is 89.19% when the CLT is recycled. When the CLT is incinerated, this reduction is equal to 49.76%.

5.2.2. Phases A1-A5 (Paris Proof Commitment)

The Paris Proof Commitment only includes the LCA phases until 2050, which are phases A1-A5. The same EPDs were used as in the previous part of this chapter in which phases A-C were included. The modifications include matching the transportation distance in phase A4 to a realistic transportation distance, rather than the assumed distance given in the EPD. Also, the units in design were matched with the units used in the EPDs.

For the threshold values stated in the Paris Proof Commitment, the carbon footprint needs to be divided by the floor area of the building, which is 5,962 m². The results for the carbon footprint are given in Figure 5.14.

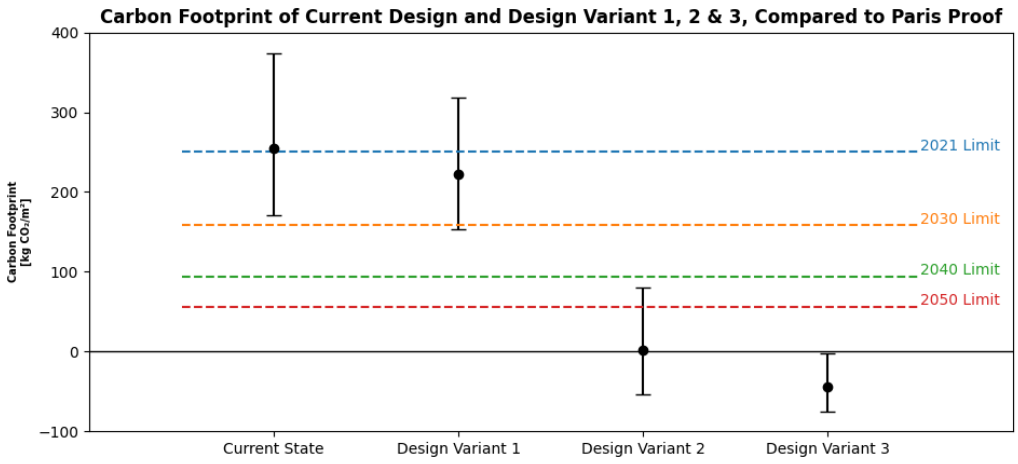

Figure 5.14: Carbon Footprint of Current Design and Design Variant 1, 2 & 3, Compared to Paris Proof

The current design, which contains no timber elements, has the highest carbon footprint: 255.17 kg CO_2-eq./m^2. When the steel columns in this design are replaced by glulam columns, such as in design variant 1, the carbon footprint is reduced by 13.01% to 221.96 kg CO_2-eq./m^2. The current design does not reach the 2021 Paris Proof limit of 250 kg/m^2, design variant 1 does. When the hollow core slab floors are replaced by CLT floors and the steel beams supporting these floors are replaced by glulam beams, such as in design variant 2, the carbon footprint is reduced by 99.57% compared to the current design to a total of 1.10 kg CO_2-eq./m^2, making the building nearly carbon neutral. In the third design variant, where the hollow core slab floors are replaced by CLT floors and the steel beams and columns are replaced by glulam beams and columns, the carbon footprint reduces 117.61% to -44.93 kg CO_2-eq./m^2, which makes the building carbon positive. The second and third design variant both reach the current and future Paris Proof limits.

6 Discussion

The previous chapter displayed the results from the carbon footprint calculation of KasseNova aan de Vaart and Apollolaan 171. This chapter includes a discussion of these results. It is divided into three parts. In the first part, the variance in results is explained, as well as how to include this in practice. In the second part, the results and the accuracy of these results are discussed. The third part focusses on the design changes which are being made.

Range in Results
In all results, a range in carbon footprint is included. For KasseNova aan de Vaart, this range is due to different EPDs being used for C30/37 concrete (current design) and CLT elements (design variants 1, 2 and 3). For Apollolaan, this range is due to different EPDs being used for steel elements (all designs). All material types lead to a significant range in carbon footprint results.

The current design of KasseNova has a carbon footprint of 3145 ton CO_2-eq., but with a range up to 4191 ton CO_2-eq. The reason behind this difference is due to the type of cement being used in the concrete. Blast furnace slag (CEM III) uses residual products, which leads to a lower carbon footprint, while Portland cement (CEM I) does not. The used carbon footprint calculation includes a combination of CEM III and CEM I, which is why the resulting carbon footprint is lower than an EPD which only uses CEM I.

The three design variants of KasseNova have a carbon footprint which is also the minimum carbon footprint. This is because the country of production, Austria, only uses 7.8% coal in its energy mix (International Energy Agency, 2021a). A CLT manufacturer based in Estonia will have a larger carbon footprint per m^3 material, since the percentage of coal in the energy mix is 63.0% (International Energy Agency, 2021b).

The range in results for Apollolaan are mainly because of the input material for steel and the method of production. If more recycled material is used, the carbon footprint is lower. The opposite is true if more virgin steel is used. The energy efficiency of a method of production is another factor in understanding the range in results.

As more EPDs are published, the range in results will be further increased. However, it is also possible to be more accurate in which EPD is used. Obviously, the EPD which is published by the actual manufacturer should be used if possible. If the manufacturer has not published an EPD, an EPD from another manufacturer should be used. If there are more EPDs to choose from, an EPD of a material which closely resembles the actual material can be used, thus leading to more accurate results.

Results and its Accuracy
In both case studies, an increase in timber in the structure leads to a reduction in carbon footprint. However, there is a difference between the end-of-life scenarios of CLT. If the CLT is recycled, the reduction in carbon footprint is significantly larger than if the CLT is incinerated. In the case of KasseNova aan de Vaart, the difference in end-of-life scenarios has a larger impact than the amount of timber being used in construction. The reduction in carbon footprint for the scenarios including

recycling of the CLT is 11.3-63.1%, while this is 1.9-12.7% in the incinerating scenario. In the case of Apollolaan, the second and third design variant both lead to a more notable reduction in carbon footprint, regardless of the end-of-life scenario. This is because not only the floors are replaced by timber, but also the beams supporting the floors. The original steel beams are a large contributor to the carbon footprint.

While the total carbon footprint of KasseNova aan de Vaart is larger than of Apollolaan for the current design and all design variants, it cannot be concluded that concrete buildings have a higher carbon footprint than steel buildings. KasseNova has twice as much floor area as Apollolaan. Besides, KasseNova is a residential building, while Apollolaan is an office building. The comparison would be more fair if the carbon footprint would be divided by the floor area, as is done for the Paris Proof limits. The results, including phases A-C, are displayed in Table 6.1:

Carbon Footprint for Phases A-C [kg CO_2-eq./m^2]		
	KasseNova	**Apollolaan**
Current Design	253.8	288.4
Design Variant 1	146.5 (CLT recycling) 233.8 (CLT incinerating)	266.0
Design Variant 2	225.1 (CLT recycling) 248.9 (CLT incinerating)	70.7 (CLT recycling) 182.2 (CLT incinerating)
Design Variant 3	93.7 (CLT recycling) 221.5 (CLT incinerating)	30.3 (CLT recycling) 140.8 (CLT incinerating)

Table 6.1: Comparison of Carbon Footprint for Phases A-C in kg CO_2-eq./m^2

When comparing the carbon footprint of the current structures per gross floor area, Apollolaan has a higher footprint. This is also true for design variant 1. However, for design variants 2 and 3, Apollolaan has a significantly lower carbon footprint than KasseNova. This is because the elements which have the highest impact on the carbon footprint of Apollolaan are the concrete floors and steel beams, which are replaced by timber in these design variants. For KasseNova, the largest contributors (concrete floors and reinforcement steel) have a lesser impact on the total carbon footprint than the main contributors for Apollolaan. However, this comparison between case studies cannot be used for all similar comparisons. For this, additional cases need to be studied.

The possible range in results have already been discussed. This is due to the input values stated in the EPDs. The manufacturers of the materials used in the designs of KasseNova and Apollolaan are not known at Van Rossum. This is knowledge of the contractor. Therefore, it is unsure if the manufacturers which published the EPDs are the same as the actual manufacturers. However, the materials, assumptions and end-of-life scenarios described in the used EPDs are all realistic. The C30/37 concrete, steel and CLT have the largest contributions to the total carbon footprint. The steel and CLT EPDs are from manufacturers which also deliver products to the Netherlands. The C30/37 concrete manufacturer is a Greek manufacturer, which does not deliver its products to the Netherlands. Therefore, the largest possible inaccuracy in carbon footprint is from the C30/37 concrete.

Module D was not included in the calculation, since this includes CO_2 from future life cycles. It is advised that all future carbon footprint calculations do not include Module D.

For this research, only the carbon footprint was considered. If a building has a low carbon footprint, it does not necessarily mean that the building can be considered sustainable. There are 13 core and 6 additional environmental impact indicators described in EN15804+A2, but even if the building is considered sustainable for all indicators, it cannot be said that the building is sustainable. There are additional indicators, such as social and financial sustainability which are not included in EN15804+A2. Sustainability is a complex and contradictory subject, for which one true definition does not exist.

Design Changes

Multiple design changes have been performed in order to make the timber-hybrid structure a realistic structure. However, in order to have a completely realistic design, additional design changes need to be made. The two main yet undiscussed topics are the connections between members and how the architectural purpose would possibly change.

The design changes do not include connections between members. This was done since the impact of connections on the carbon footprint is less significant than the change in floor plan and foundations. However, in order to have a realistic design, the connections need to be designed and calculated properly. The connections between the timber and steel or concrete could be done with steel plates and bolts. However, the connections are out of the scope of this research.

Adding load-bearing walls in design variants 1 and 3 of KasseNova is a realistic solution, as there are already architectural walls in these locations. However, there are no existing columns on the locations at which new columns need to be added in design variants 2 and 3 of Apollolaan. This could be an architectural challenge. Currently, the building is not in use, but there are three proposed concepts on how to use the space. Figures 6.1 – 6.3 show these concepts, with in red indicated where the additional columns would be.

Figure 6.1: Floor Plan Concept 1 With Additional Columns

Figure 6.2: Floor Plan Concept 2 With Additional Columns

Figure 6.3: Floor Plan Concept 3 With Additional Columns

The additional columns would best fit in the first concept, as these columns are located mostly in the walls between meeting rooms. For the second and third concept, architectural changes are needed to conform to the additional columns.

7 Conclusion

The research in discussed in this report compares the carbon footprint of a concrete and a steel-concrete hybrid building with the same buildings, but timber-hybrid versions. The main research question to be answered is:

> What is the impact on the carbon footprint when a concrete and/or steel structure is changed into a timber-hybrid structure, including various end-of-life scenarios for timber?

Carbon Footprint

- An increase in timber in the structure leads to a reduction in carbon footprint.
- If the CLT is recycled, there is a much larger reduction in carbon footprint than if the CLT is incinerated.
- When comparing the carbon footprint between two buildings, this footprint should be divided by the gross floor area for a fair comparison.
- The concrete-steel-hybrid office building had a higher carbon footprint in its current design than the concrete residential building. However, when CLT is used in design for the floors, the concrete-steel building has a lower carbon footprint. This comparison cannot be used for all similar comparisons.
- The two buildings in this research which in its current design did not reach the current Paris Proof limit of 220 (residential) or 250 (office) kg CO_2-eq./m^2 reached this limit and all future limits when the floors and walls/columns were replaced by timber elements.

Range in Carbon Footprint Results

- Concrete products which use CEM I cement have a larger carbon footprint than concrete products using CEM III cement or a combination of CEM I and CEM III cement.
- For CLT products, the range in carbon footprint results are due to the energy mix of the country producing the CLT. If a country uses a higher percentage of coal in its energy mix, the carbon footprint will increase
- The range in results for steel products are due to the amount of recycled material being used. If more recycled material is used, the carbon footprint will decrease.

Design Changes

- If CLT is used instead of concrete, it does not necessarily lead to a decrease in the number of foundation piles. Additional walls might need to be placed, leading to more foundation piles needing to be used.

- CLT floors can span a smaller distance than concrete floors. A reduction in floor span can be done by adding load-bearing walls or columns. It needs to be confirmed by the architect that this is a possibility.

8 Recommendations

One of the main causes of inaccuracy in this research is the lack of available EPDs, which provides the input data for the carbon footprint. The EPDs which currently can be used have to be published after november 2019, which is when EN 15804+A2 was published. In this period of time, only a very small fraction of the manufacturers have created EPDs for their products. As time progresses, more EPDs will be published. The first recommendation is to perform the same research after five years. It is believed that after five years, the number of EPDs for building products will be increased to a point to which a carbon footprint calculation is far more accurate. Besides, a sensitivity study as included in this thesis will yield much more accurate results as well.

The research in this study focused only on mid-rise buildings. The second recommendation is to perform similar research on low- and high-rise buildings. Timber high-rise buildings will lead to additional challenges, especially regarding the stability. Nevertheless, an increased number of timber high-rise buildings are currently being built. Therefore, in order to get more complete results on the difference in carbon footprint, a study on high-rise, but also low-rise, buildings need to be performed. Similarly, only CLT floors and walls and glulam beams and columns were used as timber elements, but there are different types of timber which can be used in buildings. Additional carbon footprint calculations should be performed with these different types of timber.

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A

EPDs

A.1. KasseNova aan de Vaart

Chosen EPDs (Current Design, Design Variant 1, 2 & 3) with argumentation:

Product	Material type	EPD ID	Argumentation
Floor/Roof	Cast in-situ concrete C30/37	A.2-7	1. Cement type is CEM I + II, which is realistic 2. Assumed not to be seaside or waterproof concrete 3. Assumed larger aggregates
Walls	Cast in-situ concrete C30/37	A.2-7	1. Cement type is CEM I + II, which is realistic 2. Assumed not to be seaside or waterproof concrete 3. Assumed larger aggregates
Small foundation beams	Cast in-situ concrete C30/37	A.2-7	1. Cement type is CEM I + II, which is realistic 2. Assumed not to be seaside or waterproof concrete 3. Assumed larger aggregates
Large foundation beams	Cast in-situ concrete C30/37	A.2-7	1. Cement type is CEM I + II, which is realistic 2. Assumed not to be seaside or waterproof concrete 3. Assumed larger aggregates
Foundation piles	Prefab concrete foundation piles	A.5-1	Only available EPD for foundation piles
Beams	Cast in-situ concrete C30/37	A.2-7	1. Cement type is CEM I + II, which is realistic 2. Assumed not to be seaside or waterproof concrete 3. Assumed larger aggregates
Reinforcement steel is (in-situ concrete)	Reinforcement steel	A.4-1	Decision between A.4-1 and A.4-5 (both Dutch), difference in % scrap used. A.4-1 is average % from multiple parties, while A.4-5 is from one company
Foundation blocks	Cast in-situ concrete C35/45	A.3-6	Same EPD as C30/37. Has CEM I + II cement.
Columns	Cast in-situ concrete C35/45	A.3-6	Same EPD as C30/37. Has CEM I + II cement.
Core element	Prefab concrete wall	A.6-3	EPDs are very similar, so every EPD would have been the right choice. However, A.6-3 has a scope of more European countries (making it more likely to be correct throughout entire EU). Also, scenario C is most similar to cast in-situ concrete.
Balcony	Prefab concrete balconies	A.7-2	EPDs are very similar, so every EPD would have been the right choice. For consistency, A.7-2 was chosen (same manufacturer as core element). Has same percentage concrete recycled as core element.
Timber floors	CLT	A.8-1 & A.8-2	Stora Enso includes four end-of-life scenarios. Only other manufacturer which has this is in Australia.
Wood flooring	Wood flooring	A.9-4	EPD is from Belgian manufacturer, so probably most relevant for the Netherlands.
Foam layer	Foam	A.10-1	Assumed to be closer to actual material (sheet = 2-3 mm thick, which is actual sheet thickness).
Fibreboard	Fibreboard	A.11-2	Producer of EPD also has a factory in NL.
Impact insulation	Impact insulation	A.12-1	Scope of producer is global.
Plasterboard	Plasterboard	A.13-5	All EPDs are similar, but the scope of this EPD is global.
Insulation	Insulation	A.14-5	According to detailed drawing, density should be >= 150 kg/m^3, this is the only product which reaches this requirement. The company is also located in NL.
Screed layer	Screed	A.15-2	EPDs are very similar, chosen EPD has A4 data.
Heating layer	Tacker layer	A.16-3	Only available EPD for tacker layer.
Steel column	HEA400	A.17-3	World steel recycling is approx. 85% (SOURCE), which is closest to this EPD.
Steel products	Steel tube	A.18-1	Dutch manufacturer, EPD is specifically for columns in multi-storey buildings.
Windows	PVC profile + Double glazing	A.19-7	Two EPDs with PVC profile and double glazing, other is located in Chile and has no end-of-life phases
Windows (ground floor)	Curtain wall system	A.20-3	Can be either one of the four Strugal systems, since these are completely similar. A.20-3 was around the average value.
Wall plasterboard	Plasterboard	A.21-1	Only available EPD for wall plasterboard.

Table A.1: Chosen EPDs for KasseNova aan de Vaart with argumentation

Cast In-Situ C30/37 Concrete

EPD	EPD ID	A1	A2	A3	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	D	Product type	Density	Source	Nationality - Geographical scope	Reference unit	Reference life	Transport distance A4	Phases C+D
Fedbeton	A.2-1	148.00	20.80	1.58	170.38	6.72	11.10	x	x	9.21	12.50	3.30	0.74	-8.26	Ready-mixed concrete, CEM III	2370 kg/m^3	(Fedbeton, 2021)	Belgium - Belgium	m^3	100 years	17 km	95% recycling, 5% landfill
ΙΟΝΙΟΣ	A.2-2	x	x	x	279.00	x	x	x	x	x	x	x	x	x	Ready-mixed concrete, S137	2375 kg/m^3	(IONIOS BETON S.A., 2022)	Greece - Greece	m^3	?	Not applicable	Not applicable
Interbeton	A.2-3	x	x	x	208.00	2.07	9.65	-6.24	x	8.99	8.81	3.22	-0.33	-9.03	Ready-mixed concrete, -SR	2360 kg/m^3	(Interbeton, 2022a)	Greece - Greece	m^3	50 years	10 km	50% recycled, 50% landfill
Unicon	A.2-4	249.00	21.30	2.95	273.25	3.88	x	x	x	8.90	5.06	1.55	0.39	-5.03	Ready-mixed concrete, CEM I	2224 kg/m^3	(Unicon A/S, 2023a)	Denmark - Denmark	m^3	50 years	20 km	97% recycled, 3% landfill
General Beton	A.2-5	x	x	x	437.00	x	x	x	x	14.90	19.10	1.00	4.76	-6.28	Ready-mixed concrete	2300 kg/m^3	(General Beton, 2017)	Romania - Romania	m^3	?	Not applicable	61% recycled, 39% landfill
Heracles (1)	A.2-6	x	x	x	257.00	3.86	8.57	-11.10	x	15.00	19.30	1.12	-6.38	-0.45	Ready-mixed concrete, CEM I + II, 16 mm aggregates	?	(Attica, 2021)	Greece - Worldwide	m^3	50 years	10 km	61% recycled, 39% landfill
Heracles (2)	A.2-7	x	x	x	239.00	3.87	8.57	-10.20	x	15.00	19.30	1.29	-5.42	-0.45	Ready-mixed concrete, CEM I + II, 31.5 mm aggregates	?	(Attica, 2021)	Greece - Worldwide	m^3	50 years	10 km	61% recycled, 39% landfill
Heracles (3)	A.2-8	x	x	x	249.00	3.89	8.57	-10.70	x	15.10	19.50	1.20	-5.97	-0.46	Ready-mixed concrete, CEM I + II, 31.5 mm aggregates (seaside)	?	(Attica, 2021)	Greece - Worldwide	m^3	50 years	10 km	61% recycled, 39% landfill
Heracles (4)	A.2-9	x	x	x	242.00	3.89	8.57	-10.30	x	15.10	19.40	1.28	-5.50	-0.46	Ready-mixed concrete, CEM I + II, 31.5 mm aggregates (waterproof)	?	(Attica, 2021)	Greece - Worldwide	m^3	50 years	10 km	61% recycled, 39% landfill
Tsouma Beton	A.2-10	x	x	x	315.00	x	x	x	x	x	x	x	x	x	Ready-mixed concrete, CEM II	2363 kg/m^3	(Tsouma Beton S.A., 2023)	Greece - Greece	m^3	?	Not applicable	Not applicable
Biompeton	A.2-11	x	x	x	348.00	x	x	x	x	x	x	x	x	x	Ready-mixed concrete, CEM II	2337 kg/m^3	(Biompeton, 2023)	Greece - Greece	m^3	?	Not applicable	Not applicable
Iston	A.2-12	309.00	35.10	0.55	344.00	5.26	29.90	x	x	28.50	11.90	6.58	3.70	-3.40	Ready-mixed concrete	2341 kg/m^3	(Iston, 2021)	Turkey - Worldwide	m^3	?	Not specified	Not specified

Cast In-Situ C35/45 Concrete

EPD	EPD ID	A1	A2	A3	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	D	Product type	Density	Source	Nationality - Geographical scope	Reference unit	Reference life	Transport distance A4	Phases C+D
Tsouma Beton	A.3-1	x	x	x	335.00	x	x	x	x	x	x	x	x	x	Ready-mixed concrete, CEM II	2389 kg/m^3	(Tsouma Beton S.A., 2023)	Greece - Greece	m^3	?	Not applicable	Not applicable
Biompeton	A.3-2	x	x	x	342.00	x	x	x	x	x	x	x	x	x	Ready-mixed concrete, CEM II	2364 kg/m^3	(Biompeton, 2023)	Greece - Greece	m^3	?	Not applicable	Not applicable
Aggelos B. Peppas	A.3-3	x	x	x	354.00	x	x	x	x	x	x	x	x	x	Ready-mixed concrete, CEM II	2376 kg/m^3	(Aggelos B. Peppas S.A., 2023)	Greece - Greece	m^3	?	Not applicable	Not applicable
Interbeton	A.3-4	x	x	x	265.00	2.07	10.10	-9.91	x	8.99	8.81	2.75	-4.34	9.03	Ready-mixed concrete	2360 kg/m^3	(Interbeton, 2022b)	Greece - Greece	m^3	50 years	10 km	50% recycled, 50% landfill
Unicon	A.3-5	313.00	26.90	3.90	343.80	3.90	x	x	x	8.96	5.09	1.56	0.31	-5.06	Ready-mixed concrete, CEM I	2240 kg/m^3	(Unicon A/S, 2023b)	Denmark - Denmark	m^3	100 years	20 km	97% recycled, 3% landfill
Heracles	A.3-6	x	x	x	299.00	3.96	8.57	-7.79	x	15.40	19.80	1.43	-4.34	-0.46	Ready-mixed concrete, CEM I + II, 31.5 mm aggregates	?	(Attica, 2021)	Greece - Worldwide	m^3	50 years	10 km	61% recycled, 39% landfill

Reinforcement Steel

EPD	EPD ID	A1	A2	A3	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	D	Product type	Density	Source	Nationality - Geographical scope	Reference unit	Reference life	Transport distance A4	Phases C+D
VWN	A.4-1	x	x	x	1020.00	x	x	x	x	x	x	x	x	x	83.4% scrap, 16.6% new steel	?	(Vereniging Wapeningsstaal Nederland, 2021)	Dutch - Dutch	ton	?	Not applicable	Not applicable
BMExport	A.4-2	x	x	x	0.41	0.07	x	x	x	0.02	0.00	0.06	0.00	0.04	Hot-rolled steel	7850 kg/m^3	(BMExport, 2023)	Latvia - Europe	kg	Same as building	Different scenarios	98% recycled, 2% landfill
Celsa	A.4-3	x	x	x	493.00	15.90	x	x	x	5.85	8.72	37.50	0.26	4.84	100% scrap	7850 kg/m^3	(Celsa Steel Service ES, 2023)	Spain - Europe	ton	Same as building	Different scenarios	100% recycled
Jindal	A.4-4	x	x	x	3450.00	x	33.80	x	x	0.00	5.24	0.00	1.82	-1550.00	Hot-rolled steel	?	(Jindal Steel and Power, 2023)	India - Worldwide	ton	?	Not applicable	88% recycled, 12% landfill
BBC	A.4-5	x	x	x	849.00	x	x	x	x	x	x	x	x	x	96.4% scrap, 3.6% new steel	?	(BBC, 2022)	Dutch - Dutch	ton	?	Not applicable	Not applicable

Prefab Foundation Piles

EPD	EPD ID	A1	A2	A3	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	D	Product type	Density	Source	Nationality - Geographical scope	Reference unit	Reference life	Transport distance A4	Phases C+D
Centrum Pæle	A.5-1	x	x	x	82.20	0.01	x	x	x	x	x	x	x	x	Precast concrete pile (450x450 mm)	491 kg/m	(Centrum Pæle A/S, 2021)	Denmark - Europe	m	100 years	100 km	Not applicable

Prefab Concrete Wall (Core Element)

EPD	EPD ID	A1	A2	A3	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	D	Product type	Density	Source	Nationality - Geographical scope	Reference unit	Reference life	Transport distance A4	Phases C+D
Gunnar	A.6-1	x	x	x	162.00	10.60	x	-6.50	x	3.02	2.10	0.61	0.00	-1.40	Precast wall 200 mm	500 kg/m^3	(Gunnar Prefab AB, 2023)	Sweden - Sweden	tonne	50 years	200 km	100% recycled
Mälarden	A.6-2	x	x	x	227.00	x	x	x	x	3.29	6.54	3.36	0.81	-40.20	Precast wall	?	(Prefab Mälardalen, 2022)	Sweden - Sweden	tonne	?	Not applicable	80% recycled, 20% landfill
INHUS	A.6-3	158.00	0.75	9.97	169.00	var.	7.35	x	x	3.30	4.55	3.32	1.55	-5.69	Precast wall	?	(INHUS Prefab, UAB, 2021b)	Lithuania - Europe	tonne	50 years	Different scenarios	70% recycled, 30% landfill
Holterman	A.6-4	935.00	78.00	110.00	x	x	x	x	x	52.40	31.80	7.74	0.31	-91.90	Precast concrete elements for walls, pillars and beams	2417 kg/m^3	(STF Holterman GmbH, 2021)	Germany - Germany	m^3	50 years	Not applicable	Concrete: 99% recycled. Reinforcing: 95% recycled

Prefab Concrete Balconies

EPD	EPD ID	A1	A2	A3	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	D	Product type	Density	Source	Nationality - Geographical scope	Reference unit	Reference life	Transport distance A4	Phases C+D
Mälarden	A.7-1	x	x	x	211.00	x	x	x	x	3.31	6.55	3.53	0.82	-30.70	Precast concrete balcony with connector (0.4% steel)	?	(Prefab Mälardalen, 2023)	Sweden - Europe	tonne	50 years	Not applicable	Concrete: 80% recycled. Reinforcing: 95% recycled
INHUS	A.7-2	182.00	1.61	12.60	196.00	var.	4.03	x	x	3.30	4.55	3.74	1.53	-5.51	Precast concrete balcony slab	?	(INHUS Prefab, UAB, 2021a)	Lithuania - Europe	tonne	50 years	Different scenarios	Concrete: 70% recycled. Reinforcing: 70% landfill

CLT Elements

EPD	EPD ID	A1	A2	A3	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	D	Product type	Density	Source	Nationality - Geographical scope	Reference unit	Reference life	Transport distance A4	Phases C+D
Stora Enso (1)	A.8-1	-729.00	8.72	11.60	-708.00	25.90	5.38	x	x	4.01	2.05	782.00	0.00	-268.00	CLT (>= 3 layers), spruce, C24, moisture content 12%	470 kg/m^3	(Stora Enso, 2023)	AT/CZ/SE - Europe	m^3	50 years	634 km	100% incineration with energy recovery
Stora Enso (2)	A.8-2	-729.00	8.72	11.60	-708.00	25.90	5.38	x	x	4.01	2.05	762.00	0.00	-45.60	CLT (>= 3 layers), spruce, C24, moisture content 12%	470 kg/m^3	(Stora Enso, 2023)	AT/CZ/SE - Europe	m^3	50 years	634 km	100% re-use in coherent form
Stora Enso (3)	A.8-3	-729.00	8.72	11.60	-708.00	25.90	5.38	x	x	4.01	2.05	768.00	0.00	-16.20	CLT (>= 3 layers), spruce, C24, moisture content 12%	470 kg/m^3	(Stora Enso, 2023)	AT/CZ/SE - Europe	m^3	50 years	634 km	100% recycling to wood chips
Stora Enso (4)	A.8-4	-729.00	8.72	11.60	-708.00	25.90	5.38	x	x	4.01	2.05	0.00	1020.00	-0.05	CLT (>= 3 layers), spruce, C24, moisture content 12%	470 kg/m^3	(Stora Enso, 2023)	AT/CZ/SE - Europe	m^3	50 years	634 km	100% landfill with energy recovery
Xilonor	A.8-5	x	x	x	-586.00	x	x	x	x	0.67	4.35	712.00	111.00	-84.00	CLT (>= 3 layers), softwood from Iberian Peninsula	480-550 kg/m^3	(Xilonor, S.L., 2023)	Spain - Global	m^3	Not specified	Not applicable	80.4% recycling, 6.1% energy recovery, 12.0% incineration, 1.5% landfill
Nextimber (1)	A.8-6	x	x	x	-576.00	x	x	x	x	0.34	1.74	0.00	932.00	-0.15	CLT, radiata pine, moisture content 11.3 %	?	(Nextimber, 2023)	Australia - Australia	m^3	Not specified	Not applicable	100% landfill with energy recovery
Nextimber (2)	A.8-7	x	x	x	-576.00	x	x	x	x	0.34	1.74	878.00	0.00	-603.00	CLT, radiata pine, moisture content 11.3 %	?	(Nextimber, 2023)	Australia - Australia	m^3	Not specified	Not applicable	100% incineration with energy recovery
Nextimber (3)	A.8-8	x	x	x	-576.00	x	x	x	x	0.34	1.74	773.00	0.00	-24.90	CLT, radiata pine, moisture content 11.3 %	?	(Nextimber, 2023)	Australia - Australia	m^3	Not specified	Not applicable	100% recycling to wood chips
Nextimber (4)	A.8-9	x	x	x	-576.00	x	x	x	x	0.34	1.74	873.00	0.00	-297.00	CLT, radiata pine, moisture content 11.3 %	?	(Nextimber, 2023)	Australia - Australia	m^3	Not specified	Not applicable	100% re-use in coherent form
KLH (1)	A.8-10	x	x	x	-675.00	45.50	13.00	x	x	9.42	3.97	776.00	0.00	-265.00	CLT (t <= 500 mm), softwoods from Austria, moisture content 12%	470 kg/m^3	(KLH, 2023)	Austria - Europe	m^3	100 years	582 km	100% incineration with energy recovery
KLH (2)	A.8-11	x	x	x	-675.00	45.50	13.00	x	x	9.42	3.97	776.00	0.00	-852.00	CLT (t <= 500 mm), softwoods from Austria, moisture content 12%	470 kg/m^3	(KLH, 2023)	Austria - Europe	m^3	100 years	582 km	100% re-use in coherent form
Rubner	A.8-12	x	x	x	-624.00	x	x	x	x	x	1.46	762.00	0.00	-410.00	CLT (>= 3 layers), coniferous, moisture content 11%	461 kg/m^3	(Rubner Holding, 2023)	Italy - Europe	m^3	50 years	Not applicable	100% reprocessing
SSAS	A.8-13	-1230.00	43.80	10.80	-1170.00	46.10	0.99	x	x	0.99	3.30	0.00	0.00	0.00	CLT mats (3-7 layers), Southern Yellow Pine from USA	512 kg/m^3	(SSAS, 2022)	USA - USA	m^3	Not specified	Unknown	CLT matting panels are ground in mulch after use
Setra	A.8-14	x	x	x	-780.00	2.60	0.67	x	x	0.24	1.30	750.00	0.00	-260.00	CLT (3-7 layers), spruce/pine from Sweden, moisture content 12%	436 kg/m^3	(Setra, 2022)	Sweden - Europe	m^3	Equal to building	248 km	95% incineration, 5% recycled
Arcwood	A.8-15	-954.00	x	392.00	-561.00	37.50	28.80	x	x	3.48	19.20	842.00	51.40	-443.00	CLT (3-9 layers), spruce from Estonia, moisture content 12%	460 kg/m^3	(Arcwood, 2022)	Estonia - Global	m^3	Not specified	900 km	97% recycled, 3% landfill

Wood Flooring

EPD	EPD ID	A1	A2	A3	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	D	Product type	Density	Source	Nationality - Geographical scope	Reference unit	Reference life	Transport distance A4	Phases C+D
Kayu Lapis	A.9-1	x	x	x	-10.50	4.86	x	x	0.25	0.02	0.32	42.10	0.39	1.40	Engineered wood flooring with thickness 14, 15 or 18 mm	595-880 kg/m^3	(Kayu Lapis, 2023)	Indonesia - Global	m^2	25 years	17895 km	39.66% wood recycling, 58.10% energy recovery
AENOR	A.9-2	0.66	1.51	2.45	4.62	x	x	x	x	0.16	0.10	0.07	12.60	0.49	Multilayer wood flooring, European oak sawnwood, birch plywood	710-750 kg/m^3	(Wood Manners, 2022)	Spain - Global	m^2	25 years	Not relevant	100% incineration with energy recovery
FTE	A.9-3	x	x	x	-2.20	0.90	2.53	x	x	1.15	0.21	1.20	0.08	-7.45	Engineered hardwood flooring (14.2 mm), Hevea Brasiliensis + layers	?	(FTE, 2023)	Indonesia - Global	m^2	25 years	Unknown	50% recycled, 35% incinerated with energy recovery, 15% landfill
Unilin	A.9-4	-11.80	1.16	6.91	-3.73	2.62	1.73	x	0.24	x	0.07	15.20	x	-11.10	Multilayer parquet flooring (12-14 mm)	600-850 kg/m^3	(Unilin BV, 2024)	Belgium - Global	m^2	40 years	12400 km (boat) + 875 km (truck)	100% incineration

Foam layer

EPD	EPD ID	A1	A2	A3	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	D	Product type	Density	Source	Nationality - Geographical scope	Reference unit	Reference life	Transport distance A4	Phases C+D
Pepi Rer	A.10-1	2.33	0.03	1.13	3.50	var.	x	x	x	x	x	x	x	x	2-3 mm polyethylene foam	20-30 kg/m^3	(Pepi Rer, 2022)	Latvia - Europe	m^2	50 years	100 km (lorry or ferry)	Not applicable
IVH	A.10-2	x	x	x	47.00	x	0.59	x	x	x	0.05	50.40	x	-21.00	Expanded polysterene hard foam	15 kg/m^3	(IVH, 2022)	Europe - Europe	m^3	40 years	Not relevant	100% thermal recycling

Fibreboard

EPD	EPD ID	A1	A2	A3	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	D	Product type	Density	Source	Nationality - Geographical scope	Reference unit	Reference life	Transport distance A4	Phases C+D
Rigips	A.11-1	x	x	x	-0.05	0.09	0.63	x	x	0.07	0.04	x	3.52	x	Gypsum Fibreboard (12.5 mm) - Type F	15.58 kg/m^2	(Rigips, 2023)	Germany - Germany	m^2	50 years	100 km	100% landfill
Fermacell	A.11-2	x	x	x	0.46	0.16	0.07	x	x	x	0.06	0.20	3.44	-0.09	Gypsum Fibreboard (12.5 mm) - Type A1, A2, B, C, D, E, F	14.75 kg/m^2	(Jamie Hardie Europe, 2022)	Europe - Europe	m^3	Same as building	100 km	Part recycled and landfilled, unclear what percentages are

Impact Insulation

EPD	EPD ID	A1	A2	A3	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	D	Product type	Density	Source	Nationality - Geographical scope	Reference unit	Reference life	Transport distance A4	Phases C+D
BUR2000	A.12-1	x	x	x	0.43	0.01	0.13	x	x	x	x	x	0.02	x Anti-impact insulators, 2-10 mm thickness	140-550 g/m^2	(BUR2000 S.A.U., 2022)	Spain - Global	m^2	20 years	24 km (van), 583 km (small truck) & 556 km (large truck)	100% landfill	
Scan Underlay	A.12-2	0.29	0.01	-0.08	0.22	0.01	0.14	x	x	x	0.02	0.00	0.00	-0.31	Acoustic Silence 700, 2 mm thickness	700 g/m^2	(Scan Underlay, 2023)	Denmark - Denmark	m^2	Not specified	177 km	99% recycled

Plasterboard

EPD	EPD ID	A1	A2	A3	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	D	Product type	Density	Source	Nationality - Geographical scope	Reference unit	Reference life	Transport distance A4	Phases C+D
Knauf Orbond	A.13-1	x	x	x	1.49	x	x	x	x	x	0.07	0.00	0.07	0.00	Regular plasterboard (12 mm thickness)	8 kg/m^2	(Knauf Orbond, 2023)	Israel - Israel/Global	m^2	50 years	Not applicable	97% landfill
Gyproc (1)	A.13-2	x	x	x	1.20	0.09	0.75	x	x	0.04	0.04	0.37	0.34	-0.01	Ceiling plasterboard (12.5 mm thickness)	9.2 kg/m^2	(Gyproc, 2023a)	Nordic - Nordic	m^2	50 years	202 km	55% recycled, 45% landfill
MADA Gypsum	A.13-3	0.34	0.06	1.22	1.62	x	x	x	x	x	x	x	x	x	Regular gypsum plasterboard (12.5 mm thickness)	9.2 kg/m^2	(MADA Gypsum, 2022)	Saudi Arabia - Saudi Arabia	m^2	50 years	Not applicable	Not applicable
Gypfor	A.13-4	x	x	x	1.92	0.72	0.32	x	x	0.08	0.04	0.00	0.04	0.00	Standard plasterboard (12.5 mm thickness)	660 kg/m^3	(Gypfor S.A., 2022)	Portugal - Global	m^2	50 years	446 km (truck) + 508 km (ship)	100% landfill
Dalsan	A.13-5	x	x	x	1.32	0.23	x	x	x	0.14	0.44	0.07	0.06	0.00	Plasterboard (12.5 mm thickness)	660 kg/m^3	(Dalsan, 2021a)	Turkey - Global	m^2	Not specified	350 km	100% landfill
Gyproc (2)	A.13-6	x	x	x	1.57	0.09	0.20	x	x	0.04	0.04	0.34	0.31	-0.01	Standard plasterboard (12.5 mm thickness)	9.0 kg/m^2	(Gyproc, 2023b)	Nordic - Nordic	m^2	50 years	202 km	55% recycled, 45% landfill

Insulation

EPD	EPD ID	A1	A2	A3	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	D	Product type	Density	Source	Nationality - Geographical scope	Reference unit	Reference life	Transport distance A4	Phases C+D
Metecno	A.14-1	x	x	x	21.60	0.00	0.23	x	1.78	0.14	0.00	0.00	0.35	0.00	Rigid insulation board (50 mm thickness)	?	(Metecno PTY Ltd, 2023)	Australia - Australia/USA/China	m^2	40 years	404 km	100% landfill
Kingspan	A.14-2	x	x	x	8.85	0.12	0.00	x	x	0.00	0.04	0.01	0.01	-0.33	K10 G2 Top Facer (50 mm thickness)	?	(Kingspan, 2023)	Australia - Asia Pacific	m^2	50 years	404 km (road) + 892 km (sea)	100% landfill
Recticel	A.14-3	13.90	0.36	1.48	15.70	0.25	0.60	x	x	x	x	13.20	0.03	-7.59	PIR foam (20 - 180 mm thickness)	5.67 kg/m^2	(Recticel Insulation Oy, 2023)	Finland - Europe	m^2	50 years	216 km (lorry) + 73 km (ferry)	95% incinerated, 5% landfill
RBS Ravago	A.14-4	x	x	x	4.48	0.13	0.05	x	x	x	0.03	0.00	0.20	-0.01	Stone wool mattress	80 kg/m^3	(RBS Ravago, 2022)	Turkey - Global	m^2	50 years	500 km (lorry)	100% landfill
Knauf	A.14-5	x	x	x	4.97	0.30	0.15	x	x	x	0.02	x	0.07	-11.10	Rock mineral wool PTS, TPE (150 mm thickness)	150 kg/m^3	(Knauf Insulation, 2022)	Belgium - Global	m^2	50 years	600 km (lorry)	100% landfill

Screed

EPD	EPD ID	A1	A2	A3	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	D	Product type	Density	Source	Nationality - Geographical scope	Reference unit	Reference life	Transport distance A4	Phases C+D
Marmoline	A.15-1	x	x	x	0.18	x	x	x	x	0.00	0.01	0.00	0.01	0.00	Cement-based floor screeds	1600-2100 kg/m^3	(Nordia S.A., 2023)	Greece - Global	kg	Not specified	Not relevant	100% landfill
Dalsan	A.15-2	x	x	x	0.10	0.03	0.00	x	x	x	0.01	0.00	0.00	0.00	Self-levelling screed	800 g/L	(Dalsan, 2021b)	Turkey - Global	kg	Not specified	350 km (lorry)	100% landfill

Floor Heating

EPD	EPD ID	A1	A2	A3	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	D	Product type	Density	Source	Nationality - Geographical scope	Reference unit	Reference life	Transport distance A4	Phases C+D
Nordic FOS	A.16-1	x	x	x	9.55	1.53	0.76	x	x	x	0.00	5.16	0.02	-1.14	Floor heating plate (24 mm thickness)	1.25 kg/m^2	(Nordic Fos, 2023)	Denmark - Europe	kg	Not specified	500 km (lorry)	95% recycled, 5% landfill
Uponor (1)	A.16-2	1.32	0.05	0.12	1.49	0.09	0.01	x	x	x	0.00	1.41	0.00	0.00	Fabric foil laminated onto EPS (25 - 34 mm thickness)	0.5 kg/m^2	(Uponor, 2023a)	Poland - Global	m^2	Not specified	Unknown	100% recycled
Uponor (2)	A.16-3	1.10	0.03	0.11	1.24	0.08	0.01	x	x	x	0.00	1.39	x	0.00	Tacker plate (20 - 40 mm thickness)	0.47 kg/m^2	(Uponor, 2023b)	Poland - Global	m^2	Not specified	Unknown	100% recycled

Steel Column

EPD	EPD ID	A1	A2	A3	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	D	Product type	Density	Source	Nationality - Geographical scope	Reference unit	Reference life	Transport distance A4	Phases C+D
BE Group	A.17-1	0.66	0.06	0.01	0.72	0.06	x	x	x	0.00	0.01	0.02	0.00	-0.12	Steel beams	?	(BE Group Sverige AB, 2021)	Swedish - Swedish	kg	Not specified	400 km (truck)	95% recycled, 5% landfill
SNS (1)	A.17-2	x	x	x	1.16	0.02	0.05	x	x	0.05	0.01	0.03	0.00	-0.23	Heavy construction steel, 16% re-use at end of life	?	(SNS/Bouwen met Staal, 2022a)	Dutch - Dutch	kg	100 years	150 km (truck)	16% re-used, 73% recycled, 1% landfill
SNS (2)	A.17-3	x	x	x	1.16	0.02	0.05	x	x	0.05	0.01	0.03	0.00	-0.79	Heavy construction steel, 80% re-use at end of life	?	(SNS/Bouwen met Staal, 2022c)	Dutch - Dutch	kg	100 years	150 km (truck)	80%re-used, 19.8% recycled, 0.2% landfill
SNS (3)	A.17-4	x	x	x	1.16	0.02	0.05	x	x	0.05	0.01	0.26	0.00	-0.66	Heavy construction steel, 65% re-use at end of life	?	(SNS/Bouwen met Staal, 2022b)	Dutch - Dutch	kg	100 years	150 km (truck)	65% re-used, 34.4% recycled, 0.5% landfill
SNS (4)	A.17-5	x	x	x	0.21	0.02	0.05	x	x	0.05	0.01	0.03	0.00	-0.18	Heavy construction steel, 16% re-use at end of life	?	(SNS/Bouwen met Staal, 2022d)	Dutch - Dutch	kg	100 years	150 km (truck)	16% re-used, 83% recycled, 1% landfill

Steel Tube

EPD	EPD ID	A1	A2	A3	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	D	Product type	Density	Source	Nationality - Geographical scope	Reference unit	Reference life	Transport distance A4	Phases C+D
Tata	A.18-1	x	x	x	2590.00	x	x	x	x	4.53	17.90	1.02	0.15	-1610.00	Structural hollow section (size 21.3 - 508 mm, thickness 2 - 16 mm)	7850 kg/m^3	(Tata Steel, 2022)	Dutch - Europe	tonne	Not specified	Not applicable	92% recycled, 1% landfill, 7% re-used
ZP	A.18-2	126.00	1.87	433.00	561.00	58.10	x	x	x	3.30	8.34	22.10	0.26	-107.00	Seamless steel tubes (size 10.2 - 139.7 mm, thickness 0.5 - 16 mm)	7000 kg/m^2	(Zeleziarne Podbrezova, 2022)	Slovakia - Europe	tonne	Not specified	647 km	16% re-used, 95% recycled, 5% landfill
Welded Tube	A.18-3	x	x	x	1701.06	x	x	x	x	1.81	20.40	0.00	5.58	-716.12	Hollow Structural Sections (HSS)	?	(Welded Tube of Canada, 2022)	Canada - North America	tonne	Not specified	Not applicable	47% recycled, 53% landfill

Windows

EPD	EPD ID	A1	A2	A3	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	D	Product type	Density	Source	Nationality - Geographical scope	Reference unit	Reference life	Transport distance A4	Phases C+D
Altus (1)	A.19-1	x	x	x	78.10	x	x	x	x	15.80	0.11	0.00	9.13	-18.30	Residential Window - Double Glazing + Aluminium Frame	25 kg/m^2	(Altus, 2023)	New Zealand - Global/New Zealand	m^2	Not specified	Not applicable	75% aluminium and stainless-steel recycled, 25% landfill
Altus (2)	A.19-2	x	x	x	99.50	x	x	x	x	19.00	0.13	0.00	6.12	-22.10	Residential Sliding Door - Double Glazing + Aluminium Frame	29.9 kg/m^2	(Altus, 2023)	New Zealand - Global/New Zealand	m^2	Not specified	Not applicable	75% aluminium and stainless-steel recycled, 25% landfill
Altus (3)	A.19-3	x	x	x	93.30	x	x	x	x	16.70	0.11	0.00	6.43	-25.00	Residential Hinged Door - Double Glazing + Aluminium Frame	26.3 kg/m^2	(Altus, 2023)	New Zealand - Global/New Zealand	m^2	Not specified	Not applicable	75% aluminium and stainless-steel recycled, 25% landfill
Novalgroup	A.19-4	x	x	x	112.00	x	x	x	x	x	0.31	0.20	0.09	-51.10	Window System - Double Glazing + Polyamide Frame	?	(Novalprogetti, 2023)	Italy - Global	m^2	Not specified	Not applicable	95% of non glass and 30% of glass recycled, remainder landfill
DVP	A.19-5	2.84	0.14	0.03	3.02	x	x	x	x	x	x	x	x	x	PVC Residential Window Grey - Double Glazing	?	(DVP, 2020)	Chile - Chile	kg	Not specified	Not applicable	Not applicable
Firat	A.19-6	2.37	0.17	0.50	3.04	0.12	x	x	x	x	0.00	x	0.05	0.20	PVC Profiles for Windows and Doors	?	(Firat, 2022)	Turkey - Global	kg	Not specified	Not applicable	10% recycled, 90% disposal
IBU	A.19-7	x	x	x	80.00	0.40	1.48	60.90	35.20	0.00	0.09	4.10	1.72	-7.07	Plastic Windows with Double Insulating Glass Unit	31 kg/m^2	(IBU, 2022)	Germany - Europe	m^2	40 years	9 km (small truck) + 69 km (large truck)	Recycling: glass 65%, PVC 59%, Steel/aluminium 92%. Rest incinerated

Curtain Wall Façade

EPD	EPD ID	A1	A2	A3	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	D	Product type	Density	Source	Nationality - Geographical scope	Reference unit	Reference life	Transport distance A4	Phases C+D
Riventi	A.20-1	x	x	x	177.00	1.06	8.54	x	0.57	5.00	0.44	8.31	0.25	-28.10	Double glazing curtain wall system	?	(Riventi, 2023)	Spain - Europe	m^2	30 years	120 km	Recycled: 30% of glass, 95% of metals, 95% of plastic and others. Remainder disposed.
Alumil	A.20-2	x	x	x	140.00	x	x	x	x	1.01	0.76	0.55	0.37	-41.60	Double glazing curtain wall system with aluminium frame	?	(Alumil, 2022)	Greece - Global	m^2	Not specified	Not applicable	Recycled: 30% of glass, 95% of non-glass. Remainder disposed.
Strugal (1)	A.20-3	x	x	x	86.50	x	x	x	x	x	1.89	0.07	0.63	-15.30	Strugal S52CR with coated aluminium frame	?	(Strugal, 2022)	Spain - Global	m^2	50 years	Not applicable	Recycled: 30% of glass, 95% of metals, 95% of plastic and others. Remainder disposed.
Strugal (2)	A.20-4	x	x	x	83.90	x	x	x	x	x	1.84	0.07	0.62	-13.90	Strugal S52CRi with coated aluminium frame	?	(Strugal, 2022)	Spain - Global	m^2	50 years	Not applicable	Recycled: 30% of glass, 95% of metals, 95% of plastic and others. Remainder disposed.
Strugal (3)	A.20-5	x	x	x	87.60	x	x	x	x	x	1.91	0.07	0.62	-15.20	Strugal S52NT with coated aluminium frame	?	(Strugal, 2022)	Spain - Global	m^2	50 years	Not applicable	Recycled: 30% of glass, 95% of metals, 95% of plastic and others. Remainder disposed.
Strugal (4)	A.20-6	x	x	x	85.40	x	x	x	x	x	1.87	0.07	0.62	-14.30	Strugal S52SGi with coated aluminium frame	?	(Strugal, 2022)	Spain - Global	m^2	50 years	Not applicable	Recycled: 30% of glass, 95% of metals, 95% of plastic and others. Remainder disposed.

Plasterboard Wall

EPD	EPD ID	A1	A2	A3	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	D		Product Type	Density	Source	Nationality - Geographical scope	Reference unit	Reference life	Transport distance A4	Phases C+D
Saint-Gobain	A.21-1	x	x	x	2.57	0.23	0.57	x	x	0.05	0.04	0.27	0.40	-0.04		15.4 mm thick Fireboard type F	825 kg/m³	(Saint-Gobain, 2024)	Sweden - Nordic countries	m²	50 years	300 km	Recycling: 40%, landfill: 60%

A.2. Apollolaan

Chosen EPDs (Current Design, Design Variant 1, 2 & 3) with argumentation:

Product	Material type	EPD ID	Argumentation
Steel products	Steel	A.22-2	80% re-use at EoL might be high for current standards, but is deemed to be realistic for 50 years in the future. There are no welded connections in the building, so re-using material is realistic. Can be used for all steel products, not only hollow sections
Concrete floor/roof	Hollow core slab	A.23-4	Only EPD from a Dutch manufacturer.
Compression layer	Compression layer	A.2-7	Only available EPD for compression layers.
Computer floor	Computer floor	A.2-7	Consistent with C30/37 EPD from KasseNova.
Basement concrete floor	Cast in-situ C30/37	A.2-7	Consistent with C30/37 EPD from KasseNova.
Basement concrete wall	Cast in-situ C30/37	A.2-7	Consistent with C30/37 EPD from KasseNova.
Walls N/E/W façade	Curtain wall system	A.20-3	Consistent with curtain wall system EPD from KasseNova.
Walls S façade	Masonry	A.25-1	Only available EPD for masonry façades.
Timber columns and beams	Glulam	A.26-3	EPD contained information on phase A4.
Timber floor	CLT	A.8-1, A.8-2	Consistent with CLT EPD from KasseNova.
Plasterboard	Plasterboard	A.13-5	Consistent with plasterboard EPD from KasseNova.
Foam layer	Foam	A.10-1	Consistent with foam EPD from KasseNova.
Insulation layer	Heavy insulation	A.14-5	Consistent with insulation EPD from KasseNova.

Table A.2: Chosen EPDs for Apollolaan 171 with argumentation

EPD	EPD ID	A1	A2	A3	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	D		Product Type	Density	Source	Nationality - Geographical scope	Reference unit	Reference life	Transport distance A4	Phases C+D
BMS/SNS	A.22-1	x	x	x	1.16	0.02	0.05	x	x	0.05	0.01	0.03	0.00	-0.23		100% new heavy construction steel	?	(BMS/SNS, 2022a)	Dutch - Dutch	kg	100 years	150 km	Recycled: 83%, re-used: 16%, landfilled: 1%
BMS/SNS	A.22-2	x	x	x	1.16	0.02	0.05	x	x	0.05	0.01	0.03	0.00	-0.79		100% new heavy construction steel	?	(BMS/SNS, 2022c)	Dutch - Dutch	kg	100 years	150 km	Recycled: 19.8%, re-used: 80%, landfilled: 0.2%
BMS/SNS	A.22-3	x	x	x	1.16	0.02	0.05	x	x	0.05	0.01	0.03	0.00	-0.66		100% new heavy construction steel	?	(BMS/SNS, 2022b)	Dutch - Dutch	kg	100 years	150 km	Recycled: 34.4%, re-used: 65%, landfilled: 0.5%
BMS/SNS	A.22-4	x	x	x	0.21	0.02	0.05	x	x	0.05	0.01	0.03	0.00	-0.18		90% re-used heavy construction steel	?	(BMS/SNS, 2022d)	Dutch - Dutch	kg	100 years	150 km	Recycled: 83%, re-used: 16%, landfilled: 1%
Tata Steel	A.22-5	x	x	x	2590	x	x	x	x	4.53	17.90	1.02	0.15	-1610		Structural hollow sections	7850 kg/m^3	(Tata Steel UK, 2022)	UK/Dutch - Europe	tonne	Not declared	150 km	Recycled: 92%, re-used: 7%, landfilled: 1%

Table A.3: Available EPDs - Steel Products

EPD	EPD ID	A1	A2	A3	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	D		Product Type	Density	Source	Nationality - Geographical scope	Reference unit	Reference life	Transport distance A4	Phases C+D
INHUS	A.23-1	135	4.05	15.1	155	2.73	37.40	x	x	3.30	4.50	3.06	1.57	-5.78		Precast hollow core slab (t=200,265,320,400mm)	?	(INHUS, 2021)	Europe - Europe	ton	50 years	30 km	Recycled: 70% (concrete), 90% (steel). Remaining landfilled
Consolis	A.23-2	141	8.46	16.5	166	0.07	1.21	x	x	3.30	3.18	0.65	0.06	-16.6		Precast hollow core slab, t<=500 mm	2400 kg/m^3	(Consolis, 2022)	Nordic/Baltics - Nordic/Baltics	ton	60 years	1 km (truck)	Recycled: 99%, landfilled: 1%
MB Grupa	A.23-3	105	4.00	4.89	114	25.6	15.2	x	x	4.51	3.82	3.76	0.00	-6.95		Precast hollow core slab	?	(MB Grupa, 2023)	Latvia - Unknown	ton	Not specified	333 km (truck), 270 km (ferry)	Recycled: 80% (concrete), 95% (steel)
Dycore	A.23-4	47.8	2.81	6.88	57.49	3.09	1.82	x	x	0.48	2.49	0.59	-0.02	-5.82		Precast hollow core slab, t=260 mm	364.78 kg/m^2	(Dycore, 2024)	Dutch - Dutch	m^2	100 years	?	Unknown

Table A.4: Available EPDs - Hollow Core Slab

EPD	EPD ID	A1	A2	A3	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	D		Product Type	Density	Source	Nationality - Geographical scope	Reference unit	Reference life	Transport distance A4	Phases C+D
Kingspan	A.24-1	x	x	x	6.26	x	x	x	x	0.00	0.10	0.07	11.70	0.00		RG3 Access Floor Panels	9-10 kg/unit	(Kingspan, 2021)	UK - Worldwide	One panel (600x600 mm)	Not specified	Not relevant	Recycled: 99%
Bathgate	A.24-2	6.02	1.34	0.31	7.67	0.22	0.01	x	x	0.00	0.02	5.03	1.41	0.00		BGM 600 Raised Access Flooring Panel	10.76 kg/unit	(Bathgate Flooring, 2022)	UK - Worldwide	One panel (600x600 mm)	Not specified	227 km (truck)	Recycled: 99%

Table A.5: Available EPDs - Computer Floor

EPD	EPD ID	A1	A2	A3	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	D		Product Type	Density	Source	Nationality - Geographical scope	Reference unit	Reference life	Transport distance A4	Phases C+D
KEBE SA	A.25-1	60.4	1.57	85.2	147	4.28	0.143	x	x	0.00	6.49	1.81	1.58	-5.36		Clay bricks	Differs	(KEBE SA, 2023)	Greece - Worldwide	ton	150 years	30 km (truck)	Recycled/Re-used: 70%

Table A.6: Available EPDs - Masonry

EPD	EPD ID	A1	A2	A3	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	D		Product Type	Density	Source	Nationality - Geographical scope	Reference unit	Reference life	Transport distance A4	Phases C+D
HASSLACHER	A.26-1	x	x	x	-608	x	x	x	x	0	1.42	753	0	-410		Glulam - Norway spruce, Silver fir, Scots pine, European larch	470 kg/m^3	(HASSLACHER, 2021)	Austria, Germany - Europe	m^3	Same as building	Not applicable	Incinerated with energy recovery: 100%
Rubner	A.26-2	x	x	x	-687	x	x	x	x	0	1.47	771	0	-416		Glulam - Coniferous wood	464 kg/m^3	(Rubner, 2023)	Austria, Italy - Europe	m^3	Same as building	Not applicable	Incinerated with energy recovery: 100%
UAB Jures Medis	A.26-3	-910	26.9	69.5	-814	67.7	x	x	x	1.57	6.49	703	0.00	-740		Glulam - Spruce, pine, larch	467 kg/m^3	(UAB JURES MEDIS, 2021)	Norway - Europe	m^3	50 years	1561 km (truck), 154 km (ferry)	Incinerated with energy recovery: 100%

Table A.7: Available EPDs - Glulam

B

Carbon Footprint Calculations

B.1. Case Study 1: KasseNova aan de Vaart

B.1.1. Recalculation Phases A4 and C2

Table B.1 displays manufacturers of the elements which were used in design which are close to the building site. As there is no available information what company is the actual manufacturer of the products, realistic scenarios need to be developed. The companies in this table are part of this realistic scenario. The realistic transportation distance is the distance from the manufacturer to the building site of KasseNova aan de Vaart (Nieuwe Vaart 13, ’s-Gravenzande), which is used in phase A4 of the LCA.

Product	Material Type	Owner of EPD	Realistic Manufacturer	EPD Transport Distance	Realistic Transport Distance
Floor/Roof	Cast in-situ concrete C30/37	HERACLES - Greece	Balak Beton - Rotterdam	10 km	27 km
Walls	Cast in-situ concrete C30/37	HERACLES - Greece	Balak Beton - Rotterdam	10 km	27 km
Small foundation beams	Cast in-situ concrete C30/37	HERACLES - Greece	Balak Beton - Rotterdam	10 km	27 km
Large foundation beams	Cast in-situ concrete C30/37	HERACLES - Greece	Balak Beton - Rotterdam	10 km	27 km
Foundation piles	Prefab foundation piles	Centrum Pæle - Vejle, Denmark	Bruil - Woerdense Verlaat	100 km	75 km
Beams	Cast in-situ concrete C30/37	HERACLES - Greece	Balak Beton - Rotterdam	10 km	27 km
Reinforcement steel	Reinforcement steel	VWN - Average over multiple locations	Betonijzer Buigcentrale - Hardinxveld-Giessendam	647 km	64 km
Foundation blocks	Cast in-situ concrete C35/45	HERACLES - Greece	Balak Beton - Rotterdam	10 km	27 km
Columns	Cast in-situ concrete C35/45	HERACLES - Greece	Balak Beton - Rotterdam	10 km	27 km
Core element	Prefab concrete wall	INHUS Prefab - Lithuania	PSD Beton - Bergschenhoek	30 km	37 km
Balconies	Prefab balconies	INHUS Prefab - Lithuania	PSD Beton - Bergschenhoek	30 km	37 km
CLT floors/walls	CLT	KLH - Austria	KLH - Austria	634 km	1084 km
Wood flooring	Wood flooring	Unilin - Malaysia	Unilin - Malaysia	12400 km (boat) & 875 km (truck)	8400 km (boat) & 320 km (truck) (assume 50%)
Foam layer	Foam	Pepi Rer - Valka, Latvia	EKI - Nijmegen	100 km	137 km
Fibreboard	Fibreboard	James Hardie Europe - Europe	International Plywood B.V. - Nieuwland	100 km	80 km
Impact insulation	Impact insulation	BUR2000 - Turkey	Akoestiekwinkel.nl - Gorinchem	177 km	74 km
Insulation	Insulation	Knauf Insulation - Global	Knauf Insulation - Gilze	600 km	100 km
Plasterboard	Plasterboard	DALSAN - Turkey	Houtwerf - Zoeterwoude	350 km	35 km
Screed	Screed	DALSAN - Turkey	BBM Vloeren - Riel	350 km	108 km
Heating layer	Tacker layer	Uponor - Wolow, Poland	Benem - Alphen aan de Rijn	500 km	43 km
Steel column	HEA400	SNS - Average over multiple locations	Huisman Gemert - Gemert	150 km	144 km
Steel tube	Steel tube	Tata Steel - Europe	Tata Steel - Zwijndrecht	647 km	53 km
Windows	PVC profile + double glazing	Multiple companies - Europe	Creon Kozijnen - Hardinxveld-Giessendam	9 km (small truck) & 69 km (large truck) (assume both equal)	62 km
Curtain wall system	Curtain wall system	Strugal - Spain	Meer Gevelsystemen - Wateringen	120 km	12 km
Wall plasterboard	Plasterboard	Saint-Gobain - Sweden	BMN Bouwmaterialen - Delft	300 km	24 km
Wall insulation	Insulation	Recitel - Finland	BMN Bouwmaterialen - Delft	216 km (lorry) + 73 km (ferry)	24 km

Table B.1: List of Manufacturer of Products Used in Design, Along with Transportation Distance to Building Site

Table B.2 displays the assumed end-of-life transportation scenario (phase C2), along with a realistic end-of-life transportation scenario. The realistic scenarios shows companies which can recycle, reuse, landfill or incinerate the product.

Product	Material Type	Owner of EPD	Realistic EoL Company	EPD Transport Distance	Realistic Transport Distance
Roof/Floor	Cast in-situ concrete C30/37	HERACLES - Greece	(recycling) Rutte Groep - Amsterdam, (landfill) Gebr. de Jongh - Rotterdam	50 km	(recycling) 71 km, (landfill) 34 km
Walls	Cast in-situ concrete C30/37	HERACLES - Greece	(recycling) Rutte Groep - Amsterdam, (landfill) Gebr. de Jongh - Rotterdam	50 km	(recycling) 71 km, (landfill) 34 km
Small foundation beams	Cast in-situ concrete C30/37	HERACLES - Greece	(recycling) Rutte Groep - Amsterdam, (landfill) Gebr. de Jongh - Rotterdam	50 km	(recycling) 71 km, (landfill) 34 km
Large foundation beams	Cast in-situ concrete C30/37	HERACLES - Greece	(recycling) Rutte Groep - Amsterdam, (landfill) Gebr. de Jongh - Rotterdam	50 km	(recycling) 71 km, (landfill) 34 km
Beams	Cast in-situ concrete C30/37	HERACLES - Greece	(recycling) Rutte Groep - Amsterdam, (landfill) Gebr. de Jongh - Rotterdam	50 km	(recycling) 71 km, (landfill) 34 km
Reinforcement steel	Reinforcement steel	VWN - Average over multiple locations	(both recycling and landfill) Bart Hülters - Rotterdam	50 km	40 km
Foundation blocks	Cast in-situ concrete C35/45	HERACLES - Greece	(recycling) Rutte Groep - Amsterdam, (landfill) Gebr. de Jongh - Rotterdam	50 km	(recycling) 71 km, (landfill) 34 km
Columns	Cast in-situ concrete C35/45	HERACLES - Greece	(recycling) Rutte Groep - Amsterdam, (landfill) Gebr. de Jongh - Rotterdam	50 km	(recycling) 71 km, (landfill) 34 km
Core element	Prefab concrete wall	INHUS Prefab - Lithuania	(recycling) Rutte Groep - Amsterdam, (landfill) Gebr. de Jongh - Rotterdam	50 km	(recycling) 71 km, (landfill) 34 km
Balconies	Prefab balconies	INHUS Prefab - Lithuania	(recycling) Rutte Groep - Amsterdam, (landfill) Gebr. de Jongh - Rotterdam	50 km	(recycling) 71 km, (landfill) 34 km
CLT floors/walls	CLT	KLH - Austria	(recycling) Spelt Afvalinzameling - Rotterdam, (incineration) AVR Rozenburg - Rotterdam	50 km	(recycling) 25 km, (incineration) 40 km
Wood flooring	Wood flooring	Unilin - Malaysia	AVR Rozenburg - Rotterdam	50 km	40 km
Foam layer	Foam	Pepi Rer - Valka, Latvia	Faes - Reusel	50 km	132 km
Fibreboard	Fibreboard	James Hardie Europe - Europe	(recycling) Gipsnem - Gorinchem, (landfill) Gebr. de Jongh - Rotterdam	50 km	(recycling) 74 km, (landfill) 34 km
Insulation	Insulation	Knauf Insulation - Global	Gebr. de Jongh - Rotterdam	50 km	34 km
Plasterboard	Plasterboard	DALSAN - Turkey	Gebr. de Jongh - Rotterdam	100 km	34 km
Screed	Screed	DALSAN - Turkey	Gebr. de Jongh - Rotterdam	100 km	34 km
Heating layer	Tacker layer	Uponor - Wolow, Poland	Gebr. de Jongh - Rotterdam	50 km	34 km
Steel column	HEA400	SNS - Average over multiple locations	(recycling, reusing & landfill) Bart Hülters - Rotterdam	(recycling & reusing) 50 km, (landfill) 100 km	40 km
Steel tube	Steel tube	Tata Steel - Europe	(recycling, reusing & landfill) Bart Hülters - Rotterdam	(recycling & reusing) 150 km, (landfill) 100 km	40 km
Windows	PVC profile + double glazing	Multiple companies - Europe	Gebr. de Jongh - Rotterdam	22 km	34 km
Curtain wall system	Curtain wall system	Strugal - Spain	Gebr. de Jongh - Rotterdam	200 km	34 km
Wall plasterboard	Plasterboard	Saint-Gobain - Sweden	Gebr. de Jongh - Rotterdam	50 km	34 km

Table B.2: List of Realistic EoL Destinations, Along with Transportation Distance from Building Site

B.1.2. Other Adjustments to EPD Data

Other adjustments made to the EPD data in order to increase the quality of the input are:

Product	Material Type	Corresponding phase(s)	Adjustment	Argumentation
Reinforcement steel	Reinforcement steel	C	Missing, so phases C are used from EPD A.4-2	As long as the product is similar, the assumption is made that the different steel products have similar EoL carbon footprint values.
Foundation blocks	Cast in-situ concrete C35/45	C1	Equal to C1 from C30/37 concrete	One type of machinery is used for the deconstruction of concrete, leading to a single value of all C1 values for concrete.
Columns	Cast in-situ concrete C35/45	C1	Equal to C1 from C30/37 concrete	One type of machinery is used for the deconstruction of concrete, leading to a single value of all C1 values for concrete.
Core element	Prefab concrete wall	C1	Equal to C1 from C30/37 concrete	One type of machinery is used for the deconstruction of concrete, leading to a single value of all C1 values for concrete.
Balcony	Prefab balconies	C1	Equal to C1 from C30/37 concrete	One type of machinery is used for the deconstruction of concrete, leading to a single value of all C1 values for concrete.
CLT floors/walls	CLT	C3 (reuse scenario)	Carbon which is taken up during phase A1 is not re-emitted into the atmosphere	Since the CO_2 is emitted into the atmosphere in a different life cycle, the CO_2 emissions should be included in that specific life cycle
Foam layer	Foam	C	Missing, so phases C are used from EPD A.10-2	As long as the product is similar, the assumption is made that the different steel products have similar EoL carbon footprint values.

Table B.3: Other Adjustments to EPD Data

B.1.3. Unit Conversion

From unit in EPD to unit in design:

Material	Phase(s)	Unit before	Unit after	Calculation	Material Properties	New values
Reinforcement Steel	A4 & C (except C1)	kg	tonne	[1/tonne] = [1/kg] * 1000	-	**A4** = 69 **C2** = 3.60, **C3** = 55.00, **C4** = 0.12
Core Element	All Phases (except C1)	tonne	m^2	[1/m^2] = [1/tonne] * [tonne/m^3] * [m]	$\rho_{concrete}$ = 2.4 tonne/m^3 Thickness = 0.2 m	**A1-A3** = 75.84, **A4** = 1.31, **A5** = 3.53 **C2** = 2.18, **C3** = 1.59, **C4** = 0.74
Foam	C	m^3	m^2	[1/m^2] = [1/m^3] * [m]	Thickness = 0.3 m	**C2** = 0.01, **C3** = 15.12
Screed	All	kg	m^2	[1/m^2] = [1/kg] * [g/L] * [m]	ρ_{screed} = 1800 g/L Thickness = 0.07 m	**A1-A3** = 12.85, **A4** = 4.03, **A5** = 0.06 **C2** = 1.13, **C3** = 0.00, **C4** = 0.13
Steel Tube	All	tonne	m	[1/m] = [1/tonne] * [tonne/m^3] * [m^2]	ρ_{steel} = 7.85 tonne/m^3 Area = 0.002565 m^2	**A1-A3** = 51.82, **A4** = 4.03 **C1** = 0.09, **C2** = 0.36, **C3** = 0.02, **C4** = 0.00
Steel Column	All	kg	m^3	[1/m^3] = [1/kg] * [kg/m^3]	ρ_{steel} = 7850 kg/m^3	**A1-A3** = 9106.00, **A4** = 159.36, **A5** = 380.73 **C1** = 380.73, **C2** = 52.28, **C3** = 200.96, **C4** = 0.08
Reinforcement Steel	C1	m^3	tonne	[1/tonne] = [1/m^3] * [m^3/tonne]	ρ_{steel} = 1/7.85 m^3/tonne	**C1** = 1.91
Core Element	C1	m^3	m^2	[1/m^2] = [1/m^3] * [m]	Thickness = 0.2 m	**C1** = 3
Prefab Balconies	C1	m^3	tonne	[1/tonne] = [1/m^3] * [m^3/tonne]	$\rho_{concrete}$ = 1/2.4 m^3/tonne	**C1** = 6.25

Table B.4: Conversion from Unit in EPD to Unit in Design

B.1.4. Carbon Footprint Calculation

Current Design

Table B.5 displays the quantity of materials used, along with data from the EPDs, which might have been adjusted, in order to calculate the carbon footprint.

Product	Material Type	Quantity	Unit	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4
Floors/Roofs	Cast in-situ concrete C30/37	2,931.00	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Walls	Cast in-situ concrete C30/37	862.43	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Small foundation beams	Cast in-situ concrete C30/37	79.61	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Large foundation beams	Cast in-situ concrete C30/37	41.81	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Foundation piles	Prefab pile 450x450 mm	6,030.98	m	82.20	0.01	x	x	x	x	x	x	x
Beams	Cast in-situ concrete C30/37	244.22	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Reinforcement steel	Reinforcement steel	486.82	tonne	1020.00	6.83	x	x	x	21.00	2.88	55.00	0.12
Foundation blocks	Cast in-situ concrete C35/45	218.34	m^3	299.00	10.69	8.57	-7.79	x	15.00	22.50	1.43	-4.23
Columns	Cast in-situ concrete C35/45	42.62	m^3	299.00	10.69	8.57	-7.79	x	15.00	22.50	1.43	-4.23
Core elements	Prefab concrete wall	400.40	m^2	75.84	1.62	3.53	x	x	3.00	2.61	1.59	0.74
Balconies	Prefab balconies	1,325.30	tonne	196.00	3.37	4.03	x	x	6.25	5.45	3.74	1.53
Screed	Screed	8,279.70	m^2	12.85	1.24	0.06	x	x	x	1.13	0.00	0.13
Heating layers	Tacker layer	8,279.70	m^2	1.24	0.13	0.01	x	x	x	0.00	1.39	x
Steel tubes	Steel tube	59.50	m	51.82	0.10	x	x	x	0.09	0.10	0.02	0.00
Windows	PVC profile + double glazing	1,980.38	m^2	80.00	0.32	1.48	60.90	35.20	0.00	0.14	4.10	1.72
Windows bottom floor	Curtain wall system	95.14	m^2	86.50	0.11	x	x	x	x	0.32	0.07	0.63

Table B.5: KasseNova Current Design Variant - Quantity of Materials and Corresponding Data from EPDs [kg CO_2-eq./unit]

Product	Material Type	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	Total A1-A5	Total A-C
Floors/Roofs	Cast in-situ concrete C30/37	700,509.00	30,626.02	25,117.67	-29,896.20	x	43,965.00	63,895.80	3,780.99	-15,886.02	756,253.69	822,113.26
Walls	Cast in-situ concrete C30/37	206,120.05	9,011.50	7,391.00	-8,796.76	x	12,936.41	18,800.91	1,112.53	-4,674.35	222,522.55	241,901.29
Small foundation beams	Cast in-situ concrete C30/37	19,027.03	831.86	682.27	-812.03	x	1,194.17	1,735.52	102.70	-431.49	20,541.15	22,330.01
Large foundation beams	Cast in-situ concrete C30/37	9,993.07	436.89	358.33	-426.48	x	627.18	911.50	53.94	-226.62	10,788.29	11,727.81
Foundation piles	Prefab pile 450x450 mm	495,746.56	45.23	x	x	x	x	x	x	x	495,791.79	495,791.79
Beams	Cast in-situ concrete C30/37	58,369.36	2,551.89	2,092.99	-2,491.08	x	3,663.35	5,324.07	315.05	-1,323.69	63,014.24	68,501.94
Reinforcement steel	Reinforcement steel	496,551.38	3,322.68	x	x	x	10,223.12	1,402.03	26,774.83	58.42	499,874.06	538,332.46
Foundation blocks	Cast in-situ concrete C35/45	65,283.66	2,334.49	1,871.17	-1,700.87	x	3,275.10	4,912.65	312.23	-947.60	69,489.33	75,340.84
Columns	Cast in-situ concrete C35/45	12,743.47	455.70	365.26	-332.01	x	639.30	958.96	60.95	-184.97	13,564.42	14,706.65
Core elements	Prefab concrete wall	30,366.34	648.65	1,412.61	x	x	1,201.20	1,045.04	638.08	297.90	32,427.60	35,609.81
Balconies	Prefab balconies	259,758.80	4,462.29	5,340.96	x	x	8,283.13	7,222.89	4,956.62	2,027.71	269,562.04	292,052.39
Screed	Screed	106,410.70	10,301.27	500.76	x	x	x	9,389.18	x	1,043.24	117,212.73	127,645.15
Heating layers	Tacker layer	10,266.83	1,089.44	53.57	x	x	x	25.92	11,508.78	x	11,409.84	22,944.54
Steel tubes	Steel tube	3,083.31	5.70	x	x	x	5.43	5.71	1.22	0.17	3,089.01	3,101.55
Windows	PVC profile + double glazing	157,430.40	629.66	2,930.96	120,605.14	69,709.38	1.98	277.25	8,119.56	3,406.25	161,991.02	364,111
Windows bottom floor	Curtain wall system	8,229.61	10.08	x	x	x	x	30.44	6.87	60.03	8,239.69	8,337.04
										Total	**2,755,771.46**	**3,144,547.09**

Floor area	12,387.8	m^2
Total/m^2	**222.46**	**kg CO_2-eq./m^2**

Table B.6: KasseNova Current Design Variant - Calculation Carbon Footprint [kg CO_2-eq.]

Design Variant 1 - Recycling Scenario

Table B.7 displays the quantity of materials used, along with data from the EPDs, which might have been adjusted, in order to calculate the carbon footprint.

Product	Material Type	Quantity	Unit	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4
Floors/Roofs	Cast in-situ concrete C30/37	959.65	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Walls	Cast in-situ concrete C30/37	1150.27	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Small foundation beams	Cast in-situ concrete C30/37	79.61	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Large foundation beams	Cast in-situ concrete C30/37	41.81	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Foundation piles	Prefab pile 450x450 mm	6,030.98	m	82.20	0.01	x	x	x	x	x	x	x
Beams	Cast in-situ concrete C30/37	244.22	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Reinforcement steel	Reinforcement steel	345.10	tonne	1020.00	6.83	x	x	x	21.00	2.88	55.00	0.12
Foundation blocks	Cast in-situ concrete C35/45	218.34	m^3	299.00	10.69	8.57	-7.79	x	15.00	22.50	1.43	-4.23
Columns	Cast in-situ concrete C35/45	42.62	m^3	299.00	10.69	8.57	-7.79	x	15.00	22.50	1.43	-4.23
Core elements	Prefab concrete wall	400.40	m^2	75.84	1.62	3.53	x	x	3.00	2.61	1.59	0.74
Balconies	Prefab balconies	1,325.30	tonne	196.00	3.37	4.03	x	x	6.25	5.45	3.74	1.53
CLT floors	CLT	1,498.08	m^3	-708.00	44.28	5.38	x	x	4.01	2.05	60.00	0.00
Wood flooring	Wood flooring	7,490.40	m^2	-3.73	1.31	1.73	x	0.24	x	0.05	15.20	x
Foam layer	Foam	7,490.40	m^2	3.50	0.01	x	x	x	x	0.04	15.12	x
Fibreboard	Fibreboard	7,490.40	m^2	-0.46	0.09	0.07	x	x	x	0.07	0.20	3.44
Impact insulation layer	Impact insulation	7,490.40	m^2	0.43	0.00	0.13	x	x	x	x	x	0.02
Insulation layer	Insulation	7,490.40	m^2	4.63	0.05	0.39	x	x	x	0.01	x	0.07
Plasterboard	Plasterboard	7,490.40	m^2	1.32	0.02	x	x	x	0.14	0.15	0.07	0.06
Steel column	HEA400	0.46	m^3	9106.00	152.98	380.73	x	x	380.73	35.50	200.96	0.08
Steel tubes	Steel tube	59.50	m	51.82	0.10	x	x	x	0.09	0.10	0.02	0.00
Windows	PVC profile + double glazing	1,980.38	m^2	80.00	0.32	1.48	60.90	35.20	0.00	0.14	4.10	1.72
Windows bottom floor	Curtain wall system	95.14	m^2	86.50	0.11	x	x	x	x	0.32	0.07	0.63

Table B.7: KasseNova Design Variant 1 (Recycling Scenario) - Quantity of Materials and Corresponding Data from EPDs [kg CO_2-eq./unit]

Product	Material Type	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	Total A1-A5	Total A-C
Floors/Roofs	Cast in-situ concrete C30/37	229,355.16	10,027.33	8,224.16	-9,788.38	x	14,394.68	20,920.29	1,237.94	-5,201.28	247,606.64	269,169.87
Walls	Cast in-situ concrete C30/37	274,913.81	12,019.14	9,857.79	-11,732.72	x	17,254.01	25,075.82	1,483.84	-6,234.45	296,790.74	322,637.24
Small foundation beams	Cast in-situ concrete C30/37	19,027.03	831.86	682.27	-812.03	x	1,194.17	1,735.52	102.70	-431.49	20,541.15	22,330.01
Large foundation beams	Cast in-situ concrete C30/37	9,993.07	436.89	358.33	-426.48	x	627.18	911.50	53.94	-226.62	10,788.29	11,727.81
Foundation piles	Prefab pile 450x450 mm	495,746.56	45.23	x	x	x	x	x	x	x	495,791.79	495,791.79
Beams	Cast in-situ concrete C30/37	58,369.36	2,551.89	2,092.99	-2,491.08	x	3,663.35	5,324.07	315.05	-1,323.69	63,014.24	68,501.94
Reinforcement steel	Reinforcement steel	352,002.80	2,355.43	x	x	x	7,247.12	993.89	18,980.54	41.41	354,358.23	381,621.19
Foundation blocks	Cast in-situ concrete C35/45	65,283.66	2,334.49	1,871.17	-1,700.87	x	3,275.10	4,912.65	312.23	-947.60	69,489.33	75,340.84
Columns	Cast in-situ concrete C35/45	12,743.47	455.70	365.26	-332.01	x	639.30	958.96	60.95	-184.97	13,564.42	14,706.65
Core elements	Prefab concrete wall	30,366.34	648.65	1,412.61	x	x	1,201.20	1,045.04	638.08	297.90	32,427.60	35,609.81
Balconies	Prefab balconies	259,758.80	4,462.29	5,340.96	x	x	8,283.13	7,222.89	4,956.62	2,027.71	269,562.04	292,052.39
CLT floors	CLT	-1,060,640.64	66,339.90	8,059.67	x	x	6,007.30	3,071.06	89,884.80	x	-986,241.07	-887,277.91
Wood flooring	Wood flooring	-27,939.19	9,812.42	12,958.39	x	1,790.21	x	396.99	113,854.08	x	-5,168.38	110,872.90
Foam Layer	Foam	26,216.40	95.02	x	x	x	x	269.65	113,254.85	x	26,311.42	139,835.93
Fibreboard	Fibreboard	-3,430.60	696.61	540.06	x	x	x	546.80	1,468.12	25,766.98	-2,193.94	25,587.96
Impact insulation	Impact insulation	3,190.91	31.32	936.30	x	x	x	x	x	121.34	8,438.40	4,279.87
Insulation	Insulation	34,680.55	374.52	2,936.24	x	x	x	89.88	x	496.61	37,991.31	38,577.81
Plasterboard	Plasterboard	9,887.33	172.28	x	x	x	1,018.69	1,123.56	501.86	434.44	10.059.61	13.138.16
Steel column	HEA400	4,188.76	70.37	175.14	x	x	175.14	16.33	92.44	0.04	4,434.27	4,718.21
Steel tubes	Steel tube	3,083.31	5.70	x	x	x	5.43	5.71	1.22	0.17	3,089.01	3,101.55
Windows	PVC profile + double glazing	157,430.40	629.66	2,930.96	120,605.14	69,709.38	1.98	277.25	8,119.56	3,406.25	161,991.02	364,110,58
Windows bottom floor	Curtain wall system	8,229.61	10.08	x	x	x	x	30.44	6.87	60.03	8,239.69	8,337.04
										Total	**1,140,885.82**	**1,814,771.62**

Floor area	12,387.8	m^2
Total/m^2	**92.10**	**kg CO_2-eq./m^2**

Table B.8: KasseNova Design Variant 1 (Recycling Scenario) - Calculation Carbon Footprint [kg CO_2-eq.]

Design Variant 1 - Incinerating Scenario

Table B.9 displays the quantity of materials used, along with data from the EPDs, which might have been adjusted, in order to calculate the carbon footprint.

Product	Material Type	Quantity	Unit	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4
Floors/Roofs	Cast in-situ concrete C30/37	959.65	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Walls	Cast in-situ concrete C30/37	1150.27	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Small foundation beams	Cast in-situ concrete C30/37	79.61	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Large foundation beams	Cast in-situ concrete C30/37	41.81	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Foundation piles	Prefab pile 450x450 mm	6,030.98	m	82.20	0.01	x	x	x	x	x	x	x
Beams	Cast in-situ concrete C30/37	244.22	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Reinforcement steel	Reinforcement steel	345.10	tonne	1020.00	6.83	x	x	x	21.00	2.88	55.00	0.12
Foundation blocks	Cast in-situ concrete C35/45	218.34	m^3	299.00	10.69	8.57	-7.79	x	15.00	22.50	1.43	-4.23
Columns	Cast in-situ concrete C35/45	42.62	m^3	299.00	10.69	8.57	-7.79	x	15.00	22.50	1.43	-4.23
Core elements	Prefab concrete wall	400.40	m^2	75.84	1.62	3.53	x	x	3.00	2.61	1.59	0.74
Balconies	Prefab balconies	1,325.30	tonne	196.00	3.37	4.03	x	x	6.25	5.45	3.74	1.53
CLT floors	CLT	1,498.08	m^3	-708.00	44.28	5.38	x	x	4.01	2.05	782.00	0.00
Wood flooring	Wood flooring	7,490.40	m^2	-3.73	1.31	1.73	x	0.24	x	0.05	15.20	x
Foam layer	Foam	7,490.40	m^2	3.50	0.01	x	x	x	x	0.04	15.12	x
Fibreboard	Fibreboard	7,490.40	m^2	-0.46	0.09	0.07	x	x	x	0.07	0.20	3.44
Impact insulation layer	Impact insulation	7,490.40	m^2	0.43	0.00	0.13	x	x	x	x	x	0.02
Insulation layer	Insulation	7,490.40	m^2	4.63	0.05	0.39	x	x	x	0.01	x	0.07
Plasterboard	Plasterboard	7,490.40	m^2	1.32	0.02	x	x	x	0.14	0.15	0.07	0.06
Steel column	HEA400	0.46	m^3	9106.00	152.98	380.73	x	x	380.73	35.50	200.96	0.08
Steel tubes	Steel tube	59.50	m	51.82	0.10	x	x	x	0.09	0.10	0.02	0.00
Windows	PVC profile + double glazing	1,980.38	m^2	80.00	0.32	1.48	60.90	35.20	0.00	0.14	4.10	1.72
Windows bottom floor	Curtain wall system	95.14	m^2	86.50	0.11	x	x	x	x	0.32	0.07	0.63

Table B.9: KasseNova Design Variant 1 (Incinerating Scenario) - Quantity of Materials and Corresponding Data from EPDs [kg CO_2-eq./unit]

Product	Material Type	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	Total A1-A5	Total A-C
Floors/Roofs	Cast in-situ concrete C30/37	229,355.16	10,027.33	8,224.16	-9,788.38	x	14,394.68	20,920.29	1,237.94	-5,201.28	247,606.64	269,169.87
Walls	Cast in-situ concrete C30/37	274,913.81	12,019.14	9,857.79	-11,732.72	x	17,254.01	25,075.82	1,483.84	-6,234.45	296,790.74	322,637.24
Small foundation beams	Cast in-situ concrete C30/37	19,027.03	831.86	682.27	-812.03	x	1,194.17	1,735.52	102.70	-431.49	20,541.15	22,330.01
Large foundation beams	Cast in-situ concrete C30/37	9,993.07	436.89	358.33	-426.48	x	627.18	911.50	53.94	-226.62	10,788.29	11,727.81
Foundation piles	Prefab pile 450x450 mm	495,746.56	45.23	x	x	x	x	x	x	x	495,791.79	495,791.79
Beams	Cast in-situ concrete C30/37	58,369.36	2,551.89	2,092.99	-2,491.08	x	3,663.35	5,324.07	315.05	-1,323.69	63,014.24	68,501.94
Reinforcement steel	Reinforcement steel	352,002.80	2,355.43	x	x	x	7,247.12	993.89	18,980.54	41.41	354,358.23	381,621.19
Foundation blocks	Cast in-situ concrete C35/45	65,283.66	2,334.49	1,871.17	-1,700.87	x	3,275.10	4,912.65	312.23	-947.60	69,489.33	75,340.84
Columns	Cast in-situ concrete C35/45	12,743.47	455.70	365.26	-332.01	x	639.30	958.96	60.95	-184.97	13,564.42	14,706.65
Core elements	Prefab concrete wall	30,366.34	648.65	1,412.61	x	x	1,201.20	1,045.04	638.08	297.90	32,427.60	35,609.81
Balconies	Prefab balconies	259,758.80	4,462.29	5,340.96	x	x	8,283.13	7,222.89	4,956.62	2,027.71	269,562.04	292,052.39
CLT floors	CLT	-1,060,640.64	66,339.90	8,059.67	x	x	6,007.30	3,071.06	1,171,498.56	x	-986,241.07	194,335.85
Wood flooring	Wood flooring	-27,939.19	9,812.42	12,958.39	x	1,790.21	x	396.99	113,854.08	x	-5,168.38	110,872.90
Foam Layer	Foam	26,216.40	95.02	x	x	x	x	269.65	113,254.85	x	26,311.42	139,835.93
Fibreboard	Fibreboard	-3,430.60	696.61	540.06	x	x	x	546.80	1,468.12	25,766.98	-2,193.94	25,587.96
Impact insulation	Impact insulation	3,190.91	31.32	936.30	x	x	x	x	x	121.34	4,279.87	12,839.61
Insulation	Insulation	34,680.55	374.52	2,936.24	x	x	x	89.88	x	496.61	37,991.31	38,577.81
Plasterboard	Plasterboard	9,887.33	172.28	x	x	x	1,018.69	1,123.56	501.86	434.44	10.059.61	13.138.16
Steel column	HEA400	4,188.76	70.37	175.14	x	x	175.14	16.33	92.44	0.04	4,434.27	4,718.21
Steel tubes	Steel tube	3,083.31	5.70	x	x	x	5.43	5.71	1.22	0.17	3,089.01	3,101.55
Windows	PVC profile + double glazing	157,430.40	629.66	2,930.96	120,605.14	69,709.38	1.98	277.25	8,119.56	3,406.25	161,991.02	364,110,58
Windows bottom floor	Curtain wall system	8,229.61	10.08	x	x	x	x	30.44	6.87	60.03	8,239.69	8,337.04
										Total	**1,140,885.82**	**2,896,385.38**

Floor area	12,387.8	m^2

Total/m²	**92.10**	**kg CO_2-eq./m²**

Table B.10: KasseNova Design Variant 1 (Incinerating Scenario) - Calculation Carbon Footprint [kg CO_2-eq.]

Design Variant 2 - Recycling Scenario

Table B.11 displays the quantity of materials used, along with data from the EPDs, which might have been adjusted, in order to calculate the carbon footprint.

Product	Material Type	Quantity	Unit	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4
Floors/Roofs	Cast in-situ concrete C30/37	2,931.00	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Walls	Cast in-situ concrete C30/37	352.87	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Small foundation beams	Cast in-situ concrete C30/37	79.61	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Large foundation beams	Cast in-situ concrete C30/37	41.81	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Foundation piles	Prefab pile 450x450 mm	6,030.98	m	82.20	0.01	x	x	x	x	x	x	x
Beams	Cast in-situ concrete C30/37	244.22	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Reinforcement steel	Reinforcement steel	451.22	tonne	1020.00	6.83	x	x	x	21.00	2.88	55.00	0.12
Foundation blocks	Cast in-situ concrete C35/45	218.34	m^3	299.00	10.69	8.57	-7.79	x	15.00	22.50	1.43	-4.23
Columns	Cast in-situ concrete C35/45	42.62	m^3	299.00	10.69	8.57	-7.79	x	15.00	22.50	1.43	-4.23
Core elements	Prefab concrete wall	400.40	m^2	75.84	1.62	3.53	x	x	3.00	2.61	1.59	0.74
Balconies	Prefab balconies	1,325.30	tonne	196.00	3.37	4.03	x	x	6.25	5.45	3.74	1.53
CLT walls	CLT	407.64	m^3	-708.00	44.28	5.38	x	x	4.01	2.05	60.00	0.00
Wall plasterboard	Plasterboard	2,038.19	m^2	2.57	0.02	0.57	x	x	0.05	0.03	0.27	0.40
Wall insulation	Insulation	2,038.19	m^2	15.70	0.02	0.60	x	x	x	x	13.20	0.03
Screed	Screed	8,279.70	m^2	12.85	1.24	0.06	x	x	x	1.13	0.00	0.13
Heating layers	Tacker layer	8,279.70	m^2	1.24	0.13	0.01	x	x	x	0.00	1.39	x
Steel tubes	Steel tube	59.50	m	51.82	0.10	x	x	x	0.09	0.10	0.02	0.00
Windows	PVC profile + double glazing	1,980.38	m^2	80.00	0.32	1.48	60.90	35.20	0.00	0.14	4.10	1.72
Windows bottom floor	Curtain wall system	95.14	m^2	86.50	0.11	x	x	x	x	0.32	0.07	0.63

Table B.11: KasseNova Design Variant 2 (Recycling Scenario) - Quantity of Materials and Corresponding Data from EPDs [kg CO_2-eq./unit]

Product	Material Type	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	Total A1-A5	Total A-C
Floors/Roofs	Cast in-situ concrete C30/37	229,355.16	10,027.33	8,224.16	-9,788.38	x	14,394.68	20,920.29	1,237.94	-5,201.28	247,606.64	269,169.87
Walls	Cast in-situ concrete C30/37	274,913.81	12,019.14	9,857.79	-11,732.72	x	17,254.01	25,075.82	1,483.84	-6,234.45	296,790.74	322,637.24
Small foundation beams	Cast in-situ concrete C30/37	19,027.03	831.86	682.27	-812.03	x	1,194.17	1,735.52	102.70	-431.49	20,541.15	22,330.01
Large foundation beams	Cast in-situ concrete C30/37	9,993.07	436.89	358.33	-426.48	x	627.18	911.50	53.94	-226.62	10,788.29	11,727.81
Foundation piles	Prefab pile 450x450 mm	495,746.56	45.23	x	x	x	x	x	x	x	495,791.79	495,791.79
Beams	Cast in-situ concrete C30/37	58,369.36	2,551.89	2,092.99	-2,491.08	x	3,663.35	5,324.07	315.05	-1,323.69	63,014.24	68,501.94
Reinforcement steel	Reinforcement steel	352,002.80	2,355.43	x	x	x	7,247.12	993.89	18,980.54	41.41	354,358.23	381,621.19
Foundation blocks	Cast in-situ concrete C35/45	65,283.66	2,334.49	1,871.17	-1,700.87	x	3,275.10	4,912.65	312.23	-947.60	69,489.33	75,340.84
Columns	Cast in-situ concrete C35/45	12,743.47	455.70	365.26	-332.01	x	639.30	958.96	60.95	-184.97	13,564.42	14,706.65
Core elements	Prefab concrete wall	30,366.34	648.65	1,412.61	x	x	1,201.20	1,045.04	638.08	297.90	32,427.60	35,609.81
Balconies	Prefab balconies	259,758.80	4,462.29	5,340.96	x	x	8,283.13	7,222.89	4,956.62	2,027.71	269,562.04	292,052.39
CLT walls	CLT	-288,609	18,052	2,193	x	x	1,635	836	24,485	x	-268,364	-241,436
Wall plasterboard	Wall plasterboard	5,238	41	1,162	x	x	x	82	550	815	6,441	7,888
Wall insulation	Wall insulation	32,000	41	1,223	x	x	x	x	26,904	61	33,263	60,229
Screed	Screed	106,411	10,301	501	x	x	x	9,389	x	1,043	117,213	127,645
Heating layers	Tacker layer	10,267	1,089	54	x	x	x	26	11,509	x	11,410	22,945
Steel tubes	Steel tube	3,083.31	5.70	x	x	x	5.43	5.71	1.22	0.17	3,089.01	3,101.55
Windows	PVC profile + double glazing	157,430.40	629.66	2,930.96	120,605.14	69,709.38	1.98	277.25	8,119.56	3,406.25	161,991.02	364,110,58
Windows bottom floor	Curtain wall system	8,229.61	10.08	x	x	x	x	30.44	6.87	60.03	8,239.69	8,337.04
										Total	**2,359,081**	**2,788,936**

Floor area	12,387.8	m^2
Total/m²	**190.44**	**kg CO_2-eq./m²**

Table B.12: KasseNova Design Variant 2 (Recycling Scenario) - Calculation Carbon Footprint [kg CO_2-eq.]

Design Variant 2 - Incineration Scenario

Table B.13 displays the quantity of materials used, along with data from the EPDs, which might have been adjusted, in order to calculate the carbon footprint.

Product	Material Type	Quantity	Unit	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4
Floors/Roofs	Cast in-situ concrete C30/37	2,931.00	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Walls	Cast in-situ concrete C30/37	352.87	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Small foundation beams	Cast in-situ concrete C30/37	79.61	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Large foundation beams	Cast in-situ concrete C30/37	41.81	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Foundation piles	Prefab pile 450x450 mm	6,030.98	m	82.20	0.01	x	x	x	x	x	x	x
Beams	Cast in-situ concrete C30/37	244.22	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Reinforcement steel	Reinforcement steel	451.22	tonne	1020.00	6.83	x	x	x	21.00	2.88	55.00	0.12
Foundation blocks	Cast in-situ concrete C35/45	218.34	m^3	299.00	10.69	8.57	-7.79	x	15.00	22.50	1.43	-4.23
Columns	Cast in-situ concrete C35/45	42.62	m^3	299.00	10.69	8.57	-7.79	x	15.00	22.50	1.43	-4.23
Core elements	Prefab concrete wall	400.40	m^2	75.84	1.62	3.53	x	x	3.00	2.61	1.59	0.74
Balconies	Prefab balconies	1,325.30	tonne	196.00	3.37	4.03	x	x	6.25	5.45	3.74	1.53
CLT walls	CLT	407.64	m^3	-708.00	44.28	5.38	x	x	4.01	2.05	782.00	0.00
Wall plasterboard	Plasterboard	2,038.19	m^2	2.57	0.02	0.57	x	x	0.05	0.03	0.27	0.40
Wall insulation	Insulation	2,038.19	m^2	15.70	0.02	0.60	x	x	x	x	13.20	0.03
Screed	Screed	8,279.70	m^2	12.85	1.24	0.06	x	x	x	1.13	0.00	0.13
Heating layers	Tacker layer	8,279.70	m^2	1.24	0.13	0.01	x	x	x	0.00	1.39	x
Steel tubes	Steel tube	59.50	m	51.82	0.10	x	x	x	0.09	0.10	0.02	0.00
Windows	PVC profile + double glazing	1,980.38	m^2	80.00	0.32	1.48	60.90	35.20	0.00	0.14	4.10	1.72
Windows bottom floor	Curtain wall system	95.14	m^2	86.50	0.11	x	x	x	x	0.32	0.07	0.63

Table B.13: KasseNova Design Variant 2 (Incineration Scenario) - Quantity of Materials and Corresponding Data from EPDs [kg CO_2-eq./unit]

Product	Material Type	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	Total A1-A5	Total A-C
Floors/Roofs	Cast in-situ concrete C30/37	229,355.16	10,027.33	8,224.16	-9,788.38	x	14,394.68	20,920.29	1,237.94	-5,201.28	247,606.64	269,169.87
Walls	Cast in-situ concrete C30/37	274,913.81	12,019.14	9,857.79	-11,732.72	x	17,254.01	25,075.82	1,483.84	-6,234.45	296,790.74	322,637.24
Small foundation beams	Cast in-situ concrete C30/37	19,027.03	831.86	682.27	-812.03	x	1,194.17	1,735.52	102.70	-431.49	20,541.15	22,330.01
Large foundation beams	Cast in-situ concrete C30/37	9,993.07	436.89	358.33	-426.48	x	627.18	911.50	53.94	-226.62	10,788.29	11,727.81
Foundation piles	Prefab pile 450x450 mm	495,746.56	45.23	x	x	x	x	x	x	x	495,791.79	495,791.79
Beams	Cast in-situ concrete C30/37	58,369.36	2,551.89	2,092.99	-2,491.08	x	3,663.35	5,324.07	315.05	-1,323.69	63,014.24	68,501.94
Reinforcement steel	Reinforcement steel	352,002.80	2,355.43	x	x	x	7,247.12	993.89	18,980.54	41.41	354,358.23	381,621.19
Foundation blocks	Cast in-situ concrete C35/45	65,283.66	2,334.49	1,871.17	-1,700.87	x	3,275.10	4,912.65	312.23	-947.60	69,489.33	75,340.84
Columns	Cast in-situ concrete C35/45	12,743.47	455.70	365.26	-332.01	x	639.30	958.96	60.95	-184.97	13,564.42	14,706.65
Core elements	Prefab concrete wall	30,366.34	648.65	1,412.61	x	x	1,201.20	1,045.04	638.08	297.90	32,427.60	35,609.81
Balconies	Prefab balconies	259,758.80	4,462.29	5,340.96	x	x	8,283.13	7,222.89	4,956.62	2,027.71	269,562.04	292,052.39
CLT walls	CLT	-288,609	18,052	2,193	x	x	1,635	836	318,774	x	-268,364	52,880
Wall plasterboard	Wall plasterboard	5,238	41	1,162	x	x	x	82	550	815	6,441	7,888
Wall insulation	Wall insulation	32,000	41	1,223	x	x	x	x	26,904	61	33,263	60,229
Screed	Screed	106,411	10,301	501	x	x	x	9,389	x	1,043	117,213	127,645
Heating layers	Tacker layer	10,267	1,089	54	x	x	x	26	11,509	x	11,410	22,945
Steel tubes	Steel tube	3,083.31	5.70	x	x	x	5.43	5.71	1.22	0.17	3,089.01	3,101.55
Windows	PVC profile + double glazing	157,430.40	629.66	2,930.96	120,605.14	69,709.38	1.98	277.25	8,119.56	3,406.25	161,991.02	364,110,58
Windows bottom floor	Curtain wall system	8,229.61	10.08	x	x	x	x	30.44	6.87	60.03	8,239.69	8,337.04
										Total	**2,359,081**	**3,083,252**

Floor area	12,387.8	m^2
Total/m²	**190.44**	**kg CO_2-eq./m²**

Table B.14: KasseNova Design Variant 2 (Incineration Scenario) - Calculation Carbon Footprint [kg CO_2-eq.]

Design Variant 3 - Recycling Scenario

Table B.15 displays the quantity of materials used, along with data from the EPDs, which might have been adjusted, in order to calculate the carbon footprint.

Product	Material Type	Quantity	Unit	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4
Floors/Roofs	Cast in-situ concrete C30/37	959.65	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Walls	Cast in-situ concrete C30/37	352.87	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Small foundation beams	Cast in-situ concrete C30/37	79.61	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Large foundation beams	Cast in-situ concrete C30/37	41.81	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Foundation piles	Prefab pile 450x450 mm	6,030.98	m	82.20	0.01	x	x	x	x	x	x	x
Beams	Cast in-situ concrete C30/37	244.22	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Reinforcement steel	Reinforcement steel	257.69	tonne	1020.00	6.83	x	x	x	21.00	2.88	55.00	0.12
Foundation blocks	Cast in-situ concrete C35/45	218.34	m^3	299.00	10.69	8.57	-7.79	x	15.00	22.50	1.43	-4.23
Columns	Cast in-situ concrete C35/45	42.62	m^3	299.00	10.69	8.57	-7.79	x	15.00	22.50	1.43	-4.23
Core elements	Prefab concrete wall	400.40	m^2	75.84	1.62	3.53	x	x	3.00	2.61	1.59	0.74
Balconies	Prefab balconies	1,325.30	tonne	196.00	3.37	4.03	x	x	6.25	5.45	3.74	1.53
CLT floors	CLT	1,498.08	m^3	-708.00	44.28	5.38	x	x	4.01	2.05	60.00	0.00
Wood flooring	Wood flooring	7,490.40	m^2	-3.73	1.31	1.73	x	0.24	x	0.05	15.20	x
Foam layer	Foam	7,490.40	m^2	3.50	0.01	x	x	x	x	0.04	15.12	x
Fibreboard	Fibreboard	7,490.40	m^2	-0.46	0.09	0.07	x	x	x	0.07	0.20	3.44
Impact insulation layer	Impact insulation	7,490.40	m^2	0.43	0.00	0.13	x	x	x	x	x	0.02
Insulation layer	Insulation	7,490.40	m^2	4.63	0.05	0.39	x	x	x	0.01	x	0.07
Plasterboard	Plasterboard	7,490.40	m^2	1.32	0.02	x	x	x	0.14	0.15	0.07	0.06
CLT walls	CLT	407.64	m^3	-708.00	44.28	5.38	x	x	4.01	2.05	60.00	0.00
Wall plasterboard	Plasterboard	2,038.19	m^2	2.57	0.02	0.57	x	x	0.05	0.03	0.27	0.40
Wall insulation	Insulation	2,038.19	m^2	15.70	0.02	0.60	x	x	x	x	13.20	0.03
Steel column	HEA400	0.46	m^3	9106.00	152.98	380.73	x	x	380.73	35.50	200.96	0.08
Steel tubes	Steel tube	59.50	m	51.82	0.10	x	x	x	0.09	0.10	0.02	0.00
Windows	PVC profile + double glazing	1,980.38	m^2	80.00	0.32	1.48	60.90	35.20	0.00	0.14	4.10	1.72
Windows bottom floor	Curtain wall system	95.14	m^2	86.50	0.11	x	x	x	x	0.32	0.07	0.63

Table B.15: KasseNova Design Variant 3 (Recycling Scenario) - Quantity of Materials and Corresponding Data from EPDs [kg CO_2-eq./unit]

Product	Material Type	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	Total A1-A5	Total A-C
Floors/Roofs	Cast in-situ concrete C30/37	229,355.16	10,027.33	8,224.16	-9,788.38	x	14,394.68	20,920.29	1,237.94	-5,201.28	247,606.64	269,169.87
Walls	Cast in-situ concrete C30/37	84,336	3,687	3,024	-3,599	x	5,293	7,693	455	-1,913	91,047	98,976
Small foundation beams	Cast in-situ concrete C30/37	19,027.03	831.86	682.27	-812.03	x	1,194.17	1,735.52	102.70	-431.49	20,541.15	22,330.01
Large foundation beams	Cast in-situ concrete C30/37	9,993.07	436.89	358.33	-426.48	x	627.18	911.50	53.94	-226.62	10,788.29	11,727.81
Foundation piles	Prefab pile 450x450 mm	495,746.56	45.23	x	x	x	x	x	x	x	495,791.79	495,791.79
Beams	Cast in-situ concrete C30/37	58,369.36	2,551.89	2,092.99	-2,491.08	x	3,663.35	5,324.07	315.05	-1,323.69	63,014.24	68,501.94
Reinforcement steel	Reinforcement steel	262,844	1,759	x	x	x	5,411	742	14,173	31	264,603	284,960
Foundation blocks	Cast in-situ concrete C35/45	65,283.66	2,334.49	1,871.17	-1,700.87	x	3,275.10	4,912.65	312.23	-947.60	69,489.33	75,340.84
Columns	Cast in-situ concrete C35/45	12,743.47	455.70	365.26	-332.01	x	639.30	958.96	60.95	-184.97	13,564.42	14,706.65
Core elements	Prefab concrete wall	30,366.34	648.65	1,412.61	x	x	1,201.20	1,045.04	638.08	297.90	32,427.60	35,609.81
Balconies	Prefab balconies	259,758.80	4,462.29	5,340.96	x	x	8,283.13	7,222.89	4,956.62	2,027.71	269,562.04	292,052.39
CLT floors	CLT	-1,060,640.64	66,339.90	8,059.67	x	x	6,007.30	3,071.06	89,884.80	x	-986,241.07	-887,277.91
Wood flooring	Wood flooring	-27,939.19	9,812.42	12,958.39	x	1,790.21	x	396.99	113,854.08	x	-5,168.38	110,872.90
Foam Layer	Foam	26,216.40	95.02	x	x	x	x	269.65	113,254.85	x	26,311.42	139,835.93
Fibreboard	Fibreboard	-3,430.60	696.61	540.06	x	x	x	546.80	1,468.12	25,766.98	-2,193.94	25,587.96
Impact insulation	Impact insulation	3,190.91	31.32	936.30	x	x	x	x	x	121.34	4,159	4,280
Insulation	Insulation	34,680.55	374.52	2,936.24	x	x	x	89.88	x	496.61	37,991.31	38,577.81
Plasterboard	Plasterboard	9,887.33	172.28	x	x	x	1,018.69	1,123.56	501.86	434.44	10.059.61	13.138.16
Steel column	HEA400	4,188.76	70.37	175.14	x	x	175.14	16.33	92.44	0.04	4,434.27	4,718.21
CLT walls	CLT	-492,400	30,798	3,742	x	x	2,789	1,426	41,729	x	-457,860	-411,917
Wall plasterboard	Wall plasterboard	5,238	41	1,162	x	x	x	82	550	815	6,441	7,888
Wall insulation	Wall insulation	32,000	41	1,223	x	x	x	x	26,904	61	33,263	60,229
Steel tubes	Steel tube	3,083.31	5.70	x	x	x	5.43	5.71	1.22	0.17	3,089.01	3,101.55
Windows	PVC profile + double glazing	157,430.40	629.66	2,930.96	120,605.14	69,709.38	1.98	277.25	8,119.56	3,406.25	161,991.02	364,110,58
Windows bottom floor	Curtain wall system	8,229.61	10.08	x	x	x	x	30.44	6.87	60.03	8,239.69	8,337.04
										Total	**422,952**	**1,152,767**

Floor area	12,387.8	m^2
Total/m²	**34.14**	**kg CO_2-eq./m²**

Table B.16: KasseNova Design Variant 3 (Recycling Scenario) - Calculation Carbon Footprint [kg CO_2-eq.]

Design Variant 3 - Incineration Scenario

Table B.17 displays the quantity of materials used, along with data from the EPDs, which might have been adjusted, in order to calculate the carbon footprint.

Product	Material Type	Quantity	Unit	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4
Floors/Roofs	Cast in-situ concrete C30/37	959.65	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Walls	Cast in-situ concrete C30/37	352.87	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Small foundation beams	Cast in-situ concrete C30/37	79.61	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Large foundation beams	Cast in-situ concrete C30/37	41.81	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Foundation piles	Prefab pile 450x450 mm	6,030.98	m	82.20	0.01	x	x	x	x	x	x	x
Beams	Cast in-situ concrete C30/37	244.22	m^3	239.00	10.45	8.57	-10.20	x	15.00	21.80	1.29	-5.42
Reinforcement steel	Reinforcement steel	257.69	tonne	1020.00	6.83	x	x	x	21.00	2.88	55.00	0.12
Foundation blocks	Cast in-situ concrete C35/45	218.34	m^3	299.00	10.69	8.57	-7.79	x	15.00	22.50	1.43	-4.23
Columns	Cast in-situ concrete C35/45	42.62	m^3	299.00	10.69	8.57	-7.79	x	15.00	22.50	1.43	-4.23
Core elements	Prefab concrete wall	400.40	m^2	75.84	1.62	3.53	x	x	3.00	2.61	1.59	0.74
Balconies	Prefab balconies	1,325.30	tonne	196.00	3.37	4.03	x	x	6.25	5.45	3.74	1.53
CLT floors	CLT	1,498.08	m^3	-708.00	44.28	5.38	x	x	4.01	2.05	782.00	0.00
Wood flooring	Wood flooring	7,490.40	m^2	-3.73	1.31	1.73	x	0.24	x	0.05	15.20	x
Foam layer	Foam	7,490.40	m^2	3.50	0.01	x	x	x	x	0.04	15.12	x
Fibreboard	Fibreboard	7,490.40	m^2	-0.46	0.09	0.07	x	x	x	0.07	0.20	3.44
Impact insulation layer	Impact insulation	7,490.40	m^2	0.43	0.00	0.13	x	x	x	x	x	0.02
Insulation layer	Insulation	7,490.40	m^2	4.63	0.05	0.39	x	x	x	0.01	x	0.07
Plasterboard	Plasterboard	7,490.40	m^2	1.32	0.02	x	x	x	0.14	0.15	0.07	0.06
CLT walls	CLT	407.64	m^3	-708.00	44.28	5.38	x	x	4.01	2.05	782.00	0.00
Wall plasterboard	Plasterboard	2,038.19	m^2	2.57	0.02	0.57	x	x	0.05	0.03	0.27	0.40
Wall insulation	Insulation	2,038.19	m^2	15.70	0.02	0.60	x	x	x	x	13.20	0.03
Steel column	HEA400	0.46	m^3	9106.00	152.98	380.73	x	x	380.73	35.50	200.96	0.08
Steel tubes	Steel tube	59.50	m	51.82	0.10	x	x	x	0.09	0.10	0.02	0.00
Windows	PVC profile + double glazing	1,980.38	m^2	80.00	0.32	1.48	60.90	35.20	0.00	0.14	4.10	1.72
Windows bottom floor	Curtain wall system	95.14	m^2	86.50	0.11	x	x	x	x	0.32	0.07	0.63

Table B.17: KasseNova Design Variant 3 (Incineration Scenario) - Quantity of Materials and Corresponding Data from EPDs [kg CO_2-eq./unit]

Product	Material Type	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	Total A1-A5	Total A-C
Floors/Roofs	Cast in-situ concrete C30/37	229,355.16	10,027.33	8,224.16	-9,788.38	x	14,394.68	20,920.29	1,237.94	-5,201.28	247,606.64	269,169.87
Walls	Cast in-situ concrete C30/37	84,336	3,687	3,024	-3,599	x	5,293	7,693	455	-1,913	91,047	98,976
Small foundation beams	Cast in-situ concrete C30/37	19,027.03	831.86	682.27	-812.03	x	1,194.17	1,735.52	102.70	-431.49	20,541.15	22,330.01
Large foundation beams	Cast in-situ concrete C30/37	9,993.07	436.89	358.33	-426.48	x	627.18	911.50	53.94	-226.62	10,788.29	11,727.81
Foundation piles	Prefab pile 450x450 mm	495,746.56	45.23	x	x	x	x	x	x	x	495,791.79	495,791.79
Beams	Cast in-situ concrete C30/37	58,369.36	2,551.89	2,092.99	-2,491.08	x	3,663.35	5,324.07	315.05	-1,323.69	63,014.24	68,501.94
Reinforcement steel	Reinforcement steel	262,844	1,759	x	x	x	5,411	742	14,173	31	264,603	284,960
Foundation blocks	Cast in-situ concrete C35/45	65,283.66	2,334.49	1,871.17	-1,700.87	x	3,275.10	4,912.65	312.23	-947.60	69,489.33	75,340.84
Columns	Cast in-situ concrete C35/45	12,743.47	455.70	365.26	-332.01	x	639.30	958.96	60.95	-184.97	13,564.42	14,706.65
Core elements	Prefab concrete wall	30,366.34	648.65	1,412.61	x	x	1,201.20	1,045.04	638.08	297.90	32,427.60	35,609.81
Balconies	Prefab balconies	259,758.80	4,462.29	5,340.96	x	x	8,283.13	7,222.89	4,956.62	2,027.71	269,562.04	292,052.39
CLT floors	CLT	-1,060,640.64	66,339.90	8,059.67	x	x	6,007.30	3,071.06	1,171,496	x	-986,241.07	194,336
Wood flooring	Wood flooring	-27,939.19	9,812.42	12,958.39	x	1,790.21	x	396.99	113,854.08	x	-5,168.38	110,872.90
Foam Layer	Foam	26,216.40	95.02	x	x	x	x	269.65	113,254.85	x	26,311.42	139,835.93
Fibreboard	Fibreboard	-3,430.60	696.61	540.06	x	x	x	546.80	1,468.12	25,766.98	-2,193.94	25,587.96
Impact insulation	Impact insulation	3,190.91	31.32	936.30	x	x	x	x	x	121.34	4,159	4,280
Insulation	Insulation	34,680.55	374.52	2,936.24	x	x	x	89.88	x	496.61	37,991.31	38,577.81
Plasterboard	Plasterboard	9,887.33	172.28	x	x	x	1,018.69	1,123.56	501.86	434.44	10.059.61	13.138.16
Steel column	HEA400	4,188.76	70.37	175.14	x	x	175.14	16.33	92.44	0.04	4,434.27	4,718.21
CLT walls	CLT	-492,400	30,798	3,742	x	x	2,789	1,426	543,865	x	-457,860	90,213
Wall plasterboard	Wall plasterboard	5,238	41	1,162	x	x	x	82	550	815	6,441	7,888
Wall insulation	Wall insulation	32,000	41	1,223	x	x	x	x	26,904	61	33,263	60,229
Steel tubes	Steel tube	3,083.31	5.70	x	x	x	5.43	5.71	1.22	0.17	3,089.01	3,101.55
Windows	PVC profile + double glazing	157,430.40	629.66	2,930.96	120,605.14	69,709.38	1.98	277.25	8,119.56	3,406.25	161,991.02	364,110,58
Windows bottom floor	Curtain wall system	8,229.61	10.08	x	x	x	x	30.44	6.87	60.03	8,239.69	8,337.04
										Total	**422,952**	**2,744,341**

Floor area	12,387.8	m^2
Total/m²	**34.14**	**kg CO_2-eq./m²**

Table B.18: KasseNova Design Variant 3 (Incineration Scenario) - Calculation Carbon Footprint [kg CO_2-eq.]

B.2. Case Study 2: Apollolaan 171

B.2.1. Recalculation Phases A4 and C2

Table B.19 displays manufacturers of the elements which were used in design which are close to the building site. As there is no available information what company is the actual manufacturer of the products, realistic scenarios need to be developed. The companies in this table are part of this realistic scenario. The realistic transportation distance is the distance from the manufacturer to the building site of Apollolaan 171, which is used in phase A4 of the LCA.

Material	Owner of EPD	Realistic Manufacturer	EPD Transport Distance	Realistic Transport Distance
Structural steel	BMS/SNS - Dutch	ThyssenKrupp - Duisburg	150 km	210 km
Compression layer	HERACLES - Greece	Albeton - Amsterdam	10 km	12 km
Computer floor	Bathgate Flooring - UK	System Floor Technics - Doetinchem	227 km	131 km
Curtain wall system	Strugal - Spain	Blitta - Venray	120 km	150 km
Masonry	KEBE SA - Greece	Aberson - Amsterdam	30 km	8 km
Glulam beams	UAB Juras Medis - Norway	UAB Juras Medis - Norway	1715 km	1715 km

Table B.19: List of Manufacturer of Products Used in Design, Along with Transportation Distance to Building Site

Table B.20 displays the assumed end-of-life transportation scenario (phase C2), along with a realistic end-of-life transportation scenario. The realistic scenarios shows companies which can recycle, reuse, landfill or incinerate the product.

Material	Owner of EPD	Realistic EoL Company	EPD Transport Distance	Realistic Transport Distance
Structural steel	BMS/SNS - Dutch	Kapiteijn Metaal - Amsterdam	50 km	8 km
Compression layer	HERACLES - Greece	Rewinn - Amsterdam	50 km	12 km
Computer floor	Bathgate Flooring - UK	PreZero - Amsterdam	16 km	11 km
C30/37 Concrete	HERACLES - Greece	Rewinn - Amsterdam	50 km	12 km
Curtain wall system	Strugal - Spain	PreZero - Amsterdam	200 km	11 km
Masonry	KEBE SA - Greece	PreZero - Amsterdam	30 km	11 km
Glulam beams	UAB Juras Medis - Norway	PreZero - Amsterdam	150 km	11 km

Table B.20: List of Manufacturer of Products Used in Design, Along with Transportation Distance from Building Site

B.2.2. Unit Conversion

From unit in EPD to unit in design:

Material	Unit before	Value before	Density	Unit after	Value after
Circ. steel tube	m^3	8.009	7850	kg	62871
Rect. steel tube, K400x200x16	m^3	3.638	7850	kg	28558
Rect. steel tube, K350x350x16	m^3	0.859	7850	kg	6743
HEB300	m^3	0.034	7850	kg	267
Rect. steel tube, K400x200x16	m^3	0.574	7850	kg	4506
HEB300	m^3	6.434	7850	kg	50507
Steel beam, 20x200	m^3	1.993	7850	kg	15645
Steel beam, 12x200	m^3	0.318	7850	kg	2496
Steel beam, 20x300	m^3	1.158	7850	kg	9090
Rect. steel tube, K220x220x16	m^3	0.318	7850	kg	2496
Rect. steel tube, K150x150x8	m^3	0.172	7850	kg	1350
Rect. steel tube, K100x100x10	m^3	0.124	7850	kg	973
Rect. steel tube, K150x150x10	m^3	0.224	7850	kg	1915
Rect. steel tube, K100x50x10	m^3	0.128	7850	kg	1005
HEA140	m^3	0.052	7850	kg	408
HEA200	m^3	0.046	7850	kg	361
HEA260	m^3	0.045	7850	kg	353
HEA450	m^3	0.46	7850	kg	3611
HEB200	m^3	0.691	7850	kg	5424
HEB280	m^3	0.26	7850	kg	2041
HEB300	m^3	3.71	7850	kg	29124
HEB320	m^3	2.937	7850	kg	23055
HEB360	m^3	6.855	7850	kg	53812
HEM450	m^3	0.46	7850	kg	3611
HEM500	m^3	1.94	7850	kg	15229
HEM700	m^3	6.415	7850	kg	50358
IPE220	m^3	0.056	7850	kg	440
IPE400	m^3	2.242	7850	kg	17600
THQ 265x6	m^3	8.704	7850	kg	68326
THQ 320x8	m^3	1.683	7850	kg	13212
THQa 265x10	m^3	5.497	7850	kg	43151
O-profile	m^3	0.785	7850	kg	6162
Computer floor	m^2	5962	2.78	#	16561
Masonry	m^3	127.11	1.7	ton	216

Table B.21: Conversion from Unit in EPD to Unit in Design

B.2.3. Carbon Footprint Calculation

Current Design

Table B.22 displays the quantity of materials used, along with data from the EPDs, which might have been adjusted, in order to calculate the carbon footprint.

Product	Material Type	Quantity	Unit	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4
Steel Columns	Circ. steel tube	62,871	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Rect. steel tube, K400x200x16	28,558	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Rect. steel tube, K350x350x16	6,743	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB300	267	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
Steel columns (stability core)	Rect. steel tube, K400x200x16	4,506	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB300	50,507	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
Stability crosses	Steel beam, 20x200	15,645	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Steel beam, 12x200	2,496	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Steel beam, 20x300	9,090	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Rect. steel tube, K220x220x10	2,496	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
Steel columns (façade)	Rect. steel tube, K150x150x8	1,350	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Rect. steel tube, K100x100x10	973	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Rect. steel tube, K150x150x10	1,915	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Rect. steel tube, K100x50x10	1,005	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
Steel beams	HEA140	408	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEA200	361	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEA260	353	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEA450	3,611	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB200	5,424	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB280	2,041	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB300	29,124	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB320	23,055	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB360	53,812	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEM450	3,611	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEM500	15,229	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEM700	50,358	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	IPE220	440	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	IPE400	17,600	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	THQ 265x6	68,326	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	THQ 320x8	13,212	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	THQa 265x10	43,151	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	O-profile	6,162	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
Concrete floor/roof	Hollow core slab	5,962	m^2	57.49	3.09	1.82	x	x	0.48	2.49	0.59	-0.02
Compression layer	Compression layer	358	m^3	239.00	4.64	8.57	-10.20	x	15.00	4.63	1.29	-5.42
Computer floor	Computer floor	16,562	#	7.67	0.13	0.01	x	x	0.00	0.01	5.03	1.41
Basement concrete floor	C30/37 concrete	1,359	m^3	0.00	0.00	0.00	0.00	x	15.00	5.23	1.29	-5.42
Basement concrete wall	C30/37 concrete	214	m^3	0.00	0.00	0.00	0.00	x	15.00	5.23	1.29	-5.42
Walls N/E/W façade	Curtain wall system	2,872	m^2	86.50	0.13	x	x	x	x	0.02	0.07	0.63
Walls S façade	Masonry	216	ton	147.00	1.14	0.14	x	x	0.00	2.38	1.81	1.58

Table B.22: Apollolaan Current Design Variant - Quantity of Materials and Corresponding Data from EPDs [kg CO_2-eq./unit]

Product	Material Type	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	Total A1-A5	Total A-C
Steel Columns	Circ. steel tube	72,930	1,787	3,049	0	0	3,049	67	1,609	0.68	77,766	82,492
	Rect. steel tube, K400x200x16	33,128	812	1,385	0	0	1,385	30	731	0.31	35,324	37,471
	Rect. steel tube, K350x350x16	7,822	192	327	0	0	327	7	173	0.07	8,341	8,848
	HEB300	310	8	13	0	0	13	0.28	7	0.00	330	350
Steel columns (stability core)	Rect. steel tube, K400x200x16	5,227	128	219	0	0	219	5	15	0.05	5,573	5,912
	HEB300	58,588	1,435	2,450	0	0	2,450	54	1,293	0.55	62,473	66,270
Stability crosses	Steel beam, 20x200	18,148	445	759	0	0	759	17	401	0.17	19,352	20,528
	Steel beam, 12x200	2,896	71	121	0	0	121	3	64	0.03	3,088	3,275
	Steel beam, 20x300	10,545	258	441	0	0	441	10	233	0.10	11,244	11,927
	Rect. steel tube, K220x220x10	2,896	71	121	0	0	121	3	64	0.03	3,088	3,275
Steel columns (façade)	Rect. steel tube, K150x150x8	1,566	38	65	0	0	65	1	35	0.01	1,670	1,772
	Rect. steel tube, K100x100x10	1,129	28	47	0	0	47	1	25	0.01	1,204	1,277
	Rect. steel tube, K150x150x10	2,222	54	93	0	0	93	2	49	0.02	2,369	2,513
	Rect. steel tube, K100x50x10	1,166	29	49	0	0	49	1	26	0.01	1,243	1,318
Steel beams	HEA140	474	12	20	0	0	20	0.43	10	0.00	505	536
	HEA200	419	10	18	0	0	18	0.38	9	0.00	447	474
	HEA260	410	10	17	0	0	17	0.38	9	0.00	437	464
	HEA450	4,189	103	175	0	0	175	4	92	0.04	4,467	4,738
	HEB200	6,292	154	263	0	0	263	5.78	139	0.06	6,709	7,117
	HEB280	2,368	58	99	0	0	99	2	52	0.02	2,525	2,678
	HEB300	33,783	828	1,412	0	0	1,412	31	746	0.31	36,023	38,213
	HEB320	26,744	655	1,118	0	0	1,118	25	590	0.25	28,518	30,521
	HEB360	62,422	1,529	2,610	0	0	2,610	57	1,378	0.58	66,561	70,606
	HEM450	4,189	103	175	0	0	175	4	92	0.04	4,467	4,738
	HEM500	17,666	433	739	0	0	739	16	390	0.16	18,837	19,982
	HEM700	58,415	1,431	2,442	0	0	2,442	54	1,289	0.54	62,289	66,074
	IPE220	510	12	21	0	0	21	0.47	11	0.00	544	577
	IPE400	20,416	500	854	0	0	854	19	451	0.19	21,769	23,093
	THQ 265x6	70,259	1,942	3,314	0	0	3,314	73	1,749	0.74	84,514	89,651
	THQ 320x8	15,325	375	641	0	0	641	14	338	0.14	16,342	17,335
	THQa 265x10	50,056	1,226	2,093	0	0	2,093	46	1,105	0.47	53,375	56,619
	O-profile	7,148	175	299	0	0	299	7	158	0.07	7,622	8,085
Concrete floor/roof	Hollow core slab	342,762	18,423	10,851	0	0	2,874	14,846	3,488	-120	372,036	393,124
Compression layer	Compression layer	85,497	1,661	3,066	-3,649	x	5,366	1,657	461	-1,939	90,224	92,120
Computer floor	Computer floor	127,031	2,103	109	0	0	0.00	179	83,307	23,352	129,242	236,080
Basement concrete floor	C30/37 concrete	0	0	0	0	0	20,392	7,113	1,754	-7,368	0	21,891
Basement concrete wall	C30/37 concrete	0	0	0	0	0	3,214	1,121	276	-1,161	0	3,450
Walls N/E/W façade	Curtain wall system	248,444	381	0	0	0	0	51	207	1,812	248,824	250,895
Walls S façade	Masonry	31,752	247	31	0	0	0	514	391	341	32,029	33,276
										Total	**1,521,370**	**1,719,295**

Floor area	5,962.1	m^2
Total/m²	**255.17**	**kg CO_2-eq./m²**

Table B.23: Apollolaan 171 Current Design - Calculation Carbon Footprint [kg CO_2-eq.]

Design Variant 1

Table B.24 displays the quantity of materials used, along with data from the EPDs, which might have been adjusted, in order to calculate the carbon footprint.

Product	Material Type	Quantity	Unit	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4
Timber columns	Glulam, 400x400 mm	102.19	m²	-813.9	67.7	x	x	x	1.57	0.48	703	0
Steel columns (stability core)	Rect. steel tube, K400x200x16	4,506	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB300	50,507	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
Stability crosses	Steel beam, 20x200	15,645	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Steel beam, 12x200	2,496	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Steel beam, 20x300	9,090	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Rect. steel tube, K220x220x10	2,496	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
Steel columns (façade)	Rect. steel tube, K150x150x8	1,350	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Rect. steel tube, K100x100x10	973	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Rect. steel tube, K150x150x10	1,915	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Rect. steel tube, K100x50x10	1,005	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
Steel beams	HEA140	408	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEA200	361	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEA260	353	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEA450	3,611	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB200	5,424	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB280	2,041	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB300	29,124	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB320	23,055	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB360	53,812	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEM450	3,611	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEM500	15,229	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEM700	50,358	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	IPE220	440	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	IPE400	17,600	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	THQ 265x6	68,326	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	THQ 320x8	13,212	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	THQa 265x10	43,151	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	O-profile	6,162	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
Concrete floor/roof	Hollow core slab	5,962	m²	57.49	3.09	1.82	x	x	0.48	2.49	0.59	-0.02
Compression layer	Compression layer	358	m³	239.00	4.64	8.57	-10.20	x	15.00	4.63	1.29	-5.42
Computer floor	Computer floor	16,562	#	7.67	0.13	0.01	x	x	0.00	0.01	5.03	1.41
Basement concrete floor	C30/37 concrete	1,359	m³	0.00	0.00	0.00	0.00	x	15.00	5.23	1.29	-5.42
Basement concrete wall	C30/37 concrete	214	m³	0.00	0.00	0.00	0.00	x	15.00	5.23	1.29	-5.42
Walls N/E/W façade	Curtain wall system	2,872	m²	86.50	0.13	x	x	x	x	0.02	0.07	0.63
Walls S façade	Masonry	216	ton	147.00	1.14	0.14	x	x	0.00	2.38	1.81	1.58

Table B.24: Apollolaan Design Variant 1 - Quantity of Materials and Corresponding Data from EPDs [kg CO_2-eq./unit]

Product	Material Type	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	Total A1-A5	Total A-C
Timber columns	Glulam, 400x400mm	-83,176	6,918	0	0	0	161	49	71,843	0	-76,258	-4,206
Steel columns (stability core)	Rect. steel tube, K400x200x16	5,227	128	219	0	0	219	5	15	0.05	5,573	5,912
	HEB300	58,588	1,435	2,450	0	0	2,450	54	1,293	0.55	62,473	66,270
Stability crosses	Steel beam, 20x200	18,148	445	759	0	0	759	17	401	0.17	19,352	20,528
	Steel beam, 12x200	2,896	71	121	0	0	121	3	64	0.03	3,088	3,275
	Steel beam, 20x300	10,545	258	441	0	0	441	10	233	0.10	11,244	11,927
	Rect. steel tube, K220x220x10	2,896	71	121	0	0	121	3	64	0.03	3,088	3,275
Steel columns (façade)	Rect. steel tube, K150x150x8	1,566	38	65	0	0	65	1	35	0.01	1,670	1,772
	Rect. steel tube, K100x100x10	1,129	28	47	0	0	47	1	25	0.01	1,204	1,277
	Rect. steel tube, K150x150x10	2,222	54	93	0	0	93	2	49	0.02	2,369	2,513
	Rect. steel tube, K100x50x10	1,166	29	49	0	0	49	1	26	0.01	1,243	1,318
Steel beams	HEA140	474	12	20	0	0	20	0.43	10	0.00	505	536
	HEA200	419	10	18	0	0	18	0.38	9	0.00	447	474
	HEA260	410	10	17	0	0	17	0.38	9	0.00	437	464
	HEA450	4,189	103	175	0	0	175	4	92	0.04	4,467	4,738
	HEB200	6,292	154	263	0	0	263	5.78	139	0.06	6,709	7,117
	HEB280	2,368	58	99	0	0	99	2	52	0.02	2,525	2,678
	HEB300	33,783	828	1,412	0	0	1,412	31	746	0.31	36,023	38,213
	HEB320	26,744	655	1,118	0	0	1,118	25	590	0.25	28,518	30,521
	HEB360	62,422	1,529	2,610	0	0	2,610	57	1,378	0.58	66,561	70,606
	HEM450	4,189	103	175	0	0	175	4	92	0.04	4,467	4,738
	HEM500	17,666	433	739	0	0	739	16	390	0.16	18,837	19,982
	HEM700	58,415	1,431	2,442	0	0	2,442	54	1,289	0.54	62,289	66,074
	IPE220	510	12	21	0	0	21	0.47	11	0.00	544	577
	IPE400	20,416	500	854	0	0	854	19	451	0.19	21,769	23,093
	THQ 265x6	70,259	1,942	3,314	0	0	3,314	73	1,749	0.74	84,514	89,651
	THQ 320x8	15,325	375	641	0	0	641	14	338	0.14	16,342	17,335
	THQa 265x10	50,056	1,226	2,093	0	0	2,093	46	1,105	0.47	53,375	56,619
	O-profile	7,148	175	299	0	0	299	7	158	0.07	7,622	8,085
Concrete floor/roof	Hollow core slab	342,762	18,423	10,851	0	0	2,874	14,846	3,488	-120	372,036	393,124
Compression layer	Compression layer	85,497	1,661	3,066	-3,649	x	5,366	1,657	461	-1,939	90,224	92,120
Computer floor	Computer floor	127,031	2,103	109	0	0	0.00	179	83,307	23,352	129,242	236,080
Basement concrete floor	C30/37 concrete	0	0	0	0	0	20,392	7,113	1,754	-7,368	0	21,891
Basement concrete wall	C30/37 concrete	0	0	0	0	0	3,214	1,121	276	-1,161	0	3,450
Walls N/E/W façade	Curtain wall system	248,444	381	0	0	0	0	51	207	1,812	248,824	250,895
Walls S façade	Masonry	31,752	247	31	0	0	0	514	391	341	32,029	33,276
										Total	**1,323,351**	**1,585,928**

Floor area	5,962.1	m²
Total/m²	**221.96**	**kg CO_2-eq./m²**

Table B.25: Apollolaan 171 Design Variant 1 - Calculation Carbon Footprint [kg CO_2-eq.]

Design Variant 2 - Recycling Scenario

Table B.26 displays the quantity of materials used, along with data from the EPDs, which might have been adjusted, in order to calculate the carbon footprint.

Product	Material Type	Quantity	Unit	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4
Steel Columns	Circ. steel tube	120,254	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Rect. steel tube, K400x200x16	28,558	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Rect. steel tube, K350x350x16	6,743	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB300	267	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
Steel columns (stability core)	Rect. steel tube, K400x200x16	4,506	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB300	50,507	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
Stability crosses	Steel beam, 20x200	15,645	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Steel beam, 12x200	2,496	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Steel beam, 20x300	9,090	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Rect. steel tube, K220x220x10	2,496	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
Steel columns (façade)	Rect. steel tube, K150x150x8	1,350	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Rect. steel tube, K100x100x10	973	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Rect. steel tube, K150x150x10	1,915	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Rect. steel tube, K100x50x10	1,005	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
Steel beams	HEA140	408	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB280	2,551	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB300	4,231	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB320	4,356	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB360	13,439	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEM700	16,548	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	IPE400	3,399	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	THQ 265x6	11,689	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	THQ 320x8	7,615	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	THQa 265x10	30,277	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	O-profile	6,162	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
Timber beams	Glulam, 400x320 mm	322.66	m^3	-813.9	67.7	x	x	x	1.57	0.48	703	0
Concrete floor/roof	Hollow core slab	5,962	m^2	57.49	3.09	1.82	x	x	0.48	2.49	0.59	-0.02
CLT floors	CLT	912.63	m^3	-708.00	44.28	5.38	x	x	4.01	2.05	782.00	0.00
Plasterboard	Plasterboard	9,126.30	m^2	1.32	0.02	x	x	x	0.14	0.15	0.07	0.06
Foam layer	Foam	4,563.15	m^2	3.50	0.01	x	x	x	x	0.04	15.12	x
Insulation layer	Insulation	4,563.15	m^2	4.63	0.05	0.39	x	x	x	0.01	x	0.07
Basement concrete floor	C30/37 concrete	1,359	m^3	0.00	0.00	0.00	0.00	x	15.00	5.23	1.29	-5.42
Basement concrete wall	C30/37 concrete	214	m^3	0.00	0.00	0.00	0.00	x	15.00	5.23	1.29	-5.42
Walls N/E/W façade	Curtain wall system	2,872	m^2	86.50	0.13	x	x	x	x	0.02	0.07	0.63
Walls S façade	Masonry	216	ton	147.00	1.14	0.14	x	x	0.00	2.38	1.81	1.58

Table B.26: Apollolaan 171 Design Variant 2 (Recycling Scenario) - Quantity of Materials and Corresponding Data from EPDs [kg CO_2-eq./unit]

Product	Material Type	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	Total A1-A5	Total A-C
Steel Columns	Circ. steel tube	139,495	3,418	5,832	0	0	5,832	128	3,079	1	148,745	157,785
	Rect. steel tube, K400x200x16	33,128	812	1,385	0	0	1,385	30	731	0.31	35,324	37,471
	Rect. steel tube, K350x350x16	7,822	192	327	0	0	327	7	173	0.07	8,341	8,848
	HEB300	310	8	13	0	0	13	0.28	7	0.00	330	350
Steel columns (stability core)	Rect. steel tube, K400x200x16	5,227	128	219	0	0	219	5	15	0.05	5,573	5,912
	HEB300	58,588	1,435	2,450	0	0	2,450	54	1,293	0.55	62,473	66,270
Stability crosses	Steel beam, 20x200	18,148	445	759	0	0	759	17	401	0.17	19,352	20,528
	Steel beam, 12x200	2,896	71	121	0	0	121	3	64	0.03	3,088	3,275
	Steel beam, 20x300	10,545	258	441	0	0	441	10	233	0.10	11,244	11,927
	Rect. steel tube, K220x220x10	2,896	71	121	0	0	121	3	64	0.03	3,088	3,275
Steel columns (façade)	Rect. steel tube, K150x150x8	1,566	38	65	0	0	65	1	35	0.01	1,670	1,772
	Rect. steel tube, K100x100x10	1,129	28	47	0	0	47	1	25	0.01	1,204	1,277
	Rect. steel tube, K150x150x10	2,222	54	93	0	0	93	2	49	0.02	2,369	2,513
	Rect. steel tube, K100x50x10	1,166	29	49	0	0	49	1	26	0.01	1,243	1,318
Steel beams	HEA140	474	12	20	0	0	20	0.43	10	0.00	505	536
	HEB280	2,959	73	124	0	0	124	3	65	0.03	3,156	3,347
	HEB300	4,908	120	205	0	0	205	5	108	0.05	5,234	5,552
	HEB320	5,054	124	211	0	0	211	5	112	0.05	5,389	5,716
	HEB360	15,589	382	652	0	0	652	14	344	0.15	16,623	17,634
	HEM700	19,195	470	803	0	0	803	18	424	0.18	20,468	21,712
	IPE400	3,942	97	165	0	0	165	4	87	0.04	4,204	4,460
	THQ 265x6	13,559	332	567	0	0	567	12	299	0.13	14,458	15,337
	THQ 320x8	8,838	216	369	0	0	369	8	195	0.08	9,419	9,991
	THQa 265x10	35,122	860	1,468	0	0	1,468	32	775	0.33	37,451	39,727
	O-profile	7,148	175	299	0	0	299	7	158	0.07	7,622	8,085
Timber beams	Glulam beams, 400x320 mm	262,616	21,844	0	0	0	0	154	226,833	0	-240,772	-13,786
Concrete floor/roof	Hollow core slab	80,427	4,323	2,546	0	0	674	3,483	818	-28.12	87,296	92,244
Timber floor	CLT	-646,142	40,142	4,910	0	0	3,660	1,871	54,785	0	-600,818	-540,530
Plasterboard	Plasterboard	12,047	210	0	0	0	0	1,369	611	529	12,257	14,766
Foam layer	Foam	15,971	58	0	0	0	0	164	68,995	0	16,029	85,188
Insulation layer	Heavy insulation	21,127	228	1,789	0	0	0	55	0	303	23,144	23,502
Basement concrete floor	C30/37 concrete	0	0	0	0	0	20,392	7,113	1,754	-7,368	0	21,891
Basement concrete wall	C30/37 concrete	0	0	0	0	0	3,214	1,121	276	-1,161	0	3,450
Walls N/E/W façade	Curtain wall system	248,444	381	0	0	0	0	51	207	1,812	248,824	250,895
Walls S façade	Masonry	31,752	247	31	0	0	0	514	391	341	32,029	33,276
										Total	**6,562**	**421,650**

Floor area	5,962.1	m^2
Total/m²	**1.10**	**kg CO_2-eq./m²**

Table B.27: Apollolaan 171 Design Variant 2 (Recycling Scenario) - Calculation Carbon Footprint [kg CO_2-eq.]

Design Variant 2 - Incineration Scenario

Table B.28 displays the quantity of materials used, along with data from the EPDs, which might have been adjusted, in order to calculate the carbon footprint.

Product	Material Type	Quantity	Unit	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4
Steel Columns	Circ. steel tube	120,254	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Rect. steel tube, K400x200x16	28,558	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Rect. steel tube, K350x350x16	6,743	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB300	267	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
Steel columns (stability core)	Rect. steel tube, K400x200x16	4,506	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB300	50,507	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
Stability crosses	Steel beam, 20x200	15,645	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Steel beam, 12x200	2,496	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Steel beam, 20x300	9,090	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Rect. steel tube, K220x220x10	2,496	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
Steel columns (façade)	Rect. steel tube, K150x150x8	1,350	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Rect. steel tube, K100x100x10	973	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Rect. steel tube, K150x150x10	1,915	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Rect. steel tube, K100x50x10	1,005	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
Steel beams	HEA140	408	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB280	2,551	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB300	4,231	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB320	4,356	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB360	13,439	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEM700	16,548	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	IPE400	3,399	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	THQ 265x6	11,689	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	THQ 320x8	7,615	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	THQa 265x10	30,277	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	O-profile	6,162	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
Timber beams	Glulam, 400x320 mm	322.66	m^3	-813.9	67.7	x	x	x	1.57	0.48	703	0
Concrete floor/roof	Hollow core slab	5,962	m^2	57.49	3.09	1.82	x	x	0.48	2.49	0.59	-0.02
CLT floors	CLT	912.63	m^3	-708.00	44.28	5.38	x	x	4.01	2.05	782.00	0.00
Plasterboard	Plasterboard	9,126.30	m^2	1.32	0.02	x	x	x	0.14	0.15	0.07	0.06
Foam layer	Foam	4,563.15	m^2	3.50	0.01	x	x	x	x	0.04	15.12	x
Insulation layer	Insulation	4,563.15	m^2	4.63	0.05	0.39	x	x	x	0.01	x	0.07
Basement concrete floor	C30/37 concrete	1,359	m^3	0.00	0.00	0.00	0.00	x	15.00	5.23	1.29	-5.42
Basement concrete wall	C30/37 concrete	214	m^3	0.00	0.00	0.00	0.00	x	15.00	5.23	1.29	-5.42
Walls N/E/W façade	Curtain wall system	2,872	m^2	86.50	0.13	x	x	x	x	0.02	0.07	0.63
Walls S façade	Masonry	216	ton	147.00	1.14	0.14	x	x	0.00	2.38	1.81	1.58

Table B.28: Apollolaan 171 Design Variant 2 (Incineration Scenario) - Quantity of Materials and Corresponding Data from EPDs [kg CO_2-eq./unit]

Product	Material Type	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	Total A1-A5	Total A-C
Steel Columns	Circ. steel tube	139,495	3,418	5,832	0	0	5,832	128	3,079	1	148,745	157,785
	Rect. steel tube, K400x200x16	33,128	812	1,385	0	0	1,385	30	731	0.31	35,324	37,471
	Rect. steel tube, K350x350x16	7,822	192	327	0	0	327	7	173	0.07	8,341	8,848
	HEB300	310	8	13	0	0	13	0.28	7	0.00	330	350
Steel columns (stability core)	Rect. steel tube, K400x200x16	5,227	128	219	0	0	219	5	15	0.05	5,573	5,912
	HEB300	58,588	1,435	2,450	0	0	2,450	54	1,293	0.55	62,473	66,270
Stability crosses	Steel beam, 20x200	18,148	445	759	0	0	759	17	401	0.17	19,352	20,528
	Steel beam, 12x200	2,896	71	121	0	0	121	3	64	0.03	3,088	3,275
	Steel beam, 20x300	10,545	258	441	0	0	441	10	233	0.10	11,244	11,927
	Rect. steel tube, K220x220x10	2,896	71	121	0	0	121	3	64	0.03	3,088	3,275
Steel columns (façade)	Rect. steel tube, K150x150x8	1,566	38	65	0	0	65	1	35	0.01	1,670	1,772
	Rect. steel tube, K100x100x10	1,129	28	47	0	0	47	1	25	0.01	1,204	1,277
	Rect. steel tube, K150x150x10	2,222	54	93	0	0	93	2	49	0.02	2,369	2,513
	Rect. steel tube, K100x50x10	1,166	29	49	0	0	49	1	26	0.01	1,243	1,318
Steel beams	HEA140	474	12	20	0	0	20	0.43	10	0.00	505	536
	HEB280	2,959	73	124	0	0	124	3	65	0.03	3,156	3,347
	HEB300	4,908	120	205	0	0	205	5	108	0.05	5,234	5,552
	HEB320	5,054	124	211	0	0	211	5	112	0.05	5,389	5,716
	HEB360	15,589	382	652	0	0	652	14	344	0.15	16,623	17,634
	HEM700	19,195	470	803	0	0	803	18	424	0.18	20,468	21,712
	IPE400	3,942	97	165	0	0	165	4	87	0.04	4,204	4,460
	THQ 265x6	13,559	332	567	0	0	567	12	299	0.13	14,458	15,337
	THQ 320x8	8,838	216	369	0	0	369	8	195	0.08	9,419	9,991
	THQa 265x10	35,122	860	1,468	0	0	1,468	32	775	0.33	37,451	39,727
	O-profile	7,148	175	299	0	0	299	7	158	0.07	7,622	8,085
Timber beams	Glulam beams, 400x320 mm	262,616	21,844	0	0	0	0	154	226,833	0	-240,772	-13,786
Concrete floor/roof	Hollow core slab	80,427	4,323	2,546	0	0	674	3,483	818	-28.12	87,296	92,244
Timber floor	CLT	-646,142	40,142	4,910	0	0	3,660	1,871	713,677	0	-600,818	118,389
Plasterboard	Plasterboard	12,047	210	0	0	0	0	1,369	611	529	12,257	14,766
Foam layer	Foam	15,971	58	0	0	0	0	164	68,995	0	16,029	85,188
Insulation layer	Heavy insulation	21,127	228	1,789	0	0	0	55	0	303	23,144	23,502
Basement concrete floor	C30/37 concrete	0	0	0	0	0	20,392	7,113	1,754	-7,368	0	21,891
Basement concrete wall	C30/37 concrete	0	0	0	0	0	3,214	1,121	276	-1,161	0	3,450
Walls N/E/W façade	Curtain wall system	248,444	381	0	0	0	0	51	207	1,812	248,824	250,895
Walls S façade	Masonry	31,752	247	31	0	0	0	514	391	341	32,029	33,276
										Total	**6,562**	**1,086,182**

Floor area	5,962.1	m^2

Total/m²	**1.10**	**kg CO_2-eq./m^2**

Table B.29: Apollolaan 171 Design Variant 2 (Incineration Scenario) - Calculation Carbon Footprint [kg CO_2-eq.]

Design Variant 3 - Recycling Scenario

Table B.30 displays the quantity of materials used, along with data from the EPDs, which might have been adjusted, in order to calculate the carbon footprint.

Product	Material Type	Quantity	Unit	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4
Timber columns	Glulam, 400x400 mm	109.50	m²	-813.9	67.7	x	x	x	1.57	0.48	703	0
Steel columns (stability core)	Rect. steel tube, K400x200x16	4,506	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB300	50,507	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
Stability crosses	Steel beam, 20x200	15,645	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Steel beam, 12x200	2,496	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Steel beam, 20x300	9,090	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Rect. steel tube, K220x220x10	2,496	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
Steel columns (façade)	Rect. steel tube, K150x150x8	1,350	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Rect. steel tube, K100x100x10	973	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Rect. steel tube, K150x150x10	1,915	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Rect. steel tube, K100x50x10	1,005	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
Steel beams	HEA140	408	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB280	2,551	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB300	4,231	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB320	4,356	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB360	13,439	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEM700	16,548	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	IPE400	3,399	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	THQ 265x6	11,689	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	THQ 320x8	7,615	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	THQa 265x10	30,277	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	O-profile	6,162	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
Timber beams	Glulam, 400x320 mm	322.66	m³	-813.9	67.7	x	x	x	1.57	0.48	703	0
Concrete floor/roof	Hollow core slab	5,962	m²	57.49	3.09	1.82	x	x	0.48	2.49	0.59	-0.02
CLT floors	CLT	912.63	m³	-708.00	44.28	5.38	x	x	4.01	2.05	60.00	0.00
Plasterboard	Plasterboard	9,126.30	m²	1.32	0.02	x	x	x	0.14	0.15	0.07	0.06
Foam layer	Foam	4,563.15	m²	3.50	0.01	x	x	x	x	0.04	15.12	x
Insulation layer	Insulation	4,563.15	m²	4.63	0.05	0.39	x	x	x	0.01	x	0.07
Basement concrete floor	C30/37 concrete	1,359	m³	0.00	0.00	0.00	0.00	x	15.00	5.23	1.29	-5.42
Basement concrete wall	C30/37 concrete	214	m³	0.00	0.00	0.00	0.00	x	15.00	5.23	1.29	-5.42
Walls N/E/W façade	Curtain wall system	2,872	m²	86.50	0.13	x	x	x	x	0.02	0.07	0.63
Walls S façade	Masonry	216	ton	147.00	1.14	0.14	x	x	0.00	2.38	1.81	1.58

Table B.30: Apollolaan 171 Design Variant 3 (Recycling Scenario) - Quantity of Materials and Corresponding Data from EPDs [kg CO_2-eq./unit]

Product	Material Type	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	Total A1-A5	Total A-C
Timber column	Glulam, 400x400 mm	89,122	7,413	0	0	0	172	52	76,779	0	81,709	4,506
Steel columns (stability core)	Rect. steel tube, K400x200x16	5,227	128	219	0	0	219	5	15	0.05	5,573	5,912
	HEB300	58,588	1,435	2,450	0	0	2,450	54	1,293	0.55	62,473	66,270
Stability crosses	Steel beam, 20x200	18,148	445	759	0	0	759	17	401	0.17	19,352	20,528
	Steel beam, 12x200	2,896	71	121	0	0	121	3	64	0.03	3,088	3,275
	Steel beam, 20x300	10,545	258	441	0	0	441	10	233	0.10	11,244	11,927
	Rect. steel tube, K220x220x10	2,896	71	121	0	0	121	3	64	0.03	3,088	3,275
Steel columns (façade)	Rect. steel tube, K150x150x8	1,566	38	65	0	0	65	1	35	0.01	1,670	1,772
	Rect. steel tube, K100x100x10	1,129	28	47	0	0	47	1	25	0.01	1,204	1,277
	Rect. steel tube, K150x150x10	2,222	54	93	0	0	93	2	49	0.02	2,369	2,513
	Rect. steel tube, K100x50x10	1,166	29	49	0	0	49	1	26	0.01	1,243	1,318
Steel beams	HEA140	474	12	20	0	0	20	0.43	10	0.00	505	536
	HEB280	2,959	73	124	0	0	124	3	65	0.03	3,156	3,347
	HEB300	4,908	120	205	0	0	205	5	108	0.05	5,234	5,552
	HEB320	5,054	124	211	0	0	211	5	112	0.05	5,389	5,716
	HEB360	15,589	382	652	0	0	652	14	344	0.15	16,623	17,634
	HEM700	19,195	470	803	0	0	803	18	424	0.18	20,468	21,712
	IPE400	3,942	97	165	0	0	165	4	87	0.04	4,204	4,460
	THQ 265x6	13,559	332	567	0	0	567	12	299	0.13	14,458	15,337
	THQ 320x8	8,838	216	369	0	0	369	8	195	0.08	9,419	9,991
	THQa 265x10	35,122	860	1,468	0	0	1,468	32	775	0.33	37,451	39,727
	O-profile	7,148	175	299	0	0	299	7	158	0.07	7,622	8,085
Timber beams	Glulam beams, 400x320 mm	262,616	21,844	0	0	0	0	154	226,833	0	-240,772	-13,786
Concrete floor/roof	Hollow core slab	80,427	4,323	2,546	0	0	674	3,483	818	-28.12	87,296	92,244
Timber floor	CLT	-646,142	40,142	4,910	0	0	3,660	1,871	54,785	0	-600,818	-540,530
Plasterboard	Plasterboard	12,047	210	0	0	0	0	1,369	611	529	12,257	14,766
Foam layer	Foam	15,971	58	0	0	0	0	164	68,995	0	16,029	85,188
Insulation layer	Heavy insulation	21,127	228	1,789	0	0	0	55	0	303	23,144	23,502
Basement concrete floor	C30/37 concrete	0	0	0	0	0	20,392	7,113	1,754	-7,368	0	21,891
Basement concrete wall	C30/37 concrete	0	0	0	0	0	3,214	1,121	276	-1,161	0	3,450
Walls N/E/W façade	Curtain wall system	248,444	381	0	0	0	0	51	207	1,812	248,824	250,895
Walls S façade	Masonry	31,752	247	31	0	0	0	514	391	341	32,029	33,276
										Total	**-267,887**	**180,749**

Floor area	5,962.1	m²

Total/m²	**-44.93**	**kg CO_2-eq./m²**

Table B.31: Apollolaan 171 Design Variant 3 (Recycling Scenario) - Calculation Carbon Footprint [kg CO_2-eq.]

Design Variant 3 - Incineration Scenario

Table B.32 displays the quantity of materials used, along with data from the EPDs, which might have been adjusted, in order to calculate the carbon footprint.

Product	Material Type	Quantity	Unit	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4
Timber columns	Glulam, 400x400 mm	109.50	m^2	-813.9	67.7	x	x	x	1.57	0.48	703	0
Steel columns (stability core)	Rect. steel tube, K400x200x16	4,506	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB300	50,507	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
Stability crosses	Steel beam, 20x200	15,645	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Steel beam, 12x200	2,496	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Steel beam, 20x300	9,090	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Rect. steel tube, K220x220x10	2,496	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
Steel columns (façade)	Rect. steel tube, K150x150x8	1,350	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Rect. steel tube, K100x100x10	973	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Rect. steel tube, K150x150x10	1,915	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	Rect. steel tube, K100x50x10	1,005	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
Steel beams	HEA140	408	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB280	2,551	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB300	4,231	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB320	4,356	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEB360	13,439	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	HEM700	16,548	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	IPE400	3,399	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	THQ 265x6	11,689	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	THQ 320x8	7,615	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	THQa 265x10	30,277	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
	O-profile	6,162	kg	1.16	0.03	0.05	x	x	0.05	0.00	0.03	0.00
Timber beams	Glulam, 400x320 mm	322.66	m^3	-813.9	67.7	x	x	x	1.57	0.48	703	0
Concrete floor/roof	Hollow core slab	5,962	m^2	57.49	3.09	1.82	x	x	0.48	2.49	0.59	-0.02
CLT floors	CLT	912.63	m^3	-708.00	44.28	5.38	x	x	4.01	2.05	782.00	0.00
Plasterboard	Plasterboard	9,126.30	m^2	1.32	0.02	x	x	x	0.14	0.15	0.07	0.06
Foam layer	Foam	4,563.15	m^2	3.50	0.01	x	x	x	x	0.04	15.12	x
Insulation layer	Insulation	4,563.15	m^2	4.63	0.05	0.39	x	x	x	0.01	x	0.07
Basement concrete floor	C30/37 concrete	1,359	m^3	0.00	0.00	0.00	0.00	x	15.00	5.23	1.29	-5.42
Basement concrete wall	C30/37 concrete	214	m^3	0.00	0.00	0.00	0.00	x	15.00	5.23	1.29	-5.42
Walls N/E/W façade	Curtain wall system	2,872	m^2	86.50	0.13	x	x	x	x	0.02	0.07	0.63
Walls S façade	Masonry	216	ton	147.00	1.14	0.14	x	x	0.00	2.38	1.81	1.58

Table B.32: Apollolaan 171 Design Variant 3 (Incineration Scenario) - Quantity of Materials and Corresponding Data from EPDs [kg CO_2-eq./unit]

Product	Material Type	A1-A3	A4	A5	B1	B2-B7	C1	C2	C3	C4	Total A1-A5	Total A-C
Timber column	Glulam, 400x400 mm	89,122	7,413	0	0	0	172	52	76,779	0	81,709	4,506
Steel columns (stability core)	Rect. steel tube, K400x200x16	5,227	128	219	0	0	219	5	15	0.05	5,573	5,912
	HEB300	58,588	1,435	2,450	0	0	2,450	54	1,293	0.55	62,473	66,270
Stability crosses	Steel beam, 20x200	18,148	445	759	0	0	759	17	401	0.17	19,352	20,528
	Steel beam, 12x200	2,896	71	121	0	0	121	3	64	0.03	3,088	3,275
	Steel beam, 20x300	10,545	258	441	0	0	441	10	233	0.10	11,244	11,927
	Rect. steel tube, K220x220x10	2,896	71	121	0	0	121	3	64	0.03	3,088	3,275
Steel columns (façade)	Rect. steel tube, K150x150x8	1,566	38	65	0	0	65	1	35	0.01	1,670	1,772
	Rect. steel tube, K100x100x10	1,129	28	47	0	0	47	1	25	0.01	1,204	1,277
	Rect. steel tube, K150x150x10	2,222	54	93	0	0	93	2	49	0.02	2,369	2,513
	Rect. steel tube, K100x50x10	1,166	29	49	0	0	49	1	26	0.01	1,243	1,318
Steel beams	HEA140	474	12	20	0	0	20	0.43	10	0.00	505	536
	HEB280	2,959	73	124	0	0	124	3	65	0.03	3,156	3,347
	HEB300	4,908	120	205	0	0	205	5	108	0.05	5,234	5,552
	HEB320	5,054	124	211	0	0	211	5	112	0.05	5,389	5,716
	HEB360	15,589	382	652	0	0	652	14	344	0.15	16,623	17,634
	HEM700	19,195	470	803	0	0	803	18	424	0.18	20,468	21,712
	IPE400	3,942	97	165	0	0	165	4	87	0.04	4,204	4,460
	THQ 265x6	13,559	332	567	0	0	567	12	299	0.13	14,458	15,337
	THQ 320x8	8,838	216	369	0	0	369	8	195	0.08	9,419	9,991
	THQa 265x10	35,122	860	1,468	0	0	1,468	32	775	0.33	37,451	39,727
	O-profile	7,148	175	299	0	0	299	7	158	0.07	7,622	8,085
Timber beams	Glulam beams, 400x320 mm	262,616	21,844	0	0	0	0	154	226,833	0	-240,772	-13,786
Concrete floor/roof	Hollow core slab	80,427	4,323	2,546	0	0	674	3,483	818	-28.12	87,296	92,244
Timber floor	CLT	-646,142	40,142	4,910	0	0	3,660	1,871	713,677	0	-600,818	114,730
Plasterboard	Plasterboard	12,047	210	0	0	0	0	1,369	611	529	12,257	14,766
Foam layer	Foam	15,971	58	0	0	0	0	164	68,995	0	16,029	85,188
Insulation layer	Heavy insulation	21,127	228	1,789	0	0	0	55	0	303	23,144	23,502
Basement concrete floor	C30/37 concrete	0	0	0	0	0	20,392	7,113	1,754	-7,368	0	21,891
Basement concrete wall	C30/37 concrete	0	0	0	0	0	3,214	1,121	276	-1,161	0	3,450
Walls N/E/W façade	Curtain wall system	248,444	381	0	0	0	0	51	207	1,812	248,824	250,895
Walls S façade	Masonry	31,752	247	31	0	0	0	514	391	341	32,029	33,276
										Total	**-267,887**	**839,668**

Floor area	5,962.1	m^2
Total/m²	**-44.93**	**kg CO_2-eq./m²**

Table B.33: Apollolaan 171 Design Variant 3 (Incineration Scenario) - Calculation Carbon Footprint [kg CO_2-eq.]

C

Structural Calculations

C.1. KasseNova aan de Vaart - Design Variant 1

C.1.1. Moment, Shear Force and Rolling Shear Force

The equations for the design moment, shear and rolling shear strength are given in Equations C.1 - C.3:

$$f_{m,d} = \frac{k_{mod} \cdot f_{m,k}}{\gamma_M} \tag{C.1}$$

$$f_{v,d} = \frac{k_{mod} \cdot f_{v,k}}{\gamma_M} \tag{C.2}$$

$$f_{Rv,d} = \frac{k_{mod} \cdot f_{Rv,k}}{\gamma_M} \tag{C.3}$$

In these equations, k_{mod} = 0.8 and γ_M = 1.25. For C24 timber, $f_{m,k}$ = 24 MPa, $f_{v,k}$ = 4 MPa and $f_{vR,k}$ = 1.4 MPa (Blaß & Sandhaas, 2017).

$$f_{m,d} = \frac{0.8 \cdot 24}{1.25} = 15.36\ MPa \tag{C.4}$$

$$f_{v,d} = \frac{0.8 \cdot 4}{1.25} = 2.56\ MPa \tag{C.5}$$

$$f_{rV,d} = \frac{0.8 \cdot 1.4}{1.25} = 0.9\ MPa \tag{C.6}$$

The largest moment and shear force in the element are obtained by taking the CLT floor as a continuous slab and using the Technosoft software for each of the floors in the building. The largest design moment was found to be 19.40 kNm, the largest shear force was found to be 20.20 kN. The design stress due to the moment can be calculated according to Equation C.7:

$$\sigma_d = \frac{M_d}{W_{x,net}} \tag{C.7}$$

$$W_{x,net} = \frac{2 \cdot I_{0,net}}{h_{CLT}} \tag{C.8}$$

In this equation, h_{CLT} is the thickness of the CLT floor (=200 mm) and $I_{0,net}$ the net moment of inertia (Equation C.9):

$$I_{0,net} = \sum \frac{b_x t_i^3}{12} + \sum b_x t_i a_i^2 = \frac{b_x t_1^3}{12} + \frac{b_x t_3^3}{12} + \frac{t_x t_5^3}{12} + b_x t_1 a_1^2 + b_x t_3 a_5^2 \tag{C.9}$$

Only the longitudinal layers in the CLT beam contribute to the net moment of inertia. For the L5s element, these are layers 1, 3 and 5, which all have a thickness of 40 mm. The distance from the neutral axis to the middle of layers 1 and 5, a_1 and a_5, respectively, are 80 mm. The strip is taken with a width b_x of 1000 mm.

$$I_{0,net} = 3 \cdot \frac{1000 \cdot 40^3}{12} + 2 \cdot 1000 \cdot 40 \cdot 80^2 = 52800 \times 10^4 \; mm^4 \tag{C.10}$$

$$W_{x,net} = \frac{2 \cdot 52800 \times 10^4}{200} = 5280 \times 10^3 \; mm^3 \tag{C.11}$$

$$\sigma_d = \frac{19.40 \times 1000}{5280} = 3.67 \; MPa \;<\; f_{m,d} = 15.36 \; MPa \tag{C.12}$$

The design shear force τ_d can be calculated according to Equation C.15:

$$\tau_d = \frac{V_d \cdot S_{x,net}}{I_{x,net} \cdot b_x} \tag{C.13}$$

$$S_{x,net} = \sum_{i=1}^{k_L} \frac{E_{x,i}}{E_{ref}} b_x t_i a_i + b_x \frac{\left(\frac{t_k}{2} - a_k\right)^2}{2} = b_x t_1 a_1 + b_x \frac{a_4^2}{8} = 1000 \cdot 40 \cdot 80 + 1000 \cdot \frac{40^2}{8} = 3400 \times 10^3 mm^3 \tag{C.14}$$

$$\tau_d = \frac{20.20 \times 1000 \cdot 3400000}{52800 \times 10^4 \cdot 1000} = 0.13 \; MPa \;<\; f_{v,d} = 2.56 \; MPa \tag{C.15}$$

For the calculation of the design rolling shear force $\tau_{Rv,d}$, Equation C.16 is used:

$$\tau_{Rv,d} = \frac{S_{Rx,net} \cdot V_d}{I_{x,net} \cdot b_x} \tag{C.16}$$

$$S_{Rx,net} = \sum_{i=1}^{m_L} \frac{E_{x,i}}{E_{ref}} \cdot b_x t_i a_i = b_x t_1 a_1 = 1000 \cdot 80 \cdot 40 = 3200 \times 10^4 \; mm^4 \tag{C.17}$$

$$\tau_{Rv,d} = \frac{3200 \times 10^4 \cdot 20.20 \times 1000}{52800 \times 10^4 \cdot 1000} = 0.12 \; MPa \;< f_{Rv,d} = 0.90 \; MPa \tag{C.18}$$

C.1.2. Deflection

The maximum deflection in the CLT element is given by Category A buildings (Housing) for a L200-5s as $L/368$, meaning that for a maximum span of 5.4 meter, the maximum deflection is equal to:

$$w_{max} = L/368 = 5400/368 = 14.7 \; mm \tag{C.19}$$

The deflection consists of a short-term deformation w_{inst} and a long-term deformation w_{fin}. The short-term deformation is the combination of the deformation due to the permanent load $w_{g,k}$ and the live load $w_{q,k}$:

$$w_{inst} = w_{g,k} + w_{q,k} \tag{C.20}$$

The deflection due to the permanent load can be calculated as:

$$w_{g,k} = \frac{5 \cdot g_k \cdot L^4}{384 \cdot E_{x,mean} \cdot I_{x,ef}} \tag{C.21}$$

In this equation, g_k is the characteristic permanent load, which for the CLT floor equals 1.79 kN/m^2, L = 5.4 m, $E_{x,mean}$ = 11000 MPa, $I_{x,mean}$ is given by Equation C.22:

$$I_{x,ef} = \sum \frac{E_{x,i}}{E_{ref}} \cdot \frac{b_x t_i^3}{12} + \sum \gamma_i \cdot \frac{E_{x,i}}{E_{ref}} \cdot b_x t_i a_i^2 = b_x \cdot \left(\frac{(t_1^3 + t_3^3 + t_5^3)}{12} + \gamma_1 t_1 a_1^2 + \gamma_5 t_5 a_5^2 \right) \tag{C.22}$$

The equation for γ_1 and γ_5 is given by Equation C.23, in which l_{ref} is the reference length = 5400 mm and $G_{9090,2}$ the mean shear modulus along boards in layer 2 = 50 MPa:

$$\gamma_1 = \gamma_5 = \frac{1}{1 + \frac{\pi^2 E_{x,1} t_1}{l_{ref}^2} \frac{t_2}{G_{9090,2}}} = \frac{1}{1 + \frac{\pi^2 \cdot 11000 \cdot 40}{5400^2} \cdot \frac{40}{50}} = 0.894 \quad (C.23)$$

$$I_{x,ef} = 1000 \cdot \left(\frac{3 \cdot 40^3}{12} + 2 \cdot 40 \cdot 80^2 \right) = 47349 \times 10^4 \; mm^4 \quad (C.24)$$

$$w_{g,k} = \frac{5 \cdot 1.79 \times 10^3 \cdot 5.4^4}{384 \cdot 11000 \times 10^6 \cdot 47349 \times 10^{-8}} = 3.81 \; mm \quad (C.25)$$

The deflection due to the live load can be calculated as:

$$w_{q,k} = \frac{5 \cdot q_k \cdot L^4}{384 \cdot E_{x,mean} \cdot I_{x,ef}} \quad (C.26)$$

The characteristic live load q_k is equal to 2.55 kN/m^2, which is the same which is used in the actual design.

$$w_{q,k} = \frac{5 \cdot 2.55 \times 10^3 \cdot 5.4^4}{384 \cdot 11000 \times 10^6 \cdot 47349 \times 10^{-8}} = 5.42 \; mm \quad (C.27)$$

The instantaneous deflection w_{inst} is calculated as:

$$w_{inst} = w_{g,k} + w_{q,k} = 3.81 + 5.42 = 9.23 \; mm \; < \; w_{max} = 14.7 \; mm \quad (C.28)$$

The final deformation due to permanent load $w_{fin,g}$ is given by Equation C.29, in which k_{def} = 0.85 (for service class 1):

$$w_{fin,g} = w_{g,k} \cdot (1 + k_{def}) = 3.81 \cdot (1 + 0.85) = 7.05 mm \quad (C.29)$$

The final deformation due to live load $w_{fin,q}$ is given by Equation C.30, in which ψ_2 = 0.3 (category A buildings):

$$w_{fin,q} = w_{q,k} \cdot (1 + \psi_2 \cdot k_{def}) = 5.42 \cdot (1 + 0.3 \cdot 0.85) = 6.80 mm \quad (C.30)$$

The total final deformation w_{fin} is calculated by adding the permanent and live load:

$$w_{fin} = w_{fin,g} + w_{fin,q} = 7.05 + 6.80 = 13.85 \; mm \; < \; w_{max} = 14.7 \; mm \quad (C.31)$$

C.1.3. Vibrations

The fundamental frequency f_1, which should be higher than 8 Hz, can be calculated with Equation C.32:

$$f_1 = \frac{\pi}{2L^2} \sqrt{\frac{(EI)_L}{m}} \quad (C.32)$$

In this equation, L = 5.4 m, m is the weight per unit area = 182.7 kg/m^2:

$$f_1 = \frac{\pi}{2 \cdot 5.4^2} \sqrt{\frac{11000 \times 10^6 \cdot 47349 \times 10^{-8}}{182.7}} = 9.10 \; Hz > 8 \; Hz \quad (C.33)$$

For the deflection w due to a point load, Equation C.34 can be utilized:

$$w = \frac{PL^3}{48 \cdot (EI)_L \cdot B_{ef}} < a = 1 mm \quad (C.34)$$

In this equation, P is the point load = 1 kN, with B_{ef} being given in Equation C.35:

$$B_{ef} = \frac{L}{1.1}\sqrt{\frac{(EI)_B}{(EI)_L}} \tag{C.35}$$

I_B is the second order moment in the stiffest direction of the floor, which is given by Equation C.36:

$$I_B = b_x \cdot \left(\frac{2 \cdot t_2^3}{12} + 2 \cdot t_2 \cdot a_2^2\right) = 1000 \cdot \left(\frac{2 \cdot 40^3}{12} + 2 \cdot 40 \cdot 40^2\right) = 13867 \times 10^4\ mm^4 \tag{C.36}$$

This leads to the equation of B_{ef} being:

$$B_{ef} = \frac{5.4}{1.1}\sqrt{\frac{11000 \cdot 13867 \times 10^4}{11000 \cdot 47439 \times 10^4}} = 2.66 \tag{C.37}$$

Which is used as input for the deflection w due to a point load:

$$w = \frac{1 \cdot 5400^3}{48 \cdot 11000 \cdot 47349 \times 10^4 \cdot 2.66} = 0.24\ mm < a = 1\ mm \tag{C.38}$$

Lastly, the impulse velocity response v needs to be compared against the maximum impulse velocity response v_{max} in order to make sure that frequencies above 8 Hz are not perceived as disturbing.

$$v_{max} = b^{f_1 \cdot \xi - 1} \tag{C.39}$$

b is a factor set at 120 $m/(Ns^2)$, according to the Dutch National Annex of NEN-EN 1995-1-1 (NEN, 2013b). ξ is a damping factor, set at 0.01 (or 1%), according to NEN-EN 1995-1-1 (NEN, 2011b).

$$v_{max} = 120^{(9.10 \cdot 0.01 - 1)} = 0.013 \tag{C.40}$$

The impulse velocity response v can be calculated according to Equation C.41:

$$v = \frac{4(0.4 + 0.6 n_{40})}{mBL + 200} \tag{C.41}$$

m is the weight of the floor slab per unit area, which equals 182.7 kg/m^2, B is the width of the slab. The CLT floor spans over the entire width of the building, which is 19.598 m, which therefore is the value of B. The length L is the maximum span in the floor span, which is 5.4 m. n_{40} is the number of first-order modes with fundamental frequencies up to 40 Hz, which can be calculated according to Equation C.42:

$$n_{40} = \left[\left(\left(\frac{40}{f_1}\right)^2 - 1\right)\left(\frac{B}{L}\right)^4 \left(\frac{(EI)_L}{(EI)_B}\right)\right]^{0.25} = \left[\left(\left(\frac{40}{9.10}\right)^2 - 1\right)\left(\frac{19.598}{5.4}\right)^4 \left(\frac{11000 \cdot 47349}{11000 \cdot 13867}\right)\right]^{0.25} = 10.21 \tag{C.42}$$

This is used in the calculation of the impulse velocity response v:

$$v = \frac{4(0.4 + 0.6 \cdot 10.21)}{182.7 \cdot 19.598 \cdot 5.4 + 200} = 0.0013 < v_{max} = 0.013 \tag{C.43}$$

C.1.4. Fire Safety

The design strengths are different during fire conditions compared to normal conditions. $f_{m,20}$, $f_{v,20}$ and $f_{Rv,20}$ are the 20% fractile moment, shear and rolling shear strength at normal temperature, respectively, which can be calculated according to Equations C.44-C.46:

$$f_{m,20} = k_{fi} f_{m,k} \tag{C.44}$$

$$f_{v,20} = k_{fi} f_{v,k} \tag{C.45}$$

$$f_{Rv,20} = k_{fi} f_{Rv,k} \tag{C.46}$$

k_{fi} is a factor to convert from the 5% fractile to the 20% fractile, which for CLT is equal to 1.15 (Swedish Wood, 2019).

$$f_{m,20} = 1.15 \cdot 24 = 27.6\ MPa \tag{C.47}$$

$$f_{v,20} = 1.15 \cdot 4 = 4.6\ MPa \tag{C.48}$$

$$f_{Rv,20} = 1.15 \cdot 1.4 = 1.61\ MPa \tag{C.49}$$

In order to calculate the design strengths during fire conditions, Equations C.50-C.52 are used:

$$f_{m,d,fi} = \frac{k_{mod,fi} \cdot f_{m,20}}{\gamma_{M,fi}} \tag{C.50}$$

$$f_{v,d,fi} = \frac{k_{mod,fi} \cdot f_{v,20}}{\gamma_{M,fi}} \tag{C.51}$$

$$f_{Rv,d,fi} = \frac{k_{mod,fi} \cdot f_{Rv,20}}{\gamma_{M,fi}} \tag{C.52}$$

In these equations, $k_{mod,fi}$ and $\gamma_{M,fi}$ both are 1.

$$f_{m,d,fi} = \frac{1 \cdot 27.6}{1} = 27.6\ MPa \tag{C.53}$$

$$f_{v,d,fi} = \frac{1 \cdot 4.6}{1} = 4.6\ MPa \tag{C.54}$$

$$f_{Rv,d,fi} = \frac{1 \cdot 1.61}{1} = 1.61\ MPa \tag{C.55}$$

A Gypsum Protect Fireboard with a thickness h_p of 13 mm was used in this design variant. The failure time of the plasterboard t_f depends on this thickness (NEN, 2011c):

$$t_f = 4.6h_p - 25 = 4.6 \cdot 13 - 25 = 34.8\ min \tag{C.56}$$

Similarly, the charring time t_{ch} depends on the thickness of the plasterboard:

$$t_{ch} = 2.8h_p - 14 = 2.8 \cdot 13 - 14 = 22.4\ min \tag{C.57}$$

The value for k_2 can be calculated according to Equation C.58:

$$k_2 = 1 - 0.018h_p = 1 - 0.018 \cdot 13 = 0.766 \tag{C.58}$$

The value for the time limit t_a uses t_f, t_{ch} and k_2 as input, as well as the constants β_0 and k_3:

$$t_a = t_f + \frac{25 - (t_f - t_{ch})k_2\beta_0}{k_3\beta_0} = 34.8 + \frac{25 - (34.8 - 22.4) \cdot 0.766 \cdot 0.65}{2 \cdot 0.65} = 49.28\ min \tag{C.59}$$

The charring depth after the required time t_{req} = 120 min is to be calculated according to Equation C.60:

$$d_{char} = 25 + (t_{req} - t_a)\beta_0 = 25 + (120 - 49.28) \cdot 0.65 = 70.97\ mm \tag{C.60}$$

With the thickness of the non-load bearing layer under tension d_0 being 10 mm, the effective charring depth d_{ef} is 80.97 mm. The effective depth of the CLT h_{ef} is:

$$h_{ef} = h_{CLT} - d_{ef} = 200 - 80.97 = 119.03\ mm \tag{C.61}$$

Layers 1, 2, and 3 (partly) remain, as visualized in Figure C.1.

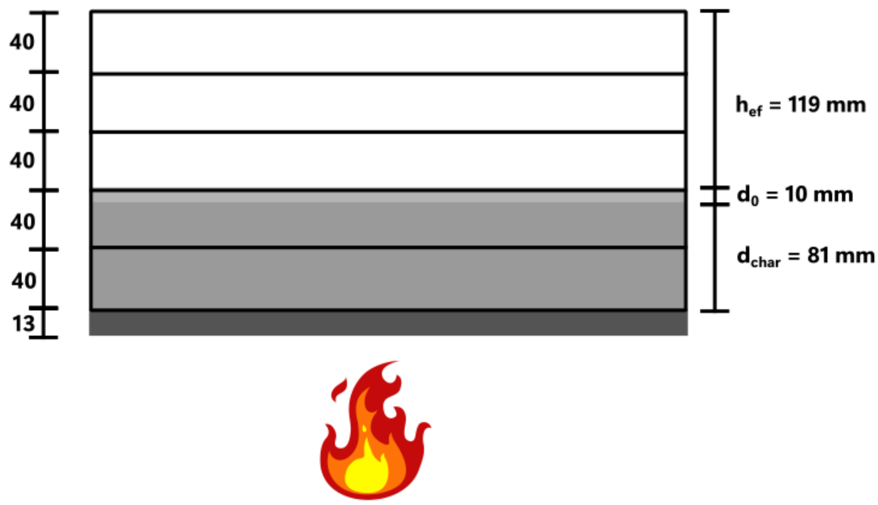

Figure C.1: CLT Floor after 120-Minute Fire, Protected Floor Structure

The distances from the neutral axis to the middle of layers 1, 2 and 3, a_1, a_2 and a_3, equal 39.52, 0.48 and 40.24 mm, respectively. The thickness of layer 3 t_3 equals 39.03 mm. The net moment of inertia under fire conditions $I_{x,net,fi}$ can be calculated according to Equation C.62:

$$I_{x,net,fi} = b_x \left(\frac{t_1^3}{12} + \frac{t_3^3}{12} + t_1 \cdot a_1^2 + t_3 \cdot a_3^2 \right) = 1000 \cdot \left(\frac{40^3}{12} + \frac{39.03^3}{12} + 40 \cdot 39.52^2 + 39.03 \cdot 40.24^2 \right) = 13406 \times 10^4 mm^4 \tag{C.62}$$

This is used as input for the net moment of resistance under fire conditions $W_{x,net,fi}$:

$$W_{x,net,fi} = \frac{2 \cdot I_{x,net,fi}}{h_{CLT}} = \frac{2 \cdot 13406 \times 10^4}{119.03} = 2253 \times 10^3\ mm^3 \tag{C.63}$$

The design stress under fire conditions $\sigma_{d,fi}$ is calculated as described in Equation C.64:

$$\sigma_{d,fi} = \frac{M_{d,fi}}{W_{x,net,fi}} = \frac{13.70 \times 10^6}{2253 \times 10^3} = 6.08\ MPa < f_{m,d,fi} = 27.6\ MPa \tag{C.64}$$

For the determination of the shear under fire conditions, the static moment of longitudinal shear $S_{x,net,fi}$ is needed. For this, the longitudinal layer closest to the neutral axis is used, which is layer 1. The calculation is shown in Equation C.65:

$$S_{x,net,fi} = b_x t_1 a_1 = 1000 \cdot 40 \cdot 39.52 = 1581 \times 10^3\ mm^3 \tag{C.65}$$

The design shear stress under fire conditions $\tau_{d,fi}$ is calculated as in Equation C.66:

$$\tau_{d,fi} = \frac{V_{d,fi} \cdot S_{x,net,fi}}{I_{x,net,fi} \cdot b_x} = \frac{14.30 \times 10^3 \cdot 1581 \times 10^3}{13406 \times 10^4 \cdot 1000} = 0.1686\ MPa < f_{v,d,fi} = 4.6\ MPa \tag{C.66}$$

For the determination of the rolling shear under fire conditions, the static moment of rolling shear $S_{Rx,net,fi}$ is needed. For this, the transverse layer closest to the neutral axis is used, which is layer 2. The calculation is shown in Equation C.67:

$$S_{Rx,net,fi} = b_x t_2 a_2 = 1000 \cdot 40 \cdot 0.48 = 19 \times 10^3\ mm^3 \tag{C.67}$$

The design rolling shear stress under fire conditions $\tau_{Rv,d,fi}$ is calculated as in Equation C.68:

$$\tau_{Rv,d,fi} = \frac{S_{Rx,net,fi} \cdot V_{d,fi}}{I_{x,net,fi} \cdot b_x} = \frac{19 \times 10^3 \cdot 14.30 \times 10^3}{13406 \times 10^4 \cdot 1000} = 0.0021\ MPa < f_{Rv,d,fi} = 1.61\ MPa \tag{C.68}$$

Since the moment, shear and rolling shear under fire conditions are all below the design strengths, it can be concluded that the floor meets the design requirements.

C.2. KasseNova aan de Vaart - Design Variant 2

C.2.1. Buckling

The wall structure consists of an insulation layer of 40 mm in the middle, C3s-100 panels on both sides of the insulation layer and 15.4 mm plasterboard on both outsides. For the buckling calculation, the two C3s-100 panels and insulation layer are relevant. The latter is relevant since it changes the moment of inertia and resistance of the CLT. The CLT panels with insulation is indicated in Table C.1:

C [mm], t_1	L, t_2	C, t_3	Insulation	C, t_4	L, t_5	C, t_6
30	40	30	40	30	40	30

Table C.1: Thickness Wall Structure Elements

The unity check for buckling of a CLT wall element is:

$$\frac{\sigma_{c,0,d}}{k_{c,y} \cdot f_{c,0,d}} + \frac{\sigma_{m,d}}{f_{m,d}} \leq 1 \tag{C.69}$$

$$f_{m,d} = \frac{k_{mod} \cdot f_{m,k}}{\gamma_M} = \frac{0.9 \cdot 24}{1.25} = 17.28\ MPa \tag{C.70}$$

$$f_{c,0,d} = \frac{k_{mod} \cdot f_{c,0,k}}{\gamma_M} = \frac{0.9 \cdot 21}{1.25} = 15.12\ MPa \tag{C.71}$$

$$A_{x,net} = b_x \cdot (t_1 + t_3 + t_4 + t_6) = 1000 \cdot (4 \cdot 30) = 1200 \times 10^2 mm \tag{C.72}$$

$$\begin{aligned} I_{x,net} &= b_x \left(2 \cdot \frac{t_1^3}{12} + 2 \cdot \frac{t_3^3}{12} + 2 \cdot t_1 \cdot a_1^2 + 2 \cdot t_3 \cdot a_3^2 \right) \\ &= 1000 \cdot \left(4 \cdot \frac{30^3}{12} + 2 \cdot 30 \cdot 105^2 + 2 \cdot 30 \cdot 35^3 \right) = 74400 \times 10^4\ mm^4 \end{aligned} \tag{C.73}$$

The centre of gravity is equal to half the thickness of the wall panel as given in Table C.1, which is 120 mm. This is used to calculate the net moment of resistance:

$$W_{x,net} = \frac{I_{x,net}}{z_s} = \frac{74400 \times 10^4}{120} = 6200 \times 10^3\ mm^3 \tag{C.74}$$

$$\begin{aligned} \gamma_1 = \gamma_6 &= \frac{1}{1 + \frac{\pi^2 E_{x,1} t_1}{l_{ref}^2} \cdot \frac{t_2}{G_{9090,2}}} = \frac{1}{1 + \frac{\pi^2 \cdot 11000 \cdot 30}{3000^2} \cdot \frac{40}{50}} = 0.775 \\ \gamma_3 = \gamma_4 &= 1 \end{aligned} \tag{C.75}$$

$$\begin{aligned} I_{x,ef} &= \frac{b_x t_1^3}{12} + \gamma_1 \cdot b_x \cdot t_1 \cdot a_1^2 + \frac{b_x t_3^3}{12} + \gamma_3 \cdot b_x \cdot t_3 \cdot a_3^2 + \frac{b_x t_4^3}{12} + \gamma_4 \cdot b_x \cdot t_4 \cdot a_4^2 + \frac{b_x t_6^3}{12} + \gamma_6 \cdot b_x \cdot t_6 \cdot a_6^2 \\ &= \frac{4 \cdot 1000 \cdot 30^3}{12} + 2 \cdot 0.775 \cdot 1000 \cdot 30 \cdot 105 + 2 \cdot 1 \cdot 1000 \cdot 30 \cdot 35 \\ &= 59549 \times 10^4\ mm^4 \end{aligned} \tag{C.76}$$

$$i_{x,ef} = \sqrt{\frac{I_{x,ef}}{A_{x,net}}} = \sqrt{\frac{59549 \times 10^4}{1200 \times 10^2}} = 70.44 \quad (C.77)$$

$$\lambda_e = \frac{l_e}{i_{x,ef}} = \frac{3000}{70.44} = 42.59 \quad (C.78)$$

$$\lambda_{rel,y} = \frac{\lambda_e}{\pi}\sqrt{\frac{f_{c,0,k}}{E_{0.05}}} = \frac{42.59}{\pi}\sqrt{\frac{21}{7400}} = 0.72 \quad (C.79)$$

$$k_y = 0.5\left(1 + 0.1\left(\lambda_{rel,y} - 0.3\right) + \lambda_{rel,y}^2\right) = 0.5(1 + 0.1(0.72 - 0.3) + 0.72^2) = 0.78 \quad (C.80)$$

$$k_{c,y} = \frac{1}{k_y + \sqrt{k_y^2 - \lambda_{rel,y}^2}} = 0.92 \quad (C.81)$$

The maximum design vertical load N_d is equal to 803.43 kN, the maximum moment of the wind load $M_{y,d}$ is equal to 1.58 kNm. The final calculation for the buckling check is given in Equation C.82:

$$\begin{gathered}\frac{N_d}{k_{c,y} \cdot A_{x,net} \cdot f_{c,0,d}} + \frac{M_{y,d}}{W_{x,net} \cdot f_{m,d}} \leq 1 \\ \frac{803.43 \times 1000}{0.92 \cdot 1200 \times 10^2 \cdot 15.12} + \frac{1.58 \times 10^6}{6200 \times 10^3 \cdot 17.28} = 0.67 \leq 1\end{gathered} \quad (C.82)$$

C.2.2. Fire Safety

In the following equations, h_p is the thickness of the plasterboard panel, which is 15.4 mm:

$$t_{ch} = 2.8h_p - 14 = 2.8 \cdot 15.4 - 14 = 29.12\ min \quad (C.83)$$

$$t_f = 4.6h_p - 25 = 4.6 \cdot 15.4 - 25 = 45.84\ min \quad (C.84)$$

$$k_2 = 1 - 0.018h_p = 1 - 0.018 \cdot 15.4 = 0.7228 \quad (C.85)$$

$$t_a = \frac{25 - (t_f - t_{ch}k_2\beta_0}{k_3\beta_0} + t_f = \frac{25 - (45.84 - 29.12) \cdot 0.7228 \cdot 0.65}{2 \cdot 0.65} + 45.84 = 59.0\ min \quad (C.86)$$

The charring depth after 60 minutes:

$$d_{char} = 25 + (t_{req} - t_a)\beta_0 = 25 + (60 - 59.0) \cdot 0.65 = 25.6\ mm \quad (C.87)$$

The thickness of the non-load-bearing layer d_0 is equal to 20 mm. The effective cross-section is calculated as:

$$h_{ef} = h_{CLT} - d_{char} - d_0 = 100 - 25.6 - 20 = 54.4\ mm \quad (C.88)$$

This is the remaining cross-section after 60 minutes of burning at both sides of the wall. The same buckling calculation is performed as before. The following unity check is the result:

$$\frac{N_{d,fi}}{k_{c,fi} \cdot A_{x,net,fi} \cdot f_{c,fi}} + \frac{M_{d,fi}}{W_{x,net,fi} \cdot f_{m,fi}} = \frac{341.4 \times 1000}{0.435 \cdot 600 \times 10^2 \cdot 24.15} + \frac{0.95 \times 10^6}{1048 \times 10^3 \cdot 27.6} = 0.57 \leq 1 \quad (C.89)$$

C.2.3. Stability

The stability of the structure was calculated by exploring if there is tension in any of the foundation piles due to wind loads. The first step in the calculation is to compute the wind load on the building, both the line load $q_{w,rep}$ and $F_{w,rep}$, as indicated in Figure D.8. The calculation for the line load is given in Equation C.90, the calculation for the point load is given in Equation C.91:

$$q_{w,rep} = b \cdot q_p(z_e) \cdot c_{pe,10} \cdot c_s c_d \cdot n/(n-1) \tag{C.90}$$

$$F_{w,rep} = b \cdot d \cdot c_f \cdot c_s c_d \cdot n/(n-1) \tag{C.91}$$

In this equation, b is the width of the building (= 21.6 m) d is the length of the building (= 94.5 m), $q_p(z_e)$ is the wind load in wind area II (= (1.07+1.14)/2 = 1.11 kN/m), $c_s c_d$ is a standard factor (= 1.0), as are c_f (= 0.04) and $n/(n-1)$ (= 1.1). h is the height of the building, which is 22.5 m.

$$\begin{aligned} q_{w,rep} &= 21.6 \cdot 1.11 \cdot (0.8 + 0.5) \cdot 0.85 \cdot 1.0 \cdot 1.1 = 29.1\ kN/m \\ q_{w,d} &= 29.1 \cdot 1.5 = 43.7\ kN/m \end{aligned} \tag{C.92}$$

$$\begin{aligned} F_{w,rep} &= 21.6 \cdot 94.5 \cdot 0.04 \cdot 1.11 \cdot (0.8 + 0.5) \cdot 0.85 \cdot 1.0 \cdot 1.1 = 114.4\ kN \\ F_{w,d} &= 114.4 \cdot 1.5 = 171.6\ kN \end{aligned} \tag{C.93}$$

Figure C.2 displays the load-bearing walls on the ground floor:

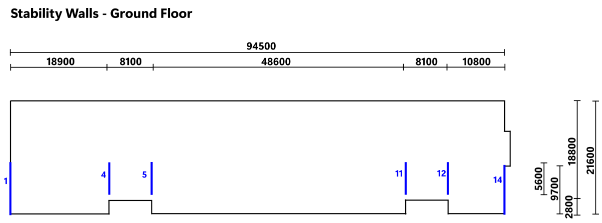

Figure C.2: Load-Bearing Walls on Ground Floor

For the horizontal stability, the walls are projected as springs, for which the spring constant depends on the value of EI of the walls. Table C.2 displays the EI of all walls, together with what percentage of loads are taken up by each wall. This percentage is the value EI of the wall in question compared to the value of all EI's combined.

Element	E-modulus [GPa]	I_{yy} $[m^4]$	EI $[kNm^2]$	%
1	9.465	19.0	180×10^6	36.1%
2	9.465	3.7	34.6×10^6	6.95%
3	9.465	3.7	34.6×10^6	6.95%
4	9.465	3.7	34.6×10^6	6.95%
5	9.465	3.7	34.6×10^6	6.95%
6	9.465	19.0	180×10^6	36.1%

Table C.2: EI and Contribution Percentages of Ground Floor Load-Bearing Walls

This process is repeated for the load-bearing walls on the remaining floors. The wind load on the ground floor load-bearing walls are divided into two loads, $q_{0;1}$ and $q_{0;2}$, which are different due to the shape of the building. The value for $q_{0;1}$ depends on $q_{w,rep}$, $F_{w,rep}$ and the height of the building and equals 4.12 kN/m. $q_{0;2}$ does not depends on $F_{w;rep}$ and results in 4.99 kN/m.

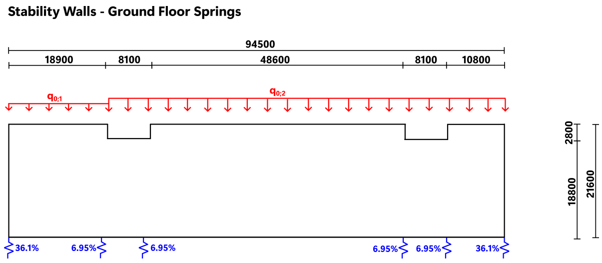

Figure C.3: Horizontal Wind Load on Ground Floor Walls

Figure C.3 is used as a model with a beam and springs, in which the changing thickness of the beam indicates that the floor width is uneven on the ground floor. When this is done for every floor, the shear force and moment on the foundation piles can be calculated, as displayed in Table C.3 for wall 4.

Level	Height [m]	F_{yd}	V_{yd}	M_{yd}
+7	22.4	0		
+6	19.4	28.82	0	0
+5	16.4	37.02	28.82	86.46
+4	13.4	44.09	65.84	283.98
+3	10.4	48.47	109.93	613.77
+2	7.4	48.47	158.4	1088.97
+1	4.4	61.34	206.87	1709.58
0	0	0	**268.21**	**2889.70**

Table C.3: Wall 4 Shear Force and Moment

The moment M_{yd} can be calculated into a line load q_M with Equation C.94. This line load is to be used as in Figure D.9.

$$q_{M;4} = \frac{M_{yd;4} \cdot 6}{b_{wall;4}^2} = \frac{2889.70 \cdot 6}{5.6^2} = 552.88kN/m \tag{C.94}$$

The last step is to compute the loads on the foundation piles, which are modelled as springs. Each pile has a spring constant of 5.66×10^5. Figure C.4 and Table C.4 show the loads on wall 4. The point loads are the loads from the columns on the ground floor, the line load q_4 is the load from the wall on the ground floor.

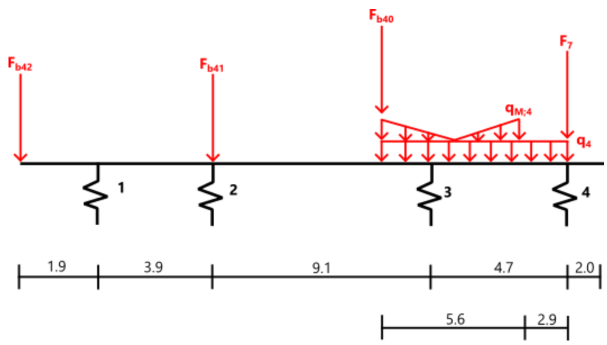

Figure C.4: Loads on Foundation Under Wall 4

Load	G	Q
$q_{M;4}$	552.88 kN/m	0
q_4	442 kN/m	62 kN/m
F_7	629 kN	81 kN
F_{b40}	1260 kN	204 kN
F_{b41}	3496 kN	481 kN
F_{b42}	862 kN	104 kN

Table C.4: Loads on Foundation Under Wall 4

The loads on the foundation are calculated in the Technosoft software. The results on the four springs are given in Table C.5. Since all results have positive values, there is no tension in the foundation piles underneath wall 4.

Foundation Pile #	Reaction Force [kN]
1	930.42
2	4394.48
3	5287.19
4	1042.07

Table C.5: Resulting Loads on Foundation Piles Under Wall 4

This process is repeated for all foundation piles. Only one pile experiences tension (-334.83 kN), which is a foundation pile underneath wall 11. A possible solution is to place a tension pile underneath the same foundation block as this pile to resist the tension.

C.3. KasseNova aan de Vaart - Design Variant 3

The design calculations of the CLT floors are the same as in design variant 1. For the CLT walls, two C3s-70 panels are used (20/30/20), as well as two 15.4 mm gypsum plasterboards. Similar to design variant 2, the charring depth after a 60-minute fire d_{char} equals 25.6 mm. The effective cross section h_{ef} is 24.4 mm for each panel. The following unity check is used to check buckling under fire conditions.

$$\frac{N_{d,fi}}{k_{c,fi} \cdot A_{x,net,fi} \cdot f_{c,fi}} + \frac{M_{d,fi}}{W_{x,net,fi} \cdot f_{m,fi}} = \frac{75.3 \times 1000}{0.329 \cdot 400 \times 10^2 \cdot 24.15} + \frac{0.95 \times 10^6}{686 \times 10^3 \cdot 27.6} = 0.29 \leq 1 \quad \text{(C.95)}$$

C.4. Apollolaan - Design Variant 1

The first design variant of Apollolaan uses 400x400 mm glulam columns (GL24h). A buckling calculation is performed.

The buckling length $l_0 = L = 4.72$ m.

$$\sigma_{cr} = \frac{\pi^2 \cdot E_{0.05} \cdot I_y}{b \cdot h \cdot l_0^2} = \frac{\pi^2 \cdot 9600 \cdot \dfrac{400^4}{12}}{400^2 \cdot (4.72 \times 10^3)^2} = 56.71\ MPa \quad \text{(C.96)}$$

Relative slenderness ratio $\lambda_{rel,y}$:

$$\lambda_{rel,y} = \sqrt{f_{c,0,k}/\lambda_{cr,y}} = \sqrt{24/56.71} = 0.65 \quad \text{(C.97)}$$

Factor k_y:

$$k_y = \frac{1}{2} \times [1 + \beta_c \times (\lambda_{rel,y} - 0.3) + \lambda_{rel,y}^2] = \frac{1}{2} \times [1 + 0.1 \times (0.65 - 0.3) + 0.65^2] = 0.73 \quad \text{(C.98)}$$

Reduction factor for buckling $k_{c,y}$:

$$k_{c,y} = \frac{1}{k_y + \sqrt{k_y^2 - \lambda_{rel,y}^2}} = \frac{1}{0.73 + \sqrt{0.73^2 - 0.65^2}} = 0.94 \tag{C.99}$$

$$\begin{aligned} M_{y,d} &= \frac{q_d \cdot l^2}{8} = \frac{1.03 \cdot 4.72^2}{8} = 2.87\ kNm \\ \sigma_{m,d} &= \frac{6 \cdot 2.87 \times 10^6}{400^3} = 0.27 MPa \end{aligned} \tag{C.100}$$

The design load P_d equals 2168.66 kN.

$$\sigma_{c,0,d} = \frac{P_d}{b^2} = \frac{2168.66 \times 10^3}{400^2} = 13.55 MPa \tag{C.101}$$

The unity check is given in Equation C.102:

$$\frac{\sigma_{c,0,d}}{k_{c,y} \cdot f_{c,0,d}} + \frac{\sigma_{m,d}}{f_{m,d}} = \frac{13.55}{0.94 \cdot 17.28} + \frac{0.27}{24} = 0.85 \leq 1 \tag{C.102}$$

C.5. Apollolaan - Design Variant 2

In design variant 2 for Apollolaan, the same calculations are performed for the CLT as in KasseNova, but with the input values from this design. A L5s-200 floor is used, the maximum span after applying the changes in floor plan is 5.4 m and the loads are 1.84 kN/m² (g_k) and 2.55 kN/m² (q_k). The design moment M_d is 24.30 kNm, the design shear force V_d is 25.80 kN.

$$\sigma_d = \frac{M_d}{W_{x,net}} = \frac{24.30 \times 10^3}{5280} = 4.60\ MPa < 15.36\ MPa \tag{C.103}$$

$$\tau_d = \frac{V_d \cdot S_{x,net}}{I_{x,net} \cdot b_x} = \frac{25.80 \times 10^3 \cdot 3400 \times 10^3}{52800 \times 10^4 \cdot 1000} = 0.17\ MPa < 2.56\ MPa \tag{C.104}$$

$$\tau_{Rv,d} = \frac{S_{Rx,net} \cdot V_d}{I_{x,net} \cdot b_x} = \frac{3200 \times 10^3 \cdot 25.80 \times 10^3}{52800 \times 10^4 \cdot 1000} = 0.16\ MPa < 0.90\ MPa \tag{C.105}$$

The maximum allowed deflection w_{max} is calculated as:

$$w_{max} = L/325 = 5400/325 = 16.6\ mm \tag{C.106}$$

The maximum deflection which occurs in the floor is a combination of the short-term and long-term deformation.

$$w_{g,k} = \frac{5 \cdot g_k \cdot L^4}{384 \cdot E_{x,mean} \cdot I_{x,ef}} = \frac{5 \cdot 1.84 \times 10^3 \cdot 5.4^4}{384 \cdot 11000 \times 10^6 \cdot 47349 \times 10^{-8}} = 3.92\ mm \tag{C.107}$$

$$w_{q,k} = \frac{5 \cdot q_k \cdot L^4}{384 \cdot E_{x,mean} \cdot I_{x,ef}} = \frac{5 \cdot 2.55 \times 10^3 \cdot 5.4^4}{384 \cdot 11000 \times 10^6 \cdot 47349 \times 10^{-8}} = 5.42\ mm \tag{C.108}$$

$$w_{inst} = w_{g,k} + w_{q,k} = 3.92 + 5.54 = 9.34\ mm \tag{C.109}$$

$$w_{fin} = w_{fin,g} + w_{fin,q} = 7.25 + 6.80 = 14.06\ mm \tag{C.110}$$

For the vibrations, the following calculations must be performed:

$$f_1 = \frac{\pi}{2L^2}\sqrt{\frac{(EI)_L}{m}} = \frac{\pi}{2 \cdot 5.4^2}\sqrt{\frac{11000 \times 10^6 \cdot 47349 \times 10^{-8}}{188}} = 8.97\ Hz > 8\ Hz \tag{C.111}$$

$$w = \frac{PL^3}{48 \cdot (EI)_L \cdot B_{ef}} = \frac{1 \cdot 5400^3}{48 \cdot 11000 \cdot 47349 \times 10^4 \cdot 0.74} = 0.85\,mm < a = 1mm \quad (C.112)$$

$$v_{max} = b^{f_1 \cdot \xi - 1} = 120^{(8.97 \cdot 0.01 - 1)} = 0.0244 \quad (C.113)$$

$$v = \frac{4(0.4 + 0.6n_{40})}{mBL + 200} = \frac{4(0.4 + 0.6 \cdot 19.53)}{188 \cdot 19.598 \cdot 5.4 + 200} = 0.0024 < v_{max} = 0.0244 \quad (C.114)$$

For the fire safety, the calculation for a protected floor structure is used with a 13 mm thick plasterboard. The value for d_{char} is 31.97 mm, using the same equations as in KasseNova aan de Vaart.

$$\sigma_{d,fi} = \frac{M_{d,fi}}{W_{x,net,fi}} = \frac{9.60 \times 10^6}{3250 \times 10^3} = 2.95\,MPa < f_{m,d,fi} = 27.6\,MPa \quad (C.115)$$

$$\tau_{d,fi} = \frac{V_{d,fi} \cdot S_{x,net,fi}}{I_{x,net,fi} \cdot b_x} = \frac{10.20 \times 10^3 \cdot 2361 \times 10^3}{25680 \times 10^4 \cdot 1000} = 0.0938\,MPa < f_{v,d,fi} = 4.6\,MPa \quad (C.116)$$

$$\tau_{Rv,d,fi} = \frac{S_{Rx,net,fi} \cdot V_{d,fi}}{I_{x,net,fi} \cdot b_x} = \frac{761 \times 10^3 \cdot 10.20 \times 10^3}{25680 \times 10^4 \cdot 1000} = 0.0302\,MPa < f_{Rv,d,fi} = 1.61\,MPa \quad (C.117)$$

D

Additional Literature Study

This Appendix includes an additional literature study related to the topic of sustainability. It is divided into several parts. The first part consists of the most commonly used definitions of sustainability. The second part describes various methods of quantifying sustainability. The third part includes calculation methods for the CLT elements and the last part includes multiple methods for changing foundation piles.

D.1. Defining Sustainability

Sustainability is a broad and context-specific topic. The etymology of the term "sustainable" can be traced back to the Latin word "sustinere", which means to maintain, defend, bear, etc. (Castiglioni & Mariotti, 1981; Bolis et al., 2014). This original version of the word does not specify what exactly to maintain. The current version of the word also does not provide any solutions and can, as shown later during this chapter, even lead to conflicting terminologies.
Efforts have been made to define sustainability in a manner that allows it to be applied independently of its context. A number of these efforts are covered in this part of the chapter. While the Sustainable Development Goals from the United Nations, described first in this chapter, do not explicitly define sustainable development, they establish a foundation for another type of definition which will be addressed later on. The most common, but also a very general, definition of sustainability is the one from the Brundtland Report, which is discussed subsequently. After this, the Three Pillars of Sustainability are described, which splits sustainability into three interconnected parts, or pillars. From these pillars, the ecological (or environmental) pillar is the most relevant for this report. Therefore, two definitions are presented for ecological sustainability. Lastly, the three impact areas of a sustainable built environment, as defined by the World Green Building Council, are presented.
The terms "sustainability" and "sustainable development" are often used interchangeably in literature. However, certain authors argue that sustainability denotes an ongoing process, while sustainable development denotes the ultimate state (Surampalli et al., 2020).

D.1.1. Sustainable Development Goals

In 2015, the United Nations released a list of pressing global economic, social and environmental challenges in the form of 17 Sustainable Development Goals (SDGs), which are illustrated in Figure D.1 (United Nations, n.d.). These goals were agreed upon by the 193 member states of the United Nations in 2015. The objective is to achieve the 17 SDGs by 2030.

Figure D.1: United Nations Sustainable Development Goals (United Nations, 2015)

For every goal, targets have been established to make the goals tangible. In total, there are 169 targets for all SDGs combined (Espey, 2022). Each target consists of indicators, which serves as a metric for the target. The United Nations attempts to reach these goals by means of organizing events and actions and by releasing publications. Each year, the United Nations releases a report with an overview of the progress made towards achieving the SDGs.

While the Sustainable Development Goals do not explicitly provide a definition of sustainable development, they do include the elements to reach it. Moreover, they are used in other definitions, one of which will be discussed later during this chapter.

D.1.2. Brundtland Report

Another commonly used definition of sustainability is defined by the United Nations Brundtland Commission in 1987 (WCED, 1987):

> "Sustainability means meeting the needs of the present without compromising the ability of future generations to meet their own needs."

This definition is different from the Three Pillars of Sustainability in the sense that it does not distinguish between types of sustainability and it accounts for future considerations. The definition from the Brundtland report received criticism as well. One common criticism is that no description is given on the courses of action to achieve the goal of reaching sustainability (Berke & Manta, 1999; Bartlett, 1994). Also, since sustainability is not further defined, another type of criticism is that the view of sustainable development in the Brundtland report is based towards economic growth (Langhelle, 1999).
Even though this definition received its criticism, it is the most widely used definition (Berke & Manta, 1999) and it gave momentum for the landmark 1992 Rio Summit (Drexhage & Murphy, 2010). This summit laid the foundation for the global institutionalization of sustainable development.

D.1.3. Three Pillars of Sustainability

One common method of illustrating sustainability is the so-called "Three Pillars of Sustainability" (Hansmann et al., 2012; Surbeck, 2018; Purvis et al., 2019; Surampalli et al., 2020; Ranjbari et al., 2021). These three pillars contain the environmental, social and economic domains of sustainability. Figure D.2 illustrates these pillars and the fact that these pillars are interrelated.

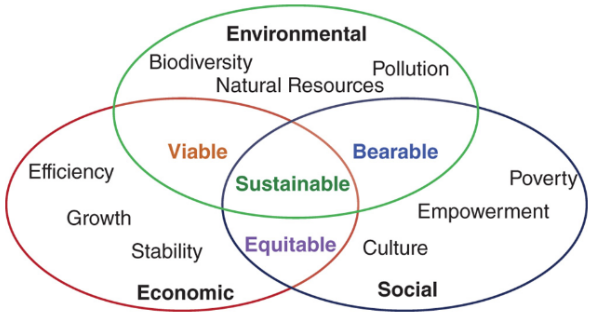

Figure D.2: Three Pillars of Sustainability (Surampalli et al., 2020)

While this definition of sustainability is commonly used, it still allows for own interpretation regarding the description of the pillars. According to Purvis, this is because the three pillars were gradually developed over time from broadly different schools of thought (Purvis et al., 2019). While the three pillars itself do not change across literature, there can be differences between the included terms for each pillar. An example from literature shows that even within a singular source are used. This example is illustrated in Figure D.3, which is sourced from the same report as Figure D.2. Apart from the fact that the pillars in Figure D.3 include different terms than Figure D.2, it does not place any emphasis on the interrelatedness. Since there is no universally accepted description of the Three Pillars of Sustainability, this description becomes context-specific.

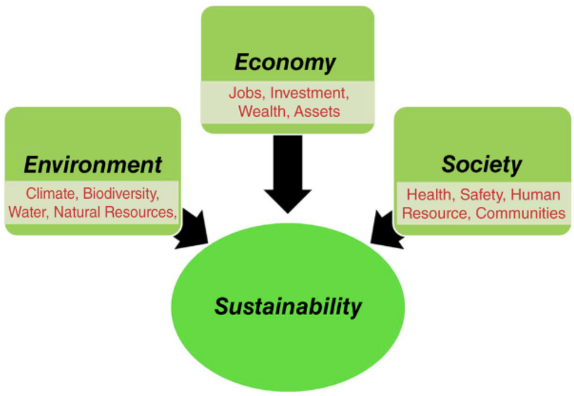

Figure D.3: Three Pillars of Sustainability (Surampalli et al., 2020)

The interrelatedness between pillars is not always positive, meaning potential conflicts may arise (Surampalli et al., 2020). For example, while a company may be responsible for environmental damage, it can simultaneously have a positive impact on the economy. This will cause an imbalance in the pillars, meaning that the prioritization of the pillars needs to be considered. Consequently, this might lead to subjectivity. Furthermore, comparing the pillars might be impossible due to different values being used, such as costs, justice, wellbeing, etc. (Hansmann et al., 2012).

D.1.4. Ecological Sustainability

Ecological sustainability, often used interchangeably with environmental sustainability, is part of the Three Pillars of Sustainability, described earlier in this chapter. One of the definitions of ecological sustainable development (or ESD) was given by the Australian government in 1992 (Council of Australian Governments, 1992):

> “Using, conserving and enhancing the community’s resources so that ecological processes, on which life depends, are maintained, and the total quality of life, now and in the future, can be increased.”

This definition has similarities with the definition from the Brundtland Report. 'Ecological processes, on which life depends', much like the word 'sustainability' from the Brundtland Report, needs more elaboration in order to become clear. Another similarity is that the definition of ESD accounts for impacts for both current and future generations.
Ecological sustainability can also be used as an umbrella term. The KTH in Stockholm describes ecological sustainability as (KTH, n.d.):

> "Ecological sustainability includes everything that is connected with the Earth's ecosystems. Amongst other things, this includes the stability of climate systems, the quality of air, land and water, land use and soil erosion, biodiversity (diversity of both species and habitats), and ecosystem services (e.g. pollination and photosynthesis)."

This definition places greater emphasis on the specific terms which are included within ecological sustainability, rather than what it actually means. The main advantage of this is that the definition becomes less ambiguous. However, it is important that all relevant terms are actually covered by this definition.

D.2. Quantifying Sustainability

In order to test and grade sustainability, quantification of this term is necessary. Like the definition of sustainability, there is no universally adopted method for this purpose. While the LEED certification method is used worldwide, every country usually has their own method besides this. The Netherlands for instance utilizes the BREEAM-NL certification method, as well as the MilieuPrestatie Gebouwen (MPG) indicator.
This section of the chapter starts with an explanation of the MPG indicator, followed by another type of sustainability index, carbon footprint. Subsequently, BREEAM-NL and LEED are addressed in detail.

D.2.1. MilieuPrestatie Gebouwen (MPG)

The MilieuPrestatie Gebouwen (MPG) is a single grade score, calculated with one decimal, and takes into account the shadow cost of each material, the gross floor area and building life span (Van Loon et al., 2019). The calculation of the MPG is shown in Equation D.1:

$$MPG = \frac{\Sigma\ (Shadow\ cost\ each\ material)}{Gross\ floor\ area\ x\ Building\ life\ span} \tag{D.1}$$

The shadow cost of each material can be extracted from the Nationale Milieudatabase (NMD), which will be further elaborated on later during the chapter. The shadow costs are given in euro's, while the gross floor area is in m^2 and the building life span in years, meaning that the MPG is calculated in €/(m^2 x year). For residential buildings, a life span of 75 years needs to be assumed. For non-residential buildings, this value should be taken as 50 years (Stichting Bouwkwaliteit, 2019).
It is mandatory to perform a MPG calculation for newly built non-residential buildings larger than 100 m^2 and for all newly built residential buildings (Stichting Bouwkwaliteit, 2017). At the January 1st, 2018, the value of the MPG should be a maximum of 1.0 was adopted into Bouwbesluit 2012. This value is for both residential and non-residential buildings. The MPG for residential buildings was lowered to 0.8 on July 1st, 2021. The aim is to reduce this value further, until it is 0.5 by 2030.

In order to understand how the shadow costs are calculated, knowledge on the Life Cycle Assessment (LCA) is necessary. The Life Cycle Assessment is a method, formalized in the 1990s by organizations such as the International Standards Organization (ISO), in order to track the energy and resource use of manufacturing processes and products (Simonen, 2014). The LCA follows ISO 14040, which describes principles and a framework for performing the Life Cycle Assessment.
The LCA consists of multiple phases. The first phase consists of the determining the goal and scope of the LCA. The goal of the LCA should include:

- The intended application (what)
- The reason for carrying out the study (why)
- The intended audience (for whom)

The scope defines what is included and excluded from the analysis. Also, it defines the parameters of the study. ISO 14040 states that the following key items should be defined within the scope of the LCA:

- The product to be studied: function, performance and functional unit
- The system boundary: included and excluded parts
- Methodological choices: including assumptions, impact assessment and interpretation methods
- Analysis details: sources of the data, data quality requirements and type of critical review

The functional unit defines a unit of analysis that includes quantity, quality and the duration which a product of service will provide. Part of the Life Cycle Assessment are the life cycle stages, which have been standardized into four stages, with an optional stage after the last stage:

- A1-A3: Product stage
- A4-A5: Construction Process Stage
- B1-B7: Use stage
- C1-C4: End of life stage
- D: Benefits and loads beyond the system boundary

Stage D is optional, since reusing, recovering or recycling is not always done at the end of a building's life cycle.

Figure D.4 illustrates these life cycle stages with its processes:

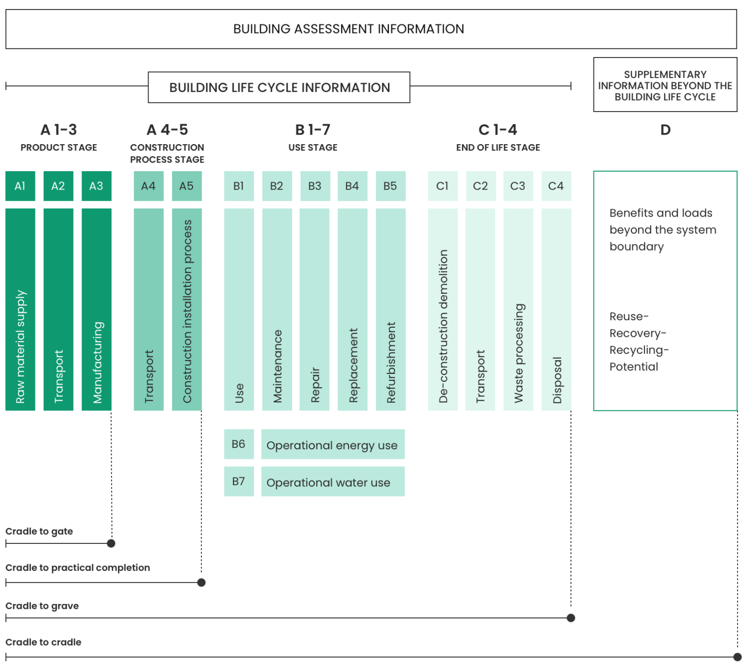

Figure D.4: Life Cycle Stages (Masson, 2023)

The next part in the Life Cycle Assessment is to define the life cycle inventory (LCI). The main activity of this step of the LCA is to collect and compile data on elementary flows from all processes in the studied product system(s) (Bjørn et al., 2018). The output is an inventory of these elementary flows, which will be used for the next step.
The next step is to perform a Life Cycle Impact Assessment (LCIA), in which life cycle inventory is used to calculate the environmental impact score (Bjørn et al., 2018). It might be necessary to normalize the

outputs, such that the elementary flows can be compared with each other. The final step in order to calculate the environmental impact score is to apply monetization, which results in the shadow cost used in the MPG.

The data which is used in the life cycle inventory can be obtained by using Environmental Product Declarations (EPDs). The method for declaring EPDs is standardized by ISO 14025, with the output being kg CO2-equivalent per environmental impact category and per life cycle stage (Del Borghi, 2013). In the Netherlands, the EPDs are saved in the Nationale Milieudatabase (NMD). All entries in this database are separated into three categories, with category 1 and 2 consisting of data which is tested by an independent third party and category 3 consisting of untested data (Nationale Milieudatabase, 2021). Category 1 and 2 can only be viewed with specific tools which can calculate the MPG, but the category 3 data can be reviewed to see how the underlying data is organized (Jonkers, 2022).

The website of Nationale Milieudatabase states there are five validated types of software in the Netherlands to calculate the MPG (Nationale Milieudatabase, n.d.):

- GPR Gebouw: the software considers energy, environment (resources and emissions), health, quality for user and future value. It is specifically developed for homes, offices and schools (Jonkers, 2022).
- MPG Toetshulp: apart from GPR/MPG-indicators, this software also displays the Paris Proof (CO_2-eq/m^2) indicators. It is specifically developed for newly built residential buildings, offices and other building functions (Bimpact, n.d.).
- One Click LCA: extensive software, used globally. Can be used to achieve credits for certifications, besides determining the environmental impact (One Click LCA, n.d.).
- DuboCalc: consists of raw material and (half) product information, as well as information on building processes. Used by Rijkswaterstaat for civil engineering constructions (Jonkers, 2022).
- MRPI-MPG Tool: calculates the use of resources and emissions of specifically building materials, elements and products (Jonkers, 2022).

The type of software which is used can differ per company. As mentioned, Rijkswaterstaat uses DuboCalc, however, Van Rossum BV uses GPR Gebouw for the calculation of the MPG. While the value for the MilieuPrestatie Gebouwen is the only environmental impact indicator, it is not the only one which is used. The next part of the chapter will cover carbon footprint, which is also used outside of the Netherlands.

D.2.2. Carbon Footprint

The carbon footprint is the amount of CO_2 (or CO_2-equivalent) emitted or taken up throughout the entire life cycle of the product. This can be calculated with Equation D.2, in which the amount of carbon footprint is calculated in kg CO2-equivalent (Orr et al., 2020):

$$Carbon\ footprint = quantity\ x\ carbon\ factor \tag{D.2}$$

The quantity is the amount of material used, while the carbon factor is the amount of CO_2-equivalent emitted gases per unit material. This unit can differ per material. For beams and columns, the used unit is m, while floors and walls use a unit of m^2 or m^3.
The amount of CO_2-equivalent emitted gases are adopted into the EPDs. These EPDs use environmental impact categories to distinguish between different types of environmental impacts related to building projects. The LCA uses 11 impact categories, quantified in units which may differ from CO2. Therefore, in order to normalize the data, all units are set to CO_2-equivalent by applying pre-determined factors (e.g. 1 kg NH_3 = 25 kg CO_2). The carbon factor can be calculated by summing the amount of CO_2-equivalent from the 11 impact categories.

It is possible to split the carbon footprint into different life cycle stages. The advantage is that it gives a better insight into which stages contribute most to the environmental impact. Care needs to be taken into which life cycle stages to consider. Stages B6 and B7, operational energy and water use, respectively, are not included in the carbon footprint calculation, as these are considered in the operation carbon calculation. Also, if a reused/recovered/recycled element is used, this will decrease the carbon footprint.

In order to limit the global temperature rise to 1.5 °C, Paris Proof emission limit of 400 Gt CO2-equivalent has been set for the entire world (Dutch Green Building Council, n.d.). When calculating for the Netherlands based on the amount of inhabitants, it means that 909 Mt CO2-equivalent emissions are allowed. Since carbon footprint accounts for 11% of the total emitted CO2, 100 Mt carbon footprint emissions are allowed for. The Dutch Green Building Council (DGBC) has set boundary values for the amount of carbon footprint per m^2 in buildings for both newly built constructions and for renovated constructions. These boundary values are illustrated in Tables D.1 and D.2.

Building Type	**Carbon Footprint [kg CO_2 per m^2]**			
	2021	2030	2040	2050
Residential building (single-family home)	200	126	65	45
Residential building (multi-family home)	220	139	83	50
Office	250	158	94	56
Retail real estate	260	164	98	59
Industry	240	151	91	54

Table D.1: Paris Proof Commitment for New Building Projects (Spitsbaard & van Leeuwen, 2021)

Building Type	**Carbon Footprint [kg CO_2 per m^2]**			
	2021	2030	2040	2050
Residential building (single-family home)	100	63	38	23
Residential building (multi-family home)	100	63	38	23
Office	125	79	47	28
Retail real estate	125	79	47	28
Industry	100	63	38	23

Table D.2: Paris Proof Commitment for Renovated Building Projects (Spitsbaard & van Leeuwen, 2021)

D.3. Calculation Methods CLT Elements

Part of the performed research is to create a design with timber which is a realistic design. In order to confirm that the design is realistic, design calculations need to be made. This part of the literature study will focus on the calculation methods of CLT elements.

The advantages of using CLT include a high in-plane dimensional stability, the ability to bear loads in and out of plane and a low variability in material properties, therefore making it a suitable option for a realistic design. In order to verify if the CLT elements fulfill the design requirements, there are several checks which have to be performed. This part of the chapter will describe the calculations needed to perform the checks for both CLT floors and walls. The equations were obtained from The CLT Handbook, which is a result of a collaboration between Swedish CLT suppliers and the industry body Swedish Wood (Swedish Wood, 2019).

D.3.1. CLT Floor Elements

The maximum span of a CLT floor depends on the total thickness of the element. A CLT floor consists of layers, which are either longitudinal or orthogonal to the direction of the span. Figure D.5 displays the standard types of CLT floors, along with the maximum span, maximum deformation and dead load for category A, B and C buildings.

Martinsons CLT panels Format: 3000 x length x thickness [mm]													
Load type[2]		Category A (Housing) 2.0 kN/m²				Category B (Offices)	2.5 kN/m²	Category C:3 3.0 kN/m²		Category C:4 4.0 kN/m²		Category C:5 5.0 kN/m²	
Panel[3]	Panel dead load [kg/m²]	Max. span width[4]	Deformation[6]	Max. span width[5]	Deformation[6]	Max. span width[4]	Deformation[6]	Max. span width[4]	Deformation[6]	Max. span width[4]	Deformation[6]	Max. span width[4]	Deformation[6]
L60-3L	24	2.3	L/315	2.0	L/465	2.2	L/310	2.4	L/211	2.2	L/218	2.1	L/206
L70-3L	28	2.6	L/321	2.6	L/321	2.5	L/309	2.7	L/218	2.5	L/217	2.4	L/203
L80-3L	32	3.1	L/304	3.0	L/333	2.9	L/315	3.2	L/211	3.0	L/203	2.8	L/207
L90-3L	36	3.4	L/312	3.4	L/312	3.2	L/320	3.5	L/217	3.3	L/208	3.1	L/207
L100-3L	40	3.7	L/316	3.7	L/316	3.5	L/318	3.9	L/206	3.6	L/211	3.4	L/207
L120-3L	48	4.5	L/302	4.3	L/341	4.2	L/318	4.6	L/218	4.3	L/214	4.1	L/206
L140-3L	56	5.1	L/313	4.7	L/395	4.9	L/306	5.3	L/217	5.0	L/209	4.6	L/204
L100-5s	40	3.5	L/318	3.5	L/318	3.4	L/301	3.7	L/208	3.4	L/214	3.2	L/213
L120-5s	48	4.0	L/317	3.9	L/315	3.8	L/319	4.2	L/212	3.9	L/212	3.7	L/208
L130-5s	52	4.6	L/319	4.4	L/336	4.4	L/317	4.9	L/205	4.6	L/201	4.3	L/205
L140-5s	56	4.5	L/308	4.3	L/350	4.3	L/305	4.7	L/211	4.4	L/208	4.1	L/214
L150-5s	60	5.2	L/302	4.6	L/397	4.9	L/312	5.3	L/222	5.1	L/202	4.8	L/203
L160-5s	64	5.7	L/311	5.0	L/420	5.5	L/302	5.7	L/244	5.6	L/210	5.3	L/208
L180-5s	72	5.7	L/335	5.0	L/446	5.6	L/309	5.7	L/263	5.6	L/227	5.5	L/202
L200-5s	80	6.3	L/368	5.6	L/514	6.3	L/325	6.3	L/290	6.3	L/240	6.3	L/205
L230-5s	92	6.8	L/422	6.0	L/594	6.8	L/374	6.8	L/335	6.8	L/279	6.8	L/239
L210-7s	84	6.3	L/380	5.6	L/528	6.3	L/335	6.3	L/300	6.3	L/248	6.3	L/211
L240-7s	96	7.1	L/455	6.3	L/643	7.1	L/406	7.1	L/364	7.1	L/303	7.1	L/260
L270-7s	108	7.4	L/500	6.5	L/722	7.4	L/446	7.4	L/404	7.4	L/338	7.4	L/290
L280-7s	112	7.4	L/493	6.6	L/673	7.4	L/440	7.4	L/398	7.4	L/332	7.4	L/286
L300-7s	120	7.7	L/538	6.9	L/726	7.7	L/481	7.7	L/438	7.7	L/367	7.7	L/317

Figure D.5: Maximum Span of Standardized CLT Floor Elements (Martisons, n.d.)

Figure D.6 provides a description of the layering within the CLT floor, as well as the dead load and U value of each CLT floor type.

Thickness (mm)	Dead load[1] (kg/m²)	Number of layers	U value[2]	Constructed dimensions
60	24	3	1.49	20+20+20
70	28	3	1.33	20+30+20
80	32	3	1.20	30+20+30
90	36	3	1.09	30+30+30
100	40	3	1.00	33.3+33+33
120	48	3	0.85	40+40+40
140	56	3	0.75	46.5+46.5+46.5
100	40	5	1.00	20+20+20+20+20
120	48	5	0.85	20+30+20+30+20
130	52	5	0.80	30+20+30+20+30
140	56	5	0.75	20+40+20+40+20
150	60	5	0.70	30+30+30+30+30
160	64	5	0.67	40+20+40+20+40
180	72	5	0.60	30+45+30+45+30
200	80	5	0.54	40+40+40+40+40
230	92	5	0.48	46+46+46+46+46
210	84	7	0.52	30+30+30+30+30+30+30
240	96	7	0.46	45+20+45+20+45+20+45
270	108	7	0.41	45+30+45+30+45+30+45
280	112	7	0.40	40+40+40+40+40+40+40
300	120	7	0.37	45+40+45+40+45+40+45

Figure D.6: Layering of Standard CLT Floor Elements (Martisons, n.d.)

The layers alternate between being longitudinal and orthogonal to the spanning direction, with the outer layers being longitudinal. The longitudinal layers can have the same strength class as the orthogonal layers, but this is not a necessity.

Moment, Shear Force and Rolling Shear Force
The cross-sectional properties which need to be tested are the moment, shear force and rolling shear force. Equations D.3 until D.5 describe how the design strengths can be calculated, with $k_{mod} = 0.8$ and $\gamma_M = 1.25$. $f_{m,d}$, $f_{v,d}$ and $f_{Rv,d}$ are the design strength and $f_{m,k}$, $f_{v,k}$ and $f_{Rv,k}$ are the characteristic strength of moment, shear and rolling shear, respectively:

$$f_{m,d} = \frac{k_{mod} \cdot f_{m,k}}{\gamma_M} \tag{D.3}$$

$$f_{v,d} = \frac{k_{mod} \cdot f_{v,k}}{\gamma_M} \tag{D.4}$$

$$f_{Rv,d} = \frac{k_{mod} \cdot f_{Rv,k}}{\gamma_M} \tag{D.5}$$

The design moment σ_d for a single-span beam can be calculated with Equation D.6:

$$\sigma_d = \frac{M_d}{W_{x,net}} \tag{D.6}$$

The cross-sectional properties can be calculated for a strip with a width of 1.0 m. For a single-span beam, the design moment can be calculated as $M_d = \frac{q_d \cdot L^2}{8}$, but for a continuous beam the software 'Technosoft Liggers' provides the maximum design moment. The net moment of resistance $W_{x,net}$ is dependent on the CLT properties, as shown in Equation D.7:

$$W_{x,net} = \frac{2 \cdot I_{0,net}}{h_{CLT}} \tag{D.7}$$

h_{CLT} is the thickness of the CLT floor and $I_{0,net}$ the net moment of inertia, which can be calculated with Equation D.8:

$$I_{0,net} = \sum \frac{b_x t_i^3}{12} + \sum b_x t_i a_i^2 \tag{D.8}$$

In this equation, E_i is the elastic modulus, b_x is the width of the slab, t_i is the thickness of the individual layer and a_i the distance between the middle of the individual layer and the centre of gravity of the slab. The only layers which are regarded in this calculation are the longitudinal layers.

The design shear force τ_d can be calculated with Equation D.9:

$$\tau_d = \frac{V_d \cdot S_{x,net}}{I_{x,net} \cdot b_x} \tag{D.9}$$

In case of a single-span beam, $V_d = 0.5 \cdot q_d \cdot L$. If the beam is continuous, this value is to be computed with Technosoft Liggers. The net moment of inertia $I_{x,net}$ is the same value as $I_{0,net}$, with the equation described in Equation D.8. b_x is the width of the slab. The static moment of longitudinal shear $S_{x,net}$ can be calculated either with Equation D.10 if the panel's centre of gravity lies in the layer in question or D.11 if the panel's centre of gravity does not lie in the layer in question:

$$S_{x,net} = \sum_{i=1}^{k_L} \frac{E_{x,i}}{E_{ref}} b_x t_i a_i + b_x \frac{\left(\frac{t_k}{2} - a_k\right)^2}{2} \tag{D.10}$$

$$S_{x,net} = \sum_{i=1}^{k_L} \frac{E_{x,i}}{E_{ref}} b_x t_i a_i \tag{D.11}$$

In these equations, k_L is the designation for the longitudinal layer nearest to the panel's centre of gravity and E_{ref} is the chosen reference value for modulus of elasticity.

The design rolling shear force $\tau_{Rv,d}$ can be calculated with Equation D.12:

$$\tau_{Rv,d} = \frac{S_{Rx,net} \cdot V_d}{I_{x,net} \cdot b_x} \tag{D.12}$$

Equation D.13 is used to calculate the static moment of rolling shear $S_{Rx,net}$:

$$S_{Rx,net} = \sum_{i=1}^{m_L} \frac{E_{x,i}}{E_{ref}} \cdot b_x t_i a_i \tag{D.13}$$

In this equation m_L is the designation for the transverse layer nearest to the panel's centre of gravity.

Deformations

A calculation need to be performed to ensure that the deformations in the CLT slab do not become too large. For this, the slab again is taken as a beam with width $b_x = 1000$ mm. The maximum allowed deformation is dependent on the type of panel and the building category, as displayed in Figure D.5. If for instance the panel L60-3L for a Category A building is used, the maximum allowed deformation is $L/315$. Both short-term and long-term deformation can be calculated and both should be below the allowed deformation. The short-term deformation w_{inst} is the sum of the short-term deformation due to the dead load $w_{g,k}$ and due to the variable load $w_{q,k}$ (Equation D.14). This short-term deformation due to the dead load and due to the variable load can be calculated with Equations D.15 and D.16, respectively, in which g_k and q_k are the characteristic value for the dead load and variable load, L is the span of the beam and $E_{x,mean}$ the mean elastic modulus in x-direction.

$$w_{inst} = w_{g,k} + w_{q,k} \tag{D.14}$$

$$w_{g,k} = \frac{5 \cdot g_k \cdot L^4}{384 \cdot E_{x,mean} \cdot I_{x,ef}} \tag{D.15}$$

$$w_{q,k} = \frac{5 \cdot q_k \cdot L^4}{384 \cdot E_{x,mean} \cdot I_{x,ef}} \tag{D.16}$$

In these equations, $I_{x,ef}$ is the effective moment of inertia. This value can be calculated with Equation D.17, in which only the longitudinal layers are taken into account:

$$I_{x,ef} = \sum \frac{E_{x,i}}{E_{ref}} \cdot \frac{b_x t_i^3}{12} + \sum \gamma_i \cdot \frac{E_{x,i}}{E_{ref}} \cdot b_x t_i a_i^2 \tag{D.17}$$

Similar to the effective moment of inertia, the gamma values γ_1 only need to be calculated for the longitudinal layers. For a 5-layer CLT floor, this means that the gamma values for layers 1, 3 and 5 are only calculated. Equations D.18 until D.20 show how this value can be calculated with for these layers, with G_{9090} being the shear modulus along the y-axis.

$$\gamma_1 = \frac{1}{1 + \frac{\pi^2 E_{x,1} t_1}{l_{ref}^2} \frac{t_2}{G_{9090,2}}} \tag{D.18}$$

$$\gamma_3 = 1 \tag{D.19}$$

$$\gamma_5 = \frac{1}{1 + \frac{\pi^2 E_{x,5} t_5}{l_{ref}^2} \frac{t_4}{G_{9090,4}}} \tag{D.20}$$

The final deformation w_{fin} is the sum of the final deformation due to dead loads $w_{fin,g}$ and variable loads $w_{fin,q}$ (Equation D.21). These deformations can be calculated with Equations D.22 and D.23, respectively:

$$w_{fin} = w_{fin,g} + w_{fin,q} \tag{D.21}$$

$$w_{fin,g} = w_{g,k} \cdot (1 + k_{def}) \tag{D.22}$$

$$w_{fin,q} = w_{q,k} \cdot (1 + \psi_2 \cdot k_{def}) \tag{D.23}$$

For service 1 buildings, the value of k_{def} equals 0.85. For category A buildings, the value of ψ_2 equals 0.3.

Vibrations

Vibrations in CLT floors can be perceived as unpleasant by the user if not taken properly care of during design. Therefore, several calculations need to be performed in order to ensure that the vibrations are limited.

The first calculation which is performed is the lowest fundamental frequency, f_1, for floor structures. This value, at peak energy, needs to be below the excitation frequency to avoid the load coinciding with the response frequencies. If the value for the lowest fundamental frequency is above the excitation frequency, measures to be taken are increasing the stiffness, reducing the mass or reducing the span. However, usually it is easier to increase the ratio of strength-to-mass than the ratio of stiffness-to-mass (Swedish Wood, 2019).

People are sensitive to vibrations below 8 Hz. Therefore, the fundamental frequency should not be below this value. The value for the fundamental frequency f_1 can be calculated with Equation D.24, in which L is the floor span, $(EI)_L$ is the bending stiffness in the floor structure's stiffest direction and m is the floor structure's mass per metre:

$$f_1 = \frac{\pi}{2L^2} \sqrt{\frac{(EI)_L}{m}} \tag{D.24}$$

The second calculation for the vibrations is a calculation of the deflection of the strip due to a point load of 1 kN, which represents a person walking over the strip. This is compared with the recommended value a, according to Equation D.25:

$$\frac{w}{F} \leq a \tag{D.25}$$

According to the Dutch National Annex of NEN-EN 1995-1-1, the value for a is equal to 1 mm/kN (NEN, 2013b). The value for w can be calculated with Equation D.26. Since the CLT floor has two load bearing directions, the stiffness of both directions can be used.

$$w = \frac{PL^3}{48 \cdot (EI)_L \cdot B_{ef}} \tag{D.26}$$

P is the value for the point load, which is equal to 1 kN. B_{ef} is a load distribution factor, which can be calculated in accordance with Equation D.27:

$$B_{ef} = \frac{L}{1.1}\sqrt{\frac{(EI)_B}{(EI)_L}} \tag{D.27}$$

In this equation, $(EI)_L$ is the bending stiffness in the floor structure's stiffest direction, $(EI)_B$ is the bending stiffness perpendicular to the floor structure's stiffest direction and L is the length in the stiffest direction.

As mentioned earlier, vibrations below 8 Hz can be perceived as disturbing. However, vibrations above 8 Hz can be disturbing as well. The impulse velocity response v is a partial indicator to measure how disturbing vibrations above 8 Hz are. This impulse velocity response is checked against the chosen floor structure quality, according to Equation D.28.

$$v \leq b^{(f_1 \xi - 1)} \tag{D.28}$$

In this equation, b is a factor which is set at 120 $m/(Ns^2)$, according to the Dutch National Annex of NEN-EN 1995-1-1 (NEN, 2013b). f_1 is the lowest fundamental frequency, according to Equation D.24. ξ is a damping factor, which equals 0.01 (or 1%), according to NEN-EN 1995-1-1 (NEN, 2011b). The impulse velocity response v can be calculated with Equation D.29:

$$v = \frac{4\,(0.4 + 0.6 n_{40})}{mBL + 200} \tag{D.29}$$

In this equation, m is the floor structure's mass per metre, B is the floor width and n_{40} is the number of first-order modes with fundamental frequencies up to 40 Hz, which can be calculated according to Equation D.30:

$$n_{40} = \left[\left(\left(\frac{40}{f_1}\right)^2 - 1\right)\left(\frac{B}{L}\right)^4 \left(\frac{(EI)_L}{(EI)_B}\right)\right]^{0.25} \tag{D.30}$$

Fire Safety

When exposed to fire, CLT floors lose part of their load-bearing capacity. This is included in the calculations by means of a reduced cross section. The floor structure is exposed to fire on the bottom, which leads to part of the CLT floor becoming a charred layer with thickness d_{char}. A non-bearing layer with thickness d_0 also develops beneath the charcoal. The remaining thickness of the CLT floor is the only load-bearing part. This is illustrated in Figure D.7. The calculations which were performed in Chapter D.3.1 need to be performed for the CLT floor with the reduced cross section.

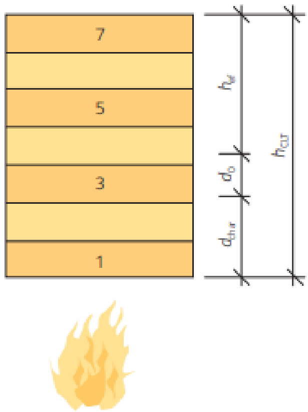

Figure D.7: Effective Cross-Section during Fire
(Swedish Wood, 2019)

The adhesive in the CLT needs to be considered during fire conditions. This adhesive can be considered fully effective or not effective during fire conditions. In the case of a fully-effective glue layer, there is no char ablation. In the case of a non-effective glue layer, there is char ablation. This has an impact on the effective depth h_{ef} of the CLT floor.

In case of no char ablation, the charring depth can be calculated according to Equation D.31:

$$d_{char,0} = \beta_0 t_{req} \tag{D.31}$$

In this equation, β_0 is the one-dimensional charring rate in a standard fire, which is equal to 0.65 mm/min. t_{req} is the fire exposure time.

The thickness of the non-load-bearing layer for fire under tension can be calculated according to Equation D.32 or Equation D.33:

$$d_0 = \frac{h_{CLT}}{6} + 2.5 \; for \; 105 \; mm \leq h_{CLT} \leq 175 \; mm \tag{D.32}$$

$$d_0 = 10 \; for \; h_{CLT} > 175 \; mm \tag{D.33}$$

The remaining thickness of the CLT floor is the effective depth h_{ef}:

$$h_{ef} = h_{CLT} - d_{char,0} - d_0 \tag{D.34}$$

When there is char ablation, the failure time for the second layer is when the first layer starts to char:

$$t_{ch} = t_{f,1} = \frac{h_1}{\beta_0} \tag{D.35}$$

The charring depth after t_{req} can be calculated according to Equation D.36:

$$d_{char} = h_1 + (t_{req} - t_f)\beta_0 k_3 \tag{D.36}$$

In this equation, k_3 is a constant equal to 2, as given in NEN-EN 1995-1-2 (NEN, 2011c).

The residual cross section can be calculated with Equation D.37, in which d_0 is the same as the non-bearing layer without char ablation, given in Equation D.32 and D.33.

$$h_{ef} = h_{CLT} - d_{char} - d_0 \tag{D.37}$$

When the fire safety requirements are not met, it is possible to add a gypsum plasterboard panel to the CLT. This will decrease the charring depth of the structure. The charring time of a protected CLT floor structure is calculated according to Equation D.38:

$$t_{ch} = 2.8h_p - 14 \tag{D.38}$$

In this equation, h_p is the thickness of the plasterboard.

The time limit t_a can be calculated with Equation D.39

$$t_a = \frac{25 - (t_f - t_{ch})k_2\beta_0}{k_3\beta_0} + t_f \tag{D.39}$$

In this equation, $k_2 = 1 - 0.018h_p$ and $t_f = 4.6h_p - 25$ (NEN, 2011c).

The charring depth d_{char} after t_{req} can be calculated according to Equation D.40:

$$d_{char} = 25 + (t_{req} - t_a)\beta_0 \tag{D.40}$$

This thickness along with the thickness of the non-bearing layer d_0, given in Equation D.32 and D.33, can be used to calculate the residual cross section according to Equation D.41:

$$h_{ef} = h_{CLT} - d_{char} - d_0 \tag{D.41}$$

During a fire, maximum deflection and vibrations are not relevant, as these are related to the comfort of the user. The moment, shear force and rolling shear force will be the only values which are tested, since the CLT floor need to be able to withstand the loads during the evacuation of the building. The design strengths are different during fire conditions compared to normal conditions. $f_{m,20}$, $f_{v,20}$ and $f_{Rv,20}$ are the 20% fractile moment, shear and rolling shear strength at normal temperature, respectively, which can be calculated according to Equations D.42-D.44:

$$f_{m,20} = k_{fi} f_{m,k} \tag{D.42}$$

$$f_{v,20} = k_{fi} f_{v,k} \tag{D.43}$$

$$f_{Rv,20} = k_{fi} f_{Rv,k} \tag{D.44}$$

k_{fi} is a factor to convert from the 5% fractile to the 20% fractile, which for CLT is equal to 1.15 (Swedish Wood, 2019).

In order to calculate the design strengths during fire conditions, Equations D.45-D.47 are used:

$$f_{m,d,fi} = \frac{k_{mod,fi} \cdot f_{m,20}}{\gamma_{M,fi}} \tag{D.45}$$

$$f_{v,d,fi} = \frac{k_{mod,fi} \cdot f_{v,20}}{\gamma_{M,fi}} \tag{D.46}$$

$$f_{Rv,d,fi} = \frac{k_{mod,fi} \cdot f_{Rv,20}}{\gamma_{M,fi}} \tag{D.47}$$

In these equations, $k_{mod,fi}$ and $\gamma_{M,fi}$ both are 1.

Not only the design strengths, but also the load combination change under fire conditions. The load combination in Equation D.48 is to be used to calculate the loads during fire, in which ψ_1 is 0.5:

$$Load\ Combination:\ G_k + \psi_1 \cdot Q_k \tag{D.48}$$

D.3.2. CLT Wall Elements

Manufacturers of CLT walls provide products which a standard number of layers and thickness. An example of these standardized products is given in Table D.3 from CLT manufacturer KLH (KLH, n.d.):

Panel Type		Panel Structure / Thickness of Lamellas [mm]				
60 mm	3s	20	20	20		
70 mm	3s	20	30	20		
80 mm	3s	30	20	30		
90 mm	3s	30	30	30		
100 mm	3s	30	40	30		
110 mm	3s	40	30	40		
120 mm	3s	40	40	40		
100 mm	5s	20	20	20	20	20
110 mm	5s	20	20	30	20	20
120 mm	5s	30	20	20	20	30
130 mm	5s	30	20	30	20	30
140 mm	5s	30	20	40	20	30
150 mm	5s	30	30	30	30	30
160 mm	5s	40	20	40	20	40

Table D.3: Standardized CLT Wall Dimensions from CLT Manufacturer KLH (KLH, n.d.)

The outer layers of the CLT wall elements span in the direction of the load, which is vertical. The next layer is positioned orthogonal to the outer layer.

Buckling

When a wall element is not designed properly, there is a chance that it will fail due to buckling. The next part of the chapter will cover how to perform the bucking calculation of CLT wall elements. The equations and information used was obtained from The CLT Handbook (Swedish Wood, 2019), unless otherwise indicated.

This calculation considers a wall panel with openings, such as windows or doors, and continuous support at the bottom. The buckling is checked in the ultimate state, as indicated in Equation D.49:

$$\frac{\sigma_{c,0,d}}{k_{c,y} \cdot f_{c,0,d}} + \frac{\sigma_{m,d}}{f_{m,d}} \leq 1 \tag{D.49}$$

In this equation, $\sigma_{c,0,d}$ is the design compression stress in the direction of the grain, which for CLT wall panels is vertical. $f_{c,0,d}$ is the design compression strength of the CLT in the direction of the grain. $\sigma_{m,d}$ is the design stress due to the moment in the wall panel. $f_{m,d}$ is the design moment resistance. The reduction factor $k_{c,y}$ can be calculated as in Equation D.50:

$$k_{c,y} = \frac{1}{k_y + \sqrt{k_y^2 - \lambda_{rel,y}^2}} \tag{D.50}$$

The factor k_y can be calculated as:

$$k_y = 0.5\left(1 + 0.1\left(\lambda_{rel,y} - 0.3\right) + \lambda_{rel,y}^2\right) \tag{D.51}$$

$\lambda_{rel,y}$ can be calculated as:

$$\lambda_{rel,y} = \frac{\lambda_y}{\pi}\sqrt{\frac{f_{c,0,k}}{E_{0.05}}} \tag{D.52}$$

$f_{c,0,k}$ is the characteristic compressive strength of the CLT wall panel in the direction of the grain, $E_{0.05}$ is the 5 percent fractile of the modulus of elasticity and λ_y is the slenderness factor, which is to be calculated according to Equation D.53:

$$\lambda_y = \frac{l_e}{i_{x,ef}} \tag{D.53}$$

l_e is the length of the wall panel, $i_{x,ef}$ is the effective radius of gyration in x direction:

$$i_{x,ef} = \sqrt{\frac{I_{x,ef}}{A_{x,net}}} \tag{D.54}$$

$A_{x,net}$ is the cross section area of the panels in the direction of the grain and $I_{x,ef}$ is the effective moment of resistance. This calculation is displayed in Equation D.55, in which only the longitudinal layers are considered:

$$I_{x,ef} = \sum \left(\frac{b_x t_i^3}{12} + \gamma_i b_x t_i a_i^2 \right) \tag{D.55}$$

For a five-layer CLT panel, the gamma values can be calculated according to the Gamma method, given in Equations D.56-D.58. The longitudinal layers are only included and each layer is numbered from 1 to n, from the bottom up.

$$\gamma_1 = \frac{1}{1 + \frac{\pi^2 E_{x,1} t_1}{l_{ref}^2} \frac{t_2}{G_{9090,2}}} \tag{D.56}$$

$$\gamma_3 = 1 \tag{D.57}$$

$$\gamma_5 = \frac{1}{1 + \frac{\pi^2 E_{x,5} t_5}{l_{ref}^2} \frac{t_4}{G_{9090,4}}} \tag{D.58}$$

The design compression stress in the direction of the grain $\sigma_{c,0,d}$ can be calculated according to Equation D.59:

$$\sigma_{c,0,d} = \frac{N_d}{A_{x,net}} \tag{D.59}$$

The vertical load N_d is calculated for a strip with an effective width b_x of 1.0 m:

$$N_d = b_x \cdot f_b \cdot P_d \tag{D.60}$$

P_d is the design load which is acting on the top of the wall element, f_b is the load distribution factor:

$$f_b = \frac{b_0}{b_{ef}} \tag{D.61}$$

b_0 is the total width of the element, while b_{ef} is the effective wall width without the openings.

The design moment strength of the CLT element, $\sigma_{m,d}$ is to be calculated as in Equation D.62:

$$\sigma_{m,d} = \frac{M_{y,d}}{W_{x,net}} \tag{D.62}$$

$M_{y,d}$ is the moment of the wind load:

$$M_{y,d} = \frac{q_d \cdot l_e^2}{8} \tag{D.63}$$

$W_{x,net}$ is the net moment of resistance:

$$W_{x,net} = \frac{I_{x,net}}{z_s} \tag{D.64}$$

z_s is the centre of gravity $\left(= \frac{h_{CLT}}{2}\right)$, $I_{x,net}$ is the net moment of inertia in which only the longitudinal layers are considered:

$$I_{x,net} = \sum \left(\frac{b_x t_i^3}{12} + b_x t_i a_i^2\right) \tag{D.65}$$

These equations are to be used for the unity check regarding buckling in CLT wall elements:

$$\frac{\sigma_{c,0,d}}{k_{c,y} \cdot f_{c,0,d}} + \frac{\sigma_{m,d}}{f_{m,d}} = \frac{N_d}{k_{c,y} \cdot A_{x,net} \cdot f_{c,0,d}} + \frac{M_{y,d}}{W_{x,net} \cdot f_{m,d}} \leq 1 \tag{D.66}$$

Fire Safety

For an unprotected wall panel, the effective panel thickness h_{ef} after the required charring time t_{req} needs to be calculated:

$$h_{ef} = h_{CLT} - d_{char} - d_0 \tag{D.67}$$

The value for the non-load-bearing layer d_0 depends on the number of layers in the panel and whether the panel's side is under tension or compression. The charring depth d_{char} is to be calculated according to Equation D.68:

$$d_{char} = \beta_0 t_{req} \tag{D.68}$$

After the effective panel thickness h_{ef} is calculated, the buckling calculation needs to be performed again with this value for the new panel thickness.

Stability

The horizontal wind loads on the CLT panels cause for the stability of the building to be checked. There are two calculations connected to stability of wall panels, which are the horizontal deformation and if there is tension on the foundation. The calculations described in this part of the chapter are from another project at Van Rossum B.V., for which the document cannot be shared. The calculations are allowed to be shared.

When considering the façade wall as a beam clamped on one side, the wind load can be divided into two loads: a line load $q_{w,rep}$ and a point load $F_{w,rep}$ at the top of the beam (Figure D.8).

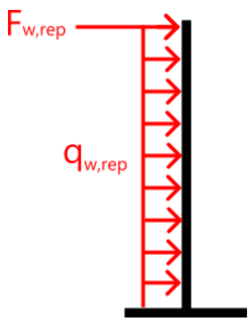

Figure D.8: Wind Loads $q_{w,rep}$ and $F_{w,rep}$

The line load $q_{w,rep}$ can be calculated according to Equation D.69, while the point load $F_{w,rep}$ can be calculated according to Equation D.70:

$$q_{w,rep} = b \cdot q_p(z_e) \cdot c_{pe,10} \cdot c_s c_d \cdot n/(n-1) \tag{D.69}$$

$$F_{w,rep} = b \cdot d \cdot c_f \cdot q_p(z_e) \cdot c_s c_d \cdot n/(n-1) \tag{D.70}$$

b = width of floor
d = length of floor
$q_p(z_e)$ = wind load, dependent on location. Can be found in the Dutch National Annex of EN 1991-1-4 (NEN, 2023).
$c_{pe,10}$ = factor dependent on the zone of the building
$c_s c_d$ = 1.0 for buildings in which $h/d < 4$ (NEN, 2011a)
c_f = pressure coefficient, can be derived from EN 1991-1-4 (NEN, 2011a)
$n/(n-1) = 1.1$, second order effect

When the building has a rectangular floor plan, the wind load will be from the x- and y-direction, meaning that the stability calculation needs to be performed for both directions. For each stability wall in a direction, the values for the modulus of elasticity E and the second moment of inertia $I_{yy} = \frac{bh^3}{12}$ need to be obtained, which when multiplied gives the value for EI. This is used to determine the contribution of each stability wall, given in percentage. If, for instance, there are four stability walls with the same EI, the contribution of each wall would be 25%.

The next step is to assume the walls to be springs and to model the wind load as a line load. The springs have a spring constant of the contribution mentioned before (in the example case, this would be 0.25). The reaction forces on each spring are the loads that each wall takes up. When the horizontal loads on each stability wall are obtained, the moment and shear force at the bottom needs to be calculated. The moment at the bottom of the shear wall can be calculated into a line load q_M with the following equation:

$$q_M = \frac{M_{y,d} \cdot 6}{b_{wall}^2} \tag{D.71}$$

This line load can be modelled as in Figure D.9:

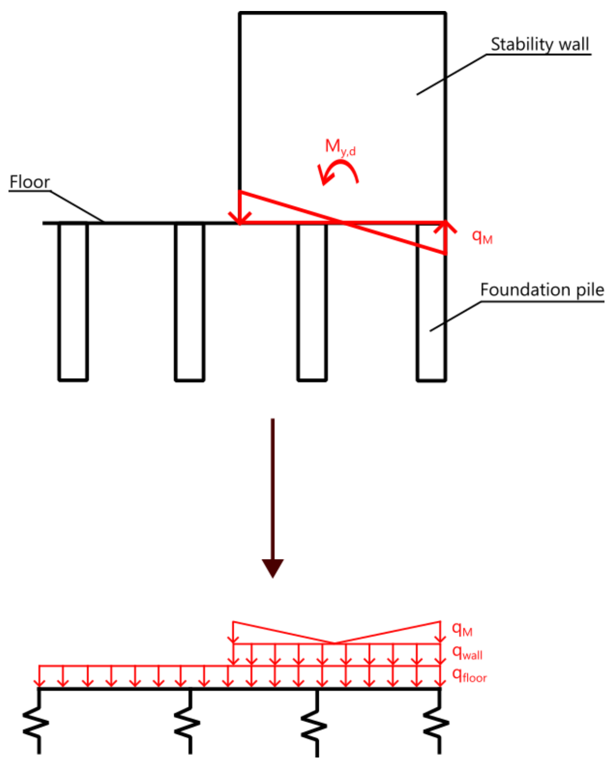

Figure D.9: How to Model Moment due to Wind Loads on Stability Walls

The foundation piles, which should be modelled as springs, should not experience any tension.

As mentioned earlier, the horizontal displacement is a part of the stability as well. This displacement should not be larger than $l/500$, in which l is the height of the building. There are two displacements in the stability walls, due to the line load $q_{w,rep}$ and due to the point load $F_{w,rep}$, as indicated in Figure D.8. The equations for the horizontal displacement are given in Equations D.72 and D.73:

$$w_q = \frac{q_w \cdot l^4}{8EI} \tag{D.72}$$

$$w_F = \frac{F_w \cdot l^4}{3EI} \tag{D.73}$$

The sum of these two displacements should not be larger than $l/500$.

D.4. Changing Foundation Piles

Three possible methods for a changing the foundation piles due to a change in applied load are:

- Adding/Removing piles
- Changing cross-sectional dimensions of pile
- Changing pile type

The calculation of the load-bearing capacity of a foundation pile $R_{c;d}$ is given in NEN 9997-1 (NEN, 2017):

$$\begin{aligned}
R_{c;d} &= R_{b;cal}/(\gamma_b \cdot \xi) + R_{s;cal}/(\gamma_s \cdot \xi) \\
R_{b;cal;max} &= A_{tip} \cdot q_{b;max} \\
q_{b;max} &= 1/2 \cdot \alpha_p \cdot \beta \cdot s \cdot [1/2 \cdot (q_{c;I;gem} + q_{c;II;gem} + q_{c;III;gem}] \\
\\
R_{s;cal;max} &= O_p \cdot q_{s;max;z} \\
q_{s;max;z} &= \alpha_s \cdot q_{c;z;a}
\end{aligned} \tag{D.74}$$

In these equations, γ_b, ξ, α_p, α_s, β and s are constants which can be found in NEN 9997-1. A_{tip} is the cross-sectional area of the pile and O_p is the circumference of the cross-section of the pile. The values for q depend on the soil and can be obtained through CPT data.

The load-bearing capacity should be larger than the applied load. When there are multiple piles underneath a single foundation block, the load bearing capacity of these piles should be summed. If there are for instance 4 foundation piles with each a capacity of 1600 kN, the total capacity is $4 \times 1600 = 6400\ kN$. If the applied load is 5000 kN, the 4 foundation piles are able to withstand this load, but it is not possible to remove any foundation piles. If the applied load decreases to 4000 kN, it is possible to remove one foundation piles, since the total capacity of 3 foundation piles is $3 \times 1600 = 6400\ kN$.

Changing the cross-sectional dimensions of the pile has an influence on the values of A_{tip} and O_p, as given in Equation D.74. Changing the pile type will change the factors of α_p, α_s and β, which are properties related to the type of pile used. Table D.4 gives the values for these factors for commonly used types of piles:

Pile Type	α_p	α_s	β
Prefab	0.7	0.010	1.0
Vibro	0.7	0.014	1.0
Concrete screw	0.56	0.006	1.0
DPA	0.56	0.010	1.0

Table D.4: Standard factors for common pile types (Vroom Funderingstechnieken, n.d.)